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1 EXECUTIVE SUMMARY

This report details the outcomes of CoRaSat WP2 Task 2.2 and Task 2.3.

The aim of Task 2.2 is to depict the regulatory environment as applied to the frequency bands of interest for the potential utilization of Cognitive Radio in the context of Satellite Communications (SatCom). The aim of Task 2.3 is to review the technology framework for the CoRaSat project.

As such, the present deliverable reviews the technological, regulatory and standardisation framework for the identified CoRaSat scenarios.

The dissemination level of this deliverable is public whereas further details on the CoRaSat regulatory and standardisation framework and on the CoRaSat technological framework are provided in the companion detailed reports D2.5 [440] and D2.6 [441], respectively, whose dissemination level is restricted (to the project consortium and the European Commission).

This deliverable reviews the current technology, regulatory and standardisation framework for spectrum sharing for seven (7) challenging SatCom scenarios, which correspond to various frequency ranges of interest in the Ka-, Ku-, C-, and S-bands. To assess the potential of more efficient utilization of spectrum in the SatCom context, particular attention is paid to specific use case scenarios where satellite services are provided as cognitive (new entrant) services, whereas the incumbent services can be either terrestrial or satellite. In this respect, the use of "incumbent" and "cognitive" (or "new-entrant") users in the context of CoRaSat is highlighted in order to avoid any confusion with the different ITU-R terminology on the use of terms "primary" and "secondary" users, respectively[1].

The identified CoRaSat scenarios are outlined as follows:

- Scenario A: Cognitive Radio GSO Satellite downlink in Ka-band [17.3 – 17.7 GHz];
- Scenario B: Cognitive Radio GSO Satellite downlink in Ka-band [17.7 – 19.7 GHz];
- Scenario C: Cognitive Radio GSO Satellite uplink in Ka-band [27.5 – 29.5 GHz];
- Scenario D: Cognitive Radio GSO Satellite uplink/downlink in Ku-band [10.7 – 12.75 GHz, 12.75 – 13.25 GHz and 13.75 – 14.5 GHz];
- Scenario E: Cognitive Radio GSO Satellite downlink in C-band [3.4 – 3.8 GHz];
- Scenario F: Cognitive Radio GSO Satellite uplink/downlink in S-band [1980 – 2010 MHz and 2170 – 2200 MHz];
- Cognitive Radio NGSO Satellite downlink/uplink in Ka-band [17.7 – 19.7 GHz, 27.8285-28.4445 GHz and 28.9485-29.4525 GHz].

On the CoRaSat technological framework, this document provides an introduction to Cognitive Radio (CR) technologies and reviews related projects, including EC, ESA and National funded projects. The scientific and technological literature in both terrestrial and satellite domains is reviewed by focusing on spectrum awareness and spectrum utilization techniques. Subsequently, relevant state-of-the-art systems and technologies are overviewed in both satellite and terrestrial domains which are pertinent

[1] In ITU-R terminology, capital letters in a table of allocations mean PRIMARY service; lower case letters mean secondary service. *Secondary services cannot create interference into PRIMARY services and cannot claim protection from interference originated in PRIMARY service transmitters.* In the CoRaSat context, to avoid any confusion with the ITU-R terminology, the terms "incumbent" and "cognitive" (or "new-entrant") are used instead of "primary" and "secondary", respectively. The terms "incumbent user" and "cognitive (or new entrant) user" are defined in Chapter 3.

to the considered CoRaSat scenarios.

On the CoRaSat regulatory framework, the regulatory requirements for applying Cognitive Radio to these frequency bands are identified. The review of the regulatory context is conducted at multiple levels, taking into account relevant EU regulations and policies (including relevant updates of the EU Radio Spectrum Policy Programme (RSPP) on shared use of spectrum and convergence), CEPT recommendations and decisions, ITU-R regulations and recommendations, as well as relevant National regulations. Moreover, recent relevant Cognitive Radio projects with focus on regulatory aspects are reviewed to complement the regulatory framework analysis. Also, the obstacles in the current regulation to be removed for enabling Cognitive Radio are identified.

In addition, the Cognitive Radio standardisation context for communication systems (referring so far mainly to terrestrial systems) is reviewed and the main principles of frequency sharing are defined. The standardisation activities under consideration and reported in this deliverable include relevant activities at a global scale, such as IEEE, ITU, ETSI, 3GPP, Wireless Innovation Forum, ECMA, IETF and DARPA activities.

Based on the overall analysis reported in this deliverable for the technology, regulatory and standardisation framework, useful conclusions are drawn for scenarios prioritization from the SatCom industry perspective. Specifically, qualitative conclusions are provided in Chapter 7 in order to prioritise the scenarios and thus to set the required basis for the subsequent CoRaSat Tasks (Task 2.4, WP3, onwards...) upon which the most promising scenarios are selected.

Disclaimer: Nothing in this report is intended to preclude or constrain existing and future satellite use in bands allocated to satellite services on a primary basis by the ITU, or to preclude consideration of other sharing possibilities (*e.g.*, co-primary sharing on a coordinated basis).

2 Scope and Structure of the Document

This report details the outcomes of CoRaSat WP2 Task 2.2 and Task 2.3, whose aim is to depict the regulatory environment as applied to the frequency bands of interest for the potential utilization of Cognitive Radio in the context of Satellite Communications (SatCom), and to review the technology framework for the CoRaSat project, respectively.

This deliverable is organized as follows:

Chapter 1 provides an Executive Summary.

Chapter 2 (current chapter) provides the scope and structure of this document.

Chapter 3 introduces the identified CoRaSat scenarios.

Chapter 4 reviews the technology framework for each identified CoRaSat scenario.

Chapter 5 reviews the current regulatory context for each identified CoRaSat scenario .

Chapter 6 reviews recent and ongoing Cognitive Radio standardisation activities in order to define the relevant standardisation context and the main principles associated to frequency sharing.

Chapter 7 contains useful conclusions on CoRaSat scenarios prioritization from the SatCom point of view, incl. technology, regulatory and standardisation framework.

Chapter 8 lists all relevant references utilized in the context of this deliverable. Chapter 9 contains a table with acronyms, definitions and abbreviations used in this document. Chapter 10 provides the document creation history. Chapter 11 provides Annexes to further support the analysis presented in the document.

3 Introduction to Baseline CoRaSat Scenarios

3.1 Introduction to Cognitive Radio Techniques

A Cognitive Radio (CR) is the key technology that allows a cognitive terminal to dynamically access the available spectral opportunities. A cognitive radio was first defined by Mitola in his seminal work as "*a radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly*" [406][407]. According to the ITU-R definition, a "*Cognitive Radio System (CRS) is a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained*" [402].

From these definitions, a cognitive radio has two key features that distinguish it from a traditional radio: the cognition capability and the re-configurability. Figure 1 illustrates how these unique features of a cognitive radio conceptually interact with the radio environment. This illustration is referred to as the cognition cycle that is continually run by the cognitive radio to observe spectral opportunities, create plans to adapt itself, decide, and act to explore the best opportunities.

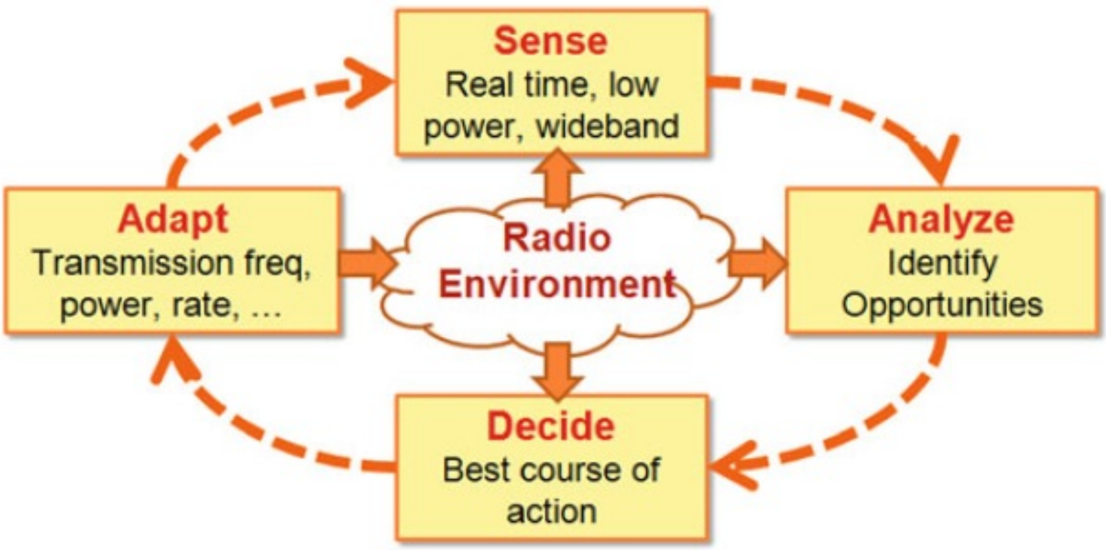

Figure 1 - Functional Architecture of Cognitive Radio

In a CRS, there are two types of users:[2]

- **Incumbent User:** a (licensed) user who has higher priority or legacy rights on the usage of a specific part of the spectrum;

[2] Note that in the CR literature, the terms "primary" and "incumbent" are synonymous and interchangeably used, as well as the terms "secondary" and "cognitive". However, in the CoRaSat context, to avoid any misunderstanding with the ITU-R terminology where the term "secondary" has a specific (different) regulatory meaning, the terms "incumbent" and "cognitive" (or "new-entrant") are used. Specifically, according to the ITU-R terminology, *a "secondary" user neither causes interference to "primary" users of the band nor claims protection from interference by primary users.*

- **Cognitive (or New Entrant) User:** an (unlicensed) user who has a lower priority and is allowed to opportunistically use spectrum assigned to an incumbent user in such a way that it does not cause any unacceptable interference to incumbent users.

So far, the potential of the CR approach to improve the efficiency of spectrum use in bands allocated to terrestrial communication systems has been explored in some detail. However, little attention has been paid to the potential benefits that CR could bring to SatCom systems. This sets a formidable technical challenge for CoRaSat which is investigating whether CR techniques could be applied in the SatCom environment and whether they could help resolve specific spectrum sharing scenarios.

The CoRaSat vision is a Cognitive Radio SatCom system implementing flexible and smart spectrum usage by satellite services to exploit frequency resources that may be currently underused or unused due to interference of terrestrial or other satellite systems (see Figure 2).

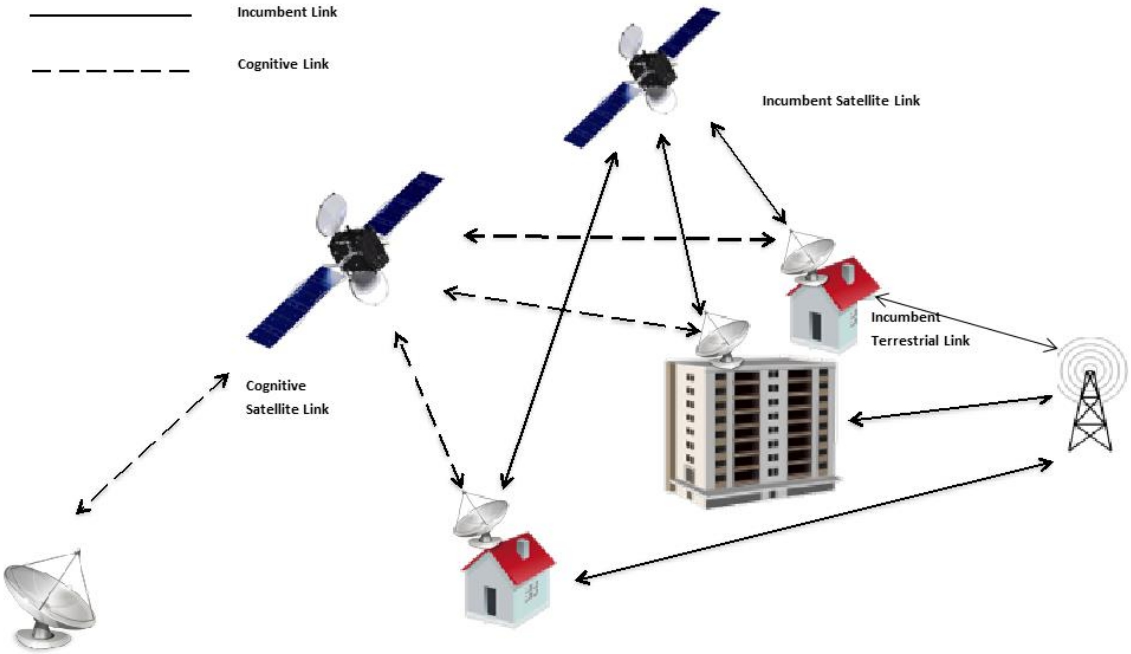

Figure 2 - CoRaSat vision on Cognitive Radio SatCom systems

Table 1 below provides an overview of CR techniques, as categorized into three broad groups: interweave techniques (which can be further broken down in databases and spectrum sensing), underlay techniques and overlay techniques. Such CR techniques and, in general, the technological framework of CoRaSat is addressed in more detail in the companion deliverable D2.2 [441] and the detailed report D2.6 [442]. Their brief introduction here aims merely to support the regulatory analysis presented hereinafter. Note that the present document focuses on the regulatory and standardisation framework of CoRaSat and, as such, it should not be read as standalone document but in combination with D2.6 [442].

Table 1 - Overview of CoRaSat Candidate Techniques

Cognitive Techniques	Interweave		Underlay (UL)	Overlay (OL)
	Databases	Spectrum Sensing		
Cognitive Information	Geolocation data	Power Spectral Density (PSD)	Channel State Information (CSI)	CSE and Primary data
QoS Constraints	Access Time	Detection Probability	Interference Threshold	Rate limit threshold
CoRaSat Challenges	Wide satellite footprint DB security and integrity	Weak signal detection LoS interference	Resource optimization problem LoS slow-fading channel	Asynchronous arrivals of signals Primary-secondary coordination
CoRaSat Candidate Techniques	Efficient database and access techniques Beaconing techniques Localization assisted techniques	Spectral shaping Polarization sensing DoA sensing Cooperative sensing Distributed sensing	Power allocation Radio Resource Management Beam steering Polarization-aware techniques Waveform detection Interference floor	Relaying Known interference precancelation Rate splitting

There are other alternatives to Cognitive Radio as a means of increasing spectrum utilization in the SatCom context, such as co-primary sharing on a coordinated basis. However, CoRaSat focuses on Cognitive Radio approaches and such alternatives are out of scope in this report.[3]

3.2 Overview of Baseline CoRaSat Scenarios

Table 2 summarizes the main scenarios of interest for CoRaSat, which are described in more detail hereinafter.

Table 2 - Cognitive Radio SatCom Scenarios

Scenario	Frequency Band	Spectrum Range	Satellite Orbit	Link Direction
A	Ka	17.3-17.7 GHz	GSO	DL
B	Ka	17.7-19.7 GHz	GSO	DL
C	Ka	27.5-29.5 GHz	GSO	UL
D	Ku	10.7-12.75 GHz 12.75-13.25 GHz 13.75-14.5GHz	GSO	DL UL UL
E	C	3.4-3.8 GHz	GSO	DL
F	S	1980-2010 MHz 2170-2200 MHz	GSO	UL DL
G	Ka	17.7-19.7 GHz 27.8285-28.4445 GHz 28.9485-29.4525 GHz	NGSO	DL UL UL

(GSO: Geostationary Satellite Orbit, NGSO: Non- Geostationary Satellite Orbit, DL: Downlink, UL: Uplink)

[3] Nothing in this report is intended to preclude or constrain existing or future satellite use in bands allocated to satellite services on a primary basis by the ITU, or to preclude consideration of other sharing possibilities (e.g. co-primary sharing on a coordinated basis).

As it can be seen in Table 2, various frequency ranges are evaluated in the Ka-, Ku-, C-, and S-bands. Note also that the scenarios are related to specific frequency ranges within the given frequency bands, to which different regulatory conditions apply. Also, both downlink and uplink satellite link directions, as well as both Geostationary Satellite Orbit (GSO) and Non-Geostationary Satellite Orbit (NGSO) are considered. Moreover, both fixed and mobile satellite terminals are taken into account.

The outline of the considered scenarios is summarized below. For each scenario, CoRaSat is investigating whether CR techniques could be applied in the SatCom environment and whether they could help resolve specific spectrum sharing scenarios.

3.3 Scenario A Description

Cognitive Radio GSO Satellite downlink in Ka-band [17.3 – 17.7 GHz]. CEPT has adopted a Decision, ECC/DEC/(05)08, which gives guidance on the use of this band by High Density applications in the Fixed-Satellite Service (HDFSS). The Decision stipulates that the designation of the band 17.3 – 17.7 GHz is without prejudice to the use of this band by Broadcasting Satellite Service (BSS) feeder uplinks and that it is not allocated to any terrestrial service on an incumbent basis (except in some countries). The deployment of uncoordinated Fixed-Satellite Service (FSS) Earth stations is also authorized in these bands. The question here is whether uncoordinated FSS stations could increase frequency exploitation by flexible usage of the spectrum portion through the adoption of Cognitive Radio techniques. Moreover, with regard to satellite terminals on mobile platforms, the ECC Decision ECC/DEC/(13)01 addresses the harmonized use of Earth Stations On Mobile Platforms (ESOMPs) operating within the given frequency band.

CoRaSat WP2 is investigating whether CR techniques could help resolve this specific sharing scenario. In this respect, the following aspects of the scenario are investigated:

a. FSS cognitive satellite terminals reusing frequency bands of other BSS GSO feeder link systems also operating in this band;
b. Support of satellite terminals on mobile platforms.

3.4 Scenario B Description

Cognitive Radio GSO Satellite downlink in Ka-band [17.7 – 19.7 GHz]. CEPT has adopted a Decision, ECC/DEC/(00)07, which gives guidance on the use of this band by Fixed Satellite Services (FSS) and Fixed Services (FS). The Decision stipulates that stations of the FSS can be deployed anywhere, but without right of protection from interference generated by FS radio stations. Cognitive Radio techniques could significantly increase the spectrum usage by FSS by enabling access to frequency spectrum in the vicinity of terrestrial transmitters. Cognitive Radio techniques could act as a dynamic and flexible protection of FSS downlink from FS interference. This scenario can be seen as an extension of the FSS exclusive frequency band 19.7 – 20.2 GHz by adding significant user capacity in the 17.7 – 19.7 GHz bandwidth. Moreover, with regard to satellite terminals on mobile platforms, the ECC Decision ECC/DEC/(13)01 addresses the harmonized use of ESOMPs operating within the given frequency band.

CoRaSat WP2 is investigating whether CR techniques could help resolve this specific sharing scenario. In this respect, the following aspects of the scenario are investigated:

a. FSS cognitive satellite terminals reusing frequency bands of FS links with priority protection;
b. Support of satellite terminals on mobile platforms.

3.5 Scenario C Description

Cognitive Radio GSO Satellite uplink in Ka-band [27.5 – 29.5 GHz]. CEPT Decision ECC/DEC/(05)01 provides a segmentation between FS and FSS stations in this band. The FS segment is lightly used through Europe. FSS stations could maximize frequency exploitation by flexible usage of the FS segment through the adoption of Cognitive Radio techniques in the satellite uplink able to dynamically control the interference generated to the FS station. ECC/DEC(05)01 was amended in March 2013, although a number of administrations raised remarks. Moreover, with regard to satellite terminals on mobile platforms, the ECC Decision ECC/DEC/(13)01 addresses the harmonized use of ESOMPs operating within the given frequency band.

CoRaSat WP2 is investigating whether CR techniques could help resolve this specific sharing scenario. In this respect, the following aspects of the scenario are investigated:

a. FSS cognitive satellite terminals reusing frequency bands of FS links with priority protection;

b. Support of satellite terminals on mobile platforms.

3.6 Scenario D Description

Cognitive Radio GSO Satellite downlink/uplink in Ku-band [10.7 – 12.75 GHz, 12.75 – 13.25 GHz, and 13.75 – 14.5 GHz]. Satellite systems are incumbent in this portion of the spectrum. Dual GSO satellite system sharing is addressed in this scenario, where a cognitive GSO satellite system using terminals with non-directive antennas (e.g., mobile devices) and employing Cognitive Radio techniques on both the uplink and downlink could potentially expand use of this frequency spectrum by dynamically adapting to the evolving interference environment of another incumbent GSO satellite system. Moreover, FS-GSO FSS sharing is also addressed, where GSO FSS cognitive satellite reuse frequency bands of incumbent FS links.

CoRaSat WP2 is investigating whether CR techniques could help resolve this specific sharing scenario. In this respect, the following aspects of the scenario are investigated:

a. Cognitive GSO satellite terminals reusing frequency bands of other incumbent GSO satellite systems in D1/D2;

b. GSO FSS cognitive satellite terminals reusing frequency bands of FS links in D1/D2;

c. Support of GSO satellite terminals on mobile platforms in D1/D2.

Where:

- D1: Ku-band downlink in the 10.7 - 12.75 GHz band;
- D2: Ku-band uplink in the 12.75 – 13.25 GHz and 13.75 - 14.5 GHz band.

3.7 Scenario E Description

Cognitive Radio GSO Satellite downlink in C-band [3.4 – 3.8 GHz]. This portion of C-band spectrum is currently shared between terrestrial fixed and satellite services, and the incumbent system can be either satellite or terrestrial. Without disturbing existing sharing arrangements between satellite and terrestrial systems in this band, CoRaSat is considering whether satellite systems can utilize this spectrum more intensively using cognitive radio techniques to dynamically adapt their frequencies usage in the downlink according to the interference environment generated by the incumbent satellite and terrestrial fixed systems.

CoRaSat WP2 is investigating whether CR techniques could help resolve this specific sharing scenario. In this respect, the following aspects of the scenario are investigated:

a. FSS cognitive satellite terminals reusing frequency bands of FS[4] links;

b. Support of satellite terminals on mobile platforms.

3.8 Scenario F Description

Cognitive Radio GSO Satellite uplink/downlink in S-band [1980 – 2010 MHz and 2170 – 2200 MHz]. In this portion of the spectrum, hybrid satellite-terrestrial networks with mobile user terminals are deployed utilizing potentially different broadcast and interactive technologies in the space and terrestrial segment. The incumbent of the integrated network is the satellite together with the integrated complementary terrestrial network. The complementary terrestrial CR link may be able to dynamically adapt its forward and return link to the changing interference scenario.

CoRaSat WP2 is investigating whether CR techniques could help resolve this specific sharing scenario. In this respect, the following aspects of the scenario are investigated:

a. Cognitive hybrid satellite/terrestrial broadcast terminals using frequency bands of F1/F2;

b. Cognitive terrestrial terminals using frequency bands of F1/F2.

Where:

- F1: S-band uplink 1980 – 2010 MHz;
- F2: S-band downlink 2170 – 2200 MHz.

3.9 Scenario G Description

Cognitive Radio NGSO Satellite downlink/uplink in Ka-band [17.7 – 19.7 GHz, 27.8285-28.4445 GHz and 28.9485-29.4525 GHz]. This scenario addresses sharing between cognitive NGSO FSS systems and incumbent FS terrestrial systems operating in Ka-band, where the cognitive satellite terminals could dynamically control the interference caused to incumbent terrestrial stations. Both downlink [17.7 – 19.7 GHz] and uplink [27.8285-28.4445 GHz and 28.9485-29.4525 GHz] frequency bands are considered. In this respect, relevant ECC Decisions are:

- ECC/DEC/(00)07: giving guidance on the use of the 17.7 – 19.7 GHz band by FSS and FS;
- ECC/DEC/(05)01: providing a segmentation between FS and FSS stations in the frequency band of 27.5 – 29.5 GHz;
- ECC/DEC/(13)01: addressing the harmonized use of ESOMPs operating within the given frequency bands.

In particular, ECC/DEC/(00)07 stipulates that stations of the FSS can be deployed anywhere, but without right of protection from interference generated by FS radio stations. Cognitive Radio techniques could significantly increase the spectrum usage by FSS by enabling access to frequency spectrum in the vicinity of terrestrial transmitters. Cognitive Radio techniques could act as a dynamic and flexible protection of FSS downlink from FS interference. The downlink part of this scenario can

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[4] When referring to FS, terrestrial Point-to-Point (PtP) and Point-to-Multipoint (PMP) Broadband Fixed Wireless Access (BFWA) services are considered.

be seen as an extension of the FSS exclusive frequency band 19.7 – 20.2 GHz by adding significant user capacity in the 17.7 – 19.7 GHz bandwidth.

In addition, ECC/DEC/(05)01 designates the bands 27.8285-28.4445 GHz and 28.9485-29.4525 GHz for the use of FS systems and stipulates that CEPT administrations shall not authorise the deployment of uncoordinated FSS Earth stations in the bands 27.8285-28.4445 GHz and 28.9485-29.4525 GHz.

CoRaSat WP2 is investigating whether CR techniques could help resolve those specific sharing scenarios. In this respect, the following aspects of the scenario are investigated:

a. NGSO FSS cognitive satellite terminals using frequency bands shared with FS links with priority protection in G1/G2;
b. NGSO FSS cognitive satellite terminals onboard mobile platforms using frequency bands shared with FS links with priority protection in G1 (downlink only).

Where:

- G1: Ka-band downlink in the 17.7 – 19.7 GHz band;
- G2: Ka-band uplink in the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz bands.

The scenarios defined above are reviewed hereinafter from the regulatory point of view. That is, the defined scenarios are reviewed within the regulatory framework defined by the usage of the frequency rights of the incumbent user and related requirements on a possible cognitive usage and gaps within this documentation.

4 TECHNOLOGY FRAMEWORK

4.1 Literature Review of Cognitive Radio Techniques

Note that the bulk of the literature review presented in this Chapter concerns terrestrial communications, with far less work directed specifically to the impact of CR upon satellite communications.

Moreover, it is important to highlight that the overview presented in this section does not reflect the position of the CoRaSat consortium but the position of the various authors whose papers are described hereinafter.

4.1.1 Terrestrial CR Techniques

The existing terrestrial CR literature is abundant **[63]**. A wide variety of solutions have been proposed to address the main functionalities required by a CR network. This section reviews the main solutions proposed in the existing literature for ***spectrum awareness*** and efficient ***spectrum utilization***. Spectrum awareness solutions are used to obtain relevant information and knowledge of the surrounding radio environment. Spectrum utilization solutions are aimed at providing a fair spectrum access to the coexisting cognitive users and/or networks. This is accomplished by coordinating the access to the available spectrum holes, while at the same time guaranteeing an adequate interference-free coexistence between incumbent and cognitive systems. The following sections provide a detailed revision of the existing literature for spectrum awareness and spectrum utilization in CR networks. The tree below shows a classification of different CR techniques that will be addressed in the following sections, along with links to these sections.

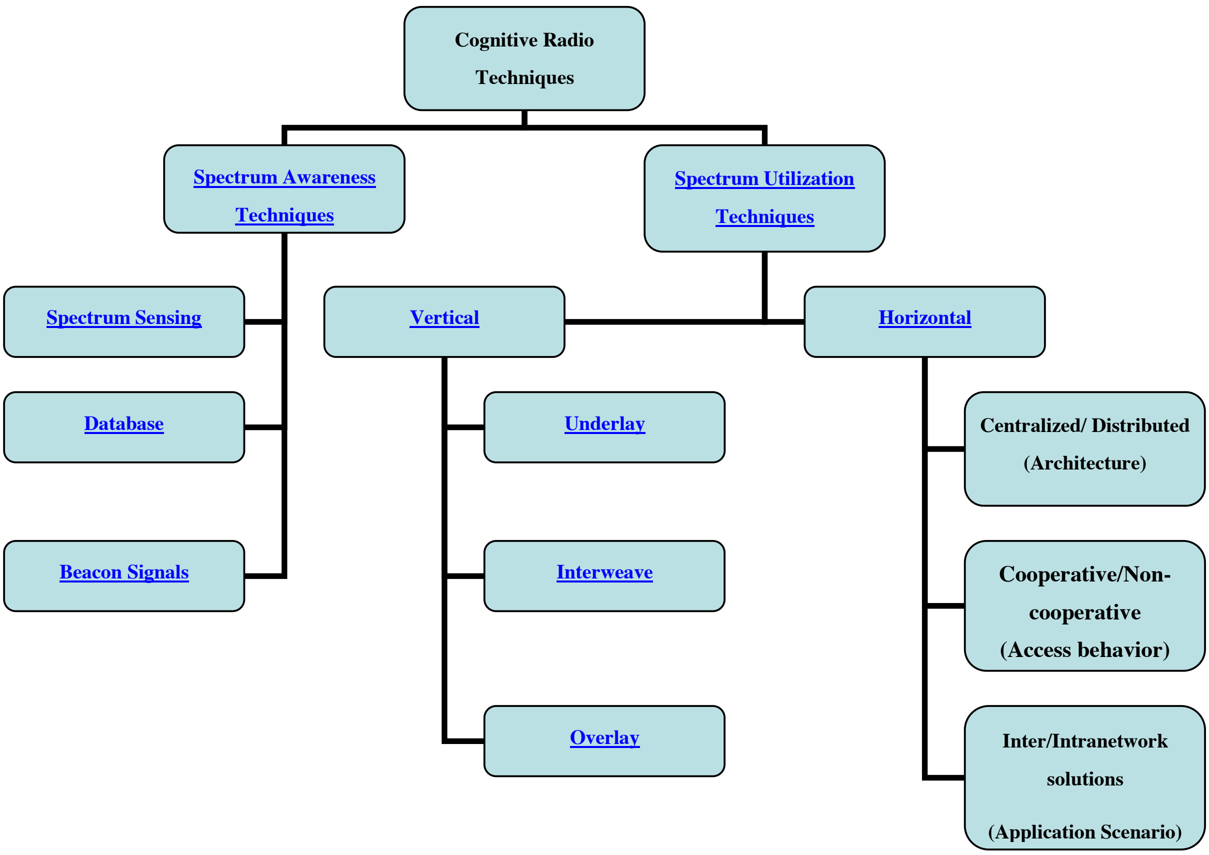

Figure 3 - Categorisation of terrestrial CR techniques

4.1.1.1 Spectrum Awareness

The Spectrum Awareness function obtains relevant information and knowledge of the surrounding radio environment. From viewpoint of CR, the most relevant aspect is accurately identifying which portions of the spectrum are available to cognitive users for opportunistic use (spectrum holes or white spaces). To this end, CRs intelligently track idle frequency bands that are dynamic in both time and space, and detect the presence of licensed users if they appear while a cognitive user operates in a licensed band. A CR can make use of various techniques to obtain knowledge of the radio environment, including *spectrum sensing*, *geolocation databases,* and *beacon signals*.

Spectrum Sensing

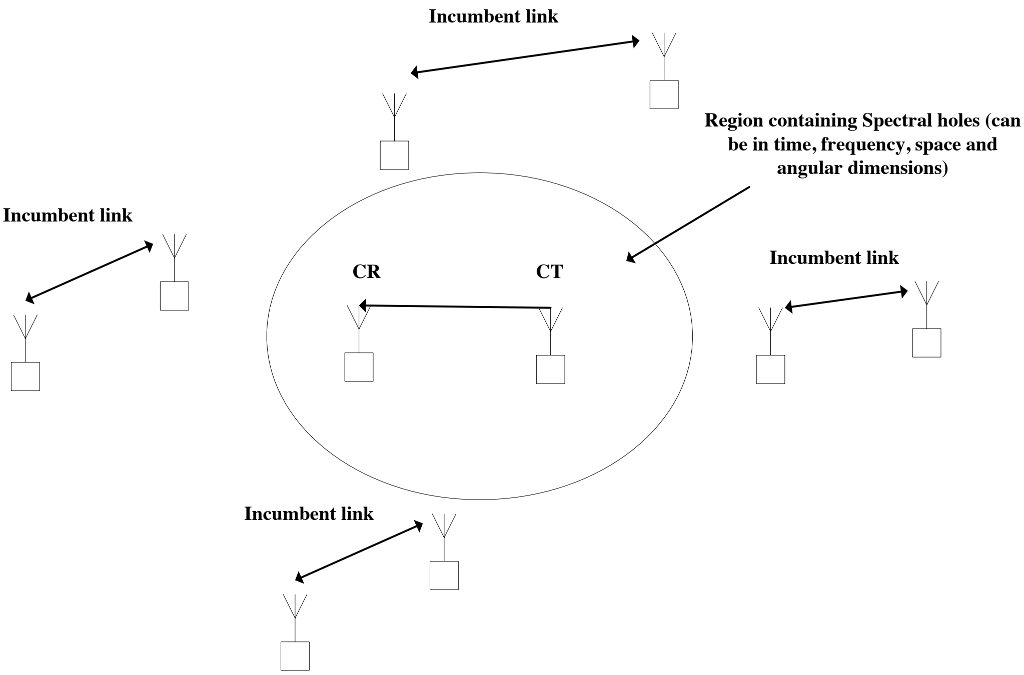

Figure 4 - Illustration of spectrum sensing-based CR technique for the coexistence of a cognitive system and incumbent systems.

A simple method to acquire knowledge of the surrounding radio environment is to perform a spectrum scan and determine, by means of appropriate signal processing methods, whether an incumbent signal is present in the scanned band. This method is referred to as Spectrum Sensing (SS) in the context of CR. An illustration of the method is in Figure 4. The cognitive system can access the incumbent occupied spectrum in different domains such as time, frequency, space, polarization, and angular dimension of the spectral space. The cognitive transmitter can be assumed to be equipped with a radio frequency RF end, by the help of which the cognitive transmitter acquires the spectrum occupancy information of the incumbent system. Based on this information, the cognitive user uses the unoccupied spectrum holes opportunistically. It should be noted that when the incumbent user reappears in a certain licensed channel, the cognitive system should instantly vacant the channel and be switched to another unoccupied channel. This spectrum utilization scheme is dynamic and effectively utilizes the spectrum holes as the incumbent spectrum utilization varies over time.

Several SS techniques have been proposed in the current state-of-the-art for CR based systems, mainly in the context of terrestrial systems. The three mainly used basic signal processing techniques for sensing the presence of an incumbent user signal are matched filter detection **[73]**, energy detection **[65]**-[68] and cyclostationary feature detection [73], **[74]**. Furthermore, waveform based sensing, radio identification based sensing and other sensing methods are described in the literature. In the following paragraphs, we briefly provide the state-of-the-art on SS techniques. The detailed literature on different SS techniques has been provided in Appendix A.

Energy detection is the most common way of spectrum sensing because of its low computational and implementation complexities **[65]**-**[68]**. The ED problem has been considered over a flat band-limited Gaussian noise channel in **[65]** and for a variety of fading channels in **[66]**-[68]. Matched filter detection requires less time to achieve a certain probability of false alarm or probability of miss detection [71] as compared to other methods due to its coherent nature. The cyclostationary feature detection is a method for detecting incumbent user transmissions by exploiting the cyclostationary features of the received signals **[74]**. Furthermore, in the presence of a known pattern, sensing can be performed by correlating the received signal with a known copy of itself **[82]**. In radio identification based sensing technique; the cognitive node can obtain the complete knowledge about the spectrum characteristics by identifying the transmission technologies used by incumbent users. Such identification enables a cognitive radio with a higher dimensional knowledge as well as providing higher accuracy **[83]**.

In wireless fading environments, cooperative sensing may lessen the problem of detecting the incumbent user by reducing the probability of interference to an incumbent user **[76]**, **[77]**. In cooperative sensing method, a large network of cognitive radios with sensing information exchanged between neighbours gets a better chance of detecting the incumbent user compared to individual sensing. Cooperative sensing decreases the probabilities of miss-detection and false alarm considerably. In addition, cooperation can solve hidden incumbent user problem and it can decrease sensing time **[78]**. Cooperation can be either among cognitive radios or external sensors can be used to build a cooperative sensing network. In the former case, cooperation can be implemented in two fashions: centralized or distributed **[79]**. Challenges of cooperative sensing include developing efficient information sharing algorithms and increased complexity **[143]**. In cooperative sensing architectures, the control channel (pilot channel) can be implemented using different methodologies. These include a dedicated band, an unlicensed band such as ISM, and an underlay system such as ultra wide band (UWB). Depending on the system requirements, one of these methods can be selected. Furthermore, various architectures for control channels are proposed in the cognitive radio literature **[144]**. A time division multiple access (TDMA)-based protocol for exchange of sensing data is proposed in **[145]**. Collaborative spectrum sensing is most effective when collaborating cognitive radios observe independent fading or shadowing **[69][146]**. Different diversity enhancing techniques such as multi-antenna, cooperative and oversampled techniques have been introduced in the literature to enhance the SS efficiency in wireless fading channels **[154]**-**[157]**. Eigenvalue based SS techniques do not require any prior information of the incumbent user's signal and it outperforms ED techniques, especially in the presence of noise covariance uncertainty **[154]**. Several eigenvalue based sensing techniques have been proposed in the literature exploiting the properties of Wishart random matrices. These techniques can be categorized into Signal Condition Number (SCN) based **[154]**, Largest Eigenvalue (LE) based **[158]** and Scaled Largest Eigenvalue (SLE) based **[159]** methods.

Other alternative spectrum sensing methods include external sensing [62], information theoretic based spectrum sensing, fast sensing, covariance based sensing, autocorrelation based sensing, multi-taper spectral estimation, wavelet transform based estimation, Hough transform, and time-frequency analysis.

A classification of different spectrum sensing techniques is presented in Figure 5.

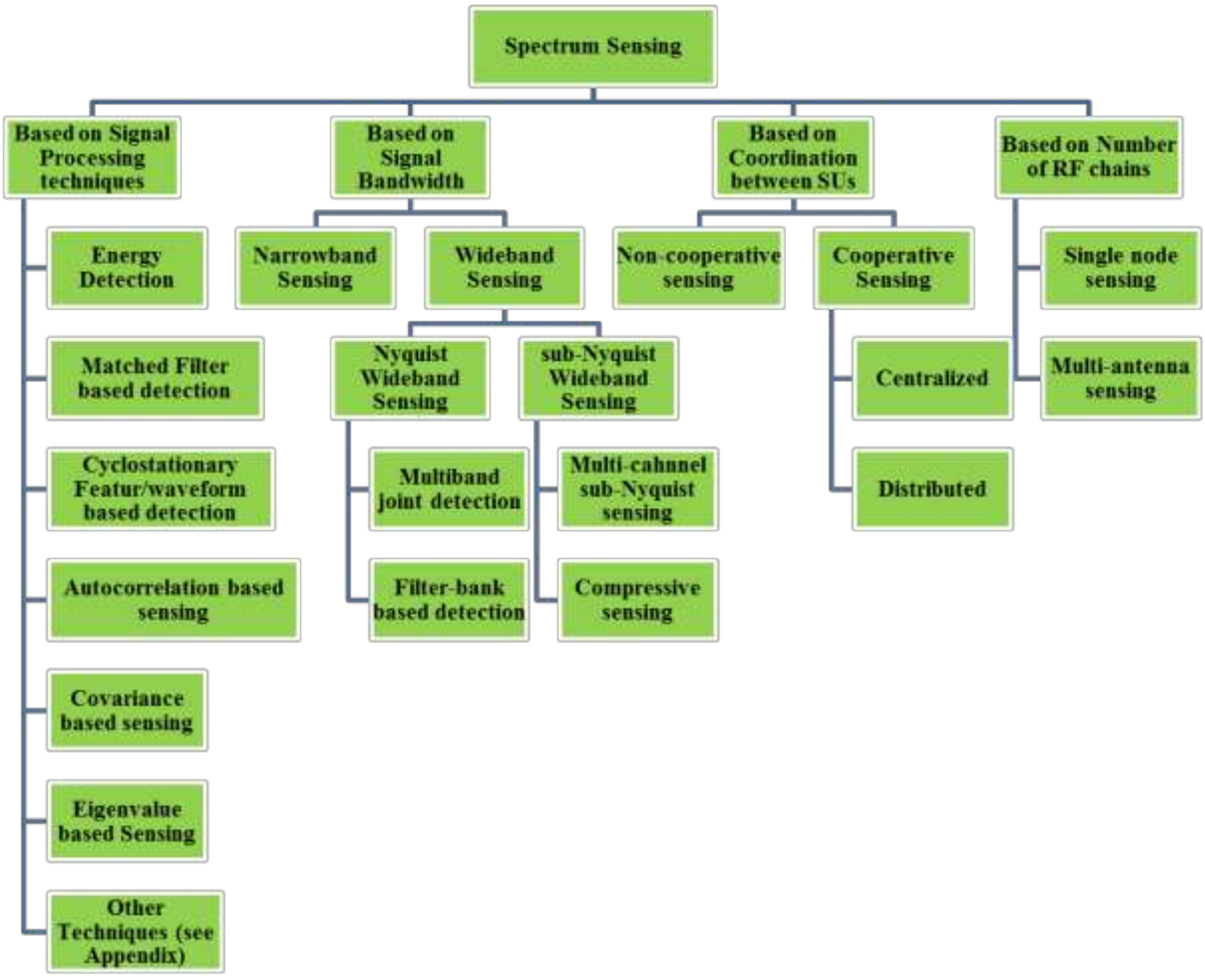

Figure 5 - Categorisation of Spectrum Sensing CR techniques.

Databases

Single-device Spectrum Sensing techniques may be deeply affected by harsh environment conditions (*e.g.*, shadowing), and thus provide to the cognitive device erroneous estimations of the channel state. Moreover, spectrum sensing of all licensed channels may consume a longer time that could be used for CR operation. In addition, channel switching based on instantaneous channel occupancy information may result in poor channel selection since the selected channel might be heavily utilized by the incumbent user even though it happened to be available during the sensing time. This may cause frequent service disruptions for SUs, thus resulting in interference to the incumbent users. That would also increase delays of transmission and limit the capacity of the system.

A CR could use the database approach including history information and prediction methods to make the operation more efficient. This approach is based on maintaining a frequently updated and centrally located database with information about the regional spectrum usage, including location of incumbent transmitters, coverage areas, frequencies of operation, transmission powers, radio technologies, operation requirements, etc. The cognitive users who want to reuse the incumbent spectrum have to make a request to the database system and based on the availability of the unoccupied channels in that location and for the requested period, the database system can grant access to those channels. This scheme is quite static and dynamicity of this scheme depends on the how fast the incumbent spectrum usage information is updated in the database. The database may also store the pre-computed signal levels that can be estimated by suitable propagation and prediction models. By taking signal levels in the neighbouring areas into account, the database system can provide information about the safe transmit power to querying cognitive devices. A model of this technique is depicted in Figure 6.

When using the database to provide necessary spectrum usage information to the CR nodes, the location of the CR nodes is required in order to provide the information that is relevant to that region, which sometimes leads to the term *geolocation database*. Databases are an alternative method to obtain knowledge of the radio environment and can be used to determine the incumbent systems in a certain region and ensure that CR nodes do not attempt to operate within protected areas where cognitive transmissions would result in harmful interference levels. Databases can also be used to obtain detailed and accurate information on the incumbent system operating in the environment of a CR network, which can be exploited by the CR system to take appropriate actions and improve the system operation.

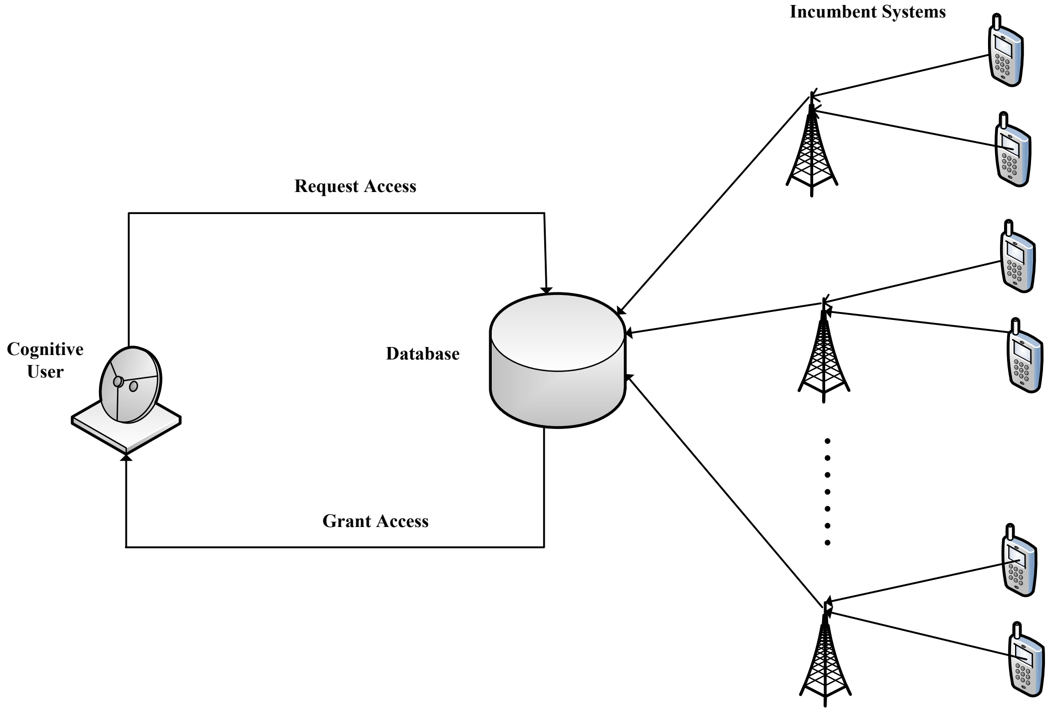

Figure 6 - Illustration of Database-based coexistence of a cognitive system and incumbent systems.

Radio environment maps (REM) are becoming a promising architectural concept for storing environmental information for use in cognitive wireless networks **[88]**. One of the sensing and measuring schemes is the Wireless Regional Area Network (WRAN) system based on Radio Environment Map (REM) as proposed in **[89]**, which can be looked as an integrated database. The operation of a cognitive engine requires data and meta-data defining the spectral environment that a terminal is operating in at a given moment in time. By referring to a REM, this data can include information on spectrum economic transactions, dropouts, handovers, available networks, and services. Standardized database structures, data formats and functionality must be defined to support the flexibility necessary to accommodate current and future cognitive radio spectrum applications, such as mobility, spectrum economic transactions, dropouts, handovers, available networks, and services.

An unlicensed wireless Wide Area Network (WAN) based on the combination of cognitive radio and Available Resource Maps (ARM) has been proposed in **[91]**, **[92]**. ARM-based cognitive radio systems are based on the same operational principles of conventional cellular networks, but with the fundamental features that spectrum is shared and a database provides spectrum availability, a public radio control channel (RCC) is used for session setup and Base Transceiver Stations (BTSs) report their spectrum usage to the ARM through a wired control channel.

In case of cognitive access to TV white space scenario, based on a CR's geolocation data and specific service requirements, the home base station queries the central database for channel availability **[93]**. The database then returns information about various operating parameters such as number of channels, center frequency and associated power levels available for use in that location. In **[88]**, it has been shown that the enhancement of the REM by means of spatial statistics and models can be obtained through a topology engine, which is an agent collecting and processing spatial information about the environment for storage in the REM. The REM-enabled WRAN system has been proposed in **[94]** and it has been shown that it can better realize different functions at the same time to ensure the protection of incumbent users. IEEE 802.22 standard considers Beacon scheme other than common detection method to protect these users.

In **[95]**, a spectrum utilization method is proposed using both long and short-term history information in radio resource management. It has been noted that pure long-term information improves the performance of cognitive radios in terms of sensing time. However, a lot of channel queries are needed when the channel changes frequently if the only the source of information is a centralized long-term database. It has been concluded that when more detailed information locally is offered with the help of a short-term database, it becomes easier to avoid congested channels and use the ones offering good transmission opportunities. In **[96]**, the effect of local white spaces databases called sensing databases (SDB), which relay regulatory information from regulatory database and contain the sensing related database provided by distributed sensing schemes, has been analyzed. It is claimed that by deploying such databases, a system can achieve up to 20 % reduction in sensing activities. In **[96]**, the approach of the European Commission funded COGEU (COGnitive radio systems for efficient sharing of TV white spaces in EUropean context) project in exploiting the TV White Spaces (TVWS) is introduced. The COGEU proposes a national geolocation database separating bands for commons usage and for cognitive spectrum trading. The commons bands would be for access without the need for guaranteed quality of service (QoS), while cognitive trading bands are for access with a need for guaranteed QoS. It has been mentioned that temporary exclusive rights for operating in the TVWS may be bought from a broker. Moreover, in case there are no spectrum buyers, a commons approach is envisioned.

The performance of sensing based scheme and database based scheme has been compared in **[97]** and it has been concluded that the throughput of the sensing based scheme is better than database based scheme in general CR environment. In **[98]**, a CogNet architecture is proposed, which is developed based on cross-layer optimized network architecture and specially designed for CR networks. It enables CRs to share the network information between the lower three layers through a common database while efficiently processing the shared information using the cognitive engine which is attached onto the common database. Cognitive engine in the proposed CogNet architecture is primarily used for routing function in network layer and is served as an example of use of CogNet architecture.

In **[99]**, an overview of spectrum monitoring requirement for maintaining of database has been presented for the deployment of CR technology based services. In **[100]**, an overview about how location aided information can help to enhance the performance of wireless communication systems has been presented including the context of CR systems. In **[101]**, the potential security vulnerabilities and the remedies for the same in a CR network are addressed together with an example using a commercial IEEE 802.22 standard. It has been mentioned that IEEE 802.22 Standard has done pioneering work to take the first step towards ensuring security in CR networks in the context of external incumbent database and management planes.

In **[102]**, different algorithms for improving the accuracy of the geolocation databases have been presented by simulating spectrum sensing samples obtained in a cellular-type white space system operating within the incumbent TV network area. Furthermore, the effect of the considered methods on the cognitive throughput and interference level towards incumbent system has been analyzed. In **[103]**, a novel REM construction platform that integrates the mid and low-end spectrum sensing devices into a single heterogeneous testbed has been presented. Furthermore, this work evaluates the performance of realized heterogeneous spectrum sensing testbed in terms of accurate REM derivation and additional statistics for indoor environments.

Combined Spectrum Awareness Approach (Spectrum Sensing and Database)

Spectrum sensing and database approaches are two important methods for acquiring incumbent spectrum usage information by the CRs. In general, SS is more dynamic way of obtaining information than the database approach but have several disadvantages such as hidden node problem, difficulty of realizing for wide-bands and wide coverage areas. The database only approach can provide only the predefined stored information and the dynamicity of the spectrum occupancy is not reflected. When the SS approach is combined with the database approach, reliable spatial spectrum measurements can be made and Radio Environmental Maps (REMs) can be constructed in order to provide accurate information regarding the spectrum utilization over time, space and frequency. The REMs store a variety of information types such as locations of transmitters and receivers, models of the propagation environment, and various spectrum use measurements conducted by wireless devices. Based on the stored information, the radio environmental characteristics such as levels of interference, spectrum usage over time and space can be estimated and modelled. Such environmental information can then be used by the cognitive devices in order to find out the spectrum holes in different domains, apply transmit power control for interference minimization, and also for radio resource management.

The cognitive devices can be equipped with the following different capabilities depending on the techniques employed **[105]**: (i) geolocation ability through GPS (or any other form of localisation tool), (ii) 3G/4G connectivity which allows sending queries for requesting spectrum information and (iii) local spectrum sensing hardware. The combination of these capabilities may lead to different mode of operations defined by FCC **[105]**. In this context, reference **[105]** provides an analytical framework for determining the topology of a CR based vehicular network, where the network components are the spectrum database, multiple BSs and moving vehicles in different traffic conditions. Reference **[106]** studies a measurement based radio environment database (RDB) whose parameters are the observed average values of the incumbent user's signal power received at cognitive users and the number of observations at different locations. The stored RDB information is then used by the cognitive users to estimate the incumbent signal accurately.

Reference **[107]** discusses the construction of a large-scale spectrum database through cooperative spectrum sensing for CR network considering the existing infrastructure of two tiered macrocell-femtocell network. A single framework has been proposed to solve cooperative spectrum sensing for cognitive users and also self-organization of femtocells by enabling the cooperation between cognitive users and the femtocells.

While considering the exploitation of TV whitespaces, the radiation power of a TV base station (BS) basically covers a wide area which is beyond the reach of the transmit power of a mobile device. Due to this reason, the development of power propagation map of even a single TV BS requires sensing reports from devices located in different positions inside the TV's coverage area, hence requiring involvement of cooperative spectrum sensing in order to form the database of the TV white spaces. In this context, the contribution in **[108]** proposes a CR cloud network model for wireless communications in TV whitespaces and a combined approach has been developed using a database and a sparse Baysian learning algorithm for cooperative spectrum sensing.

In practice, SS process may involve heterogeneous devices with different capabilities, which can be classified as high-end, mid-end and low-end devices **[109]**. The high-end devices, typically represented by signal/spectrum analyzers, offer the highest performance and capabilities at the highest price. The mid-end devices are a trade-off between price and performance while offering a set of measurement capabilities. The low-end devices are low-price solutions but have limited measurement capabilities. In this context, reference **[109]** proposes a novel REM construction platform that integrates several mid-end and low-end spectrum sensing devices into a single heterogeneous testbed. In the similar context, the contribution in **[110]** describes a prototype of an REM for storing and reasoning about spectrum data obtained from heterogeneous sources. Furthermore, illustrations regarding how the information such as transmitter locations and estimates of spectrum occupancy over space and time can be inferred and made available through the REM based on information obtained from a network of different spectrum sensors have been presented. Reference **[111]** analyzes several spatial interpolation techniques based on Inverse Distance Weighting (IDW) and compares them in terms of reliability bounds of the interpolation errors for an indoor environment. It has been concluded that the spatial interpolation techniques can provide a robust and reliable Radio Interference Field (RIF) estimation.

In a multihop ad hoc network, CR nodes must perform all the tasks from identifying spectrum opportunities to the exploitation of information for communication on their own subject to the constraints of interference thresholds and the desired Quality QoS. In this context, reference **[112]** introduces a Distributed Resource Map (DRM) for cooperation and knowledge aggregation in CR ad hoc networks. The DRM is considered as a database driven approach in order to exploit distributed sensing performed by heterogeneous CR nodes and inter-nodes cooperation to maintain network-wide support architecture. Reference **[113]** proposes and evaluates a cost-efficient cognitive approach for sharing the spectrum with incumbent user networks by exploiting the REM. This contribution further investigates the impact of imperfect knowledge in a Global REM due to node mobility and REM dissemination delay.

Beacon Signals

Another alternative method to obtain knowledge of the radio environment relies on the use of regional beacon signals that are broadcast in appropriate signalling channels. Beacon signals convey real-time information about the incumbent systems present in the geographical area where the beacon signal is broadcast along with various kinds of information on spectrum usage. CR terminals can then detect the regional beacon signals present at their location and obtain information about the surrounding environment. The use of beacon signals can be envisaged as a network-aided approach based on an active agreement between the cognitive network and the original spectrum licensee whereby the incumbent network shares real-time information with the cognitive network regarding spectrum utilization. This approach would allow cognitive systems to conceptually have perfect knowledge of current spectrum usage as well as possibly knowledge about traffic trends and future frequency usage **[114]**. However, if the incumbent system is based on a legacy radio technology, enabling such interaction would require additional modifications to the already existing incumbent network, which might not be possible or economically feasible. Alternatively, beacon signals can also broadcast information obtained from spectrum databases. In this case, beacon signals can be thought of as an alternative means to access spectrum databases.

The essence of the beacon-signals approach has been realized in various particular definitions such as the spectrum information channel in **[115]**, the Common Spectrum Coordination Channel (CSCC) in **[116]** and the Cognitive Pilot Channel (CPC) concept **[117]**-**[119]**. The latter concept has received great attention and constitutes an especially interesting approach in the context of heterogeneous wireless networks. The CPC was originally conceived as a solution for conveying the necessary information from the network side to allow mobile terminals to be aware of the surrounding environment and available Radio Access Technologies (RATs) in order to facilitate their connection to the network in a heterogeneous wireless environment. However, the scope of CPC was extended to become a means of spectrum awareness **[118]** and an enabler for radio systems coexistence **[119]**. CR systems can exploit the information transmitted in the CPC to gain knowledge the incumbent radio systems operating within a certain geographical area and their specific characteristics.

The design and deployment of the CPC concept (and beacon signals in general) require some practical aspects to be taken into consideration. One important aspect is the CPC operating frequency. The CPC can be broadcast at a fixed frequency harmonized among incumbent RATs at a global or regional level, which facilitates the operation of mobile terminals. A simpler solution from the incumbent operators' viewpoint is to use a set of convenient frequencies that may be neither harmonized nor fixed, which requires terminals to scan frequency bands to search for the CPC signal. Another aspect is the RAT used to convey the CPC, which can be one or more of the RATs deployed making use of the logical channels already provided by the set of available RATs (in-band CPC) or a separate CPC-specific RAT operating in another frequency (out-band CPC). The main advantage of the out-band approach is that any CPC-compliant terminal can retrieve the information conveyed in the CPC regardless of the supported RATs. However, this approach requires new infrastructure and a harmonized frequency to transmit the CPC channel. By contrast, the in-band approach reuses the existing infrastructure and does not require frequency harmonization. However, it requires that terminals scan several frequency bands to find the RAT where the CPC is transmitted. Moreover, the CPC cannot be found if the particular RAT is not supported by the terminal. This problem can be solved with a combined CPC approach where an out-band CPC broadcasts a list of incumbent RATs and the frequencies where the in-band CPC for each RAT can be found, and each in-band CPC transmits detailed information for the corresponding RAT. This approach prevents terminals from having to scan frequency bands and allows the information to be retrieved regardless of the supported RATs. However, a harmonized out-band CPC frequency is still needed. Depending on the considered delivery mode, CPC can be deployed in broadcast or on-demand modes. In broadcast CPC the information is transmitted periodically and continuously making use of a downlink broadcast channel. In on-demand CPC the information is transmitted under request when needed by the terminal, which requires uplink communication channels to request the CPC information (in addition to the downlink channels) but is more efficient in terms of power consumption and required bit-rates **[120]**.

Comparison of spectrum awareness methods

While spectrum sensing methods provide binary information about the busy/idle state of the channels in a frequency band, geolocation databases can provide more detailed and reliable information about the incumbent system, which can be exploited for a more efficient use of the spectrum. With geolocation databases, CR nodes do not need to implement computationally complex spectrum sensing methods but instead implement geolocation methods such as Global Positioning System (GPS) or triangulation, which can be moved to base stations in infrastructure-based CR networks in order to reduce terminal costs. However, the use of databases involves some practical problems. From a technical point of view, an important problem is the location accuracy. The locations of CR nodes need to be determined with acceptable accuracy levels to ensure that the information provided by the database corresponds to the real environment where the CR nodes operate. Existing geolocation alternatives are not perfect and are characterized by certain accuracy errors. Another important technical problem is the selection of the information contained in the database and the structure of the database.

Geolocation databases do not constitute an adequate choice for spectrum bands where the characteristics of the incumbent system and the spectrum occupancy patterns are highly dynamic. Updating the database after a change of the operation conditions of the incumbent system and retrieving the updated information from the cognitive system is a process that requires some time. The use of databases in incumbent systems with highly dynamic characteristics may result in retrieving outdated information that does not reflect the instantaneous circumstance of the incumbent system. For this reason, the deployment of geolocation databases has been proposed for incumbent systems that are static or vary over long time scales such as TV and Radioastronomy systems. The transmitter characteristics (location, frequency, power, etc.) in these bands are stable or change very infrequently. From an administrative point of view, the most notable drawback of geolocation databases is the significant economic cost associated to the infrastructure required to deploy and maintain databases. Another controversial issue is who owns and maintains the database (the incumbent network, the cognitive network, a new commercial operator or a governmental/regulatory organism) and the way the database is managed and accessed depending on the ownership.

Table 3 provides a comparison of spectrum awareness methods. Geolocation databases and beacon signals place on the incumbent system the responsibility of providing spectrum awareness to the cognitive system by either updating the information contained at a centralized database or broadcasting the relevant data on regional beacons. Spectrum occupancy information is reliable since it is provided by the incumbent system, which guarantees minimum interference and an efficient use of spectrum. However, these approaches need a communication means between incumbent and cognitive systems, which may involve some modifications to legacy incumbent systems and hence lead to compatibility issues. The deployment of geolocation databases and beacon signals implies a significant cost in infrastructure and requires location information along with either ubiquitous connectivity to the spectrum database or standardized channels to broadcast the beacon signals. On the other hand, spectrum sensing solely relies on local observations of the spectrum occupancy without the need of an external system providing spectrum awareness. While spectrum sensing leads to more complex cognitive terminals, no modifications to the incumbent system are required (i.e., it is compatible with legacy systems) and infrastructure costs are notably lower. Spectrum sensing, however, consumes time and energy and is somewhat unreliable due to practical limitations.

Table 3 - Comparison of spectrum awareness methods.

	Spectrum sensing	**Geolocation databases**	**Beacon signals**
Infrastructure complexity/cost	Low	High	Medium/High
Terminal complexity/cost	High	Medium	Low
Legacy compatibility	High	Medium/Low	Low
Reliability	Low/Medium	High	Medium/High
Spectrum dynamism	High	Low	High
Need for external system/provider	No	Yes	Yes
Need for additional spectrum	No	No	Yes/No
Specific issues	Time and energy consumption	Positioning system	Standardized solution

4.1.1.2 Spectrum Utilization

The purpose of the spectrum utilization function is to provide spectrum access to the cognitive users and/or networks by coordinating the access to the available spectrum holes while at the same time guaranteeing an adequate interference-free coexistence between incumbent and cognitive systems. Spectrum utilization among wireless terminals or networks may occur either horizontally or vertically **[121]**. In horizontal spectrum utilization all the terminals or networks have the same right to access a particular spectrum band. In vertical spectrum utilization one wireless system (typically, the owner of the spectrum license) has a higher priority to access the spectrum band and its right to exploit the spectrum prevails over the rest of systems. In CR systems, vertical spectrum utilization takes place between incumbent and cognitive users, while horizontal spectrum utilization takes place among cognitive users and/or networks. Given the hierarchical access structure of CR where the incumbent or licensed users are given a higher spectrum access priority, the mechanisms required for spectrum utilization between incumbent and cognitive users (vertical spectrum utilization) are different compared to the methods employed for spectrum utilization between cognitive users and/or networks (horizontal spectrum utilization). Both cases are discussed separately in the following.

Vertical spectrum utilization

Three main methods for vertical spectrum sharing can be identified, namely interweave, underlay, and overlay **[122]**. The following sections review the main concepts and existing solutions.

4.1.1.2..1 Interweave

The basic idea of the interweave strategy is to identify temporal and spatial spectrum gaps not occupied by incumbent users (*i.e.*, spectrum holes or white spaces) and place cognitive transmissions within such gaps. The interweave method follows an interference avoidance strategy where CR users are allowed to use the licensed spectrum when incumbent users are not present either temporally or spatially. This approach does not impose restrictions on the transmission power of CR terminals but rather on when and where they transmit. The main drawback of the interweave scheme is the need to accurately identify the available spectrum holes to avoid interference to the incumbent system. Depending on the particular characteristics of the incumbent band to exploit, one or more spectrum awareness methods may be required. Interweave CRs need to be very agile in order to switch on and off very quickly over various frequency bands in order to exploit spectrum holes.

4.1.1.2..2 Underlay

The underlay approach consists in ensuring that cognitive transmissions remain below the maximum allowable interference temperature at the incumbent receivers so that their operation is not disturbed. As opposed to the interweave approach, underlay CRs are allowed to transmit anywhere and anytime but under severe constraints on their transmission power so that they operate below the noise floor of the incumbent users. To meet such requirements, cognitive transmissions must be spread over a wide frequency band, which is normally achieved by means of UltraWide Band (UWB) technology. The UWB signal is limited by a strict spectral mask and allows very low power transmissions over a large bandwidth. The actual bandwidth of the spectral mask varies in different countries as defined by their corresponding regulatory bodies but normally overlaps with several licensed systems. The spectral mask ensures that cognitive UWB transmissions do not interfere with the incumbent systems as the received UWB power at any incumbent receiver is typically well below the noise floor. Compared to the interweave approach, the main advantage of underlay is that the activity of incumbent users does not need to be tracked (overlapping transmissions are allowed provided that power constraints are respected). However, the strict power limitations imposed by UWB spectral masks reduce the applicability of the underlay approach to short-range scenarios (typically below 10 meters). Longer transmission ranges (up to 300 meters) are possible but at reduced data rates. Figure 7 illustrates an Exclusion Zone method, which is one underlay method for allowing the coexistence of the incumbent and cognitive systems within the same spectrum for short-range scenarios (typically below 10 meters) where underlay is possible (due to strict power limitations imposed by UWB spectral masks). In this scheme, a region is defined around an incumbent receiver based on its interference threshold, called Exclusion Zone (EZ), where no cognitive users are allowed to reuse the incumbent spectrum. The cognitive users which are outside this zone but are very near to the EZ may be allowed to reuse the incumbent spectrum with power control and cognitive users which are sufficiently far from the EZ are allowed to reuse with the full power. In this way, cognitive system can reuse the incumbent spectrum by guaranteeing sufficient protection of the incumbent users.

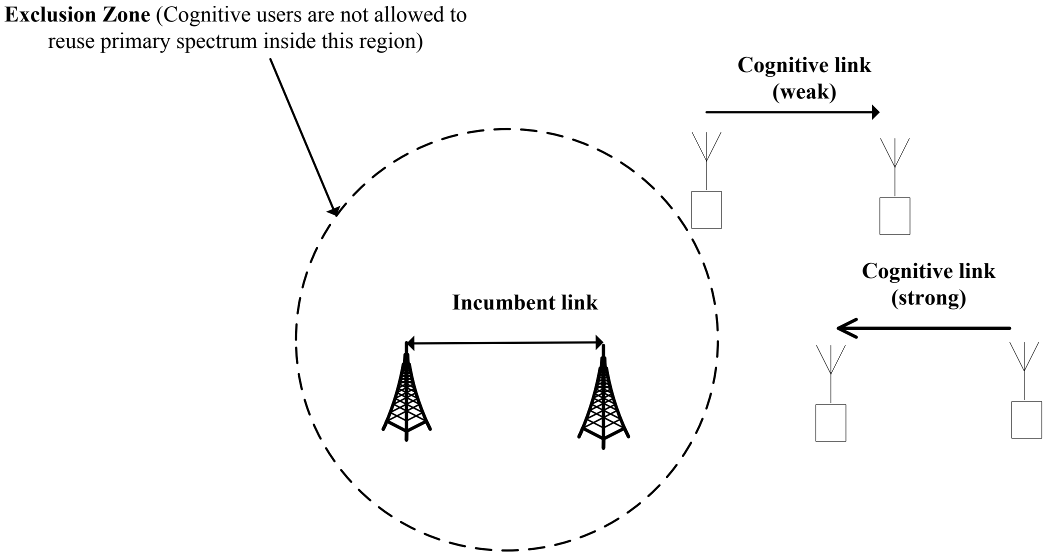

Figure 7 - Illustration of an underlay technique based on Exclusion Zone method for the coexistence of cognitive systems with an incumbent system.

Another concern of the underlay approach is the real interference impact on the incumbent receivers. Although a single UWB device may be far from affecting the operation of incumbent receivers in a significant way, the aggregated interference of a large number of UWB devices might raise the noise floor in an area and thus cause an adverse impact on incumbent systems.[5]

Beamforming

Beamforming is a technique commonly used in Multiple Antenna Systems (MIMO), and thus is very much relevant for cognitive radio systems, where users and base stations are often equipped with several antennas. The idea is to transmit/receive the user data at the cognitive user/incumbent user base station along certain spatial directions favorable to the channel. The definition of “favorable” varies, and many different criteria have been considered in the literature. Some of them, which encapsulate the main ideas in the CR underlay literature, are now shortly described. The work in **[168]** finds spatial directions minimizing the total transmit power or balancing the mean square error in a downlink scenario. In **[173]**, the aim is to minimize the total transmit power of the cognitive transmitters and to design receive beamformers at the cognitive user base station, such that the Signal-to-Interference-plus-Noise-Ratio (SINR) is of the cognitive users is above a certain threshold, while guaranteeing that the interference of the incumbent users is below another threshold. Similar problem setup is investigated in **[172]**, where the worst cognitive user SINR is maximized, while ensuring that interference leakage to incumbent users is below specific thresholds. Additional work in this direction is **[189]**, where beamforming along with user maximization (scheduling) is proposed in order to maximize the number of transmitting cognitive users, while guaranteeing interference constraints to incumbent users and satisfying additional quality of service constraints on each transmitting cognitive

[5] Note that this aggregation issue is currently being discussed between Commission and Member States who are concerned that, in 3.6-3.8 GHz C-band, their existing FS links are getting interfered by the foreseen multiplication of MS links.

user. Exploiting degrees of freedom resulting from multiple antennas, **[169]** considers maximization of the up-link sum rate for OFDMA CR systems, where each cognitive user uses one of two antennas to insert a null in the direction of the incumbent user, thus causing no/low interference to the incumbent user. The concept of null interference constraints on the incumbent users is also investigated in **[171]**, where it is claimed that the achievable rate region of the cognitive users operating under the null interference constraint can be achieved by a game theoretic approach. User scheduling, along with beamforming, is studied in **[179]**, where incumbent users that receive too much interference from cognitive users during a time slot are not scheduled for transmission; the objective is to maximize the total network throughput (total rate of scheduled incumbent users and cognitive users).

Beamforming is also applied in wave propagation models. In **[174]**, it is claimed that if dominant signal rays arrive in a cluster, a beamforming receiver performs better than energy detection for spectrum sensing. Adjusting the carrier phase of each transmitter in a way that reduces interference to the incumbent user is investigated in **[178]**, where also the effect of noise in phase synchronization is analyzed. The latter technique resembles research on imperfect channel state information (CSI), which arose from practical applications. In most practical scenarios, perfect knowledge of physical channels is unrealistic, which spurs research on the impact of channel errors on the performance of communication systems. In the cognitive literature, papers like **[175]-[177]** address the issue of imperfect CSI. In **[175]**, the aim is to maximize the service probability of one cognitive user, with constraints on the interference caused to an incumbent network of multiple incumbent users. This is done under the assumption of imperfect CSI, where the imperfection is modelled by added Gaussian noise, and by deriving the optimal beamformer that achieves these goals. The objective in **[176]** is similar, but where the focus is on maximizing the minimum of the received SINRs of the cognitive users, subject to constraints of the total cognitive user transmit power and the received interference power at the incumbent users. This is again done by optimizing the beamforming vectors at the cognitive user's transmitter, and with imperfect CSI being modelled by bounding the region for possible channel matrices or channel covariance matrices. In **[177]**, it is assumed that a multi-antenna cognitive user transmitter knows the link to the single antenna cognitive user receiver, while the channel uncertainty between the cognitive user transmitter and incumbent user receiver is again modelled by constraining the set of possible realizations of the channel.

4.1.1.2..2.1 Interference Alignment

The principle of Interference Alignment (IA) is based on aligning the interference on a signal subspace with respect to the non-intended receiver so that it can be easily filtered out by sacrificing some signal dimensions [224]. This technique has been shown to achieve the degrees of freedom for a range of interference channels [224], **[225]**. It should be noted that the IA technique can be classified as an underlay CR technique since it deals with interference mitigation towards the incumbent system in spectral coexistence scenarios. Several contributions have investigated the IA technique in the context of cellular networks showing that it can effectively suppress co-channel interference **[226]-[228]**. In **[229]**, a projection based IA technique including the concepts of signal alignment and channel alignment has been investigated. In the context of cognitive scenarios, the IA technique has been applied in several contributions **[180]-[185]**. In **[180]**, the IA technique has been applied for a peer-to-peer CR network with single incumbent user and multiple cognitive users. In **[181]**, an interference draining scheme has been proposed for a CR exploring the impact of propagation delay on the degree of freedoms of the CR. In **[182]**, IA has been applied to a peer-to-peer underlay MIMO CR network in which the transmit precoding and receiver interference subspace are chosen to minimize the total interference leakage while limiting the interference level to the incumbent user. A robust joint signal and interference alignment for cognitive MIMO interference channel is proposed in **[183]** and robustness of the worst-case design against channel uncertainties has been investigated. In **[184]**, the IA technique has been applied in the coexistence scenario of small cells and a macrocell and it is claimed that the proposed coordinated IA technique can provide perfect protection to the incumbent system.

Despite various literature about IA in the terrestrial context, only few contributions have been reported about IA in the satellite literature. In **[185]**, different IA techniques have been applied for the spectral coexistence of a multi-beam and a single-beam satellite with the single-beam satellite as the incumbent and the multi-beam satellite as the cognitive. It has been concluded that the proposed coordinated IA technique can provide an almost perfect protection to the incumbent satellite, while achieving the highest sum-rate compared to other techniques. The feasibility of implementing Subspace Interference Alignment (SIA) in a multibeam satellite system has been studied in **[186]** and it has been concluded that the SIA using frequency domain is advantageous for a multibeam satellite.

4.1.1.2..2.2 Resource Allocation

The resource allocation in cognitive underlay networks deals with the optimal use of radio resources by the cognitive users such that temperature constraints for the incumbent users are met. This problem has been studied in detail in different settings **[191]**. Reference **[190]** provides an overview of the state-of-art results on communication resource allocation over space, time, and frequency for emerging cognitive radio (CR) wireless networks.

Reference **[160]** proposes a hybrid cognitive radio system where underlay and overlay CR approaches are combined. Occasional switches from an overlay CR mode to an underlay CR mode enable to maximize the average throughput of a cognitive (unlicensed) network and stable transmission of a cognitive user. A similar work in **[163]** investigates the energy-efficient transmission under hybrid spectrum utilization scenario, where cognitive users can select a proper spectrum utilization method based on the active state of incumbent users. In **[165]**, the authors investigate joint overlay and underlay power allocation for OFDM-based CR systems.

The work in **[161]** focuses on a mathematical analysis of the interference temperature model in an effort to examine the relationships between the capacity achieved by the unlicensed network and the interference caused to the licensed network. The authors in **[162]** study two problems in cognitive spectrum access with minimum signal to interference noise ratio (QoS) guarantee under an interference temperature constraint. Similarly, the authors in **[164]** formulate two NP-hard optimal scheduling methods that meet the interference temperature constraints for cognitive radio networks. The first one maximizes the network throughput, whereas the second one minimizes the scheduling delay.

Power allocation is another area of research in underlay cognitive radio research. Reference **[166]** considers reliability/availability of subcarriers or incumbent user activity for power allocation. This aspect is modelled mathematically with a risk-return model by defining a general rate loss function. The work in **[167]** investigates the problem of uplink subcarrier and power allocation in a CR network that operates opportunistically within vacant licensed Incumbent Users spectrum. The resource allocation algorithm aims to maximize the CR network throughput under incumbent users' interference constraints.

The authors in **[187]** propose an adaptive scheme using transmit power adaptation, switched transmit diversity, and adaptive modulation in order to improve the performance of existing switching efficient schemes and bandwidth efficient schemes (BES). The proposed scheme is analyzed in terms of the average number of branch switching, average delay and a closed-form expression of the average bit error rate (BER) is provided. Reference **[188]** investigates the effects of multi-user diversity in a spectrum utilization system where cognitive users restrictively utilize spectrum licensed to incumbent users where interference perceived at incumbent users is regulated below a predetermined level. This interference regulation affects the characteristics of multiuser diversity gains previously known in non-spectrum utilization systems

The work in **[192]** presents new design formulations that aim at optimizing the performance of an orthogonal frequency-division multiple-access (OFDMA) ad hoc cognitive radio network through joint subcarrier assignment and power allocation. Aside from an important constraint on the tolerable interference induced to incumbent networks, to efficiently implement spectrum-utilization control within the unlicensed network, the optimization problems considered here strictly enforce upper and lower bounds on the total amount of temporarily available bandwidth that is granted to individual cognitive users.

Figure 8 shows a categorisation of different underlay techniques.

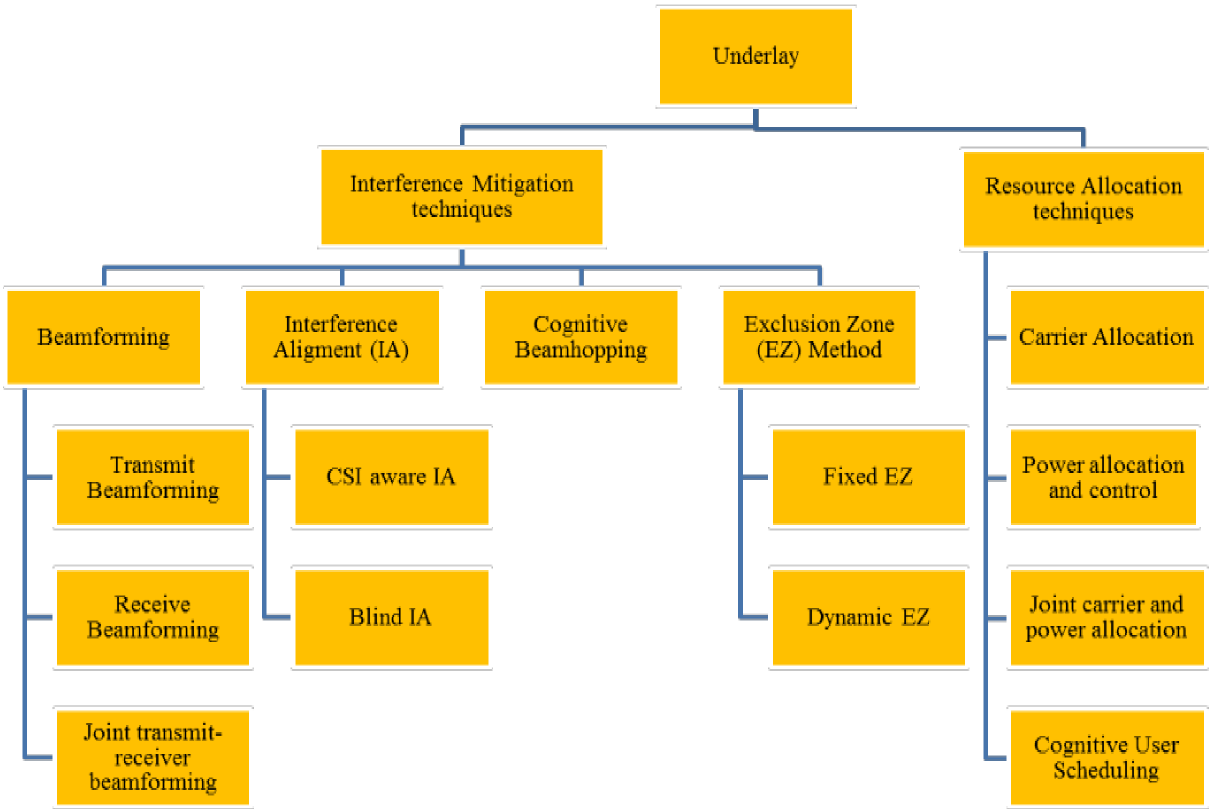

Figure 8 - Categorisation of underlay techniques.

4.1.1.2..3 Overlay

Similarly to the underlay approach, the overlay strategy also allows concurrent incumbent and cognitive transmissions. The basic idea of the overlay approach is that a fraction of the transmission power available at the cognitive users is used for cognitive communications and the remainder of the power is employed to assist the incumbent transmissions by relaying the incumbent signal from the incumbent transmitter to the incumbent receiver. This concept is illustrated in Figure 9.

By an adequate selection of the power split, the reduction in the incumbent receiver's SINR due to the interference caused by the fraction of power that is employed for the cognitive transmissions can be compensated by the assistance from the cognitive relaying. In other words, the power employed for cognitive transmissions results in an increased interference component at the incumbent receiver and thus in a reduced SINR. However, the fraction of cognitive power used to relay the incumbent signal is carefully selected to increase the signal component at the incumbent receiver by the same amount so that the effective SINR at the incumbent receiver is the same regardless of the presence of the cognitive transmission.

The main advantage of the overlay approach is that cognitive transmitters may be allowed to increase the interference temperature level beyond the strict limits imposed in the underlay approach and the detection of the incumbent signal can be improved. However, there are many significant drawbacks and practical limitations, mainly the degree of complexity in the cognitive transceivers. First, the overlay approach assumes that the cognitive system has sufficient information and knowledge of the incumbent message to produce a compatible signal that complements the incumbent signal and improves the detection probability at the incumbent receiver. At the same time, the cognitive transmitter needs to be able to communicate with the cognitive receiver, which implies the use of techniques such as dirty paper coding or successive interference cancellation depending on whether the cognitive transmitter, the cognitive receiver or both have knowledge of the incumbent signal. Moreover, a sophisticated power control mechanism is required to decide the power split between cognitive transmissions and relayed incumbent transmissions.

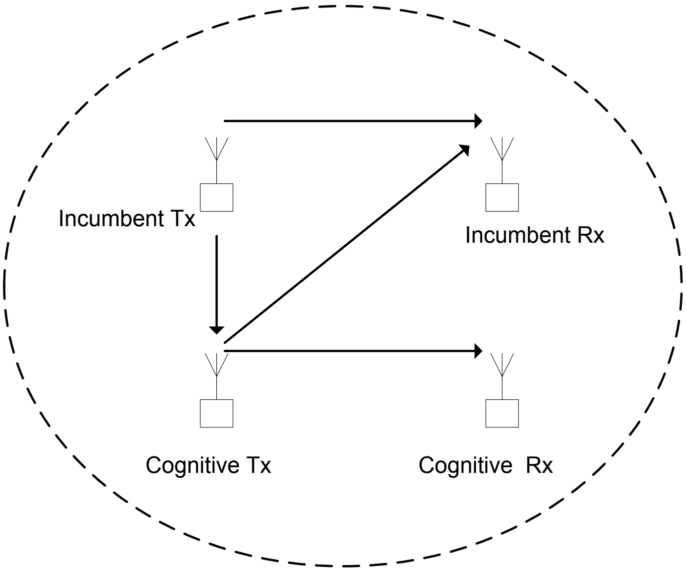

Figure 9 - Illustration of an overlay technique for the coexistence of a cognitive system with an incumbent system.

Overlay SS techniques are receiving an ever increasing attention from the information-theoretic community, as they are considered the optimal approach for two interfering communication systems to share the available spectrum **[195]-[215]**. These techniques are based on three fundamental assumptions: i) both incumbent and cognitive systems communicate concurrently over the same frequency bands; ii) the cognitive system is aware of the channel state as well as of the message of the incumbent system; and iii) advanced transmission techniques are exploited in order to avoid harmful interference towards the incumbent system.

In **[195]**, the authors focus on a two-sender/two-receiver channel model, and develop an achievable region for rate pairs obtained through the combination of the Gel'fand-Pinkser coding scheme with an achievable region construction for the interference channel. Such analysis is performed by taking into account two different cases related to the procedure which allows the cognitive transmitter to obtain the incumbent transmitter's message: i) a genie-aided cognitive channel, in which the cognitive transmitter is able to non-casually gather information; and ii) a casual cognitive channel, in which the data to be sent by the incumbent transmitter is casually obtained. In the former case, two use cases are envisaged: i) the cognitive transmitter treats the incumbent transmitter's message as interference, and tries to compensate it by using a binning technique similar to Gel'fand-Pinkser coding for channels with side information know at the transmitter; and ii) the cognitive transmitter avoids the transmission of its message, and only acts as a relay for the incumbent transmission, thus yielding to a 2x1 MISO channel. As for the casual scenario, four protocols are proposed. Two of them consist in a two-phase approach: i) the cognitive transmitter receives a portion of the incumbent message being transmitted (listening phase); and ii) both the incumbent and the cognitive transmitter send their message, relying on the genie-aided solutions to cancel/limit the interference. In the third protocol, the two transmitters remain independent, i.e., no message knowledge is required at the cognitive transmitter. In the last protocol, a casual scenario is analyzed. It is worthwhile noting that in all the above protocols, the incumbent transmitter knows the channel between it and the cognitive transmitter. Numerical results are provided, and compared to inner and outer bounds, respectively given by the interference channel and the Gaussian MIMO broadcast channel.

The work in **[195]** is extended in **[196]**, where the authors generalize the two-sender/two-receiver channel to include three messages: two for the incumbent receiver, and one for the cognitive receiver. This channel is referred to as overlay cognitive MAC channel, as it incorporates a MAC component between the incumbent and the cognitive transmitters. The achievable rate region, inner, and outer bounds are provided for both a memoryless and a Gaussian overlay cognitive MAC channel. Moreover, both weak and strong interference regimes are analyzed. In the former case, an exact characterization of the rate region is provided, while in the latter inner and outer bounds are obtained.

A two-sender/two-receiver channel is also considered in **[197]**. In this work, the achievable rate regions obtained in previous studies are improved by splitting the cognitive message in two submessages, which are then both encoded with the Gel'fand-Pinkser coding scheme. The incumbent receiver is required to jointly decode one of the two submessages from the cognitive transmitter and the incumbent message. Basically, rate splitting is applied as to enable the incumbent receiver to crossly observe partial information from the cognitive transmitter, thus reducing the effective interference it receives, while the Gel-fand-Pinkser coding scheme allows to exploit *a priori* knowledge of the interference from the cognitive transmitter. The memoryless channel is considered as the baseline scenario, and it is then extended to the Gaussian case showing that this approach strictly improves previous solutions in the high-interference-gain regime (*i.e.*, the interfering signal has a gain greater than one, while the intended one has a unit-gain). It is worthwhile noting that, in this case, interference is dealt with at the incumbent receiver, rather than at the cognitive transmitter.

Outer and inner bounds of the rate region for the two-sender/two-receiver interference channel are also provided in **[198]**, respectively based on the Nair-El Gamal broadcast outer bound and on rate splitting, Dirty Paper Coding, and carbon-copying schemes. In this work, the cognitive transmitter is assumed to have full knowledge of the incumbent transmitter's message. The achievable region and outer bounds for a two-sender/two-receiver discrete memoryless channel are also obtained in **[199]**, as well as an achievable region for the Gaussian case in the weak interference regime.

In **[200]**, four different two-sender/two-receiver channel are considered: i) a compound MAC channel with common information, in which the incumbent and cognitive transmitters have their own messages as well as a common one, and at the incumbent and cognitive receivers all of the three messages are decoded; ii) a compound MAC channel with conference encoders, which is similar to the previous one exception made for the presence of two separate links allowing the two transmitters to communicate and the absence of a common message; iii) an interference channel with common information, which is similar to the compound MAC channel with common information exception made at the receivers' side, where the incumbent and cognitive receivers decode the common and the incumbent or cognitive message, respectively; and iv) an interference channel with unidirectional cooperation, in which the message of only one of the transmitters is available to the other one, and no common information is present. The authors provide the achievable rate regions for all of these four channel models. This work is extended in **[201]**, where the authors provide some generalizations based on rate splitting, Gel'fand-Pinsker coding scheme, and cooperative transmission. The bounds obtained in this analysis are also evaluated and compared to the case of Gaussian channels. It is claimed that the optimal behaviour of a particular coding scheme is related to the channel being considered. As for the Gaussian case with weak interference, Dirty Paper Coding seems to provide better performance, while in the presence of strong interference, super-position coding and rate splitting seem to be the most fitting approaches.

In **[202]**, inner and outer bounds of the achievable rate region are computed for two-sender/two-receiver channels with non-casual knowledge at the cognitive transmitter. Moreover, it is assumed that the cognitive transmitter knows the channel's states sequence. The asymmetric Gaussian channel, with non-casual information and in the weak interference regime, is also analyzed, and a closed-form expression for the achievable rate region is provided.

In **[203]**, a discrete memoryless channel is considered as the baseline scenario for a two-sender/two-receiver system. The incumbent and cognitive transmitters have both private and common messages to be sent. The achievable rate region is obtained by applying a superposition coding that consists of successive encoding and simultaneous decoding, extending the Carleial's successive coding scheme. The resulting region includes previous results on interference channel with or without common information. The authors also extend this analysis to the following two cases: i) a scenario in which one of the two transmitters has no private information; and ii) a deterministic channel with common information, which is also further extended to the Gaussian case.

In **[204]**, the authors provide a short insight on the two-sender/two-receiver channel, taking into account cooperation both between transmitters and receivers. In the former case, it is claimed that if the transmitters are allowed to jointly decode their messages, the channel is a multi-antenna broadcast channel and Dirty Paper Coding (DPC) is the best approach. In the latter, assuming similar channel between each transmitter-receiver pair, a combined strategy in which the transmitters exchange messages and cooperatively transmit, and the receivers perform amplify-and-forward, is considered. It is claimed that cooperation at the transmitting side provides significantly improved performance when compared to cooperation at the receiving side.

In **[205]**, the authors analyze an arbitrary network and show hot it can be decomposed into a cognitive graph in the Gaussian case. An achievable rate region is provided, taking into account a cognitive radio channel defined as a two-sender/two-receiver channel. Both asymmetric and non-casual (*a priori*) transmitter cooperation are considered. It is also assumed that nodes cannot simultaneously transmit. At each given time instant, certain cognitive nodes may be able to obtain the messages to be transmitted by other nodes, depending on: i) device capabilities; ii) network geometry; and iii) channel gains between these nodes. It is assumed that if a node is able to obtain the message, it is a full knowledge. The authors then provide means to obtain a cognitive graph starting from: i) the information graph (*i.e.*, a graph which captures those nodes having independent information to be sent); ii) the interference graph, which captures the interference; and iii) the capabilities classification, *i.e.*, a graph defining which nodes have cognitive capabilities. For both intra- and inter-cluster behaviours, three cases are considered: i) competitive, where the transmitting nodes do not know the other nodes' messages; ii) cooperative, where the transmitting nodes know these messages; and iii) cognitive, where a subset of the transmitting nodes knows the messages of other nodes'.

In **[206]**, the authors generalize the Gel'fand-Pinsker coding scheme to quasi-static fading channels. In particular, the proposed model reflects fading channels when the channel state information may be estimated at the receiver, but is unknown at the transmitter (which without side information is denoted by compound channel). The authors provide bounds on the capacity of the considered channels with side information at the transmitter, for both finite and standard alphabets. Moreover, bounds for twosided state information problems (*i.e.*, a side information sequence at the transmitter and another one at the receiver) are derived as special cases. Then, a scenario in which a fading interference signal, but not the fading coefficient, is known at the transmitter is studied. In this case, achievable rates are derived for given outage probabilities. It is claimed that significant gains can be obtained by treating the interference as noise, while in the low SNR regime performance are near the upper bound of an interference-free scenario.

In **[207]**, the authors provide an insight on a scenario where the cognitive user is allowed to use the same spectrum of the incumbent user as long as: i) the incumbent encoder/decoder are the same as in the non-cognitive scenario; and ii) the incumbent user achieves the same instantaneous rate as in the non-cognitive scenario. In this work, three different environments are considered: i) a SISO-SISO channel; ii) a MISO-MISO channel; and iii) a SIMO-MISO channel, where the multi-antenna transmitter is the cognitive one. In the first case, it is claimed that a Decoding-Forwarding-Dirty Paper Coding (DF-DPC) scheme does not provide a significant gain in both low and high SNR scenarios. In the second channel model, the gain in terms of achievable cognitive rate is limited by the need to forward the incumbent signal. Thus, a novel Decoding-Dirty Paper Coding-Zero Forcing (D-DPC-ZF) scheme is proposed, which actually allows improving the performance. The DF-DPC scheme is also shown to fail in the last channel model. Here, the authors propose a ZF scheme to cancel the incumbent signal at the cognitive receiver and *vice versa*, in order to improve the performance.

In **[210]**, the authors consider a two-sender/two-receiver scenario, where one link is cognitive and the other is incumbent. The cognitive user is allowed to transmit at the same time and on the same bands of the incumbent user. This paper moves from previous works by taking into account both measurement errors at the incumbent transmitter and random packet arrivals, under the assumption of transmitters with infinite queues. Expressions of the maximum average throughput that the cognitive link can sustain while guaranteeing stability to the system are provided. In order to obtain this, an average throughput is independently fixed by the incumbent transmitter for its link. It is claimed that unavoidable errors in sensing the activity of the incumbent link actually limit the maximum achievable stable throughput on the cognitive link. Finally, the possibility of using the cognitive transmitter as a relay for the incumbent communication is analyzed. In this case, it is claimed that the advantages of such a solution depend on the network topology

In **[212]**, an overlay scheme is proposed in which the cognitive transmitter is rewarded with more transmission opportunities if it enforces the reliability of the incumbent link. In particular, a cognitive node is deployed close to the incumbent receiver, and it is assumed able to gather complete CSI on the incumbent link. When the incumbent signal is not properly received at the incumbent receiver, the incumbent transmitter sends again its message, and a cognitive transmitter, which received the incumbent link CSI from the cognitive node, constructively sends a message that helps the incumbent receiver. This is achieved by proper beamforming at the cognitive transmitter, for which the choice of the beam weights is analyzed. Moreover, the authors also take into account the best-relay selection problem based on a Decode-and-Forward scheme, as well as the performance assessment in terms of both incumbent outage probability and incumbent throughput.

In **[213]**, the authors provide both achievable rates and outer bounds for a cognitive radio interference channel with partial knowledge, *i.e.*, a scenario in which the cognitive transmitter only has a partial knowledge on the incumbent transmitter's information. It is claimed that, according to the level of cognition on the incumbent user's message, the channel performance range from those of the conventional interference channel to those of the interference channel with degraded message sets. For the general discrete memoryless interference channel, an outer bound for the rate region and the achievable rate region under the assumption of weak interference are obtained. Moreover, when taking into account a Gaussian interference channel, a combination of Han-Kobayashi and Dirty Paper Coding schemes allows obtaining outer bounds and achievable rate regions as well.

Beamforming is also considered in **[214]**, where the authors optimize it together with the transmit power allocation in order to maximize the achievable rate of the cognitive user, while keeping the achievable rate of the incumbent user at a fixed value. These transmission rates are analyzed in both a SIMO and a MISO configuration, and the cognitive user is assumed to casually obtain knowledge on the incumbent transmitter's message. In particular, the cognitive transmitter uses a part of its transmission power to assist the incumbent transmitter in delivering its message.

Finally, in **[215]**, the authors apply constrained optimization methods to study joint spectral shaping and power control in overlay cognitive radio systems, also taking into account operating constraints expressed in terms of target values for their SINR. A precoded OFDM-based communication systems with a MMSE receiver is considered, and the sufficient and necessary conditions for optimal assignment of OFDM subcarriers and transmit power are analyzed. Moreover, an algorithm aiming at adjusting the OFDM precoder and transmit power matrices until a specified SINR is achieved with minimum transmit power is also provided. The convergence of the proposed algorithm is also numerically evaluated through extensive simulations.

Performance improvement of flexible spectrum utilization approaches

Although the interweave, underlay and overlay approaches are based on different principles for a more flexible utilization of the spectral resources, all them can bring important benefits in terms of capacity improvement for an opportunistic system. Taking as a reference a non-cognitive system that makes use of an allocated spectrum B_2, Figure 10 shows the capacity improvements that can be attained when the same system makes use not only of its allocated spectrum B_2 but also of an additional spectrum B_1 in a cognitive way, following the interweave, underlay and overlay (both with Amplify and Forward, AF, and Decode and Forward, DF) approaches, as a function of the P_2/N_0 ratio (i.e., transmission power to noise spectral density ratio) and for various values of the duty cycle d_2 (30% and 90%).

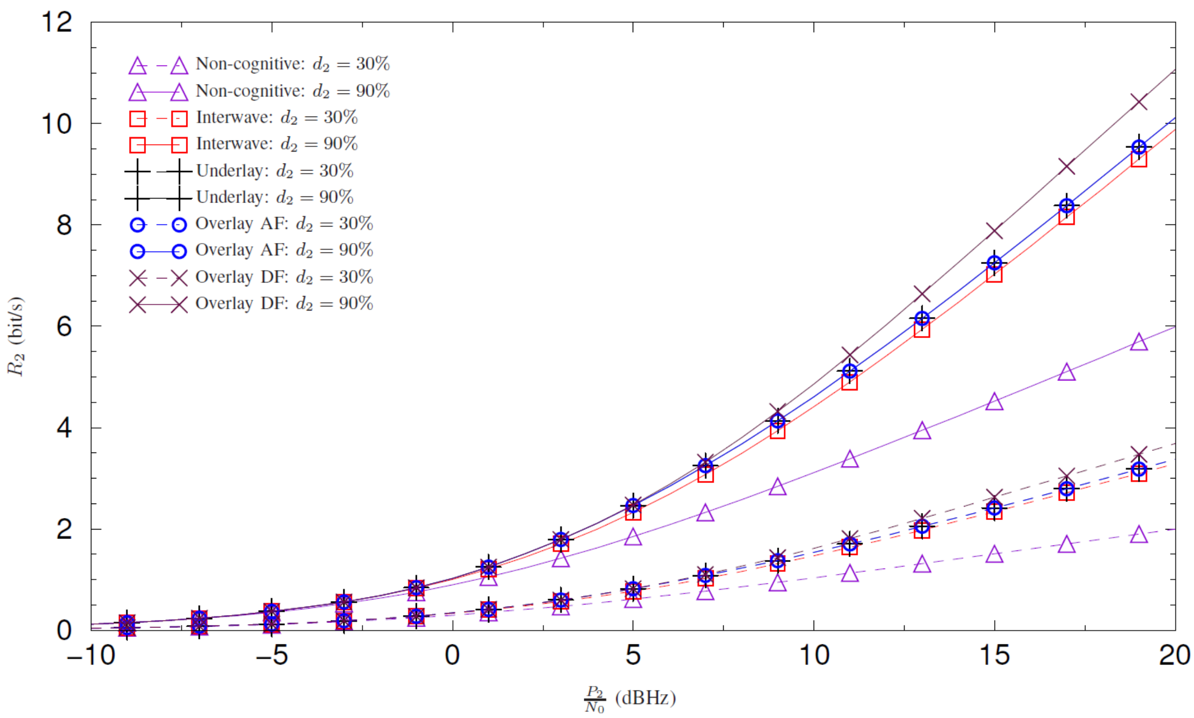

Figure 10 - Opportunistic capacity R_2 (bit/s) improvement as a function of P_2/N_0 ($B_1 = 2B_2$, $B_2 = 1$Hz) (Source: **[252]**).

As shown in Figure 10, the highest capacity improvement can be attained by the overlay DF approach (up to 83%), followed by the overlay AF and underlay approaches (up to 68%) and the interweave approach (up to 65%). It is interesting to observe that higher capacity improvements can be attained by those approaches requiring more channel information, thus leading to a trade-off between the amount of channel information available and the capacity improvement that can be expected. In any case, the example shown in Figure 10 illustrates the extent to which the overall system capacity can be improved by means of flexible spectrum utilization based on cognitive approaches.

Horizontal spectrum utilization

In horizontal spectrum utilization all the terminals have the same right to access the spectrum and it is the responsibility of the spectrum utilization function to provide a fair spectrum access to the coexisting cognitive users and/or networks. The main purpose of horizontal spectrum utilization is to coordinate the access of a group of CR users/networks to the available spectrum holes, determining who and when will access which channel, in order to prevent multiple users from colliding in overlapping portions of the spectrum. To some extent, this problem is similar to the Medium Access Control (MAC) problem in conventional wireless communication systems. However, existing MAC methods are in general inappropriate for CR systems due to some particular problems not present in other wireless systems. First, CR users need to coexist not only among them but also with incumbent users. While collisions among cognitive users are undesirable but acceptable within some limits, collisions with incumbent users are absolutely unacceptable and must be avoided. Moreover, while conventional wireless systems have a certain amount of spectral resources (channels) to share among the wireless users, which in general is fixed and known beforehand, the resources available to a CR system may change constantly in an unpredictable manner. In the worst possible case, there may be no channels to allocate to the CR users if all the spectral resources are used by the incumbent system. Furthermore, the same licensed band may be accessed opportunistically by cognitive users belonging to different CR systems or networks without a predefined or established inter-network communication mechanism. The particular characteristics and issues of CR systems require specific spectrum utilization solutions. Horizontal spectrum utilization solutions can be broadly categorized according to the architecture, access behavior and scope/field of application.

Architecture

According to the architecture, horizontal spectrum utilization solutions can be classified as centralized or distributed. In centralized solutions, a central entity controls and decides the user/network that is granted access to the spectrum based on a set of selected access procedures. The central entity can collect reports and measurements from a set of distributed nodes and use this information to build up a spectrum allocation map according to a predefined policy, which is then communicated to the CR users/networks. On the other hand, in distributed solutions, each CR user or network decides when and how to access the spectrum based on their own observations and a local or global spectrum access policy.

Access behavior

Based on the access behavior, horizontal spectrum utilization solutions can be classified as cooperative or non-cooperative. Cooperative solutions decide on the spectrum allocation taking into account the potential impact on other CR users. Cognitive users exchange information (*e.g.*, interference measurements) that is taken into account in the spectrum allocation and access decisions. While centralized solutions can in general be regarded as cooperative, distributed cooperative solutions can be possible as well. On the other hand, in non-cooperative solutions CR users do not exchange information and decide on the spectrum allocations in a selfish manner without considering the effect of a particular spectrum allocation on the rest of CR users. In general, cooperative approaches outperform non-cooperative strategies **[123]** but the minimal communication requirements of the latter and the resulting lower energy consumption make non-cooperative schemes attractive in some practical scenarios.

Scope/field of application

According to the scope/field of application, horizontal spectrum utilization solutions can be classified as inter-network solutions or intra-network solutions. The aim of internetwork solutions is to enable the coordinated coexistence of multiple CR systems or networks being deployed in overlapping spectrum and location areas. On the other hand, intra-network schemes are aimed at coordinating spectrum access among the entities (i.e., terminals or users) inside the same CR system or network.

Traditionally, inter-network spectrum utilization has been dictated by the regulatory bodies via static frequency allocations. However, spectrum utilization among multiple CR systems poses unique challenges that have not been considered before in wireless communication systems and require alternative, more flexible solutions. Existing solutions for inter-network spectrum utilization can be categorized into centralized and distributed schemes.

Centralized inter-network spectrum utilization commonly relies on a central entity that plays the role of a spectrum broker deciding which spectrum is allocated to each CR network. A spectrum broker is a central network entity that controls the spectrum utilization among different cognitive networks. A spectrum broker can be connected to each network and can serve as a spectrum information manager to enable coexistence of multiple cognitive networks. One option is to deploy a Spectrum Allocation Server (SAS) equipped with CR capabilities that senses the surrounding environment and acquires spectrum utilization information in its coverage area. Upon request, the SAS allocates the available spectrum to overloaded vendors (*i.e.*, service providers such as wireless operators) **[124]**. Another option is the definition of a spectrum auction framework where a Spectrum Policy Server (SPS) performs the centralized allocation of available spectrum in a specified geographical region **[125]**. In this scheme, the operators dynamically compete for customers as well as portions of available spectrum. The operators bid for the spectrum indicating the amount they are willing to pay for a given portion of spectrum and for a given time interval. The SPS then decides the spectrum allocation to each operator maximizing its profit from the bids received. Through demand responsive pricing, the operators try to come up with convincing service offers for the customers, while trying to maximize their profits. Users then select which operator to use for a given service type. Spectrum auction frameworks are aimed at achieving conflict-free spectrum allocations that maximize auction revenue and spectrum utilization **[126]**. The design of such frameworks involves compact bidding languages, pricing models to control trade-offs between revenue and fairness as well as fast auction clearing algorithms to compute revenue-maximizing prices and allocations.

Distributed inter-network spectrum utilization commonly relies on a Common Control Channel (CCC) that is used to coordinate distributed spectrum reservations and exchange information among various CR systems on the current spectrum in use. An example of such CCC is the CPC (Cognitive Pilot Channel). Although the CPC was not specifically designed for the spectrum utilization problem, it can actually be employed as a mechanism to report the spectrum usage of various wireless systems, including the CR systems present in a certain geographical area. This information can be employed by the terminals of other CR systems to select in a distributed manner a spectrum band not used by any other wireless (incumbent or cognitive) system.

Another example of CCC is the CSCC etiquette protocol proposed in **[116]**. The Common Spectrum Coordination Channel (CSCC) protocol coordinates radio nodes of different wireless technologies in a proactive way, where a common spectrum coordination channel at the edge of the available spectrum bands is allocated for announcement of radio parameters (*e.g.*, node identifier, center frequency, bandwidth, transmit power, data rate, modulation type, data burst duration, interference margin, and service type). Each node is equipped with a low bitrate, narrow-band control radio for listening to announcements and broadcasting its own parameters in the CSCC channel. Radio nodes receiving CSCC control information can then initiate appropriate spectrum utilization policies such as First-Come First-Served (FCFS), priority-based utilization or dynamic pricing auction, to resolve conflicts in spectrum demand and share the resources more efficiently. The hidden-receiver problem can also be solved because the range of the CSCC can be designed to exceed that of regular service data and CR terminals can also explicitly announce their presence. It has been shown that a simple CSCC implementation can be used to significantly reduce interference between 802.11b and Bluetooth devices operating in close proximity **[116]** and enable spectrum coexistence between short-range IEEE 802.11b and wide area IEEE 802.16a networks **[127]**. Another example of CCC is the Distributed QoS-based Dynamic Channel Reservation (D-QDCR) proposed in **[128]**, which allows base stations of different networks not only to compete among them and reserve spectrum based on data volumes or QoS demands but also to distribute the allocated spectrum to the internal CR terminals.

Intra-network spectrum utilization solutions can also be classified into centralized (infrastructure-based) and distributed (ad hoc) schemes. While centralized solutions are mainly based on cooperative schemes **[129][130]**, distributed methods can be cooperative **[131]**–**[136]** or non-cooperative **[137]**–**[139]**. The number and variety of existing solutions is notably prominent, including methods for both infrastructure-based and ad hoc networks based on random, time-slotted and hybrid protocols **[140]**, **[141]**. However, they are frequently based on ideas and principles that have been borrowed from already existing MAC solutions developed for conventional wireless systems such as, for example, the Request-To-Send (RTS)/Clear-To-Send (CTS) and Network Allocation Vector (NAV) concepts of the IEEE 802.11 MAC protocol, busy tones, beacon signals and clustering methods. A significant number of intra-network spectrum utilization solutions for CR systems are based on variations and adaptations of classical MAC methods, which are modified to cope with the particular characteristics and issues of CR systems.

It is worth noting that inter- and intra-network spectrum utilization solutions are not necessarily mutually incompatible. Some inter-network solutions can be applied to allocate spectrum at the network level and decide how to share a certain amount of spectrum among several CR systems, while intra-network solutions can then be employed to allocate spectrum at the terminal/user level and arbitrate the access of users inside the same CR system.

4.1.1.3 Spectrum Fragmentation and Aggregation

Within heavily used incumbent spectrum allocations, there are a high number of operational activities to activate, deactivate or relocate carriers resulting in often undesired fragmentation and un-utilized spectrum blocks. The possible applications of cognitive radios could provide substantial benefits within the incumbent spectrum allocations by overcoming the problem of spectrum fragmentation in various ways. Spectrum aggregation has recently received much attention due to the rapid increase of services. This technique makes it possible for multiple fragmented spectrum gaps or even spectrum bands to be utilized by the same user in order to satisfy large bandwidth service demands and achieve better performance. In this way, the discrete spectrum holes can sustain information flows in the same way as a contiguous portion of spectrum.

An important problem in spectrum aggregation is to provide homogeneous information communication by taking advantage of non-contiguous spectrum gaps with potentially different properties. Considering the use of non-contiguous spectrum gaps with different properties to fulfill the bandwidth requirements of users, the most difficult tasks are maximizing the information flow as well as guaranteeing the reliability of the information flow by spectrum aggregation and scheduling.

Spectrum aggregation is a communication method that makes possible the transmission of integral information flows through discontinuous spectrum gaps with different properties. A proper scheduling scheme is necessary to facilitate communication using non-contiguous spectrum gaps with the same average error and delay performance as that using contiguous spectrum communication.

One of the key technologies for spectrum aggregation is the use of Non-Contiguous Multi-Carrier Modulation (NC-MCM) schemes that can turn on/off each subcarrier arbitrarily. This approach can be used to enable the exploitation of non-contiguous spectrum gaps by switching off those subcarriers that overlap with the busy regions of the spectrum and that would therefore cause interference. The most popular physical-layer technique for realizing this approach is Orthogonal Frequency-Division Multiplexing (OFDM). OFDM allows transmissions in vacant channels and avoids interference to active ones by placing data zeros in the appropriate IFFT bins.

Another important component of spectrum aggregation is scheduling, which tries to achieve the same performance as contiguous spectrum bands by carefully selecting the transmissions. The scheduler is in charge of assigning spectrum resources for the transmission of information flows at the transmitter. At the receiver side, the information flows received through different channels will need to be combined into the single original information flow.

In the terrestrial domain, spectrum aggregation has been identified as promising and candidate technology for future LTE-advanced systems. During the evolution from LTE to LTE-advanced, the most influential factor is the demand for wider radio spectrum band. As a result, 3GPP proposed the spectrum aggregation technology (which is also referred to as *carrier aggregation* in LTE-advance standards). It aggregates several carriers into one wider channel, regardless of whether these carriers or spectrum fragments are contiguous or non-contiguous. The bandwidth that the LTE-advanced system is able to support is 100 MHz, while the LTE system can only support 20 MHz. Spectrum aggregation (carrier aggregation) in LTE-advanced permits several carriers of the LTE system to be aggregated into one wider channel in order to provide the up to 100 MHz channels that support high data rates and exploit spectrum more efficiently.

The progress of spectrum/carrier aggregation mainly focuses in the following aspects **[265]**:

- *design of guard bandwidth between carriers* **[266]**. When the aggregated LTE carriers are in contiguous frequency bands, it may be possible to reduce reasonably the guard bandwidth between carriers in order to improve the spectrum utilization efficiency;
- *selection of carrier bandwidths* **[267]**. In the process of spectrum aggregation, it should be taken into consideration that both the aggregated carriers in LTE and the wider channel in LTE-advanced have different bandwidths. Consequently, there are several feasible alternatives of aggregation in order to obtain the desired total bandwidth. For example, a total bandwidth of 30 MHz can be achieved by means of different combinations of aggregated bandwidths: 30 MHz = 20 MHz + 10 MHz = 20 MHz + 5 MHz + 5 MHz, etc. In order to reduce the design complexity of transceivers, the concept of bandwidth factor is proposed, which indicates the multiple relationship between the bandwidth of aggregated carriers in LTE (e.g., when the bandwidth factor is 2, we can only choose the solution 30 MHz = 20 MHz + 10 MHz where the factor between the aggregated bandwidths is 20 MHz / 10 MHz = 2). The proposal of bandwidth factor can restrict the number of alternative options for spectrum aggregation and hence reduce the design complexity of transceivers to a great extent;
- *aggregation of data streams* **[266]**. In the process of spectrum aggregation, each carrier corresponds to an independent data stream. Data streams can be aggregated at either the physical or MAC layers;

- *design of control channels* **[267]**. The design of control channels should be considered carefully in the technology aggregation since these channels carry the relevant information required to reconstruct the original data stream from the individual data flows received through different channels. Control channels can be implemented in different ways (e.g., including headers in the packets of each individual channel, devoting a specific channel for the transmission of control info, etc.).

The problem of spectrum fragmentation and the corresponding spectrum aggregation solutions have arisen and been extensively studied mainly in the context of the LTE technology. However, many of problems faced by spectrum aggregation approaches can be found in general in any fragmented spectrum band and therefore the same principles and ideas could potentially be applied to solve the problem of spectrum fragmentation is SatComs.

4.1.1.4 Summary of CR techniques

The Table below summarizes the merits and challenges of the main CR techniques in spectrum utilization awareness and utilization.

Table 4 - Merits and challenges of the different CR techniques

Cognitive Radio Techniques		Merits	Challenges
Interweave	Spectrum Sensing	▪ Seamless interruption-free end-to-end communication with defined availability for incumbent links ▪ Identifies spectrum opportunities in different domains such as frequency, time, space and angular positions for enhancing capacity of cognitive networks ▪ Dynamic spectrum allocation ▪ Allows adaptive cognitive transmission over wide bandwidth ▪ Best choice for high interference region.	▪ Weak signal Detection ▪ Wideband and advanced front-ends required for detecting wideband signals ▪ Hidden node problem ▪ No prior knowledge of interference/noise uncertainty ▪ Sensing time and throughput and energy efficiency multiple trade-offs ▪ Complexity
	Database	▪ Higher technology readiness level ▪ Centralized solution ▪ Already considered by regulators and companies like Spectrum Bridge for TV whitespace solution	▪ Static spectrum assignments ▪ Requirement of third party for database management ▪ Accurate prediction models and history information required
Underlay		▪ No need of spectrum holes ▪ Efficient use of available spectrum ▪ Existing interference mitigation techniques such as beamforming, interference alignment and other spread spectrum-based as well power control techniques are easily applicable in an underlay mode.	▪ Requirement of knowledge about CSI/location/interference threshold ▪ Constrain induced interference within regulatory limits ▪ Synchronization issues ▪ Not suitable for high interference region.
Overlay		▪ Mutual Benefit (cognitive transmits incumbent message as well) ▪ No need of spectrum holes ▪ Network-wide knowledge ▪ Applicable for high as well as low/medium interference regions. ▪ This approach is applicable for both the licensed (sharing) and unlicensed (only cognitive) band communications.	▪ Requirement of incumbent users' codebooks and message as well. ▪ High level of coordination ▪ Requirement of advanced transmission and coding schemes ▪ Information-theoretic approach and difficult to realize in practice. ▪ Security Aspects

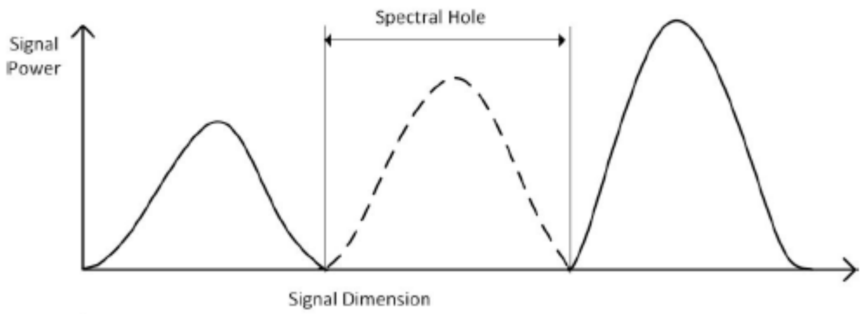

Figure 11 - Interweave Techniques (With "interweaving," the cognitive users are able to occupy the portions of the spectrum left temporarily free by the incumbent users.)

Note that "Spectrum Sensing" and "Databases" are specific CR techniques falling under the (more general) category of "Interweave" CR techniques.

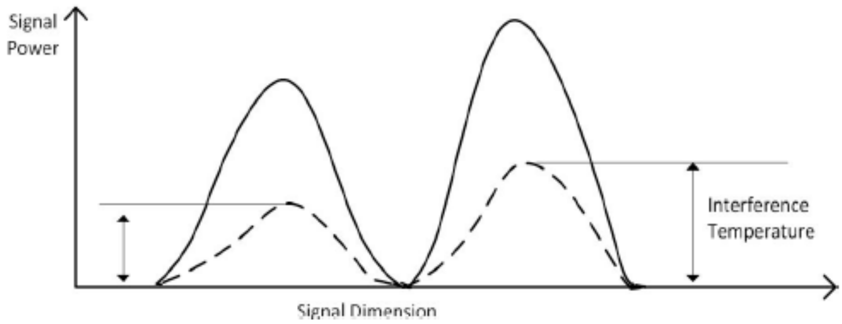

Figure 12 - Underlay Techniques (In the "underlay" paradigm, the cognitive transmitter overlaps in frequency with the incumbent user, after making sure that the interference level it causes is below a given threshold.)

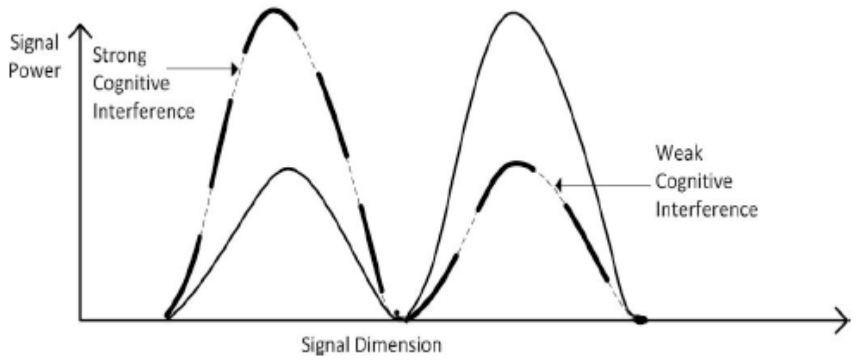

Figure 13 - Overlay Techniques (The "overlay" paradigm uses the cognitive user's knowledge of the incumbent users transmission scheme and of the channel to choose a transmission scheme that causes an acceptable amount of interference.)

4.1.2 Satellite CR Techniques

The existing satellite cognitive literature can be categorized into following three types depending on the coexistence scenario: i) Hybrid satellite-terrestrial scenario; ii) Dual satellite Scenario; and iii) others (which are applicable for both scenarios). The references **[4]-[50]** are closely related to hybrid satellite-terrestrial scenario, the references **[51]-[56]** are closely related to dual satellite context and references **[57]-[62]** are generic and can be applicable to both scenarios. We review the existing literature related to above scenarios in the following subsections.

4.1.2.1 *Hybrid Satellite-Terrestrial Scenario*

In **[4]**, the problem of exploiting SS techniques for a dual polarized fading channel has been considered. Since dual polarized channel is getting important attention in current state-of-the-art related to cognitive communication, it remains an open challenge to explore the best SS technique in this channel. In this context, in **[5]**, performance analysis of an ED based SS technique in a dual polarized fading channel using different combining techniques such as SC and EGC has been considered. Starting with single antenna case, analytical expressions for probability of detection and probability of a false alarm have been presented for these techniques in AWGN, SIMO and MIMO Rayleigh fading channels. Then the sensing performance of these techniques has been studied through analytical and simulation results in a dual polarized fading channel. The simulations as well as theoretical results show that the performance of ED technique in a MIMO fading channel is much better than in SIMO and SISO fading channels. Furthermore, the effect of cross polar discrimination (XPD) on SS efficiency has been analyzed and it has been concluded that the detection performance in a dual polarized fading channel increases with the value of cross polar ratio (XPR) and its lower and upper bounds occur for a SIMO fading channel and an ideal MIMO fading channel respectively.

In **[5]**, different cognitive techniques such as underlay, overlay, interweave and database related techniques have been discussed with their salient features by reviewing the current state-of-the-art. Different transmission modes for hybrid satellite/terrestrial cognitive scenario have been presented. Exact beam patterns of a multi-beam satellite have been plotted over the map of Europe and interference modelling between terrestrial Base Station (BS) and satellite (SAT) terminal has been carried out on the basis of interference power level. Based on results obtained from the interference modelling between terrestrial BS and SAT terminal, it has been observed that satellite terminals near polar region get more interference from a terrestrial BS than the SAT terminals located near the equator due to variation in elevation angle. Furthermore, it has been concluded that different cognitive techniques can be considered based on interference power level. SS and DB techniques seem to provide best performance in high interference region and in low or medium interference region, interference from cognitive system to incumbent system can be suppressed by using some form of underlay technique. Although the overlay technique can be used in both high interference and low interference scenario by using advanced coding and suitable modulation, it appears to be suitable only for integrated systems with very high level of interaction.

In the field of satellite communications, the main available literature related to cognitive techniques has considered hybrid or integrated satellite networks. In both the hybrid and integrated scenarios, a satellite system based on DVB-SH has been taken as an incumbent system and terrestrial wireless networks are cognitive systems **[6]**. In hybrid satellite-terrestrial network, the network management of the satellite and the terrestrial component is performed separately with the collaboration of a satellite and a terrestrial operator, whereas, in an integrated system, the network management is carried out by a single entity.

In **[7]**, the convergence of mobile, fixed and broadcasting systems has been considered by taking into account the possibility of co-existence of future satellite networks with terrestrial systems. The architecture of integrated network and a discussion on the technical challenges for its realization has been presented in **[7]**. Cross-layer based simulation results of physical layer interaction with the application layer are presented for a hybrid network and the effect of fading on dynamic resource allocation and QoS parameters, i.e., delay and jitter on different multimedia applications has been studied. Satellite component of NGN for hybrid and integrated networks has been presented in **[8]**. In this paper, the design of integrated/hybrid systems taking into account of physical, MAC, and network layers issues has been presented and cooperative diversity techniques as well as traffic engineering issues for overflow traffic has also been discussed. Two hybrid satellite-terrestrial wireless network scenarios have been considered. One scenario is SATCOM network connected with WiMax terrestrial segment and another scenario is SATCOM network with a WiFi terrestrial segment. In the first scenario, the considered DVB-S2 terminal is fixed while the user device is either fixed or nomadic. The satellite is GEO with Multibeam Broadband Satellite (MBS) links based on DVB-S2/-RCS. DVB-S2 has been considered for the forward link and DVB-RCS for the return link in SATCOM network. Furthermore, this paper considers cross-layer design based simulation framework in order to analyze the impact of rain fade and mitigation due to DVB-S2 on the multimedia applications for above two scenarios. Furthermore, the advantage of cross layer design in system capacity gains for VoIP users in hybrid network with WiMAX as terrestrial segment has been presented. In the second scenario, the interconnection of a satellite DVB-RCS network with WiFi based on the IEEE 802.11e standard has been considered. The WiFi network in this scenario can be used to provide a local coverage on a plane, a train, or a ship. The scenarios considered in this paper can be put under underlay scheme.

The coexistence and integration of satellite and terrestrial networks on the same frequency bands can exploit an additional degree of freedom **[9]** for spectrum utilization purpose. It has been mentioned in **[9]** that since the satellite is seen at a high elevation angle (depending on latitude), a proper design of antenna radiation diagrams can allow to reduce mutual interference and enable cognitive frequency reuse. In **[10]**, a cognitive application scenario has been considered in terms of UWB SATCOM, in which satellite services can use the unoccupied bands of terrestrial multiband UWB spectrum on cognitive basis.

A satellite/terrestrial integrated mobile communication system operating in the S-band has been considered in **[11]**. In this paper, it has been stated that such a system can be used to achieve dual communication and can connect to both terrestrial and satellite systems, with a common terminal being used for both systems. Two frequency allocation methods i.e. normal mode and reverse mode have been considered with the conclusion that normal mode has advantage over reverse mode in terms of interference issues. The Earth station and the base station are both equipped with a controller, simultaneously managed by a common controller in a core network. By using different frequency plans, cluster configurations, satellite beam designs, and widths of the spatial guard band, simulations have been carried out to maximize the spectral efficiency.

Recently, transmit diversity techniques have been proposed for integrated networks, using repeaters as the ground components with appropriate signal processing capabilities. An efficient diversity technique using Space-Time Coding (STC) for an integrated MSS system has been proposed in **[12]**. In this system, ground components are terrestrial repeaters that cooperate with the satellite to transmit space–time coded signals. Synergies between terrestrial and satellite systems can be used to reduce fade margins in satellite communications operating under fading conditions by implementing multi-radio diversity **[13]**.

An integrated system composed of a Complementary Ground Component (CGC) and a multibeam Satellite Based Network (SBN) has been considered in **[14]**. This paper presents a model of an integrated mobile network composed of a multibeam fixed satellite, terrestrial base stations for mobile users and hybrid satellite/terrestrial user terminals. Both systems are considered to operate at L- or S-band and both systems are assumed to be controlled by the same resource management module. Satellite system has been considered to be incumbent and terrestrial system to be cognitive. This system can be considered as underlay cognitive scheme. It has been mentioned that satellite frequency can be reused by terrestrial users based on the Exclusion Zone (EZ) principle by defining exclusion zones around each satellite spot beam. This paper mainly deals with the interference scenario in which the uplink terrestrial signals interfere with the uplink satellite signals. In using EZ principle, it has been found that the most harmful cases of inter-component interferences on the satellite uplink are caused by a small number of terrestrial users, which are close to EZ border, in LOS (Line-of-Sight) of the satellite and radiating with high power values. Using proper cognitive techniques and dynamic channel allocation mechanisms, the analysis in **[14]** concluded that the interference effects in such integrated systems can be reduced.

In **[15]**, the considered scenario is constituted by an incumbent licensed system and a cognitive system whose terminals implement cognitive resource allocations. A mobile satellite system compatible with DVB-SH standard has been considered as incumbent system in the considered scenario and an infrastructured (*i.e.*, all the cognitive terminals communicate with a local base station) wireless terrestrial network is considered as a cognitive system. These two systems are considered to operate in the L band frequency spectrum (0.39-1.55 GHz). For the satellite based incumbent system at L band, Lutz propagation model has been considered and multipath fading channel has been considered for terrestrial wireless network. Furthermore, two approaches, heuristic and Game theory based approaches, have been considered for incumbent spare resource allocation. The results have shown that heuristic method achieves higher rates, although it cannot be implemented in a distributed way like Game Theory based allocation.

There are more than 160 FSS geostationary satellites operating in C-band. Satellite operators are using the C-band globally to provide essential telecommunication services. In many countries it serves as the core network for national and international communication. Certain new terrestrial IMT 2000 services are designated by the International Telecommunication Union (ITU) to use the same spectrum which could cause interference in satellite downlinks. Interference is the main threat to satellite downlink performance because harmful signals originate from the terrestrial wireless application from many locations, in all directions **[16]**. Many satellites today operate communication channels in other higher frequency bands but carry out telemetry operations (Telemetry, Tracking and Control) in C-band. In **[16]**, a hypothesis about interference effect on satellite downlink receivers is proposed and then the hypothesis is confirmed with experimental results. This study show that when no particular shielding or blocking with the respect to the interfering signal can be guaranteed, the minimum required separation distances would be 140 Km. Furthermore, it is claimed that co-existence between FSS and IMT 2000 is more difficult without using interference mitigation techniques.

Since a satellite system relies on coverage beams that cover a wide area, frequency coordination between the satellite and terrestrial systems is essential to utilize the spectrum properly. The possibility of utilizing the same frequency band between satellite and terrestrial networks in Ka-band has been studied in **[17]**. It has been noted that for satellite systems using Ka-bands, spectrum efficiency can be increased by considering off-axis angles of the Earth station antennas. This paper also analyzes the interference between Geostationary Satellite Orbit (GSO) and terrestrial services at 19 GHz frequency band.

In **[18]**, an advanced high-capacity Ka-band satellite that can ubiquitously extend the reach of broadband services to areas unserved or underserved by terrestrial networks is proposed. The advantages of Ka-band are large bandwidth, small antennas, and reduced interference potential. The challenges in this band include significant propagation induced impairments and new development costs for both satellite and terminals **[18]**. In order to utilize the satellite resources in an efficient manner, adaptive modulation techniques and cognitive techniques need to be applied. Various techniques such as site diversity for gateways, large user antennas for critical applications, advanced adaptive modems to reduce bit rate, code rate and modulation efficiency, enhanced satellite EIRP for forward link can be applied to reduce the effect of rain fade in this band. In **[19]**, the use of Mobile WiMAX (IEEE 802.16e) as terrestrial multicast/broadcast segment for the delivery of multimedia content to mobile users in DVB-SH networks is investigated. Symbiotic Mobile WiMAX and DVB-SH architecture are presented and key issues are listed.

In **[20]**, an adaptive space-time signal processing technique comprising interference suppression and multi-user detection in a CDMA Mobile Satellite System (MSS) environment is presented. Optimum beam-forming technique based on a Minimum Mean-Squared Error (MMSE) performance index is used to maximize the SINR of MSS links in an environment of significant terrestrial reuse of the satellite service link frequencies by Ancillary Terrestrial Components (ATCs). It has been shown that the technique substantially mitigates both ATC-induced cochannel interference and Multiple-Access Interference (MAI). Furthermore, at the satellite gateway, a pilot-based MMSE algorithm is used to adaptively form an optimum return-channel beam for each user by processing the raw antenna feed element signals provided to the satellite gateway by a satellite return feeder link.

In **[21]**, the construction of the coordination contour for mobile (except aeronautical mobile) Earth stations operating in frequency bands shared with the terrestrial services has been examined. Consequently, a new method of developing the coordination contour is proposed for this type of stations. It is argued that the adoption of this method could contribute considerably to the development and wide use of mobile Earth stations and eases the harmonic coexistence of this service with the terrestrial services.

The interference problem between satellite terminals and co-channel terrestrial services was addressed back in 1961 **[22]**. In **[23]**, a power allocation scheme for satellite terrestrial hybrid network based on game theory has been proposed. A DVB-SH based satellite network has been considered as the incumbent system, while an infrastructured wireless terrestrial network has been considered as a cognitive system. It has been shown that the proposed approach is suitable for distributed implementation; furthermore it provides performances comparable to a heuristic power allocation method representing the optimum scheme.

In **[24]**, the coexistence issues of Broadcasting Satellite Service (BSS) and the Fixed Service (FS) within the same spectrum band have been discussed. Although regulatory institutions have issued general guidelines concerning future systems, the effect of frequency utilization by numerous operating satellite Earth terminals should be examined. This paper proposes an analytical methodology for the prediction of the carrier-to-noise plus interference ratio (CNIR) of BSS systems, suffering from interference from an adjacent terrestrial link at frequencies above 10 GHz. The proposed model takes into account the aggravation of intersystem interference due to the spatial inhomogeneity of precipitation and a simplified version of the analytical model along with some case studies is presented.

In **[25]**, the coexistence scenario of BSS and Multi-channel Multipoint Distribution Systems (MMDS) has been considered. With the development of MMDS working on the same frequency band as the BSS, and theoretically with identical technical parameters, an important question arises of how to set up the parameters of terrestrial distribution systems so that their coexistence with satellite systems is enabled while at the same time terrestrial systems are not made technically too limited. In this context, **[25]** presents the results of practical measurements performed on MMDS and BSS systems. From the analysis of the empirical measurements and calculations, it is concluded that following parameters significantly influence such coexistence: the geographical position of BSS and MMDS transmitters, symbol Rate, code Rate, MMDS transmitter Frequency, and MMDS transmitter power.

In **[26]**, a cost-effective wireless broadband service provision from High Altitude Platforms (HAPs) is proposed with an economical business model design. Different deployment strategies of HAP system are illustrated in terms of a stand-alone HAP system and in collaboration with terrestrial or satellite systems. The major advantages of the system are claimed to provide wide coverage area and cost-effective deployment in conjunction with terrestrial or satellite systems.

In **[27]**, a satellite assisted cognitive radio architecture consisting of a LEO satellite and Smart Base Station (SBS) has been considered. A novel protocol has been proposed to combat the hidden incumbent problem during network entry, initialization and handover, while at the same time taking the mobility pattern of the cognitive devices into consideration. It is argued that the proposed model outperforms the current IEEE 802.22 scheme and other work in the literature in terms of connection setup delay.

In **[28]**, the performance of a cognitive communication to the coexistence problem of a meshed OFDM-based cognitive wireless service in coexistence with an incumbent terrestrial and satellite DVB-SH system has been evaluated. It is claimed that performances in terms of rate for the cognitive system under scenarios of terrestrial and hybrid satellite/terrestrial can maximize cognitive bit rate by maintaining unchanged the target performances of the corresponding incumbent service.

In **[29]**, another concept on HAP driven smart radios (HDSRs) is presented where CR devices are dynamically configured and policies for dynamic spectrum access are applied with the help of a HAP and a back end satellite subsystem. It has been claimed that the proposed concept aims to address some of the issues in the network-side efficiently and with minimal impact on the legacy network and CR end devices.

In **[30]**, another satellite-based spectrum sensing method for cognitive radio networks (CRNs) is proposed using a multibeam satellite in large-scale coverage ground areas. It has been mentioned that using simple linear transformation and energy detection at the satellite multibeam receiver, spectrum sensing can be simultaneously performed for multiple cells and this approach overcomes the limitations of the traditional sensing method, which therefore considerably improves the spectrum utilization. The paper concludes that satellite-based spectrum sensing method is very efficientfor the CRNs in large-scale scenarios under different conditions (equivalent signal-to-noise ratio, threshold, antenna beam pattern, etc.).

Different frequency utilization studies have been carried out considering the coexistence of satellite and terrestrial services within the same spectrum. In **[31]**, field test measurements have been carried out to study WiMax frequency utilization with FSS stations. The measurement results show that the criteria where FSS antennas cannot co-exist with WiMAX systems ranges from 50 to over 200 Km depending upon the local terrain. Reference **[32]** includes the ITU-R recommendations considering the utilization studies between IMT-Advanced systems and geostationary satellite networks in the FSS in 3400-4200 and 4500-4800 MHz frequency bands. Similarly, reference **[33]** studies the compatibility of services using WiMAX technology with satellite services in the 2.3-2.7 GHz and 3.3-3.8 GHz bands. Furthermore, reference **[34]** includes the utilization studies between Aeronautical Earth stations on Mobile Platforms (ESOMP) and FS operating at Ka-band.

The work in **[38]** proposes a radio interface and radio resource management (RRM) strategy for delivery of multicast/broadcast services via an integrated satellite-terrestrial system. This approach resulted from work carried out within the EU SATIN project. A system architecture concept is proposed, which includes new satellite elements in the standardized 3GPP MBMS architecture, in order to enable a satellite broadcasting service. Moreover, a strategy for the RRM is proposed, as well as adaptations of the different layers in the 3GPP MBMS architecture. This is all done by having as few changes in the 3GPP standard as possible, while enabling satellite broadcasting to terrestrial mobile devices.

In **[44]**, a space-frequency coding technique is proposed for dual polarized hybrid mobile systems. The satellite and the terrestrial repeater, equipped with polarized antennas, transmit same data to a mobile terrestrial user with polarized antennas that uses the ML decoder. By using 2x2 full rate full diversity codes across the dual antennas in the satellite and terrestrial repeater, a diversity gain of 4 is achieved.

Moreover, it is maintained that the hybrid system achieves a higher coding gain compared to satellite only/terrestrial only transmissions.

The work in **[41]** investigates a satellite relaying scenario, where complementary ground components act as relays to the destination. The satellite and the relays transmit the same signal to an Earth receiver. The signals arrive with different delays at the receiver, thus resulting in a frequency selective single input single output (SISO) model at the receiver. This increases the frequency selectivity and enables improved performance, as claimed by the simulation results in the paper. In **[39]**, the work from **[41]** is extended to also include channel estimation, by using the cyclic left sample-shift technique in order to estimate the frequency response of the resulting frequency selective SISO channel. This technique results in no performance degradation of the cooperative relaying technique, while it simplifies the channel estimation at the receiver.

A game theoretic approach to spectrum utilization between a LEO satellite and terrestrial CRN is pursued in **[47]**. The goal for each player is to maximize its achievable rate. A new scheme for spectrum utilization is derived, which is proposed to be the optimal one from a game theoretic point of view.

In **[40]**, an architecture for terrestrial relaying of a real-time IP multicast audio-video stream broadcasted by a satellite is proposed. The stream is sent by an audio-video streamer to the satellite, which broadcasts the streams. The idea is to have some terrestrial sites receive the satellite signal, and relay it to sites that are not equipped with a satellite receiver. Only a description of the architecture along with implementation details is presented.

Deployment of IMT-Advanced systems on FSS in C-band in Pakistan is investigated in **[45]**. Several well-known techniques mitigating interference from IMT-Advanced base stations to FSS Earth stations are described. The conclusions are that separation distances between the base stations of IMT-Advanced and the Paksat FSS receive Earth stations is required. The magnitude of this separation depends on the parameters of the networks, the protection criteria of concerned Paksat satellite networks and the deployment of the two services, and if the two services operate in the same or in adjacent frequency bands.

4.1.2.2 Dual Satellite Scenario

In **[51]**, the problem of enhancing Spectrum Sensing (SS) efficiency in the context of cognitive satellite communications (SatComs) has been considered and the polarization domain has been exploited as an additional degree of freedom to explore efficient SS and transmission schemes. By deploying two orthogonally polarized antennas, any type of receive or transmit polarization can be derived. Detecting the polarization state in addition to energy of a certain carrier frequency can significantly enhance the spectrum efficiency by investigating suitable cognitive techniques in the polarization domain. In this direction, the analysis of different combining techniques has been carried out for SS using a dual polarized antenna. Furthermore, polarization states of the received signals have been exploited and based on obtained polarization states, Optimum Polarization Based Combining (OPBC) technique has been used for carrying out SS in the satellite terminal equipped with a dual polarized antenna. The sensing performance of the proposed OPBC technique has been compared to Selection Combining (SC), Equal Gain Combining (EGC) and Maximum Ratio Combining (MRC) techniques. With the help of simulation results, it is maintained that the OPBC technique achieves a significant improvement in sensing performance over other considered techniques at the expense of complexity in a dual polarized AWGN channel.

In **[52]**, a partial cooperation between two coexisting transmitters is proposed in order to reduce interferences and enhance the performance of whole system in the context of dual satellite systems.

Consequently, a heuristic, iterative and low complexity algorithm is presented to allocate users in the two interfering sets. It is claimed that the proposed algorithm improves the performance of each satellite by maximizing orthogonally between users allocated in the same set and the overall system performance improves by minimizing the level of interference between two sets.

In **[53]**, the analysis of the interference between complementary ground component (CGC) base station and mobile Earth station (MES) has been carried out for frequency utilization purpose in satellite systems. In the frequency utilization scenario between CGC base station and MES, the interference from the adjacent beams must be considered. In this paper, the interference to MES of an integrated satellite system has been estimated and the result is presented as the carrier to interference ratio(C/I) with respect to the number of CGC base station in the adjacent beam and the ratio of satellite beam center radius to the total beam radius. It has been claimed that the minimum separation distance between the CGC base stations of adjacent beam and MES can be determined using presented results.

In **[54]**, the problem of distributed power control has been considered for cognitive satellite networks. A utility function that measures the user's satisfaction, as a function of signal to interference plus noise ratio has been defined and then a distributed power control algorithm has been proposed based on the defined utility function. It has been concluded that the proposed algorithm can guarantee the protection of the incumbent user and meet quality of service requirements of the cognitive users.

In **[55]**, the frequency utilization of HAPS gateway links with the uplinks of FSS in 6 GHz band has been studied and interference from the HAPS gateway uplinks into the FSS uplink has been evaluated.

In **[56]**, utilization alternatives for up to four CDMA MSS operating in the same frequency bands have been investigated. Consequently, the analysis has been presented for both downlink and uplink cases. It has been concluded that 4 CDMA systems may share the same band and terminal specifications are a determining factor to success of the sharing.

4.1.2.3 Other Satellite CR Techniques

In **[57]**, starting with the rationale of cognitive communication, two different coexistence scenarios have been presented in the context of satellite cognitive communication. The coexistence scenarios mentioned in this paper are hybrid satellite/terrestrial scenario and dual satellite scenario. Furthermore, the benefits and challenges of cognitive SatComs have been provided and possible frequency bands for cognitive coexistence of hybrid and dual satellite networks have been listed. Then stating the importance of spectrum regulation in the context of cognitive SatComs, the current status of spectrum regulation has been presented and the relevant decisions of World Radiocommunication Conference 2012 (WRC-12) have been included. Finally, the technical aspects and regulatory challenges of this technology have been presented and future roadmap from research, industrial and regulatory perspectives has been provided.

In **[58]**, overlaying of a cognitive-user signal over a satellite communication channel occupied by an incumbent user has been considered. The authors attempt to find the jointly optimal transmitter and receiver pair of a cognitive system to minimize the mean squared error (MSE) at the output of the cognitive receiver, subject to zero interference induced at the output samples of the incumbent receiver. It is assumed that both the incumbent and the cognitive transmitters employ linear modulation and the receivers employ linear filter front-ends. The cognitive user is allowed to transmit data symbols at a fraction of the incumbent user's symbol rate and this rate reduction technique enables the cognitive user to achieve the additive white Gaussian noise (AWGN) bound or the performance close to the AWGN bound even when the excess bandwidth of the incumbent user is very small but positive. It has been shown that the proposed scheme significantly improves the spectral efficiency by exploiting the cyclostationarity of the incumbent-user signal. Furthermore, many factors such as frequency selection, modulation schemes and power level should be taken into consideration to capture the variation in radio environment to mitigate the possible interference to other users **[58]**.

In **[59]**, resource management issues in Wireless Heterogeneous Networks (WHNs) have been discussed. This paper explains the market and business cases for wireless heterogeneity and reflects on the most common radio resource management frameworks. Furthermore, this paper explains two network architectures, RIWCoS and the ARAGORN architecture, designed to deal with resource management under various possible access technologies. The RIWCoS architecture is specifically designed to meet the demands of emergency situations, whereas, the ARAGORN architecture introduces the notion of cognitive resource management and policy regulated networking.

Reference **[60]** studies the applicability of cognitive radio technology to satellite communication networks and this study was carried out as part of the ESA project "ACROSS" (see Section 0). In this report, four technical notes are presented. Technical note 1 covers the state-of-the-art of cognitive radio technology and provides a thorough overview of channel models and existing satellite systems. Technical note 2 describes the application scenarios for cognitive radio technologies in future satellite systems. Technical note 3 presents the use cases in the area of application of CR technology to satellite communications and technical note 4 provides technology roadmap for the study area outlining the proposals for future works.

In **[62]**, specific proposals for a dual-satellite MIMO scheme have been studied based on delay-tolerant and spectral-efficient schemes. Furthermore, a hybrid satellite-terrestrial scheme has been studied with specific proposals for MIMO processing. A new mathematical model for multi-satellite transmission has been presented. The analytical models used in this reference may be helpful for the analysis of cognitive coexistence models in both hybrid and dual satellite scenarios.

4.1.3 CR Testbeds, Prototypes and Field Trials

A number of testbeds **[253][254]**, prototypes **[255][256][257]** and field trials **[255][258][259][260]** have demonstrated the feasibility and readiness of the CR technology for insertion into specific commercial and military radio systems in the terrestrial domain. The section provides an overview of some relevant experimental validation activities in the terrestrial domain **[261]**.

- ***Cognitive Radio Network Testbed (Virginia Tech University):*** Virginia Tech staff and graduate students developed a testbed composed of a high number of SDR nodes and backed up by powerful processing power for signal processing[6]. A web-based open access reservation allows researchers to prototype and test CR, SDR and DSA techniques on a large scale environment located in the campus.
- ***Berkeley Wireless Research Center (BWRC):*** BWRC have developed a testbed that allows sensing experiments (particularly cooperative sensing) and prototyping of an indoor CR network[7]. The testbed consists of 18 radio front-ends and is based on the Berkeley Emulation Engine 2 (BEE2)[8].
- ***Network Centric Cognitive Radio Hardware Platform (WINLAB @ Rutgers University):*** The WiNC2R platform has the capability of multi-band fast spectrum sensing, dynamic switching between Orthogonal Frequency Division Multiplex (OFDM) and Direct Sequence

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[6] http://cornet.wireless.vt.edu/trac/wiki/CORNET
[7] http://bwrc.eecs.berkeley.edu/Research/Cognitive/prototyping_platform.htm
[8] http://bee2.eecs.berkeley.edu/

Spread Spectrum (DSSS) systems and several MAC protocols, flexible processing at PHY, MAC and network layers, resulting in bitrates reaching and exceeding 10 Mbps **[262]**.

- ***Implementation of Radio In Software (Trinity College, Centre for Telecommunications Value-Chain Research):*** The platform consists of a software radio engine implemented through a general purpose processor and a hardware front-end, together with a radio manager for real-time reconfiguration of the structure and the characteristics of the software components according to observations and/or triggers coming from the environment **[263]**.
- ***Networking Over White Spaces (Microsoft Research):*** Microsoft Research has deployed a CR network in its campus, which is based on a Wi-Fi like system called WhiteFi, operating on TVWS[9]. The network also uses a geo-location database to obtain information on unused TV channels and avoid harmful interference.
- ***Trial Environment for Cognitive Radio and Networks 2011–2014 (Finnish Funding Agency for Technology and Innovation):*** The main public funding organization for research, development and organization in Finland has identified CR as one of the main driving forces of the wireless technology and of creation of new business opportunities[10]. Therefore, they have recently launched the Finnish Funding Agency for Technology and Innovation (TEKES) programme to create a unique experimentation and test environment for future networks based on CR technology. The license covers the 470-790 MHz frequency range and a 40 km x 40 km area surrounding Turku, Finland. Several projects have already been launched and field trials have been ongoing. Further details can be found in TEKES website under: http://www.tekes.fi/programmes/trial
- ***White Space Rural Broadband Trial on the Isle of Bute:*** In April 2011, a six-partner consortium, with support from the UK government's Technology Strategy Board, started work on a rural broadband trial network that would use white space radio spectrum to provide broadband connectivity to a small community on the south part of the Isle of Bute, Scotland. A key aim was to investigate and demonstrate the potential of white space spectrum for providing broadband access to remote, difficult-to-reach rural areas in challenging terrain. The 18-month project involved the planning and installation of white space radio links from the local telephone exchange to eight premises in the surrounding area, as well as backhaul connectivity from the telephone exchange to the mainland and then on to BT's IP backbone for access to the Internet. The project provided insight into the viability of using white space spectrum for rural broadband provision and demonstrated the potential of white space technology through the use of real-world applications such as video streaming and video conferencing[11] **[264]**.
- ***Cambridge TV White Spaces Trial:*** The Cambridge TV White Spaces Consortium analyzed the potential of TV white spaces following more than 10 months of comprehensive testing in urban and rural areas in and around Cambridge. The consortium (consisting of international and UK technology and media companies including the DTG, Microsoft, BBC, BT, and Arqiva) explored and measured rural wireless broadband, urban pop-up coverage and the emerging "machine-to-machine" (M2M) communication and found TV white spaces can be utilised to help satisfy the demand for wireless connectivity. The trial analysis found Cambridge has significant television white spaces capacity: 20 white spaces channels

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[9] http://research.microsoft.com/en-us/projects/KNOWS/default.aspx
[10] http://www.tekes.fi/programmes/trial
[11] http://www.wirelesswhitespace.org/media/28341/tsb100912_bute_ws_report_v01_00.pdf

corresponding to 160 MHz in total, of which 13 (104 MHz) were allowed in the test licence from Ofcom, which can be used to help augment existing broadband networks, extend broadband access to rural areas and allow for machine-to-machine communications. Further, geolocation databases, provided by Microsoft and Spectrum Bridge, proved a way to control frequency use by the white spaces radios and to adapt to changes in spectrum usage by the licensed users.

- ***Ofcom white space trial in the UK:*** Ofcom has announced plans for a pilot of white space technology in the UK in autumn 2013, with a view to a full roll out across the country during 2014. Industry will be invited to take part in the pilot with locations determined once trial participants have been identified. Ofcom's test will use the 700 MHz frequencies reserved for digital terrestrial television (DTT) and wireless microphones and could be used for applications such as rural broadband, wireless Internet or even M2M networks.
- ***FCC white space database trial:*** FCC has authorized a white-space database trial for the German telecom software provider LS telecom AG, which has been designated as a white-space database administrator for tracking unoccupied TV frequencies in the U.S. market. The databases are pinged by unlicensed devices, which are then free to transmit on those unoccupied frequencies.
- ***Google trials in USA and South Africa:*** Google supported its first TV white space trial in the US in 2010 along with Spectrum Bridge and the Hocking Valley Community Hospital, demonstrating the potential of the TV white spaces to improve broadband and spark new applications in healthcare. First responder vehicles, hospital grounds as well as the health department were equipped with high-speed wireless Internet access. Additionally, the hospital used the network to manage its outdoor video surveillance system. To prevent interference with other signals, the network used Spectrum Bridge's real-time TV white spaces database. This deployment operated on an experimental white spaces license granted by the FCC. More recently, Google announced a partnership with the Independent Communications Authority of South Africa (ICASA) and Carlson wireless to deliver wireless access to 10 schools through 3 base stations at the campus of Stellenbosch University's Faculty of Medicine and Health Sciences in Tygerberg, Cape Town, South Africa. The trial maintained that broadband can be offered over white spaces without interfering with licensed spectrum holders. To prevent interference with other channels, the network used Google's spectrum database to determine white space availability. To confirm results, the CSIR Meraka Institute took spectrum measurements and frequently reported back to ICASA and the local broadcasters.
- ***CREW Trial Platform in Europe:*** The Cognitive Radio Experimentation World (CREW) project is an EU funded project under the FP7 framework and has developed a comprehensive trial and test platform environment with heterogeneous environments available for system and algorithm testing at different European Universities, including Ghent University, TU Berlin, Trinity College Dublin. This includes indoor environments as well as large scale halls with artificial regular base stations and moving test radios. Commercially available software radio platforms are used in the implementations as well as custom made systems. The CREW project team is open for test proposals of different scenarios. Further details on the CREW projects are provided in Section 0.

4.1.4 CR Security Considerations

The introduction of the cognitive principle in wireless communications, allowing advanced radio technologies to exploit unused or partially-used frequency resources, has increased the importance of security considerations. Differently from security considerations in classical wireless, in the case of cognitive radio networks, the problem of an existing planned incumbent network and the presence of multiple unplanned cognitive networks able to set-up new networks have to be coped with.

In **[219]**, a survey on security issues in cognitive radio technology is presented. Apart from the classical wireless security objectives, as confidentiality, integrity, availability and access control, the cognitive nature of the system introduces several new categories of security issues: i) the incumbent user emulation attack occurs when a malicious device mimics an incumbent transmitter, so that the cognitive transmitter is forced to vacate the spectral resource being used. Several papers are referenced which deal with this type of attack by considering the knowledge of the incumbent localization, the cooperation among the users and the modification of the signal of the incumbent; ii) the spectrum sensing data falsification (SSDF), which occurs when a malicious cognitive user sends false observations on the sensed data. The proposed techniques differ in terms of reporting type (*i.e.*, if it is binary or continuous), the considered fusion rule in case of cooperative sensing and the reputation of the metric restored; and iii) MAC layer vulnerability and standard specific threats are finally considered. The former was analyzed by introducing MAC spoofing, congestion attacks and jamming attacks as possible threats, while the latter was studied by introducing the IEEE 802.22 protocol vulnerabilities. Security issues related to cross-layer attacks and Software Defined Radio are also introduced.

In **[218]**, a general overview on security problems for cognitive radio networks is given. The focus is on specific characteristics of the cognitive radio technology, as spectrum sensing and utilization, spectrum mobility, spectrum management, spectrum utilization in MAC layer, security of network merge, access security, transmission security and learning engine. Each characteristic is analyzed by discussing countermeasures in terms of security mechanisms, key generation and distribution, and identity authentication mechanisms.

In **[217]**, cognitive radio networks vulnerabilities are introduced, providing a deeper insight on IEEE 802.22. The design of a strong security model is studied, identifying potential vulnerabilities along with a high-level security model that could lead to potential mitigation approaches. In particular, the analysis deals with the identification of possible features for a cognitive radio network from an attacker's perspective.

In **[221]**, the focus is on security vulnerabilities in the physical layer of a cognitive radio network. A security threats classification is introduced by considering insider and outsider threats. While insider threats consider the vulnerability to user legitimate access to the cognitive radio infrastructure, outsider threats consider the case of devices that cannot access the cognitive network, thus disrupting the cognitive communication. In particular, in both cases the physical RF jamming is considered as the source of the damage: a testbed for studying this type of vulnerabilities has been implemented. The focus is on three types of attacks, performed by using RF jamming: i) Incumbent User Emulation; ii) Denial of Service; and iii) Spectrum Herding.

In **[223]**, the focus is on specific aspects of physical layer (PHY) security issues, and collaborative sensing is considered in the presence of malicious attacks. In particular, the impact of malicious users interfering with the cooperation by reporting false information is considered by introducing a detailed analytical study. This study is based on scenarios where a different number of malicious users with respect to the total number of reporting users is considered, and by taking into account channel errors as well. An optimization rule is defined aiming at finding false alarm and miss detection probabilities under a varying number of malicious users.

In **[222]**, the security scenario is focused on ad-hoc collaborative cognitive networks. In particular, the vulnerabilities of a common control channel exploited by the MAC layer under its operation are considered. The aim is to verify the correctness of the messages received by other nodes in a collaborative channel negotiation environment, thus limiting the propagation of falsified messages. A framework for reducing this effect also in a multihop environment is proposed, even if limited to theoretical assumptions and without numerical results.

In **[220]**, security issues are considered at network layer by considering an 802.1X-based architecture concerning the authentication server. The idea is to introduce modified DHCP and ARP mechanisms, completely transparent with respect to the original protocols, in order to limit the access of untrusted devices to the cognitive network. The proposed mechanism exploits a Key Distribution Centre that shares a secret with each cognitive radio device.

In **[216]**, the focus is on Electronic and Cyber Warfare in Cognitive Radio Security. In particular, the paper focuses on the effects of a potential Cognitive Jammer against a cognitive radio network, by considering the effects on the physical and the application layers. For both cases, possible countermeasures are also introduced.

In Table 5, a summary of the most important security attacks is listed highlighting possible countermeasures and their applicability in each CR technique.

Table 5 - Summary of the CR Security attacks

Type of attack	Description	CR Techniques applicability	Possible countermeasures
Incumbent User Emulation Attack	An attacker emulates itself as an incumbent user so that the cognitive user is needed to leave the radio resource	• Spectrum awareness (Spectrum sensing) • Spectrum Utilization(Overlay,Underlay, Interweave)	• RSS and localization of the possible incumbent user • Knowledge of the incumbent user waveform • Presence of a incumbent user signature
Spectrum sense data falsification attack	The sensed data are falsified so that a malicious user can send false data about its sensing. It is used in collaborative, distributed and centralized sensing architectures	• Spectrum awareness (Spectrum sensing) • Spectrum Utilization(Overlay, Underlay, Interweave)	• Multiple sensing report are crosschecked • RSS and localization of the outlier • Sensed reporting frequency check
Common Control Channel attacks	Attack to the out of band CCC used for exchanging information among CR devices. The attack can cause MAC spoofing, congestion and jamming problems on CCC.	• Spectrum awareness (Spectrum sensing, Database, Beaconing) • Spectrum Utilization(Overlay, Underlay, Interweave)	• MAC layer technology dependent security mechanisms • Sender authentication
Beacon Falsification	Malicious users send	• Spectrum awareness	• Authentication

attacks	spurious beacons aiming either to disrupt synchronization between BSs or to disrupt exclusive spectrum utilization	(Database, Beaconing) • Spectrum Utilization(Overlay, Underlay, Interweave)	mechanisms of the beacons

4.2 State-of-the-Art Systems and Technologies

4.2.1 Terrestrial State-of-the-Art Systems

4.2.1.1 Ku/Ka-band Terrestrial Systems

Microwave point-to-point radio is a line of sight radio communication that originally, since early 1930's, was used with analog transmission. First use of radio was for broadcasting; subsequently radio was used for long distance telephone service also. To improve the voice quality, in the late 1960's, digital radio-relay came into being for the first time. To improve the frequency spectrum efficiency, high-status modulation modes 64QAM, 128QAM, 512QAM appeared and the frequency spectrum efficiency rose to 10 bit/s/Hz. In the year of 1988, based on the American SONET, the ITU formulated the SDH transmission network standard. Compared with the former PDH, SDH unified the standards of Europe and North America and made intercommunication of STM-1 and higher rate in the world become available.

In the following of this section we introduce the most used backhaul wireless communication networks which are supported by microwave links in the Ku-band (from 12.4 to 18 GHz) and in the Ka-band (from 26.5 to 40 GHz). One of the biggest impacts of Ka-band on ground terminals is antenna size. The equivalent of a 1.8m diameter antenna at Ku-band need be only 1m or less at Ka-band. The comparison with C-band antenna sizes is even more significant. Given the higher satellite EIRP and G/T levels of the Ka-band beams, reliable, high capacity Ka-band services are available from antennas with diameters of only 80-100 cm compared to 2.4-3.0m antennas needed at C-band. Even though the capacity in the millimeter part of the spectrum is considerable, there are many systems competing for frequency worldwide allocations in Ku-band and Ka-band **[245]**.

LMDS/MMDS

The local multipoint distribution system (LMDS) is well suited to interoperation with broadcast-based satellite systems for local distribution, and the satellite system likewise for connecting remote LDMS cells **[246]**. Interactive LMDS has a point-to-multi- point downlink and a point-to-point uplink. The LDMS systems can be typical multipoint business systems with some capacity for private users. Licensing and deployment in Europe indicate that there will be systems in different frequency bands from 24 GHz up to 43.5 GHz. The frequency band 24.5-26.6 GHz with sub-bands of 56 MHz has been opened for point-to- multipoint applications in many European countries. These bands may then be used for either LMDS or related systems called fixed wireless access (FWA). The 40 GHz band will normally be shared among two or three licenses, limiting the available spectrum per operator to 500-2000 MHz with two polarizations. The licensing policy may vary from country to country.

The multi-channel multipoint distribution system (MMDS) is the wireless alternative to ATM technology for the last mile. In the ITU Region 1, in which Europe belongs, the allocated frequency band for MMDS ranges from 11.7 to 12.5 GHz. This band is shared entirely with broadcasting satellite systems (BSS) whose services should be protected. In [24], the coexistence scenario of MMDS and

BSS has been considered, as discussed above in the Sec. 5.1.1 on terrestrial and satellite cognitive radio techniques.

4.2.1.2 C-band Terrestrial Systems

3GPP

The 3rd Generation Partnership Project (3GPP) is an initiative for collaboration among telecommunications associations. The 3GPP initiative came with the initial objective of defining a global specification for third-generation (3G) mobile communication systems, based on the evolution of the specifications for the existing second-generation (2G) system, *i.e.*, the Global System for Mobile Communications (GSM), and within the scope of the International Mobile Telecommunications 2000 (IMT-2000) project of the ITU. However, the scope was later enlarged to include the further development and maintenance of the already existing 2G standards for mobile communication systems, including GSM and its evolved versions, *i.e.*, General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE). The 3GPP initiative has been in charge of standardising the specification of 3G mobile communication systems, i.e., the Universal Mobile Telecommunications System (UMTS) and the High Speed Packet Access (HSPA) extension, and nowadays is also responsible for the standards for the fourth generation (4G) of mobile communication systems based on the Long-Term Evolution (LTE) technology, which is specified in Release 8 of the standards, with further additions in Releases 9-12.

LTE is based on GSM/EDGE and UMTS/HSPA network technologies, with a new radio interface (based on new digital signal processing techniques and modulations) envisaged to provide an enhanced spectrum efficiency and increased data rates, along with several network simplifications and improvements, based on the IP technology, that significantly reduce the transfer latency compared to the previous 2G/3G architecture.

4.2.1.2..1 Frequency bands

After the appearance of mobile telephony with the first analogical mobile communication systems, commonly referred to as first-generation (1G), the GSM (2G) system introduced the digital technology into mobile communication systems for the provision of voice services (and very low-rate data services such as SMS), while the UMTS (3G) system introduced the provision of data services with higher data rates of up to 384 kbps per user for Release 99 (*i.e.*, the original UMTS specification) and 7.2 Mbps per user for HSDPA. The evolution of LTE is aimed at providing higher transmission rates in the region of mega/giga-bits per second.

The introduction of higher data-rate requirements has pushed mobile communication systems to make use of higher frequency bands, where larger portions of spectrum can be exploited. A wide range of operating frequencies is considered by 3GPP specifications. 2G systems have traditionally been deployed in the 800/900 MHz and 1700/1800 MHz bands, while 3G systems have usually been deployed in the 1800/1900/2000 MHz bands. The deployments of 4G LTE systems have started in these same bands, but the 3GPP standards also consider the possibility of deploying 4G LTE systems in the 3.4-3.6 GHz band (i.e., within the extended C-band) and 3.6-3.8 GHz band (*i.e.*, within the standard C-band) which is expected to introduce significant interference problems with Satellite Communications. The radio interface of LTE is incompatible with 2G and 3G networks, meaning that 4G LTE systems need to operate in separate frequency bands.

4.2.1.2..2 4G Radio interface

The introduction of new digital signal processing techniques (*e.g.*, multi-antenna techniques such as MIMO as well as beamforming) and modulations (OFDMA in the downlink and SC-FDMA in the uplink to control power consumption) enable a more efficient exploitation of the spectrum, reaching downlink peak data-rates up to 300 Mbps and uplink peak data-rates up to 75 Mbps, depending on the user equipment category (with 4x4 antennas using 20 MHz of spectrum). 4G LTE supports Frequency-Division Duplexing (FDD) and Time-Division Duplexing (TDD) as well as half-duplex FDD with the same radio access technology. The 4G LTE specifications support cell sizes from tens of metres radius (*i.e.*, in the range of femto and picocells) up to 100 km (62 miles) radius (*i.e.*, in the range of macrocells). In the lower frequency bands to be used in rural areas, optimum performance is obtained with cell sizes around 5 km (3.1 miles). However, a reasonable performance can still be attained with cell sizes of 30 km (19 miles). Cell sizes of 100 km cell are also supported with an acceptable performance. In city and urban areas, higher frequency bands are used in order to support high-speed mobile broadband. In this case, cell sizes may be in the order of 1 km (0.62 miles) or even less.

WiMAX

WiMAX is a PHY and MAC layer technology, not taking higher layers into account. The higher layers are left for third parties to innovate and standardize **[241]**. Below follows a brief summary of the WiMAX technology for the MAC and PHY layers.

4.2.1.2..3 PHY Layer

WiMAX uses OFDMA as the main access technique. The IEEE 802.16e-2005 Wireless MAN OFDMA is based on the scalable OFDMA (S-OFDMA) concept, which supports a wide range of bandwidths to flexibly address the need for various spectrum allocation and usage model requirements **[242]**.

The 802.16e PHY **[243]** supports TDD and Full and Half-Duplex FDD operation; however the initial release of Mobile WiMAX certification profiles will only include TDD. With ongoing releases, FDD profiles will be considered by the WiMAX Forum to address specific market opportunities where local spectrum regulatory requirements either prohibit TDD or are more suitable for FDD deployments. TDD is preferred due to the following reasons:

- TDD enables adjustment of the downlink/uplink (DL/UL) ratio to efficiently support asymmetric DL/UL traffic, while with FDD, DL and UL always have fixed and generally equal DL and UL bandwidths;
- TDD assures channel reciprocity for better support of link adaptation, MIMO and other closed loop advanced antenna technologies;
- unlike FDD, which requires a pair of channels, TDD only requires a single channel for both downlink and uplink providing greater flexibility for adaptation to varied global spectrum allocations;
- transceiver designs for TDD implementations are less complex and therefore less expensive.

Adaptive modulation and coding (AMC), Hybrid Automatic Repeat Request (HARQ) and Fast Channel Feedback (CQICH) were introduced with Mobile WiMAX to enhance coverage and capacity for WiMAX in mobile applications. Support for QPSK, 16QAM and 64QAM are mandatory in the DL with Mobile WiMAX. In the UL, 64QAM is optional. Both Convolutional Code (CC) and Convolutional Turbo Code (CTC) with variable code rate and repetition coding are supported. Block Turbo Code and Low Density Parity Check Code (LDPC) are supported as optional features.

4.2.1.2..4 MAC Layer

The MAC layer is based on the time-proven DOCSIS standard and can support bursty data traffic with high peak rate demand **[244]** while simultaneously supporting streaming video and latency-sensitive voice traffic over the same channel. The resource allocated to one terminal by the MAC scheduler can vary from a single time slot to the entire frame, thus providing a very large dynamic range of throughput to a specific user terminal at any given time.

4.2.1.2..5 Mobility Management

Battery life and handoff are two critical issues for mobile applications. Mobile WiMAX supports Sleep Mode and Idle Mode to enable power-efficient MS operation. Mobile WiMAX also supports seamless handoff to enable the MS to switch from one base station to another at vehicular speeds without interrupting the connection.

Sleep Mode is a state in which the MS conducts pre-negotiated periods of absence from the Serving Base Station air interface. These periods are characterized by the unavailability of the MS, as observed from the Serving Base Station, to DL or UL traffic. Sleep Mode is intended to minimize MS power usage and minimize the usage of the Serving Base Station air interface resources

Idle Mode provides a mechanism for the MS to become periodically available for DL broadcast traffic messaging without registration at a specific base station as the MS traverses an air link environment populated by multiple base stations.

4.2.1.2..6 Handoff

There are three handoff methods supported within the 802.16e standard – Hard Handoff (HHO), Fast Base Station Switching (FBSS) and Macro Diversity Handover (MDHO). Of these, the HHO is mandatory while FBSS and MDHO are two optional modes. The WiMAX Forum has developed several techniques for optimizing hard handoff within the framework of the 802.16e standard. These improvements have been developed with the goal of keeping Layer 2 handoff delays to less than 50 milliseconds.

4.2.1.2..7 Security

Mobile WiMAX supports advanced security features by adopting mutual device/user authentication, flexible key management protocol, strong traffic encryption, control and management plane message protection and security protocol optimizations for fast handovers.

4.2.2 Satellite State-of-the-Art Systems

4.2.2.1 Ka-band SatCom Systems

Ka-band GSO SatCom Systems

Satellites featuring Ka-band transponders have existed for more than a decade. The band [27.5 – 30] GHz has been allocated to Fixed Satellite Services, whereas the corresponding band on downlink is [17.3 – 20] GHz.

With respect to the traditional SatCom systems in Ku-band, the benefit to use Ka-band is four-fold:

- a larger bandwidth is available;
- more orbital slots are available;
- physics of antenna allows the use of narrow spot beams with high gain, paving the way to additional frequency re-use;
- the size of the equipment (filters, waveguides, etc.) is smaller, thus allowing dense payloads.

However, the use of Ka-band implies higher equipment complexity. For instance the precision of the antenna surface is typically increased by factor 2. In addition the attenuation of the signal due to atmospheric events, especially rain, becomes important in Ka-band. Indeed the mean attenuation due to rain over the EU27 exceeds 7 dB during 0.3% of an average year at 20 GHz, according to recommendation ITU-R 618-10.

The typical system architecture of a Ka-band system is described below. The description is general and fits to High-Throughput Satellite (HTS) system featuring 50-200 spots or more as well as multi-mission spacecraft with a small Ka-band mission.

Figure 14 shows the reference SatCom system architecture in Ka-band. A multi-star topology is considered with a set of gateways in charge of point-to-multipoint connections with satellite terminals. The latter either connects one single user or a group of users through a local area network. The space segment is composed of a "bent-pipe" satellite, as well as a TTC station in charge of the transmission of the Telemetry, Tracking and Control of the satellite. The gateways, but also the TTC station, the Network Control Center and the Satellite Control Center are connected through an interconnection network.

The forward link goes from the gateway to the terminal through the satellite, whereas the return link goes from the terminal to the same gateway via the satellite. The reference air interface on the forward link is the DVB-S2 whereas the DVB-RCS(2) or IPoS are used on the return link.

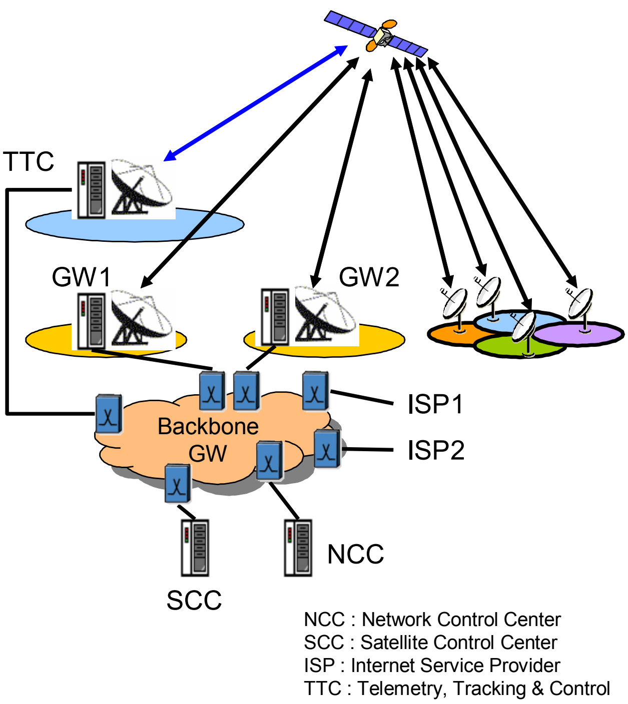


Figure 14 - Reference Ka-band SatCom system architecture.

The terminals are located into the satellite spot beams, which overlap in order to provide a full coverage. Different spot sizes can be considered in order to adapt the capacity per spot to the traffic demand, while managing the complexity of the payload. A mobile spot is sometimes envisaged to complete the coverage so as to provide flexibility in term of capacity, when and where required.

A 4-color scheme is often used on two orthogonal circular polarizations. Figure 15 presents a typical frequency plan in Ka-band, whereas Figure 16 illustrates a 4-color scheme beam layout.

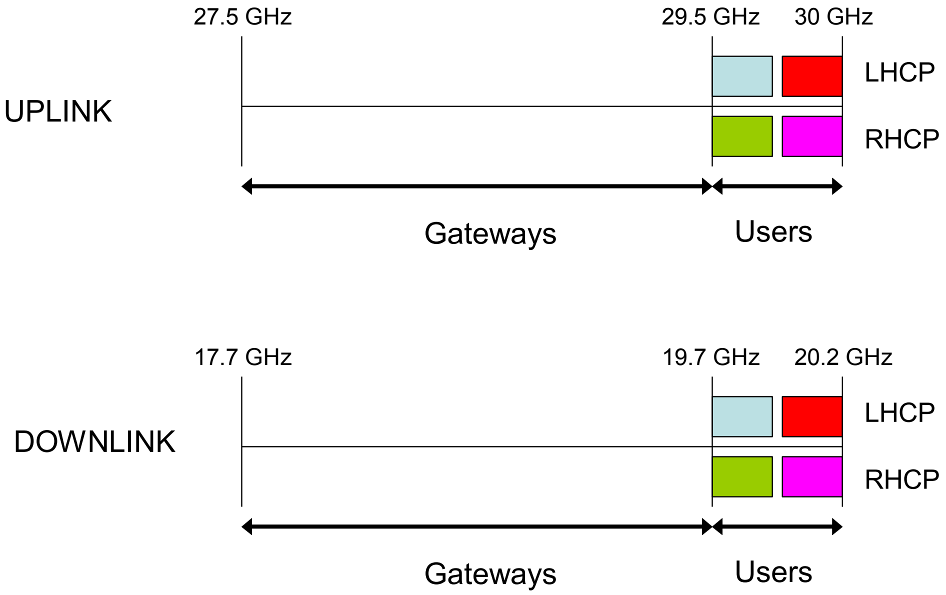


Figure 15 - Typical 4-color frequency plan.

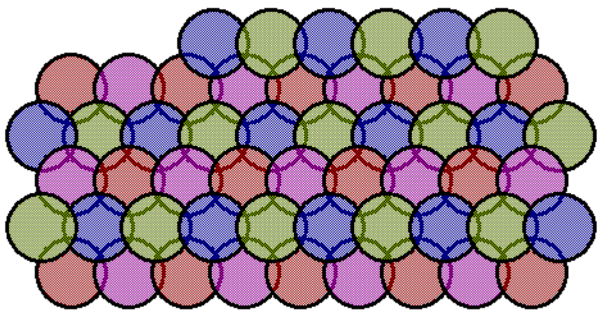


Figure 16 - Illustration of a 4-color beam layout.

Figure 17 below presents a selected review of existing FSS satellites in Ka-band. All these satellites are bent-pipe and Ka-band only. Purely commercial satellites propose a capacity close to or beyond 100 Gbps, while others such as YAHSAT 1B mixes commercial and non-commercial missions. All of them rely on the bands [19.7 – 20.2] GHz on user downlink and [29.5 – 30] GHz on uplink, whereas the feeder link uses the other portions of the Ka-band spectrum.

Satellite	Anik-F2	Wildblue-1	Ka-Sat	Viasat-1	Hylas-2	Yahsat-1B	Jupiter-1
Operator	Telesat	Viasat	Eutelsat	Viasat	Avanti	Al Yah Satellite Communications	HNS
Launch date	2004Q3	2006Q4	2010Q4	2011Q3	2012Q2	2012Q2	2012Q3
Service coverage	CONUS / Canada	CONUS	Europe	CONUS	East Europe - North Africa - Middle East	CONUS / Canada	CONUS
User frequency Band (down & up)		19.7 - 20.2 GHz & 29.5 - 30 GHz	19.7 - 20.2 GHz & 29.5 - 30 GHz	19.7 - 20.2 GHz & 29.5 - 30 GHz	19.7 - 20.2 GHz & 29.5 - 30 GHz	19.7 - 20.2 GHz & 29.5 - 30 GHz	19.7 - 20.2 GHz & 29.5 - 30 GHz
Number of spots (user + feeder)	45	35 + 6	82 + 10	63 + 17	24 + 6	61 + 7	60 + 15
Satellite platform	Boeing BS-702, 5.9 tons, 16 kW	SS/L FS1300, 4.7 tons, 9.6 kW	Astrium E3000, 6.1 tons, 14 kW	SS/L LS-1300SX, 6.1 tons, 16 kW	OSC Star-2.4 Bus, 3.1 tons, 5KW	Astrium E3000, 6 tons, 15 kW	Loral LS-1300, 6.5 tons, 14KW
User terminal	66 cm / 1 W	66cm	68 cm / 3W	66 cm	74 cm / 2W		68 cm
Service		FWD: 1.5 Mbps RTN: 256 kbps	FWD: 10 Mbps RTN: 4 Mbps	FWD: 1.5 Mbps RTN: 256 kbps	FWD: 500kbps – 8Mbps RTN:128kbps-2Mbps		FWD : 1 - 5 Mbps
System capacity (forward + return)	2.1 + 1.4 Gbps	3 + 2 Gbps	42 + 28 Gbps	130 Gbps	9 + 6 Gbps		80 + 20 Gbps

Figure 17 - Review of existing FSS Ka-band satellites.

SES Ka-Band Broadband Services

SES Ka-Band Broadband Service over Europe is detailed in [276].

A significant step in Ka-band is the three ASTRA-2 replacement satellites (*i.e.*, ASTRA 2F, 2E, and 2G), which each include a steerable Ka-band beam that may be flexibly pointed over Europe, and ASTRA 5B satellite, which includes a jointly steerable twin-beam Ka-band payload. This capacity is expected to be deployed by 2014 according to the SES fleet replacement plan with the objective to complement the current pan-European Ku-band broadband coverage with incremental Ka-band capacity over selected areas.

Each of the ASTRA 2F, 2E, and 2G spacecraft has a steerable Ka-band spot beam reflector with a simple low-loss repeater implementation. This allows flexibility as well as mutual backup (in case that may be needed.) Each spot beam is approximately 1.5 degrees in diameter (hence providing country-size coverage) and supports 1100 MHz of user forward bandwidth and dedicated user return bandwidth on implemented circular polarisations. Forward bandwidth is in two separate transponders in the Ka- FSS and Ka- BSS bands at 19.7-20.2 GHz and 21.4-22.0 GHz, respectively. To aid gateway Earth station pointing, each satellite emits a tracking beacon near 18.8 GHz.

Regarding Ka-band consumer equipment, SES has followed a two-fold approach by extending a long-standing partnership with Newtec and signing a new supplier agreement with Gilat. Both networks are star-based with a TDM/TDMA access scheme and have been operated from SES' headquarters in Betzdorf (Luxembourg) in order to leverage existing expertise and uplink infrastructure towards 28.2ºE and 31.5ºE. Betzdorf also hosts the MNOC (Multimedia Network Operation Centre) for H24 monitoring and second level support to the ISPs, the necessary Internet backbone connectivity and the BSO (Broadband Service Operation) unit interfacing with customers for service management (see Figure 18).

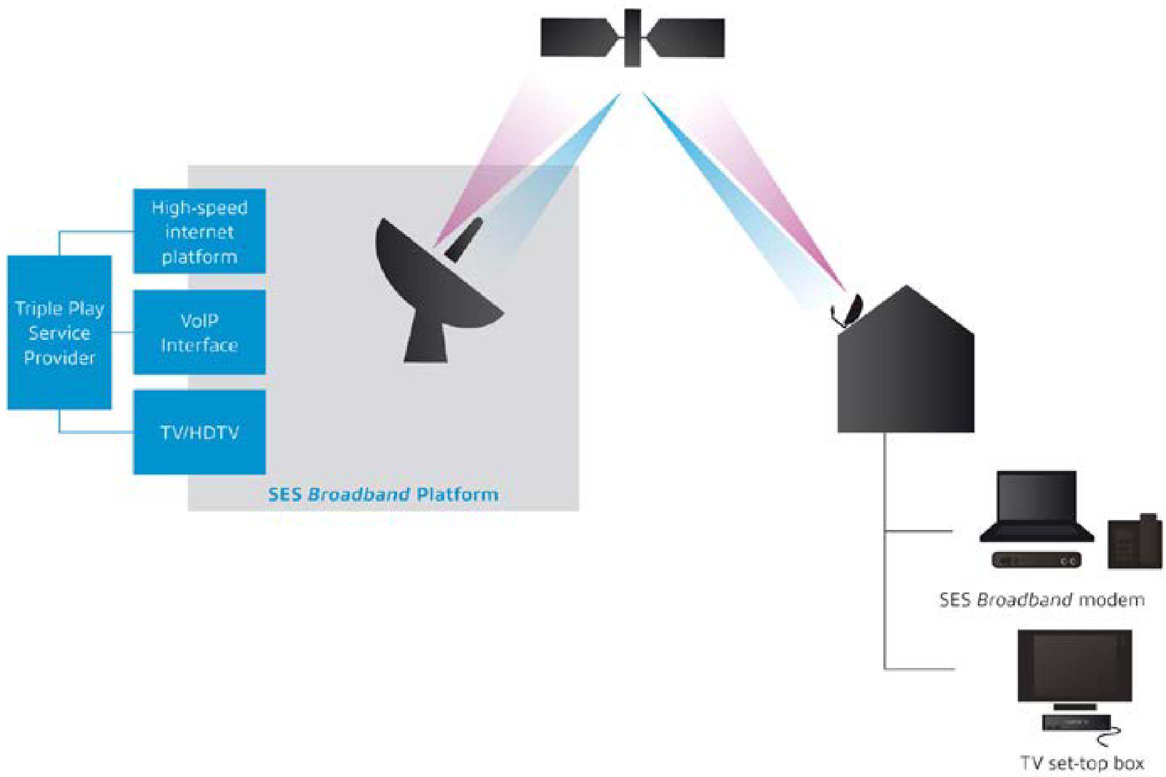


Figure 18 - SES Satellite broadband for individual households

In particular, Newtec is a longstanding partner of SES Broadband Services and manufacturer of the Sat3Play platform at the basis of the service formerly known as Astra2Connect that is commercialised across Europe, Middle East and Africa since 2007. Rather than designing a completely new product, Newtec has been focusing on the development of the current platform in order to provide existing customers the possibility of a smooth transition from Ku to Ka. As customers can be migrated between the two frequency bands by simply replacing the ODU (Outdoor Unit), this provides an additional degree of freedom to those aiming to minimise hardware cost. Sat3Play also features a large set of bandwidth and performance optimisation techniques and supports a successfully proven self-installation procedure. In addition, a microSD slot and a USB port are installed in order to enable future added value services. VoIP support is fully integrated allowing triple-play services when a traditional Ku-band LNB (Low Noise Block down-converter) is installed on a side-arm.

From a technology point of view, a key difference between the two platforms is represented by the return link implementation with Newtec relying on 4CPM (Quaternary Continuous Phase Modulation) modulation and a MUC (Multiplying Up Converter) for saturating the terminal's SSPA (Solid State Power Amplifier), whilst Gilat features QPSK/8PSK linear modulation with a standard BUC (Block Up Converter).

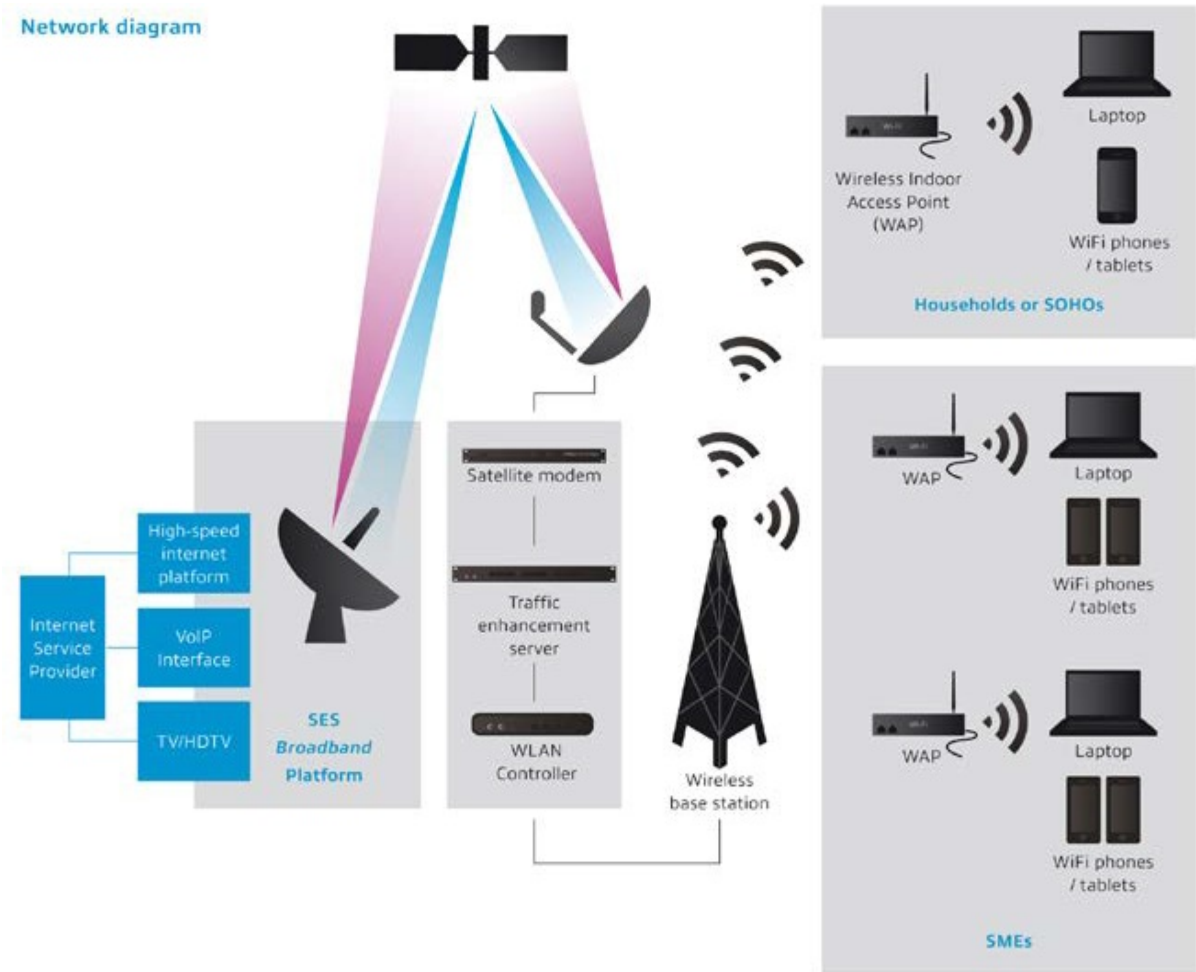


Figure 19 - SES Satellite broadband for communities - WiFi distribution case

In the recent years, SES Broadband Services has been evolving its business strategy in an effort to capture European households at different aggregation levels. A strong request for service integration is driving the development of user-centric triple-play platforms with the potential to interact with modern consumer devices such as smartphones, tablets, and laptops to deliver transparently voice, video, and data services. In a hybrid satellite/terrestrial scenario, Telcos and local ISPs can provide capillary penetration of the territory by simply targeting the main points of traffic aggregation via satellite and leveraging existing last mile technologies without the need for large investments for network upgrades not always justified by the market potential. To this end, SES Broadband has developed a satellite-based solution for connecting users behind an aggregation point irrespectively of the deployed last-mile technology. In contrast to standard trunking solutions, a service layer has been integrated which allows each ISP to manage individual end users behind the aggregation point while the satellite operator shapes and prioritises traffic according to congestion and channel conditions. In addition, the distribution line can also be easily extended to include TV reception and voice services hence providing a full triple play solution well-suited to serve small communities with a single installation (see Figure 19).

Ka-band NGSO SatCom Systems: The case of O3b Networks

O3b Networks (http://www.o3bnetworks.com) is an innovative satellite network, which combines the reach of satellite with the speed of fiber, providing around 70% of the world's population with fiber quality internet connectivity. The O3b system is based on a Ka-band MEO satellite constellation (on a single 8060 km orbit), with high link trunking capacity (theoretical speed up to 1.2Gbps per beam). The service was planned to be provided in late 2013 (year of first satellites launches). The first batch of four O3b satellites was launched in June 2013. The second batch of four O3b satellites was scheduled to be launched in September 2013, but this has been delayed until the first quarter of 2014. A particularity for that system is an incremental deployment; initially 8 satellites will be launched and will form the constellation (45° spacing on the equatorial orbit). Later on, additional capacity might be added, by increasing the number of satellites in the orbit (16 more satellites).

The main targeted communication services are mobile backhauling and IP trunking (telcos sector), which are further complemented by maritime and energy services (enterprise sector) as well as governmental services.

O3b's NGSO constellation design is based on the following:

- Initial constellation of 8 satellites and scalable to meet market demand
- Orbital spacing: 45˚
- Circular equatorial orbit at 8,062 km altitude
- Orbital inclination: <0.1˚
- Ground period: 360 min / number of contacts: 4 per day
- 288 minute orbit period
- Inherent in-orbit redundancy
- 10 years minimum life time
- 12 steerable spot beam antennas on each satellite

O3b's Beams:

- Spectrum: Ka-band
- Optimal coverage between 45˚ north/south latitudes
- 10 beams per region (7 regions) totalling 70 remote beams per 8 satellite constellation
- Up to 1.2 Gbps per beam (600 Mbps x 2)
- 84 Gbps available per 8 satellite constellation
- Beam coverage: 700km diameter

- Transponder bandwidth: 216 MHz; 2 x 216 MHz per beam

O3b Networks will deliver broadband connectivity everywhere on Earth within 45 degrees of latitude north and south of the equator. As can be illustrated in the Figure below, its coverage area includes emerging and insufficiently connected markets in Latin America, Africa, the Middle East, Asia, and Australia, with a collective population of “other 3 billion” (O3b) people.

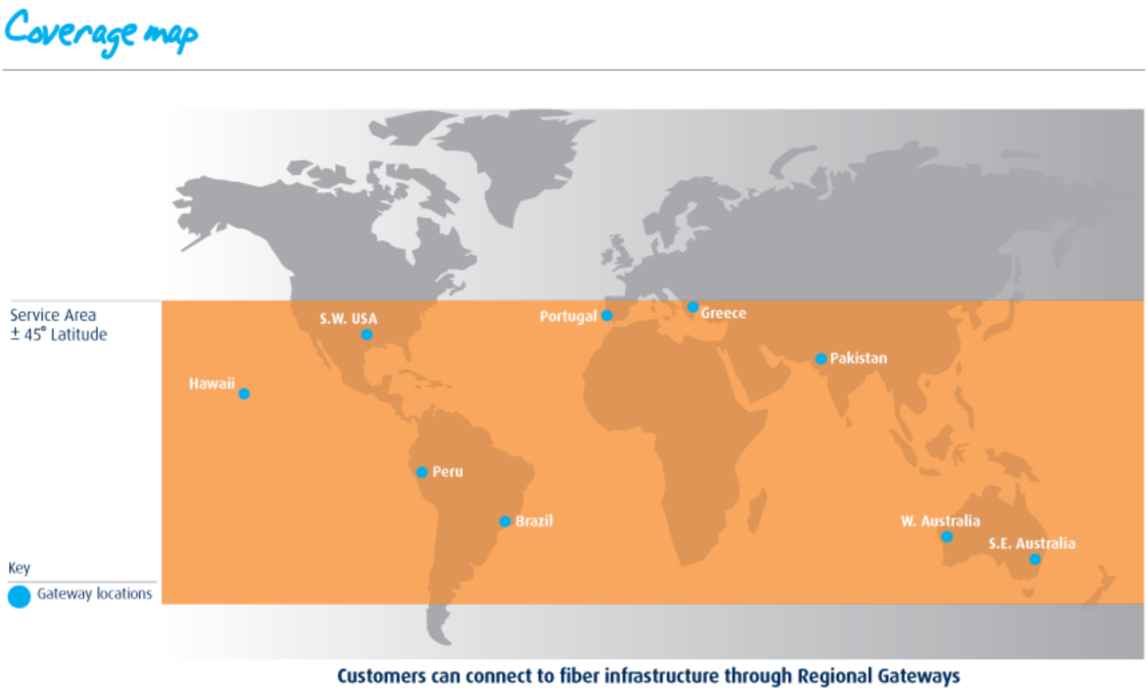


Figure 20 - O3b Networks Coverage.

O3b’s Communications Concept:

- Steerable Ka-band spot beams
- Seamless handover between satellites
- Bent-pipe connecting gateways with customers for internet access
- 2 beams per satellite for gateways
- 10 beams per satellite for customers
- Customers use:
  - Medium/large Earth Stations only for high capacity fixed links
  - Medium/small Earth Stations for mobile applications
- Beam coverage: ~700 km diameter
- Channel bandwidth: 216 MHz
- Coverage ~45 N˚ N/S latitude

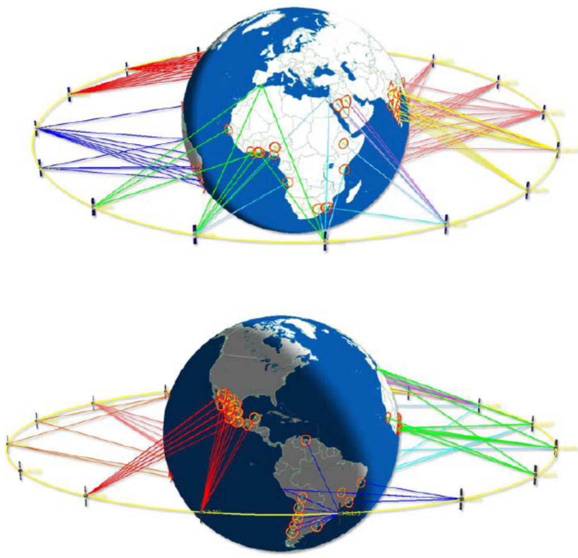


Figure 21 - O3b's Communications Concept.

O3b's Spectral Efficiency:

- Dual polarization:
    - Full frequency re-use achieved by dual orthogonal polarization for both gateway beams and customer beams
- Spatial frequency re-use:
    - Additional spatial frequency re-use between gateway beams and customer beams
- Total frequency re-use factor is therefore 4 times

The O3b system is expected to be as transparent as possible to different waveforms options as well as network topologies; it will support any of the star configuration, mesh configuration and point-to-point and loopback configuration. Flexible and steerable spot beam coverage will also support dynamic mission reconfiguration. Each spot beam is 700 km of diameter, and a given transponder will process a 216 MHz bandwidth. Also, O3B core network architecture will be interconnected to a global MPLS network, MPLS nodes being located at the place of global Internet exchange points (GIX).

Additionally, the MEO satellites will use steerable antennas for ground stations tracking; however ground stations will also have to implement satellite tracking, each satellite being visible at most for 3 hours.

The choice of a MEO system is justified to benefit from small delays; indeed with respect to GEO system with high station-to-station delay (250 ms), the delay is only about 100 ms and completely compatible with interactive/real service like conversational voice and/video according to most stringent ITU requirements (maximum 100 ms required for transfer delay according to ITU Y.1541).

Future Trends of Ka-band SatCom Systems

In 2010, the European Commission quantified the need of European citizens in terms of broadband services. Based on social and economic analysis, the European Digital Agenda (EDA) defines the key objectives: the EU aims "to bring basic broadband to all Europeans by 2013 and seeks to ensure that, by 2020, (i) all Europeans have access to much higher Internet speeds of above 30 Mbps and (ii) 50% or more of European households subscribe to Internet connections above 100 Mbps."

As recognised by the Commission, satellite technology has obviously a role to play, especially when considering rural areas, which would likely never otherwise be fully served by terrestrial network technologies.

In this frame, future Ka-band satellites shall face two programmatic challenges so as to propose broadband connection to customers at a limited fee:

- increase the system capacity in order to decrease the system Cost / Capacity ratio. In particular the cost per unit of payload mass and power shall be optimized, while the cost of the feeder ground segment shall be controlled;
- increase the capacity per km^2.

To meet these challenges, some trends at system level have been identified:

- consider a beam size lower than 0.3° in order to increase the beam density and the number of beams over a given service zone;
- increase the available bandwidth for the user beams in Ka-band. Typically the band [17.3 – 20.2] GHz on the user downlink and the bands [27.5 – 27.82] + [28.45 – 28.95] + [29.5 – 30] GHz are considered. On the downlink it accounts for a multiplication factor of 5.8 with respect to the current generation above described. The consequence of this trend is the necessary shift of the feeder link towards higher frequencies, such as Q (40 GHz) and V (50 GHz) bands. A typical frequency plan could be as follows:
    - User downlink: [17.3 – 18.7] GHz + [18.8 – 20.2] GHz used on two circular orthogonal polarizations so as to define a 4 color-scheme with 1.4 GHz allocated per spot.
    - User uplink: [28.45 – 28.95] GHz + [29.5 – 30] GHz used on two circular orthogonal polarizations so as to define a 4 color-scheme with 0.5 GHz allocated per spot.
- Increase the efficiency of air interfaces, especially through a closer carrier packing down to 1.05 x Symbol rate of the carrier. This trend is supported by efficient on-ground signal processing so as to mitigate the deleterious effects.

At space segment level, these trends lead to consider:

- large reflector so as to form narrow beams, up to 3.5m if solid reflector and beyond (typically 5m class) if other technologies such as foldable tips or mesh reflectors are envisaged;
- wideband repeater technologies so as to cope with the large spectrum in Ka-bands. In particular linearized TWTA operating over 2.9 GHz are now under development. It will allow one TWTA to handle two spots (if a 4-color scheme over two polarizations is considered), which contributes to improve the payload mass efficiency. Flexibility of the repeater architecture will be also a key point so as to adapt the capacity to the traffic demand over the coverage;
- efficient platform thermal control to meet the thermal dissipation constraints of very dense and capacitive payloads, typically in the range of 10 – 14 kW;
- electric propulsion for all station-keeping manoeuvers and a part or all the transfer to GTO so as to increase the affordable payload mass.

4.2.2.2 Ku-band SatCom Systems

Ku-band contains allocations for BSS, FSS and a bit of MSS.

Most SatCom systems operating in Ku-band are providing broadcast services based on DVB-S and increasingly DVB-S2 standards.

EN 300 421 V1.1.2 (1997-08): Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for 11/12 GHz satellite services

ETSI EN 302 307 V1.2.1 (2009-08) : Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2)

In Europe, 85 million TV homes receive their signals from satellites of which 41% receives TV in High Definition **[238]**.

SES introduced the Sat>IP protocol which converts DVB-S and DVB-S2 signals to IP stream, similar to IPTV, that can be distributed to any IP-enabled client multimedia devices. Thanks to recent developments **[239]**, the IP streams are generated directly from the antenna dish and conveyed over Ethernet to the home network environment.

Some SatCom systems are providing broadband services based on DVB-RCS, DVB-RCS2 or related technologies.

- ETSI EN 301 790 V1.5.1 (2009-05): Digital Video Broadcasting (DVB);Interaction channel for satellite distribution systems (DVB-RCS system: 1st generation).
- ETSI TS 101 545-1 V1.1.1 (2012-05): Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2);Part 1: Overview and System Level specification.
- ETSI EN 301 545-2 V1.1.1 (2012-01): Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 2: Lower Layers for Satellite standard.

ETSI TS 101 545-3 V1.1.1 (2012-05): Digital Video Broadcasting (DVB);Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 3: Higher Layers Satellite Specification

Among the most popular satellite networks in Europe, one should note Astra2Connect based on the Sat3Play technology developed by Newtec. This technology has been deployed in more than 80.000 sites in Europe **[240]**. It offers internet access and communications by satellite to SoHo, small and medium enterprises and small branches of large companies, with flexible subscriptions, state-of-the-art equipment and an attractive price-setting. It allows reception at speed up to 10 Mbps downlink and 256 kbps uplink over Ku-band satellites.

4.2.2.3 C-band SatCom Systems

The C-band frequency band has been traditionally used extensively by satellite communication systems. The atmospheric fading conditions are excellent for highly reliable links and C-band service supports a significant amount of service deployments for satellite communications to date. These include mainly point-to-point and point-to-multi-point links for IP backbone connections. The used C-band capacity for satellite services includes:

Downlink channels

- 3.4-3.8 GHz, extended C-band.
- 3.8-4.2 GHz, regular C-band.

Uplink channels

- 5.85-6.725 GHz.

The C-band usage is currently used by satellite services with typically antennas of 1.8 m to 2.4 m terminals and antenna systems of 3.4m-3.8m for larger Earth stations.

A key characteristic of C-band satellite systems is the large coverage areas, which make the systems well suited for reliable (weather independent) interconnections over large distances, but as well very sensitive to interference. The satellite coverages are typically on visible Earth or so called “Hemi-beams” covering half of the visible Earth.

The common polarization used is circular polarization but also a few linear polarization systems are in operation. The spacing between C-band geostationary satellite systems can range from 2.0° to 3.5° in some areas.

Typical SatCom systems include point-to-point and point to multi-point links. The used standards are either proprietary systems or eventually standards based systems, DVB-S2 and DVB-RCS for example. In the future, we expect also DVB-Sx and DVB-RCS2 to become more widely used.

The satellite C-band is especially useful in areas with a significant rainfall, because of the relatively low rainfall impact on the transmissions. This makes it a popular frequency band for links planned with a high availability target, such as critical communications for the functioning of navigation systems (*e.g.*, Galileo or ICAO), public protection & disaster relief (PPDR) (*e.g.*, for the UNHCR or the emergency.lu platform), military needs, etc.

Other typical C-band satellite services include mobile backhauling and point-to-point links as well as IP backbone services for remote areas. The C-band is still used extensively, especially in rural areas of tropical rainfall regions along Africa, South America, Asia, Pacific region. In Europe and North America the usage is somewhat more limited. The global demand for satellite C-band systems is increasing globally, and Europe remains an important hub in global communications with Africa or Americas.

Several C-band satellite geostationary slots experience interference from adjacent satellites. In addition, C-band GSO ground stations experience interference potentially from new terrestrial links. This is largely related to the fact that C-band has a large coverage area and directional (spatial) frequency reuse is less practical than at higher frequencies like Ku- or Ka-band. Interference problems are for these reasons common in C-band satellite reception and can originate from adjacent satellite systems, radars used on adjacent frequencies or (recently as well) WiMAX terrestrial systems that can cause severe interference issues. Several studies documented with trials on the field have demonstrated that LTE would also cause severe interference to C-band SatComs. Report ITU-R M.2109 demonstrates that required separation distances to avoid IMT harmful interference to FSS Earth stations are at least 10s of km, and in some cases more than 100 km. Measurement studies in Europe in 2009 confirmed the impact of IMT interference and the need to establish separation distances of 10 s to 100 s of km. Satellite operators conducted: i) long term studies in the Netherlands to confirm short-term propagation events and to take abnormal propagation conditions into account; and ii) short-term studies in Leeheim to confirm long-term propagation results. This makes C-band one of the major interference concerns for the satellite operators.

4.2.2.4 L/S-band SatCom Systems

L-band BSS

Inside the L-band, ITU has allocated the band 1452-1492 MHz to Broadcast Satellite Services (BSS) worldwide except in the USA. In Europe, CEPT has planned the band 1452-1479.5 MHz for Terrestrial Digital Audio Broadcasting (DAB). CEPT has designated the band 1479.5-1492 MHz to DAB via satellite, or S-DAB.

The DAB system applies OFDM in order to allow Single Frequency Networks (SFN). In a SFN the different transmitters of a certain programme all use the same frequency and transmit the same signal synchronously. The DAB transmission signal is defined in standard ETSI EN 300 401 **[236]**.

The DAB modulation and coding scheme is optimized for terrestrial transmission, but also suitable for satellite transmission. The DAB system foresees in-band repeaters, which receive an S-DAB signal from satellite by a directional antenna and transmit it on the same frequency. The satellite appears like another transmitter in the SFN.

DAB is deployed and in use in Europe. Several extensions and modernizations have been introduced over the years, including DAB+. An operational S-DAB service does not exist today.

The ESDR standard ETSI EN 302 550 **[237]** has been created specifically for hybrid satellite terrestrial networks, where satellite transmission provides wide coverage and terrestrial transmitters enable reception without line-of-sight to the satellite. The standard contains a mode of operation that allows using the L-band BSS band with the channelization defined for DAB. It is foreseen that broadcast receivers have two paths, which process satellite and terrestrial signals and combine them before decoding the error correction coding.

ESDR has not been deployed so far. Plans existed for networks with satellites in Highly Elliptical Orbit and terrestrial high power transmitters.

S-band MSS

Inside the S-band, the band 2170-2200 MHz is allocated to Mobile Satellite Services (MSS) downlink, 1980-2010 MHz is allocated to the corresponding uplink. Hybrid satellite terrestrial networks are foreseen. Details about the regulatory framework can be found in other CoRaSat deliverables.

The bands are next to UMTS bands, which facilitate user equipment that works with hybrid satellite terrestrial networks as well as conventional terrestrial UMTS networks.

ETSI has created standards for this frequency band and the kind of network, including S-UMTS. The work has been performed by the ETSI Technical Committee for Earth Stations and Systems (ETSI TC-SES).

It has been considered to use the downlink band for a mobile broadcast satellite services. The DVB-SH standard has been created particularly for this band. Also the ESDR standard has got a mode of operation for this frequency band.

An important difference between ESDR and DVB-SH is the order of interleaving, modulation and coding in the processing chain. With ESDR the order enables that the same link margin can be used for coping with noise as well as for overcoming line-of-sight interruptions. DVB-SH requires separate margins for noise and interruptions due to the order chosen there. This less efficient order comes from heritage of older DVB standards.

An interesting concept for frequency re-use has been proposed. The satellite transmits spot beams with frequency re-use. Terrestrial transmitters located inside a spot beam can use frequencies of the other spot beams, as long as they are located with some distance to the other spot beams.

S-band BSS

Part of the S-band around 2500 MHz is allocated in several countries to broadcast satellite services with hybrid satellite terrestrial networks. The satellite allows nationwide coverage; the terrestrial transmitters allow reception also where no line-of-sight to the satellite exists.

Successful networks have been deployed in the USA, South Korea and Japan. In the USA, XM Radio uses two geostationary satellites that transmit the same content. Sirius Satellite Radio uses satellites in Highly Elliptical Orbit, with the aim of high elevation. Today both networks have joined commercially. In South Korea and Japan the system MBSat provided broadcast services for several years, but has ceased meanwhile.

Typically, the available frequency band is split up into parts for satellite and for terrestrial transmission. OFDM is used on the terrestrial transmitters, in order to enable a Single Frequency Network (SFN). Normal single carrier modulation is used on satellite, which enables efficient use of power by operating amplifiers close to saturation.

4.2.3 State-of-the-Art Ground Segment Technologies

The state-of-the-art techniques considered comprise satellite specific technologies that are considered as basis for dynamic spectrum access to be defined.

On the different layers we consider the following techniques as state-of-the-art for the satellite transmission context:

Table 6 - State-of-the-Art Ground Segment Technologies per associated Layer

Layer	Techniques considered
Physical layer	DVB-S2 DVB-TM Sx: S2evolutions / S2revolutionary DVB-RCS2 (proprietary “Dynamic-SBC”) adaptive transmission technique: Dynamic-SBC
Link Layer	DVB-RCS2 Higher Layer Specifications (HLS)
Networking layer	DVB-RCS2 Higher Layer Specifications (HLS)
Transport and application access layer	TCP acceleration HTTP pre-fetching Dynamic predictive content caching

The following figure illustrates the contexts of the considered scenarios. We use as reference the hierarchical structures as defined in DVB-RCS Next Generation (NG) or DVB-RCS2/HLS.

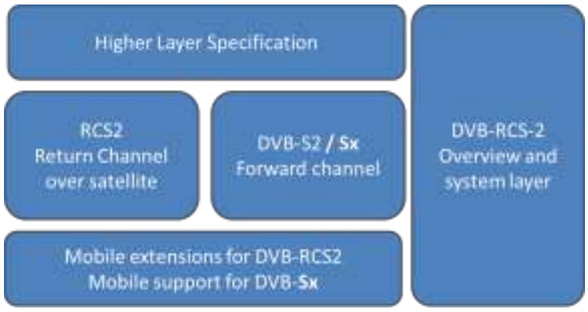


Figure 22 - DVB-RCS2 and DVB-S2 / Sx (extended) overall protocol structure considered.

The DVB-RCS2 standard describes the physical and link layer aspects of a multi-access return channel based on MF-TDMA access.

The DVB-S2 and Sx update (under discussion at DVB-TM) define a forward link or broadcast channel from a central access point (hub or central gateway) that multiplexes content to multiple receivers.

The extension of the DVB-RCS2 and the Sx standards to lower SNR ranges allow for mobile applications that can be defined on the basis of these standards (up to now these are mainly proprietary systems, not standardized).

The adaptations of the quality of services and service level agreements to the physical layer aspects and the acceleration and optimization of the higher layer protocols are addressed in the DVB-RCS2 HLS standard.

4.2.3.1 Physical Layer

The current state-of-the-art of satellite transmission technologies comprises a set of proprietary and standards for different applications. This section focuses on the satellite system, gateway and terminal ground segment state-of-the-art transmission technologies and key system aspects. (This section does not intend to be exhaustive of all currently applicable satellite transmission standards but describe the most used standards and key technologies.)

Satellite communications use cases foresee typically different categories of services. The main applications are broadcasting, broadband services as well as point-to-point communications. Fix and mobile use cases are typically separate use cases because of the significantly different requirements and challenges of mobile satellite communications.

For the state-of-the-art standards, the following list enumerates the most important used standards to date (February 2013).

Table 7 - State-of-the-art standards related to SatCom Physical Layer

DVB-S2	Broadcast standard used in many satellite networks. ETSI EN 302 307 **[2]**
DVB-RCS2	Two-way satellite systems standard, defining physical layer, higher layer and system aspects. Higher Layer Specification, Physical Layer Specification, System descriptions **[233][234][235]**
Dyn-SBC	Dynamic-SBC Flexible short block coding used in combination with fully synchronous dynamic spectrum access adapting the symbol rate, MODCOD, power per carrier and frequency in a continuous dynamic manner without link loss.

DVB-S2 for broadband and broadcast networks

DVB-S2 is considered the second generation satellite broadcast standard, after the first generation standard DVB-S2 has been devised and implemented successfully for about a decade from 1994 onwards, the DVB-S2 standard has replaced DVB-S on the basis of significant efficiency improvements and extensions in the range of usable modulation and coding signal to noise ratios.

A new call for technologies (CfT) was launched by the DVB-S2 working group, aiming at defining a new standard with additional efficiency improvements and also extensions of the usable signal to noise ratios and granularity of configurable modulation and coding sets.

The framework of this new call for technologies is to extend the DVB-S2 standard towards more efficient transmission schemes for the medium and long term. In fact the CfT contains both a so-called "evolutionary" as well as a "revolutionary" part.

The "evolutionary" part or "S2evo" focuses on improving the DVB-S2 efficiency within the near future timeframe. The aim is to have the standard ready by 2013 with a technical performance assessment completed with hardware tests.

The primary envisaged application is Direct To Home (DTH) broadcasting via satellite and especially the next evolution of broadcasting in 2015-2016 towards 4k HD "Quad High Definition" or "Ultra High Definition" TV broadcasting and a new generation of Set-Top Boxes (STB) aiming at this Ultra HD (UHD) market introduction.

Secondary application areas foresee the usage of the new efficient transmission stream for forward link usage in VSAT networks, fix and mobile as well as in professional IP trunking and IP backhauling applications.

The DVB-S2 transmission is a continuous transmission of a stream of frames. Either constant coding and modulation (CCM) or variable/adaptive coding and modulation (VCM/ACM) can be used to adapt to changing link conditions. Typical applications of the DVB-S2 standard include today the following:

- satellite broadcast of video/audio content (SDTV/HDTV content) in constant coding and modulation schemes (CCM);
- forward link of a two way satellite systems, hub to terminal links using adaptive coding and modulation (ACM), if possible;
- contribution links and point-to-point access links with high rate transmissions for backhauling and IP trunking applications.

Both the evolutionary and revolutionary tracks of the DVB working groups to improve the DVB-S2 standard are focusing on the broadcast context as main field of applications, however new areas are added in the context of broadband services: mobile applications at very low SNR ranges and very high SNR ranges as well. The extended range of the used signal to noise ratio on the call for technologies ranges from Csat/N0 = -10 dB to 24 dB and the overall applications in that range vary significantly consequently, from mobile broadcast to small car antennas to two-way trunking of IP data. The granularity is also significantly increased with the proposed new MODCOD ranges.

This increases however also significantly the flexibility of ACM services, which can now react to fading events of significantly larger magnitudes.

The current proprietary S2extensions scheme provides already today a practical transmission scheme with significantly increased spectral efficiencies as well as with an extension in granularity and range of the usable MODCODs.

The S2evo standard will build on this or similar extended S2 technologies with a limited amount of additional complexity and aiming at an implementation in the near future for applications in STBs in combination with Quad HD.

On the longer term, the S2revo or revolutionary part foresees the implementation of significant improvements. These include techniques to further improve efficiency and also facilitate new use cases related to DVB-S2, including mainly:

- improved support for adaptive MODCODs and decoding/demapping iterative receivers;
- support of advanced detection techniques such as interference mitigation, MIMO, and joint detection in the receivers;
- support of wideband transmissions transmission modes;
- techniques suitable and adapted for multi-beam frequency reuse spot beam satellite systems;
- transmission techniques adapted for mobile broadcast and interactive applications.

4.2.3.2 Link layer

The encapsulation on the DVB-S2/Sx system is based on either MPEG transport stream (TS) or generic stream encapsulation (GSE). While MPEG transport stream encapsulation has been widely used for legacy video/audio systems, it is recently more and more replaced with generic stream encapsulation and GSE-Lite to enable potentially more efficient IP based encapsulation onto the DVB-S2 baseband and physical layer frames.

While GSE defines a multi-protocol transparent encapsulation mechanism for DVB-S2 and an efficient mechanism for fragmenting the capacity, the overhead can be reduced and a GSE Lite version is (currently) discussed with optimized encapsulation overhead efficiency.

DVB-RCS2

Interactive systems and access schemes for two-way satellite systems based on DVB-RCS2

The state-of-the-art basis for interactive systems and return channel technologies is among others the currently defined DVB-RCS2 standard for interactive systems under the DVB project.

This standard focuses on VSAT networks for consumer and professional applications for fix and mobile use cases. An efficient return channel for linear and constant envelope modulation is presented in this standard, which in this second updated version also addresses the higher layers and system aspects.

Within this standard an MF-TDMA return channel is defined to share the return link capacity and for sustained rates on the return link an optional SCPC dynamically allocated channel is defined. Within Newtec, a dynamic short block code (Dyn-SBC) channel is implemented, which addresses the requirements of higher rate return link applications for a variety of use cases.

For two-way satellite systems several multi access standard exist since the start of VSAT networking. Single channel per carrier (SCPC) systems have been replaced in the second generation standards by multi frequency time division multiple access (MF-TDMA) systems, which are currently the state-of-the-art for VSAT typical return channels. Most standards and proprietary solutions use MF-TDMA as access scheme. The high degree of flexibility of MF-TDMA to respond to variable traffic demand has a price in physical layer efficiency, which is necessary for the multi carrier burst detection.

In this context, Newtec is introducing a significantly improved access system based on the usage of highly efficient single carrier systems, with flexible rate adaptation to respond to changing traffic demands. This so called "Dynamic Short Block Codes" Dyn-SBC[12] system improves overall access efficiency for a variable but sustained traffic load on the return channel.

The Dyn-SBC channel provides a basis for the flexible allocation of bandwidth according to traffic demands in the terminals and allows on a per second basis to reassign a frequency and symbol rate to a fix channel allocation. A multiplex of several carriers can share the same spectral resources while keeping a flexible resource mapping during the operation.

The MF-TDMA and Dyn-SBC technologies are both a possible basis for the physical layer of a secondary use cognitive radio system.

4.2.3.3 Networking layer

DVB-RCS2 Higher Layer Specification

Within the standardization effort of DVB-RCS2 that was completed in 2012, the higher layer aspects have been defined in the context of two-way broadband access networks using DVB-RCS2.

This specification foresees the definition of the quality of service classes used in the access system as well as the signaling for the higher layer aspects that can be used to make the system interoperable in an end-to-end network.

DVB-RCS2 HLS defines the following features for support within DVB-RCS2 networks:

- reference network architecture for the HLS context and HLS defines an satellite virtual network (SVN) concept;
- Satellite Independent Adaptation Functions (SI-SAP) functions to access the link layer functionalities of DVB-RCS2;
- Quality of Service and Service Level Agreement (SLA) definitions and support;
- Performance Enhancement Proxy (PEP) for higher layer acceleration and performance enhancement features;
- an OSS/NMC context (operations and management context).

The detailed HLS architecture is defined in the related guidelines document form DVB [233]-[235].

4.2.3.4 Higher layer performance enhancement techniques

The satellite link suffers from an inherent significant round trip delay of messages from the terminals to the hub via a geostationary satellite link. This delay is well known to cause performance issues for a number of higher layer applications and protocols commonly used in internetworking types of applications:

TCP suffers from a particular delay caused by slow start of the protocol. It has been designed for congestion avoidance and control and not for long delay links. An adaption is required to avoid unnecessary delays caused by the TCP mechanisms to control the throughput.

---

[12] Proprietary flexible access system.

TCP acceleration - TCPe

For an end-to-end IP connectivity, it is important to adapt to the long satellite delay for geostationary satellites. The transmission control protocol (TCP) has to be adapted to avoid building up slowly during its slow start procedure and to avoid it reacting to delay with timeouts and congestion avoidance. Standards such as DVB-RCS provide for the use of Performance Enhancing Proxies (PEPs) that are generally proprietary in nature. For this purpose a set of solutions exist. Newtec's subsidiary Tellitec has developed adapted TCP acceleration methods TCPe with improved accelerated reaction speeds and throughputs over satellite links with delay.

Application layer acceleration techniques

Applications can be boosted in performance by selectively pre-fetching content and conditioning the transmission over the satellite link. Specific higher layer application tuning mechanisms can be applied to avoid delay impact on the applications. Caching may be used in the terminals to store content that has been downloaded in anticipation of user's demand and is used to fill possible idle times in the transmission. This avoids delay and saves bandwidth. Different techniques are implemented as traffic prediction tools that may anticipate user's demand based on learned past behavior.

4.2.3.5 Network topologies

Within the context of two-way satellite networks, we consider two types of networks:

- star access networks with a centralized hub or gateway and a large number of potential terminals accessing the same gateway network;
- mesh networks interconnecting a small number of terminals interconnected by a terminal to terminal connection.

Star networks

The star network topology is concentrating around one central hub station and connects a number of terminals to a central hub system. Such hub systems can scale to a large number of terminals in case of consumer broadband systems.

Typical VSAT networks are organized in STAR system networks.

As an example of a considered system, Newtec currently integrates a system called "DIALOG," which allows the interconnection of different classes of terminals to a central hub system and the integrated network management of this network in a centralized system.

This concept regroups then the MDM2200 terminals for consumer grade VSAT applications, the MDM3000 and MDM3100 modems for professional VSAT applications as well as the high end MDM6000 modem systems tailored for the needs of high throughputs and teleport class of reliability, efficiency and management.

This DIALOG platform represents a common centralized scalable gateway, ideal for usage within multi-spot beam networks on the gateway side. This permits to deploy gradually links over multiple spot-beams and using different terminal classes in a common network gateway infrastructure.

Mesh networks

Mesh networks are often used in governmental and military contexts to provide direct interconnection between a number of actors in a typically smaller network, which foresee the interconnection between terminals directly without the intermediate step of passing through a central hub station. This eliminates the double satellite hop delay and reduces it to only one hop in case of terminal to terminal connections (typical for government type of networks).

4.2.3.6 Future Trends of Broadcast and Forward Links

The broadcast or forward channel of broadband systems relies commonly on efficient stream transmissions like DVB-S2. Currently there is an effort ongoing to extend and improve the current DVB-S2 transmission standard towards a next generation transmission scheme with as basis DVB-S2 complexity but without a backwards compatibility requirement.

To this end, evolutionary and revolutionary efforts have been defined by the DVB Technical Module DVB-S2 working group.

The current proprietary S2extensions scheme provides a practical transmission scheme with significantly increased spectral efficiencies as well as with an extension in granularity and range of the usable MODCODs.

The S2evo standard will build on this or similar extended S2 technologies with a limited amount of additional complexity and aiming at an implementation in the near future for applications in STBs in combination with Quad HD.

On the longer term, the S2revo or revolutionary part foresees the implementation of significant improvements on the long term. These include techniques to further improve efficiency and also facilitate new use cases related to DVB-S2, including mainly:

- improved support for adaptive MODCODs and decoding/demapping iterative receivers;
- support of advanced detection techniques such as interference mitigation, MIMO, and joint detection in the receivers;
- support of wideband transmissions transmission modes;
- techniques suitable and adapted for multi-beam frequency reuse spot beam satellite systems;
- transmission techniques adapted for mobile broadcast and interactive applications;
- improved support of interference mitigating techniques.

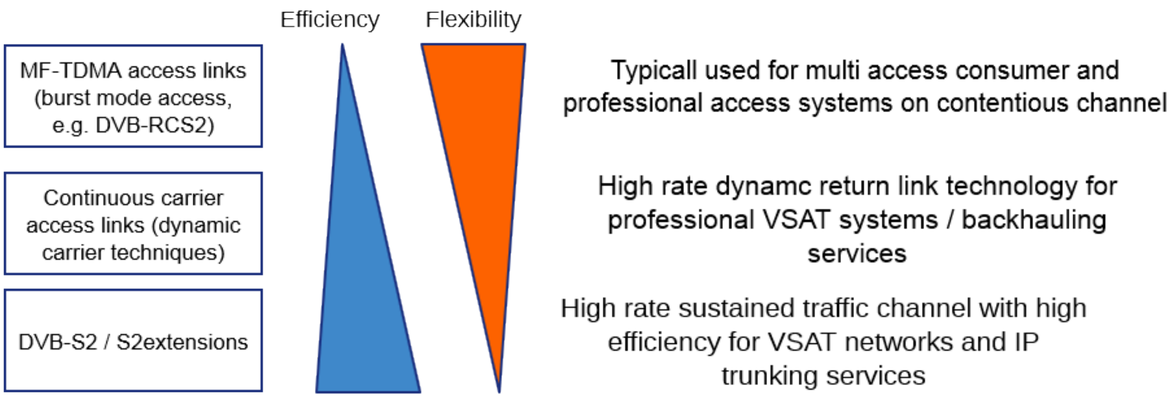


Figure 23 - Generic categorisation of the air interface technology options available to respond to the requirements of both flexible capacity assignments over time and frequency allocations and of efficiency on the other hand.

The defined transmission standard stack within the next generation platforms developed at Newtec (and by other VSAT vendors) includes physical layer techniques, which are well suited to respond to the requirement of frequency agile links, such as certain cognitive radio systems.

What remains to be defined in a detailed end-to-end system context is which techniques are maintained as end-to-end link. This will require input from system perspective on reaction speed to different interference requirements, interference detection accuracy, link reliability, network topology aspects to conclude on these aspects.

Also on link layer there are different approaches that can be foreseen to frame the content in interference resilient manner over multiple links and protect the data as defined by the end-to-end communication system requirements.

Based on the physical layer possibilities introduced with efficient MF-TDMA as well as the very low signal to noise ratios (VLSNR) considered in the context of DVB-S2 evolutions, the physical layer provides a set of basic techniques that can serve the implementation of requirements of interference mitigation and possible frequency sharing schemes.

5 CURRENT REGULATORY CONTEXT

5.1 Introduction to EU Policy Context and Background

The European Commission Communication COM(2012) 478, dated 03 September 2012 *on the promotion of the shared use of radio spectrum resources in the internal market* [280], provides a clear guidance on the ways technology research can help while ensuring compliance with spectrum policy objectives. This Communication addresses the following issues relevant to the shared use of spectrum:

- launching a debate on creating market-based incentives for spectrum sharing in Europe;
- defining a common regulatory principle to foster different modes of spectrum sharing [see, *e.g.*, Beneficial Sharing Opportunities (BSO)];
- setting out a strategy to promote shared access to spectrum in the internal market [see, *e.g.*, License-Exempt (LE) or Licensed Shared Access (LSA)];
- sending a clear signal to innovators that Europe supports advanced wireless technologies [see, *e.g.*, Cognitive Radio (CR), White Spaces].

Moreover, of relevance to CoRaSat is the EU Radio Spectrum Policy Programme (RSPP) [409] with respect to the shared use of spectrum and convergence (see, *e.g.*, [382]) as well as the forthcoming Radio Spectrum Policy Group (RSPG) Opinion on LSA to be adopted by end 2013 (see, *e.g.*, RSPG 12-424 final [385]). The following analysis considers relevant objectives of the RSPP, such as:

- maximizing the socio-economic and environmental benefits that can be generated through the use of radio spectrum "*... to foster the collective use of spectrum as well as the shared use of spectrum*";
- fostering wireless innovation in Europe "*... to foster the development of current and new technologies, for example in cognitive radio, including those using white spaces*";
- ensuring the *"promotion of competition and innovation, taking account of the need to avoid harmful interference and of the need to ensure technical quality of service"*.

In 2011, the RSPG issued a *Report on Collective Use of Spectrum* that noted the high demand for shared use [322]. The RSPG stated that "*there is a need to progress further on appropriate regulatory mechanisms in regard to sharing of spectrum*".

The key challenge for National Regulatory Authorities (NRAs) is to find appropriate ways to authorize *shared spectrum access* to a band, *i.e.*, to allow two or more users to use the same frequency range under a defined sharing arrangement. To date, users sharing LE bands, such as short range devices ("SRDs"), have no rights to be protected against harmful interference, while users sharing frequencies on the basis of individual licenses may benefit from regulatory guarantees in this regard. Ensuring co-existence between different applications in the same range of frequencies is essential for exploiting sharing opportunities. Acceptable levels of interference and appropriate mitigation strategies must be defined between users or set out in regulatory conditions for shared access to a band. Interference mitigation can be achieved through reliable sharing arrangements based on clear, effective sharing rules and conditions in a band, creating certainty for both incumbent and prospective users.

To exploit the full potential benefits of spectrum sharing, dedicated research is required into dynamic spectrum access with research projects addressing technologies that foster cognitive radio, dynamic spectrum sharing and spectrum aggregation. In this context, several R&D projects have been selected for co-funding as part of the 7th Framework Programme (FP7), which have clustered together within the Radio Access and Spectrum (RAS) cluster [386]. CoRaSat project is one of such projects addressing the applicability of Cognitive Radio (CR) techniques to SatCom systems for more efficient spectrum utilization.

The present document serves as the regulatory basis for further development of CR techniques in the SatCom context and aims to map the current regulatory landscape with the relevant issues for the scope of CoRaSat. As such, for each identified CoRaSat scenario, it takes into account relevant EU regulations and policies, CEPT recommendations and decisions, ITU-R regulations and recommendations, as well as relevant recent and ongoing CR projects addressing regulatory issues.

At this point, before going further to the regulatory analysis, it shall be noted that in ITU-R terminology, capital letters in a table of allocations mean PRIMARY service; lower case letters mean secondary service. Secondary services cannot create interference into PRIMARY services and cannot claim protection from interference originated in PRIMARY service transmitters. In the CoRaSat context, to avoid any confusion with the ITU-R terminology, the terms "**incumbent**" and "**cognitive**" (or "**new-entrant**") are used instead of "primary" and "secondary", respectively. The terms "incumbent user" and "cognitive (or "new entrant") user are defined in Chapter 3.

5.2 Scenario A Regulatory Context

Scenario A addresses a Cognitive Radio GSO Satellite downlink in Ka-band [17.3 – 17.7 GHz]. Specifically:

a. FSS cognitive satellite terminals reusing frequency bands of other BSS GSO feeder link systems also operating in this band;
b. Support of satellite terminals on mobile platforms.

CEPT has adopted a Decision, ECC/DEC/(05)08, which gives guidance on the use of this band by High Density applications in the Fixed-Satellite Service (HDFSS). The Decision stipulates that the designation of the band 17.3 – 17.7 GHz is without prejudice to the use of this band by Broadcasting Satellite Service (BSS) feeder uplinks and that it is not allocated to any terrestrial service on an incumbent basis (except in some countries). The deployment of uncoordinated Fixed-Satellite Service (FSS) Earth stations is also authorized in these bands. The question here is whether uncoordinated FSS stations could increase frequency exploitation by flexible usage of the spectrum portion through the adoption of Cognitive Radio techniques.

Regarding the support of satellite terminals on mobile platforms, of relevance is the ECC Decision ECC/DEC/(13)01 on the harmonized use of ESOMPs operating within the given frequency band.

5.2.1 ECA and ITU-R Tables of Allocations in this frequency band

This scenario concerns the band 17.3-17.7 GHz. In addition to the FSS, this band shows a number of allocations to other services, notably Radiolocation on a secondary basis in the three ITU-R Regions and in Region 2 an allocation to BSS on a primary basis as depicted in the following tables.

Table 8 - ECA Table of Allocation in 17.3-17.7 GHz band (Source: [424])

17.3 - 17.7 GHz					
FIXED-SATELLITE (E/S) 5.516 (S/E)	FIXED-SATELLITE (E/S) 5.516 (S/E)	ECC/DEC/(05)08	FSS Earth stations		High Density FSS
5.516A 5.516B	5.516A 5.516B		Feeder links		Feeder links for the BSS service. Appendix 30A of RR
		ECC/DEC/(13)01	ESOMPs	EN 303 978	
Radiolocation	Radiolocation		Defence systems		Military radar applications
5.514	EU2				

Table 9 - ITU-R Table of Allocations in the 17.3-17.7 GHz band

Region 1	Region 2	Region 3
17.3-17.7 FIXED-SATELLITE (Earth-to-space) 5.516 (space-to-Earth) 5.516A 5.516B Radiolocation 5.514	**17.3-17.7** FIXED-SATELLITE (Earth-to-space) 5.516 BROADCASTING-SATELLITE Radiolocation 5.514 5.515	**17.3-17.7** FIXED-SATELLITE (Earth-to-space) 5.516 Radiolocation 5.514

Footnote 5.514 stipulates that in certain countries this band is attributed to Fixed and Mobile Service on a secondary basis, subject to power limits given in Articles Nos. 21.3 and 21.5. Italy is the sole European country concerned. As this allocation is on a secondary basis, the Italian FS/MS allocation is not considered as an issue.

Footnote 5.515 stipulates that in the band 17.3-17.8 GHz, sharing between the fixed-satellite service (Earth-to-space) and the broadcasting-satellite service shall also be in accordance with the provisions of § 1 of Annex 4 of Appendix 30A.

Footnote 5.516 (limited to the concerned band) stipulates the use of the band 17.3-18.1 GHz by geostationary-satellite systems in the fixed-satellite service (Earth-to-space) is limited to feeder links for the broadcasting-satellite service.

Footnote 5.516A, limited to Region 1, stipulates that in the band 17.3-17.7 GHz, Earth stations of the fixed-satellite service (space-to-Earth) shall not claim protection from the broadcasting-satellite service feeder-link Earth stations operating under Appendix 30A, nor put any limitations or restrictions on the locations of the broadcasting-satellite service feeder-link Earth stations anywhere within the service area of the feeder link.

Part of the footnote 5.516B, stipulates that the band 17.3-17.7 GHz, in Region 1, is identified for use by high-density applications in the fixed-satellite service.

5.2.2 European regulatory status in this frequency band

The European regulation for this band relies mostly on CEPT Decision ECC/DEC(05)08. The status of implementation of this decision within CEPT, and the allocation of the band 17.3-17.7 GHz in CEPT countries, is summarized in the table below.

At this point, it should be noted that ECC Decisions are not mandatory instruments, and CEPT administrations may choose not to implement them or to provide complete information on national implementation. As such, the following table, and subsequent tables indicating implementation of ECC Decisions, are not totally reliable.

Table 10 - EU Regulatory Status in 17.3-17.7 GHz band (ECC/DEC/(05)08 Implementation Status)

	ECC/DEC/(05)08	
Documentation	***Status***	***Remark***
Montenegro	Yes	Through reference in the NFAT
Albania	Yes	Implemented through reference in the National Frequency Allocation Table, Government Decision Nr.479, Dt. 06.05.2009
Andorra	No info	
Austria	Yes	Implemented with the Frequency Utilisation Ordinance
Belgium	No	
Bosnia and Herzegovina	No info	
Bulgaria	Yes	Implemented through reference in the National Frequency Allocation Table and Technical requirements for the operation of the electronic communications networks and relevant equipment in fixed-satelite and mobile-satellite services
Vatican City	No info	
Cyprus	Yes	
Czech Republic	Yes	Plan of Radio Spectrum Utilisation, Part No. PV-P/17/02.2010-3
Germany	Yes	Terminals are exempted from individual licensing but the operation is allowed only under the control of a satellite network, which needs to be authorised by the NRA
Denmark	Yes	Implementation through reference in the national table of frequency allocations
Spain	Yes	
Estonia	Yes	Implemented through reference in "The Estonian radio frequency allocation plan"
France	Yes	This ECC Decision is implemented in the NFTA.
Finland	Yes	Implemented by Regulation FICORA 4 on radio frequency regulation, see http://www.ficora.fi/en/index/palvelut/palvelutaiheittain/radiotaajuudet/radiotaajuusmaarays4.html
United Kingdom	No info	
Greece	No info	
Hungary	Yes	National footnotes H193A, H194B of the National Table of Frequency Allocations, which was published by Government Decree No. 346/2004 (XII.22.)Korm._x00D_ Note: All the bands listed in Decides 1 are made available
Netherlands	Yes	Implemented by reference in the National Frequency Table
Croatia	Yes	
Italy	Yes	Implemented by the decree of Ministry of the Economic Development of 13 November 2008 and published in the Italian Official Gazette No. 273 dated 21 November 2008
Ireland	No info	
Iceland	Yes	Implementation through reference in the National Table of Frequency Allocation
Liechtenstein	Yes	
Lithuania	Yes	
Luxembourg	Yes	Through reference in Luxembourg's national table of frequency allocations
Latvia	No	
Monaco	No info	
Moldova	No info	
Macedonia (FYROM)	Yes	
Malta	Under study	
Norway	Yes	
Poland	No info	
Portugal	Yes	Press release containing the Decision published (Spectru no 123, September/October 2009)
Romania	Yes	Included in the National Table of Frequency Allocations (www.ancom.org.ro)
Russian Federation	No info	
Sweden	Yes	Implemented by the National Frequency Allocation Table and by PTS licence exemption regulations
San Marino	No info	
Switzerland	No info	
Slovak Republic	No info	
Slovenia	Yes	NTFA
Turkey	Yes	
Ukraine	No	
Serbia	No	
Georgia	No info	
Azerbaijan	No info	
Belarus	Under study	

It is to be noted that ECC/DEC(05)08 has been substantially amended in the course of work in ECC FM44. In the updated version, amended in March 2013, it is indicated that administrations shall exempt from individual licensing and allow the free circulation and use of the uncoordinated FSS Earth stations operating in the band 17.3-17.7 GHz [296].

5.2.2.1 BSS feeder links use

The frequency band 17.3-18.4 GHz is allocated to the Fixed Satellite services in the Earth-to-space direction and space-to-Earth. The FSS allocation in the direction Earth-to-space is limited to feeder links for the BSS.

The 17.3-17.7 GHz band is also allocated to the FSS in the space-to-Earth direction and designated as HDFSS.

Earth stations of the FSS shall not claim protection from interferences caused by the BSS feeder link Earth stations.

This gives to the BSS feeder link station a superior status with respect to FSS. For example, even if a FSS system is already deployed, the implementation of a new BSS feeder link Earth station can cause unacceptable interferences to the FSS Earth stations close to this feeder link station without any possibility for the FSS system to claim protection (see Article 5, footnote 5.516A of RR).

ITU studies realized before the WRC-03 calculated FSS receivers may be interfered in a beam around 30 km close to the BSS feeder links (see D2.5 [441]).

It also has to be noted that the number of BSS feeder link Earth station sites is relatively limited, even if the services they provide are important.

From the ITU database, European and Middle Eastern satellite operators who are using BSS feeder links in the band 17.3-17.7 GHz are listed below:

- SES, for the orbital slots: 5E, 19.2E, 23.2E, 28.2E;
- Eutelsat for the orbital slots: 7W, 9E, 13E, 36E;
- Hispasat for the orbital slot 30W;
- Telenor for the orbital slot 0.8W;
- Nilesat for the orbital slot 7W;
- Arabsat for the orbital slot 26E.

It should be noted that the BSS feeder link Earth stations might not be pointed at only these orbital locations. For example, these Earth stations can also perform the TT&C for launch operations and satellite relocations, and so could point to anywhere in the geostationary arc.

Satellite operators willing to obtain international recognition of the frequency assignments associated to their transmit stations may notify to the ITU the characteristics of their BSS feeder links in addition to their geographical location. This is not systematically realized, especially when no coordination is required outside the BSS feeder implementation countries.

Concerning the band 17.3-18.1 GHz, a non-exhaustive list of BSS feeder links Earth stations is presented in the following table.

Table 11 - Non-exhaustive list of BSS feeder links Earth stations in 17.3-18.1 GHz band (Source: FM44(11)041 [437])

Geographical location (Note)	Geographical coordinates (Long.; Lat.)
Betzdorf	49°N40; 6°E20
Boulogne-Billancourt	48°N52; 2°E19
Bratislava	48°N08; 17°E07
Burum	-
Chalfont St Peter	51°N37; 0°W34
Chilworth	50°N57; 1°W25
Cologne	50°N55; 6°E57
Crawley Court – Winchester	51°N07; 1°W23
Ecully	45°N45; 4°E50
Frankfurt	50°N07; 8°E40
Hatfield	53°N34; 00°W58
Helmond	-
Hilversum	-
Langenberg	-
London Teleport	51°N30; 0°W07
Mainz-Lerchenberg	50°N00; 8°E16
Moscow	55°N45; 37°E36
Nantes	47°N13; 1°W33
Potsdam	52°N23; 13°E04
Prague	50°N04; 14°E28
Saarbruecken	49°N13; 7°E00
Sofia	42°N40; 23°E19
Unterföhring	48°N12; 11°E37
Usingen	50°N19; 8°E31
Vilnius	54°N40; 25°E19
Wien	48°N12; 16°E22

Note: in many cases above, several Earth Stations are co-located, which increases the separation distance.

FM44 considered that the number of feeder link sites was *limited*, and hence compatibility issues with FSS receive Earth-station have a geographically limited impact (see FM44(11)041 [437]). Further details are provided in D2.5 [441].

5.2.3 FSS on ESOMPs

Users, and consequently operators of FSS satellites, are increasing their demands for the use of FSS Earth stations on board mobile platforms (trains, ships, trucks, etc.).

ECC Decision ECC/DEC/(13)01 [304] addresses the harmonized use of Earth Stations On Mobile Platforms (ESOMPs) which operate within the frequency bands 17.3-20.2 GHz (space-to-Earth) and 27.5-30.0 GHz (Earth-to-space).

Only the frequency band 17.3-17.7 GHz regulatory status is discussed here. For this frequency range, the Decision ECC/DEC/(13)01 aims to [304]:

- allow harmonised use, free circulation, and exemption from individual licensing of ESOMPs of geostationary satellite networks operating within this frequency band (17.3-17.7 GHz, receive band);
- apply the technical conditions necessary to ensure harmful interference is not caused by ESOMPs to stations of the FSS and other services.

For this frequency range (17.3-17.7 GHz), the Decision ECC/DEC/(13)01 further recommends CEPT Administrations to [304]:

- designate the frequency band 17.3-17.7 GHz (space-to-Earth) for the operation of ESOMPs;
- inform the [European Communications] Office of the necessity for ESOMPs operating on the Earth surface in the vicinity of airfields to be coordinated (see also Annex 3 of ECC/DEC/(13)01);
- allow the free circulation and use of ESOMPs that satisfy the provisions of this Decision, including the provision of the information contained in Annex 4 of ECC/DEC/(13)01;
- exempt ESOMPs from individual licensing.

In addition, for the purpose of this Decision ECC/DEC/(13)01 and for this frequency range (17.3-17.7 GHz), the following technical and operational parameters apply [304]:

- ESOMPs shall operate only in the frequency bands identified for their use within the territory of operation;
- ESOMPs receiving in the band 17.3-17.7 GHz shall not claim protection from BSS feeder links operating in the same band and in conformity with their national regulations.

5.3 Scenario B Regulatory Context

Scenario B addresses Cognitive Radio GSO Satellite downlink in Ka-band [17.7 – 19.7 GHz]. Specifically:

a. FSS cognitive satellite terminals reusing frequency bands of FS links with priority protection;
b. support of satellite terminals on mobile platforms.

CEPT has adopted a Decision, ECC/DEC/(00)07, which gives guidance on the use of this band by FSS and FS. The Decision stipulates that stations of the FSS can be deployed anywhere, but without right of protection from interference generated by FS radio stations. Cognitive Radio techniques could significantly increase the spectrum usage allocated to FSS by enabling access to frequency spectrum in the vicinity of terrestrial transmitters. Cognitive Radio techniques could act as a dynamic and flexible protection of FSS downlink from FS interference. This scenario can be seen as an extension of the FSS exclusive frequency band 19.7 – 20.2 GHz by adding significant user capacity in the 17.7 – 19.7 GHz bandwidth.

Regarding the support of satellite terminals on mobile platforms, of relevance is the ECC Decision ECC/DEC/(13)01 on the harmonized use of ESOMPs operating within the given frequency band.

5.3.1 ECA and ITU-R Tables of Allocations in this frequency band

This scenario concerns the frequency band 17.7-19.7 GHz. This band shows a number of allocations to several services, notably FSS and FS in the three ITU-R Regions as depicted in the tables below. Particularly, in the ITU-R table, extracted from the General ITU-R Table of Allocations for the specific frequency range 17.7-19.7 GHz, the allocation of services is mentioned together with RR provisions (*e.g.*, 5.484A means a specific note of the Radio Regulations) which further set conditions for the use of the related service in each sub band and Region.

Table 12 - ECA Table of Allocations in 17.7-19.7 GHz band (Source: [424])

RR Region 1 Allocation and RR footnotes applicable to CEPT	European Common Allocation	ECC/ERC harmonisation measure	Applications	European footnotes	Standard	Notes
17.7 - 18.1 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516	FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516		Feeder Links			Feeder links for the BSS service. Appendix 30A of RR
MOBILE			FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
18.1 - 18.3 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A (E/S) 5.520	FIXED-SATELLITE (S/E) 5.484A	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
			Feeder links			Feeder links for the BSS service.
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE	METEOROLOGICAL-SATELLITE (S/E)		WeatherSatellites			
5.519 5.521	5.519					
18.3 - 18.4 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A (E/S) 5.520	FIXED-SATELLITE (S/E) 5.484A (E/S) 5.520	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks'
			Feeder links			Feeder links for the BSS service
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE 5.519 5.521	METEOROLOGICAL SATELLITE (S/E) 5.519					
18.4 - 18.6 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A	FIXED-SATELLITE (S/E) 5.484A	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
MOBILE		ECC/DEC/(13)01	ESOMPs		EN 303 978	
18.6 - 18.8 GHz						
EARTH EXPLORATION-SATELLITE (passive)	EARTH EXPLORATION-SATELLITE (passive)					
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.522B	FIXED-SATELLITE (S/E) 5.522B	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE except aeronautical mobile						
Space research (passive)	5.522A		Passive sensors (satellite)			Surface emmissivity, snow, sea, ice and precipitation
5.522A 5.522C						
18.8 - 19.3 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.523A	FIXED-SATELLITE (S/E) 5.523A	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated earth stations. Priority for civil networks
MOBILE		ECC/DEC/(13)01	ESOMPs		EN 303 978	
19.3 - 19.7 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) (E/S) 5.523B 5.523C 5.523D 5.523E	FIXED-SATELLITE (S/E) (E/S) 5.523B 5.523C 5.523D 5.523E	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
MOBILE		ECC/DEC/(13)01	ESOMPs		EN 303 978	
19.7 - 20.1 GHz						
FIXED-SATELLITE (S/E) 5.484A 5.516B	FIXED-SATELLITE (S/E) 5.484A 5.516B		MSS Earth stations		EN 301 459 EN 301 360	For uncoordinated Earth stations SUT
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
Mobile-satellite (S/E)	Mobile-satellite (S/E)	ECC/DEC/(06)03	HEST		EN 301 459 EN 301 360	

Table 13 - ITU-R Table of Allocations in 17.7-19.7 GHz band[13]

Region 1	Region 2	Region 3
17.7 – 18.1 FIXED FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516 FIXED FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516 MOBILE	**17.7 – 17.8** FIXED FIXED SATELITE (space-Earth) 5.517 (Earth-space) 5.516 BROADCAST SATELLITE Mobile 5.518 5.515 5.517 **17.8 -18.1** FIXED FIXED SATELLITE (Space-Earth) 5.484A (Earth-space) 5.516 MOBILE	**17.7 – 18.1** FIXED FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516 FIXED FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516 MOBILE
18.1 – 18.4 FIXED FIXED SATELLITE (Space-Earth) 5.484A 5.516B (Earth-space) 5.520 MOBILE 5.519 5.521		
18.4 – 18.6 FIXED FIXED SATELLITE (space-Earth) 5.484A 5.516B MOBILE		
18.6 – 18.8 SATELLITE EARTH RESEARCH (passive) FIXED FIXED SATELLITE (Space - Earth) 5.522B MOBILE, except aeronautical mobile Space research (passive) 5.522A 5.522C	**18.6 – 18.8** SATELLITE EARTH RESEARCH (passive) FIXED FIXED SATELLITE (Space - Earth) 5.516B 5.522B MOBILE, except aeronautical mobile SPACE RESEARCH (passive) 5.522A	**18.6 – 18.8** SATELLITE EARTH RESEARCH (passive) FIXED FIXED SATELLITE (Space - Earth) 5.522B MOBILE, except aeronautical mobile Space research (passive) 5.522A
18.8 – 19.3 FIXED FIXED SATELLITE (Space-Earth) 5.516B 5.523A MOBILE		

[13] Note that these are the most up-to-date entries. The majority of WRC-12 revisions have entered into force as from 1 January 2013.

19.3 – 19.7 FIXED FIXED SATELLITE (Space-Earth) (Earth-space) 5.523B 5.523C 5.523D 5.523E MOBILE		
Main Sharing Usage		
Region 1	**Region 2**	**Region 3**
Feeder links for the BSS FSS (space-Earth) FS	FSS (space-Earth) FS	Feeder links for the BSS FSS (space-Earth) FS

5.3.2 European regulatory status in this frequency band

European regulation for this band relies mostly on CEPT Decision ECC/DEC(00)07. The status of implementation of ECC/DEC(00)07 with CEPT, and the allocation of the band 17.7-19.7 GHz in CEPT countries is summarized in the table below. As noted above, information from the following table may not be complete or totally reliable.

Table 14 - EU Regulatory Status in 17.7-19.7 GHz band (Source: FM44(12)049)

Country	FSS (space-to-Earth) allocation in 17.7-19.7 GHz - Source EFIS	Implementation of ECC/DEC(00)07
Albania	Yes	Yes
Andorra	-	No info
Austria	Yes	Yes
Azerbaijan	-	No info
Belarus	Yes	Under study
Belgium	None	Yes
Bosnia and Herzegovina	Yes	Yes
Bulgaria	Yes	Yes
Vatican City	-	No info
Croatia	Yes	Yes
Cyprus	Yes	Yes
Czech Republic	Yes	Yes
Denmark	Yes	Yes
Estonia	Yes	Yes
Finland	Yes	Yes
France	Yes	Yes
Georgia	Yes	Yes
Germany	Yes	Yes
Greece	Yes	Yes
Hungary	Yes	Yes

Country	FSS (space-to-Earth) allocation in 17.7-19.7 GHz - Source EFIS	Implementation of ECC/DEC(00)07
Iceland	Yes	Yes
Ireland	Yes	Yes
Italy	Yes	Yes
Latvia	Yes	Yes
Liechtenstein	Yes	Yes
Lithuania	Yes	Yes
Luxembourg	Yes	Yes
Macedonia	Yes	Yes
Malta	Yes	Yes
Moldova	Yes	Yes
Monaco	-	No info
Montenegro	None	Yes
Netherlands	18.4-19.7 GHz only	Yes
Norway	None	Yes
Poland	Yes	Yes
Portugal	Yes	Yes
Romania	Yes	Yes
Russia Federation	Yes	Yes
San Marino	-	No info
Serbia	Yes	Yes
Slovakia	17.7-18.1 GHz only	Yes
Slovenia	Yes	Yes
Spain	Yes	Yes
Sweden	Yes	Yes
Switzerland	Yes	Yes
Turkey	Yes	Yes
United Kingdom	Yes	Yes
Ukraine	Yes	Planned

The table above indicates that Decision ECC/DEC(00)07 is widely implemented within CEPT, and FSS allocations are present in most CEPT countries according to EFIS.

Decision ECC/DEC(00)07 stipulates that uncoordinated Earth stations shall operate on an unprotected basis, but requires both FS and FSS systems to implement interference mitigation measures. Both FS and FSS systems should operate under the general conditions set by the RR. The Decision does not limit technical parameters but identifies qualitative and conceptual mitigation techniques. These technical mitigation measures are appropriate to protect FS, but the current regime is not sufficient to enable FSS uncoordinated stations to be widely deployed in the 17.7-19.7 GHz band, as there is uncertainty to provide FSS services in the band.

While there are some parallels with the situation in the band 10.7-12.5 GHz, there are also some relevant differences. The band 10.7-12.5 GHz is extensively used throughout Europe for TV receive-only applications. Users of TV receive-only systems typically require reception of emissions in a very large band (*e.g.*, 1 GHz or more) and interference even on a smaller range of frequencies could lead to certain TV channels being unavailable and hence be considered unacceptable by the users. In contrast, the band 17.7-19.7 GHz is planned to be used mostly for telecommunication services, in particular for broadband Internet access, but nothing prevents the use of this band also for any other application, including TV. For telecommunications and similar applications, the occurrence of interference on some frequencies can be overcome if other channels within the same frequency band are available to accommodate the users traffic requirement. In this case, the user could be entirely unaware of interference being received on some frequencies within the same band.

5.3.2.1 FS use of the 17.7-19.7 GHz band

The FS channelling arrangements of the CEPT ERC/REC Recommendation 12-03 for medium and high capacity systems are depicted below. This is the typical channelling for the FS service. It is based on a Recommendation, not legal mandate, but most operational equipment is commissioned to meet this channelling arrangement.

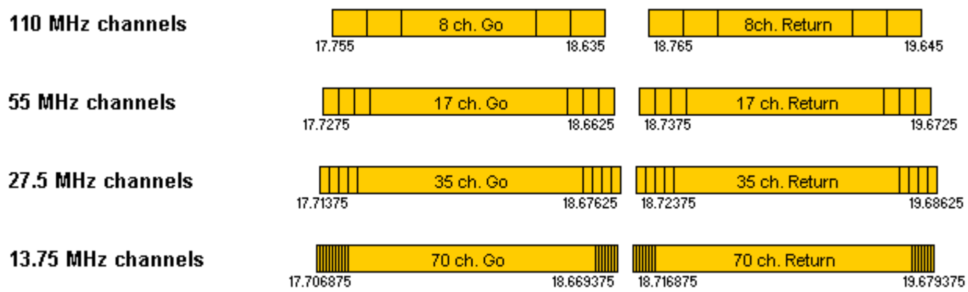


Figure 24 - FS Channel assignments in 17.7-19.7 GHz band

Recommendation 12-03 states that channel frequency arrangements for low capacity digital systems may be accommodated, on a national basis, within any of the high capacity channels or guard bands. Recommendation ITU-R F.595-10 [316] is also applicable to the 17.7 – 19.7 GHz band. This includes specific arrangements in use within the UK, where some legacy links also operate within the center gap.

FS Deployment Scenario

The 17.7-19.7 GHz band has been heavily used historically for PtP FS with about 90,000 deployed links. The 95% percentile of hop length indicated as "typical" is about 20 km (9.5 km for those indicated as "minimum") [287].

The major utilization is for high capacity links, with a comparable usage of medium and low capacity applications. Most links are individually licensed, and the majority is allocated to fixed and mobile infrastructure. The channel plan is based on the CEPT ERC/REC 12-03 [421] for medium and high capacity; several national arrangements are used for low capacity.

Concerning the usage, significant increase occurred in the period 2001-2010 in about 21 countries, although only moderate congestion has been experienced after 2010. The comparison chart is provided below [287].

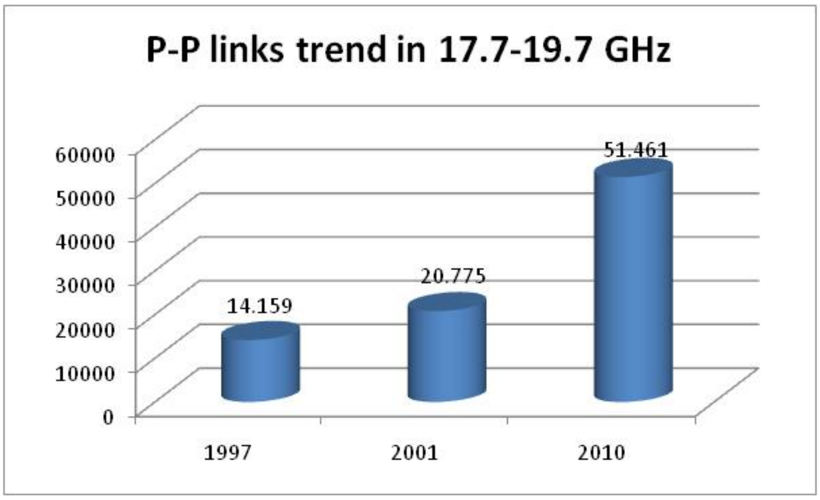


Figure 25 - Trend for the PtP links in the band 17.7-19.7 GHz in the 19 CEPT Countries available for comparison (Source: [287])

Although the numbers on FS deployment in Figure 25 seem to be precise, the accurate number of FS links deployed at European or worldwide level is unknown. The above gross numbers provide an indication about FS deployment. Studies conducted in recent years for specific areas (Madrid, Barcelona, Hungary, Slovenia, etc.) provide more accurate references on specific deployment in those regions; thus, they serve as a basis to extrapolate the FS density deployed in other Regions. Further details on these aspects are provided in D2.5 [441].

The assignment methods currently present in the FS regulatory framework of most CEPT countries may be summarized in the following four categories:

1. **Individual licensing**: this is the conventional link-by-link coordination, usually made under the administration's responsibility. Sometime, the administration delegates this task to the operators, but it keeps control of the national and cross-border interference situation. This is currently assumed to be the most efficient method of spectrum usage for PtP links networks.

2. **Light licensing**: even if the terminology itself is not completely agreed among CEPT administrations (see ECC Report 132), the common understanding, when fixed PtP links are concerned, refers to a link-by-link coordination under users' responsibility, reflected in the definition given by ECC Report 80 (at page 11) as:

   "*A 'light licensing regime' is a combination of license-exempt use and protection of users of spectrum. This model has a 'first come first served' feature where the user notifies the regulator with the position and characteristics of the stations. The database of installed stations containing appropriate technical parameters (location, frequency, power, antenna, etc.) is publicly available and should thus be consulted before installing new stations. If the transmitter can be installed without affecting stations already registered (i.e., not exceeding a pre-defined interference criteria), the new station can be recorded in the database. A mechanism remains necessary to enable a new entrant to challenge whether a station already recorded is really used or not. New entrants should be able to find an agreement with existing users in case interference criteria are exceeded.*"

3. **Block assignment**: the assignment might be made through licensing (renewable, but not permanent) or through public auction. This is most common when BFWA (PMP) is concerned and the user is usually free to use the block at best to deploy its network; in some cases, there might even be no limitation to the wireless communications methods used in the block (*e.g.*,

PtP and/or PMP, terrestrial and/or satellite or any other innovative technology or architecture). In the most popular bands for this method, ECC recommendations suggest intra-blocks protections guidelines in terms of guard bands or block-edge masks (BEM). For some frequency bands this method is considered the best compromise between efficient spectrum usage and flexibility for the user.

4. **License exempt**: this method offers the most flexible and cheap usage, but does not guarantee any interference protection. It is most popular in specific bands (*e.g.*, 2.4 and 5 GHz) where SRD are allocated, but FS applications may also be accommodated.

From the studies carried out by ECC, supported to questionnaires and as indicated in the ECC Report 173, individual licensing (frequency assignment of each individual link assignment method) continues to be the predominant method in making assignments in the majority of bands. Block allocation is on par with link by link assignment in the 3.4 – 4.2 GHz range and 24.5 – 26.5 GHz bands.

The decision of an administration for a particular assignment procedure for a particular band or an application can be influenced by a number of factors, which could have different backgrounds such as regulatory, administrative, technology/application or market driven:

- National Regulatory Framework: An administration is bound by its regulatory framework to be in line with the EU Electronic Communications Regulatory Framework, which gives administrations certain possibilities, or flexibility limits in terms of the frequency assignment. On the other hand, this legal framework could also impose to the administration to obey certain procedures and principles, which may not always be beneficial under specific circumstances.
- Administrative Factors: The choice for an assignment procedure is also very much influenced by administrative factors. The ability to handle the incoming amount of frequency assignment applications largely depends on the efficiency of the administrative handling, the assignment tool used and the manpower available in a particular administration.
- Technology Drivers: As reported as early as in ECC Report 003 in 2002, the decision for or against the individual assignment or block assignment also depends on the technology employed by a particular application in question. For example, in the case of PMP systems, an individual assignment of each single link could produce an unnecessary administrative burden for the operator and the administration. In this case, the individual frequency assignment for the base station or at least information on the base station location could be sufficient for the administration to impose measures to ensure co-existence with neighbouring assignments of the same or different systems (operators).
- Market Forces: Market forces also influence the decision for the assignment method. The time pressure for the introduction of new systems could impose the use of a speedy process for the frequency assignment in order not to hinder the rollout of networks, which are intended to enter the market quickly. Also the expected/desired overall utilization (e.g. for private or public infrastructures) may have a role in selecting the assignment method.

In the context of the CoRaSat project, all the FS licensing scenarios should be considered. However, the mitigation techniques to be applied in each case (individual licensing or licensing exempt) may be different.

5.3.3 FSS on ESOMPs

Users, and consequently operators of FSS satellites, are increasing their demands for the use of FSS Earth stations on board mobile platforms (vessels, aircrafts, etc).

ECC Decision ECC/DEC/(13)01[14] addresses the use of ESOMPs which operate in the FSS networks and are terminals with small directional antennas for the provision of broadband communication services [304]. The terminals may be mounted on aircrafts, ships or land vehicles, or may be transportable devices used in motion or at temporary halts. ESOMPs on aircrafts and ships may operate in national airspace and waters, or may also operate in international airspace and waters. This Decision relates only to ESOMPs operating in geostationary satellite networks.

In recent years a number of FSS networks have been launched which operate in 17.0-30.0 GHz Ka-band frequencies. More FSS networks are under construction and are expected to be launched over the coming years. Ka-band satellites typically use small spot beams, which leads to increased efficiency of spectrum usage and allows for small user terminal antennas. Also, the increased efficiency allows for broadband communications at lower cost than typical Ku-band systems.

The ECC has adopted several Decisions related to the operation of FSS systems in the Ka-band, in particular ECC/DEC/(05)01, ECC/DEC/(05)08, ECC/DEC/(06)02, and ECC/DEC/(06)03.

Work has been conducted within the ITU-R to examine the issues related to the operation of ESOMPs in Ka-band FSS networks. The ITU-R Report S.2223 [306] identifies technical and regulatory issues to be considered in regulations for ESOMPs. In ECC Report 184 [305], CEPT has studied the technical and regulatory requirements related to the operation of ESOMPs and determined technical limits required for ESOMP operations. These technical conditions would ensure that FSS networks and terrestrial services do not suffer from harmful interference from ESOMPs.

For the given frequency range of interest (17.7-19.7 GHz), ECC Decision ECC/DEC/(13)01 aims at [304]:

- allow harmonised use, free circulation and exemption from individual licensing of ESOMPs of geostationary satellite networks operating within the frequency bands 17.7-19.7 GHz (receive band);
- apply the technical conditions necessary to ensure harmful interference is not caused by ESOMPs to stations of the FSS and other services.

Also, for the given frequency range of interest (17.7-19.7 GHz), ECC Decision ECC/DEC/(13)01 further recommends CEPT administrations to [304]:

- Designate the frequency band 17.7-19.7 GHz (space-to-Earth) for the operation of ESOMPs;
- Inform the Office of the necessity for ESOMPs operating on the Earth surface in the vicinity of airfields to be coordinated (see also Annex 3 of the ECC Decision ECC/DEC/(13)01);
- Allow the free circulation and use of ESOMPs that satisfy the provisions of this Decision, including the provision of the information contained in Annex 4 of the ECC Decision ECC/DEC/(13)01;
- Exempt ESOMPs from individual licensing.

---

[14] Note that ECC Decision ECC/DEC/(13)01 addresses a wider frequency range (17.3-20.2 GHz) than the specific one of interest for this scenario , i.e., 17.7-19.7 GHz.

And also, for the purpose of this ECC Decision and for the given frequency range of interest (17.7-19.7 GHz), the following technical and operational parameters apply [304]:

- ESOMPs shall operate only in the frequency bands identified for their use within the territory of operation;
- ESOMPs receiving in the band 17.7-19.7 GHz shall not claim protection from interference from fixed stations operating in the same band and in conformity with their national regulations.

5.4 Scenario C Regulatory Context

Scenario C addresses Cognitive Radio GSO Satellite uplink in Ka-band [27.5 – 29.5 GHz]. Specifically:

a. FSS cognitive satellite terminals reusing frequency bands of FS links with priority protection;

b. support of satellite terminals on mobile platforms.

CEPT Decision ECC/DEC/(05)01 provides a segmentation between FS and FSS stations in this band. The FS segment is lightly used through Europe in these frequencies. FSS stations could maximize frequency exploitation by flexible usage of the FS segment through the adoption of Cognitive Radio techniques in the satellite uplink able to dynamically control the interference generated to the FS stations. As further elaborated in Section 5.4.2.4, ECC/DEC/(05)01 was amended in March 2013, although a number of administrations raised remarks.

Regarding the support of satellite terminals on mobile platforms, of relevance is the ECC Decision ECC/DEC/(13)01 on the harmonized use of ESOMPs operating within the given frequency band.

5.4.1 ECA and ITU-R Tables of Allocations in this frequency band

The 27.5-29.5 GHz band is allocated to terrestrial services (Fixed and Mobile), and to Fixed Satellite Service (Earth-to-space). The allocation to these services is valid throughout the whole band 27.5-29.5 GHz.

Table 15 - ECA Frequency allocation in the 27.5-29.5GHz band (Source: [424])

RR Region 1 Allocation and RR footnotes applicable to CEPT	*European Common Allocation*	*ECC/ERC harmonisation measure*	*Applications*	*European footnotes*	*Standard*	*Notes*
27.5 - 28.5 GHz						
FIXED 5.537A	FIXED		Feeder links			Feeder links to be used for Broadcasting satellites (HDTV) 27.5-29.5 GHz
FIXED-SATELLITE (E/S) 5.484A 5.516B 5.539	FIXED-SATELLITE (E/S) 5.484A 5.516B 5.539	ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE		ECC/DEC/(05)01 T/R 13-02	Fixed		EN 302 217	For frequency arrangement between FS and FSS see ECC/DEC/(05)01
5.538 5.540	5.538 5.540	ECC/DEC/(05)01	FSS Earth stations		EN 301 360	The Earth-to-Space direction for uncoordinated Earth stations within the band 27.5-27.8285 GHz. The Space-to-Earth direction is limited to beacons for uplink power control 27.5-27.501 GHz
		ECC/REC/(11)01 ECC/DEC/(05)01	BFWA		EN 302 326	CRS paired with 28.5-29.5 GHz for FDD systems. The Earth-to-Space direction for uncoordinated Earth stations within the band 27.5-27.8285 GHz. The Space-to-Earth direction is limited to beacons for uplink power control 27.5-27.501 GHz
28.5 - 29.1 GHz						
FIXED	FIXED		Feeder links			Feeder links to be used for Broadcasting satellites (HDTV) 27.5-29.5 GHz
FIXED-SATELLITE (E/S) 5.484A 5.516B 5.523A 5.539	FIXED-SATELLITE (E/S) 5.484A 5.516B 5.523A 5.539					
MOBILE Earth exploration-satellite (E/S) 5.541	Earth exploration-satellite (E/S) 5.541	ECC/DEC/(05)01 T/R 13-02	Fixed		EN 302 217	For frequency arrangement between FS and FSS see ECC/DEC/(05)01
5.540		ECC/DEC/(05)01	FSS Earth stations		EN 301 360	Uncoordinated Earth stations within the band 28.4445-28.8365 GHz
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
		ECC/REC/(11)01 ECC/DEC/(05)01	BFWA		EN 302 326	TS paired with 27.5-28.5 GHz for FDD systems. Uncoordinated Earth stations within the band 28.4445-28.8365 GHz
29.1 - 29.5 GHz						
FIXED	FIXED		Feeder links			Feeder links to be used for Broadcasting satellites (HDTV) 27.5-29.5 GHz
FIXED-SATELLITE (E/S) 5.516B 5.523C 5.523E 5.535A 5.539 5.541A	FIXED-SATELLITE (E/S) 5.516B 5.523C 5.523E 5.535A 5.539 5.541A	ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE		ECC/DEC/(05)01 T/R 13-02	Fixed		EN 302 217	Within the band 29.0605-29.4525 GHz
Earth exploration-satellite (E/S) 5.541	Earth exploration-satellite (E/S) 5.541	ECC/DEC/(05)01	FSS Earth stations		EN 301 360	Uncoordinated Earth stations within the band 29.4525-29.5 GHz
5.540	5.540					
		ECC/REC/(11)01 ECC/DEC/(05)01	BFWA		EN 302 326	TS paired with 27.5-28.5 GHz for FDD systems. Uncoordinated Earth stations within the band 29.4525-29.5 GHz

Table 16 - ITU-R Table of Allocations in 27.5-29.5 GHz band

Region 1	Region 2	Region 3
27.5 -28.5 FIXED 5.537A FIXED SATELLITE (Earth-space) 5.5484A 5.516B 5.539 MOBILE 5.538 5.540		

28.5 – 29.1 FIXED FIXED SATELLITE (Earth-space) 5.5484A 5.516B 5.523A 5.539 MOBILE Earth research Satellite (Earth-space) 5.541 5.540
29.1 – 29.5 FIXED FIXED SATELLITE SERVICE (Earth-space) 5.516B 5.523C 5.523E 5.535A 5.539 5.541A MOBILE Earth Exploration by satellite (Earth-space) 5.541 5.540

However, the ITU has acknowledged the fact that certain portions are less used by FS and have been identified for an intensive use by FSS. These band segments are known in ITU as High Density FSS, and are shown in the graph below.

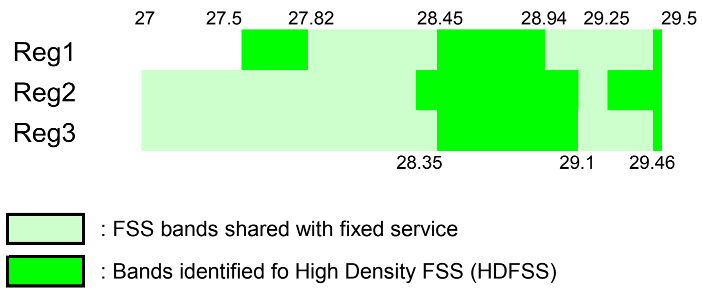


Figure 26 - Frequency allocations in 27.5-29.5 GHz band (Source: ECC/DEC/(05)01 [292])

The bands identified for HDFSS are given by ITU as a guideline. An extract of the footnote 5.516B from Article 5 of the ITU Radio Regulations, limited to the concerned bands of this scenario, is set forth below:

> The following bands are identified for use by high-density applications in the fixed-satellite service:
>
> - 27.5-27.82 GHz (Earth-to-space) in Region 1;
> - 28.35-28.45 GHz (Earth-to-space) in Region 2;
> - 28.45-28.94 GHz (Earth-to-space) in all Regions;
> - 28.94-29.1 GHz (Earth-to-space) in Region 2 and 3;
> - 29.25-29.46 GHz (Earth-to-space) in Region 2;

- 29.46-30 GHz (Earth-to-space) in all Regions.

This identification does not preclude the use of these bands by other fixed-satellite service applications or by other services to which these bands are allocated on a co-primary basis and does not establish priority among users of the bands. Administrations should take this into account when considering regulatory provisions in relation to these bands, as specified in Resolution 143 (WRC-03).

Administrations are free to implement the HDFSS arrangements in their national policies. Some specific cases are examined in the sections below.

5.4.2 Regulations applicable to incumbent services and actual use

5.4.2.1 Regulation applicable to FSS Earth stations for intra-service sharing

ITU-R level:

At ITU-R level, and as indicated above, the frequency allocations to the FSS (Earth-to-space) span across the band 27.5-29.5 GHz. The limitations applying to GSO FSS uplinks in the various parts of the band depend mostly upon the services and applications with which the band is shared. These can be summarized as follows:

- other GSO FSS systems: ensuring the compatibility between GSO FSS systems results in off-axis EIRP limitations;
- NGSO FSS systems: Coordination procedures are applicable in certain portions of the band 27.7-29.5 GHz. In these portions of spectrum, the sharing arrangements are determined on a case-by-case basis (see section 5.4.2.2 and scenario G);
- Fixed and Mobile Service: At the ITU level, there is no prioritization between FSS and terrestrial services. Individual administrations are sovereign to determine their priority for either service in all or part of the band. The HDFSS identifications (ITU-R footnote 5.516B) reflects however a certain degree of harmonization within the ITU Regions.

The ITU-R Recommendation S.524-9 is applicable to FSS Earth stations operations in C-, Ku- and Ka-bands. For the band 27.5-30 GHz it provides the following radiation pattern:

Angle off-axis	*Maximum EIRP per 40 kHz*
$2° \leq \varphi \leq 7°$	$(19 - 25 \log \varphi)$ dB(W/40 kHz)
$7° < \varphi \leq 9.2°$	–2 dB(W/40 kHz)
$9.2° < \varphi \leq 48°$	$(22 - 25 \log \varphi)$ dB(W/40 kHz)
$48° < \varphi \leq 180°$	–10 dB(W/40 kHz)

These values are applicable within ±3° of the geostationary arc. Beyond 3° from the GSO arc, these values may be exceeded by no more than 3dB.

Europe:

In Europe, the CEPT framework provides for FSS Earth stations exemption of individual licensing for Earth stations in certain parts of the Ka-band.

The applicable ECC Decision is ECC/DEC/(05)01 [292], which was amended in March 2013. This decision addresses inter-service sharing aspects which result in regulatory requirements that are described in section 5.4.2.3 below.

This Decision requires that the equipment concerned must comply with Article 3.2 of the R&TTE Directive of the EU. Such compliance may be shown through compliance to ETSI Harmonized Standards.

For Satellite Interactive Terminals and Satellite User Terminals: the applicable standard is EN 301360.

For ESOMPs: the applicable standard is EN 303978.

These standards establish, inter alia, the following Earth Station off-axis EIRP mask. This mask is aimed at establishing minimum requirement to ensure compatibility between FSS systems.

Co-polarization:

$19 - 25 \log \phi - 10 \log N$	dBW	for	1,8°	≤	φ	≤ 7,0°;
$-2 - 10 \log N$	dBW	for	7,0°	<	φ	≤ 9,2°;
$22 - 25 \log \phi - 10 \log N$	dBW	for	9,2°	<	φ	≤ 48°;
$-10 - 10 \log N$	dBW	for			φ	> 48°.

These values (in dBW/40kHz) apply within ±3° from the geostationary arc. They are relaxed by 3dB beyond 3° from the GSO arc. Information on the implementation of this relaxation is defined in ETSI TR102375.

Cross-polarization:

$9 - 25 \log \phi - 10 \log N$	dBW	for	1,8°	≤	φ	≤ 7,0°;
$-12 - 10 \log N$	dBW	for	7,0°	<	φ	≤ 9,2°,

Power control: +20dB allowed in case of rain fade[15].

US:

The main provisions of FCC rule 25.138 [327] dealing with the deployment of terminals without individual licensing are identified below. This rule applies to the bands 28.35-28.6 GHz and 29.25-30 GHz for GSO satellites.

- *Off-axis radiation pattern applicable within 3° from the GSO arc(co-polarization)*

18.5–25log(Θ)–10log(N)	dBW/40kHz	For 2.0° ≤ Θ ≤ 7°
−2.63–10log(N)	dBW/40kHz	For 7° ≤ Θ ≤ 9.23°
21.5–25log(Θ)–10log(N)	dBW/40kHz	For 9.23° ≤ Θ ≤ 48°
−10.5–10log(N)	dBW/40kHz	For 48° < Θ ≤ 180°

- *Off-axis radiation pattern applicable outside 3° from the GSO arc(co-polarization)*

15 Note that this power control is limited to rain fade only. Complementary studies would be required if used in case of interference.

21.5–25log(Θ)–10log(N)	dBW/40kHz	for 3.5° ≤ Θ ≤ 7°
0.37–10log(N)	dBW/40kHz	for 7° < Θ ≤ 9.23°
24.5–25log(Θ)–10log(N)	dBW/40kHz	for 9.23° < Θ ≤ 48°
−7.5–10log(N)	dBW/40kHz	for 48° < Θ ≤ 180°

The values given in the above two tables may be exceeded by 3 dB, for values of Θ >10°, provided that the total angular range over which this occurs does not exceed 20° when measured along both sides of the GSO arc.

- *Off-axis radiation pattern (cross-polarization)*

8.5–25log(Θ)–10log(N)	dBW/40 kHz	For	2.0° < Θ ≤ 7.0°
−12.63–10log(N)	dBW/40 kHz	For	7.0° < Θ ≤ 9.23°

For the above three tables, *N* is the likely maximum number of simultaneously transmitting co-frequency Earth stations in the receive beam of the satellite; N=1 for TDMA and FDMA systems.

- *Power Control :* Up to + 20dB

The following table provides a comparison of the various patterns:

Table 17 - Comparison of antenna patterns in 27.5-29.5 GHz band

Pattern	**Applicability**	**Relative level with respect to ITU-R Rec S.524-9**	**Pattern start angle**
Article 22	Mandatory limit within 29.5-30 GHz. This limit does not apply in the band 27.5-29.5 GHz	+9 dB	3°
ITU-R Rec. S.524-9	Recommended for all E/S within 27.5-30 GHz.	0 dB	2°
ETSI Standards	Allows exemption of individual license.	0 dB	1.8°
FCC Part 25	Allows exemption of individual license in 28.35-28.6 GHz et 29.25-30 GHz.	-0.5 dB *	2°

** : approximate, depending on off-axis angle value.*

Brazil:

Brazil has recently adopted a regulation for Ka-band systems, where the off-axis EIRP requirement for user terminals is approximately 2 dB more stringent than the recommendation ITU-R S.524-9. Nevertheless, in general off-axis EIRP requirements for terminals are internationally well harmonized, with few national variations.

5.4.2.2 GSO systems versus NGSO systems

- 27.5-28.6 GHz: GSO have priority over NGSO (RR Article 22.2).

- 28.6-29.1 GHz: GSO and NGSO FSS systems coordinate on a “first come – first served basis”.
- 29.1-29.5 GHz: GSO and NGSO FSS systems (limited to feeder-links for NGSO Mobile Satellite Service (MSS) systems) coordinate on a “first come – first served basis”.

The sharing issues between GSO and NGSO systems are studied under Scenario G.

5.4.2.3 Licensing conditions in Europe

ECC Decision ECC/DEC/(05)01 sets the following band segmentation between FSS and FS in the band 27.5-29.5 GHz:

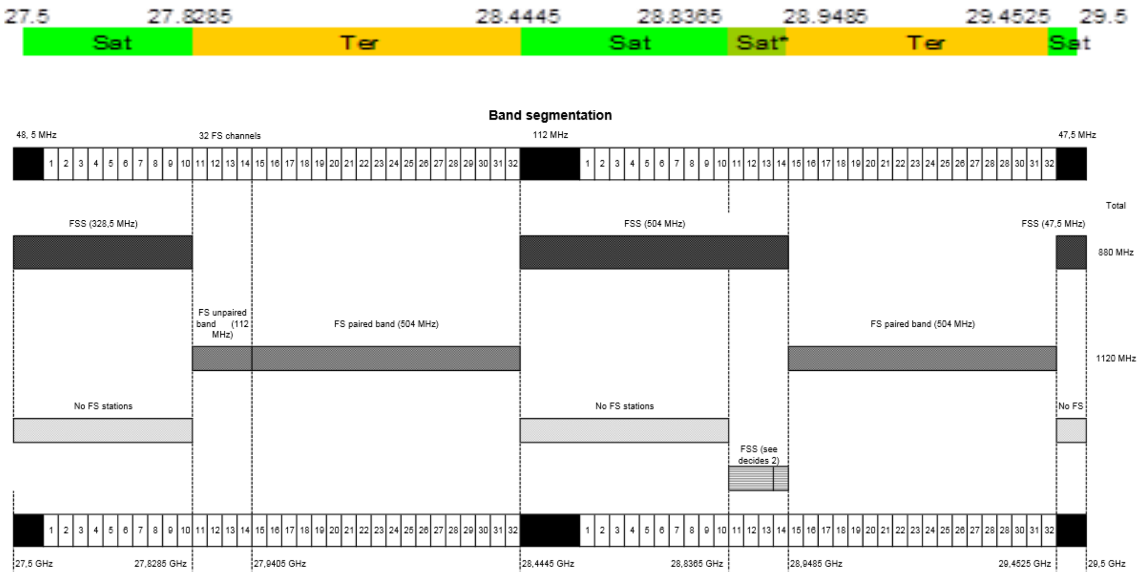


Figure 27 - Band segmentation for FSS and FS in the band 27.5-29.5 GHz (Source: ECC/DEC(05)01 [292])

Decision ECC/DEC(05)01 was amended in March 2013 [292][16]. The segmentation has not changed, but the provisions applicable to the various sub-bands have significantly evolved. The main points to be noted from this Decision are:

- terminals employing bands labelled “Sat” do not need site coordination, and are exempted from individual license. The bands 27.5-27.8285 GHz, 28.4445-28.8365 GHz and 29.4525-29.5 GHz are therefore designated for the use of uncoordinated FSS Earth stations;
- in the band labelled “Sat*” (28.8365-29.9485 MHz) there are legacy FS in a few countries. The FS links licensed in these countries before 18 March 2005 could require protection, but not after 1 January 2020. No new FS links can be deployed in this band;
- the bands labelled “Ter”, i.e., 27.8285-28.4445 GHz and 28.9485-29.4525 GHz, are designated for the use of FS systems;

[16] It should be noted that ECC Decisions are not mandatory instruments, and CEPT administrations may choose not to implement them. In any event, there typically is a time lag between ECC adoption and implementation by a substantial number of administrations. Thus, even for those administrations that did not expressly state they would not implement this ECC Decision, the final date for implementation could be delayed substantially.

- CEPT administrations shall not authorize the deployment of FS stations in the bands mentioned in 1st bullet above, nor authorize any new FS stations except in an already licensed network in the band specified in 2nd bullet above;
- the out-of-band EIRP radiated by FSS terminals in FS bands below 3° elevation shall not exceed –35dBW/MHz;
- FSS terminals shall operate above 3° elevation;
- Power Control is mandatory for FSS terminals. The maximum EIRP of FSS terminals shall not exceed a value in a range from 60dBW to 55dBW. The maximum value may be fixed nationally;
- FSS terminals shall implement a minimum guard band of 10 MHz from bands identified for FS.

In addition to the above, in the Annex 3 of the ECC/DEC(05)01 [292], there are provisions to protect airfields as derived from the ECC Report 66 [317]. The following table provides coordination distances from airfield fence, as a function of Terminal maximum EIRP within the frequency bands 17.3-20.2 GHz and 27.5-30.0 GHz.

Table 18 - Coordination distances vs. terminal maximum EIRP (Source: ECC/DEC(05)01 [292])

ES_EIRP range	34 dBW to 50 dBW	> 50 dBW to 55.3 dBW	>55.3 dBW to 57 dBW	>57 dBW to 60 dBW
ES_latitude	**From boundary**	**From boundary**	**From boundary**	**From boundary**
>35-70°/N	500 m	1800 m	2300 m	3500 m
30-35°/N	600 m	2000 m	2600 m	3900 m

5.4.2.4 Remarks of Administrations on ECC/DEC/(05)01 Amendment

Decision ECC/DEC/(05)01 was amended in March 2013, although a number of administrations raised remarks [426]. In particular, based on the proposal from WG FM, ECC also decided to keep implementation status for the amended Decision ECC/DEC/(05)01 without changes and also noted that Denmark, Austria, Sweden, and Lithuania will not change implementation status of amended Decision ECC/DEC/(05)01 from “partly implemented” to “implemented” [426]. As an illustration, statements from a number of administrations are quoted below [426]:

- statement from the United Kingdom [426]: The UK did not implement this Decision in its original form and is unable to implement the revised Decision;
- statement from Austria [426]: In Austria the decision can only be implemented partly. The frequency band 28.8365-28.9485 GHz is designated to FS and currently licensed to Mobile Operators. After the termination of the valid licenses (according to decides 2) and depending on the future need in the Mobile backhaul market, Austria will decide on the future application of the band 28.8365-28.9485 GHz for FS or FSS, taking into account the most beneficial usage;
- statement from Sweden [426]: Since 28 GHz licenses in Sweden stipulates that Earth stations shall have a minimum elevation angle of at least 10° the amended ECC Decision (05)01 will only be partially implemented;

- statement from Denmark [426]: Denmark will only partly implement the amended ECC Decision (05)01, since priority to FS services will be given in parts of the 27.5-29.5 GHz band. In Denmark the band 28.8365-28.9485 GHz will not be made available for satellite services;
- statement from Lithuania [426]: Lithuania has already implemented decision ECC/DEC/(05)01 partly by designating relevant bands for FS. Because 27.5-29.5 GHz band is still extensively used by radio relay links and we do not observe solid demand for FSS services in Lithuania, after amendment of the mentioned decision we stand with the same position and meanwhile restrain from setting additional restrictions for terrestrial stations.

5.4.2.5 FS situation in Europe

The ECC Report 173 indicates the following (see Figure 28 below) [287]:

2600 links and about 380 PMP Base Stations are reported in 31 countries as of the end of 2010. It has to be noted that in many countries the block allocation does not require any link notification. Therefore the figures provided for this kind of band could be substantially underestimated. Germany, Czech Republic, Austria, Slovakia, Finland and Spain count for 94% of these links, which means that the band is very little used by FS in the other European countries. Germany alone gathers more than half of links deployed in Europe in this band. In UK, there are no reported deployments in this band, although licenses were auctioned in 2000. On 19 December 2012 (with 15 February 2013 being the end date), the UK regulator (OFCOM) published a consultation titled “Variation of 28 GHz Broadband Fixed Wireless Access Licenses” on the use of this band after the current licenses expire in 2015 [328]. The responses received to this public consultation (in total, 12 responses) can be found in [328], whereas the summary of consultation responses and next steps has not yet been published by OFCOM. In France, the 27.5-29.5 GHz band is at this stage not available for FS assignment.

The 95% of hop lengths indicated as “typical” is about 4 km, whereas the 95% of hop lengths indicated as “minimum” is about 2.5 km.

Use for medium and high capacity is mostly reported.

Licenses are assigned by blocks or by link, according to the use, and the majority of the links is allocated to fixed and mobile infrastructure.

The PtP channel plan follows the Recommendation T/R 13-02.

Nine countries indicate expectations to increase the use in next years (10-0%; Finland indicates 90%), no country indicates decrease; local congestion is reported only by Finland.

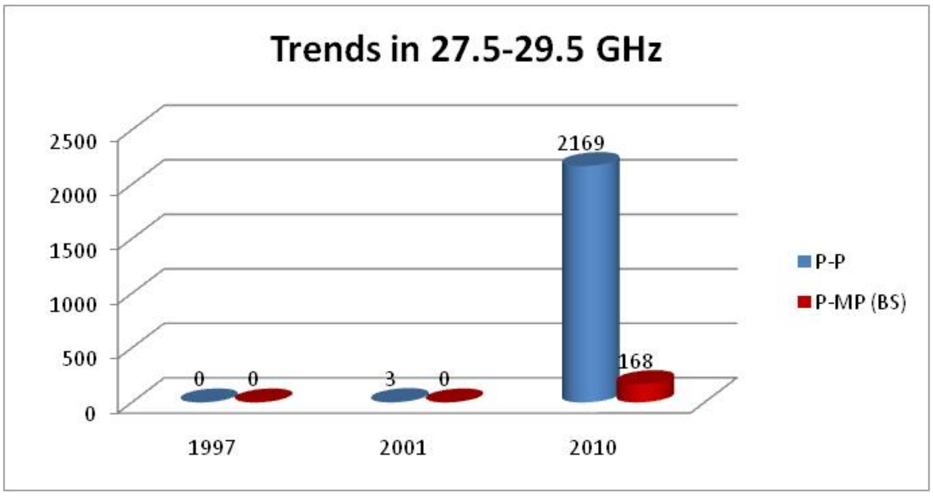


Figure 28 - Trend for the PtP links in the band 27.5-29.5 GHz in the 19 CEPT countries available for comparison (this does not include numbers of PtP links in auctioned blocks)

5.4.2.6 FS / FSS sharing in the US

The US Ka-band plan in the 27.5-29.5 GHz band sets the following band segmentation between the Fixed Service (FS) and the Fixed-Satellite-Service (FSS):

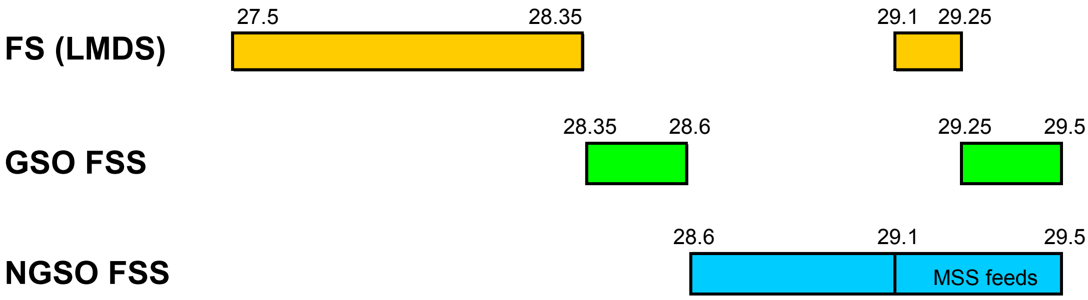


Figure 29 - FS – FSS band segmentation according to US Ka-band plan in 27.5-29.5 GHz band

The bands 28.35-28.6 GHz and 29.25-30 GHz can be used for “blanket-licensed” Earth stations associated with GSO systems, *i.e.*, stations operated with an exemption from individual license.

The blanket-license regime also applies in the 28.6-29.1 GHz frequency band for Earth stations operating with non-GSO systems. Some GSO operators have shown interest to use this band for their operations on a secondary basis with respect to NGSO systems.

In US, the Fixed Service in this band operates in the band 27.5-28.35 GHz and 29.1-29.25 GHz mainly for LMDS (Local Multipoint Distribution Service). For some satellite systems, the FCC has authorized FSS operations in the lower LMDS band (27.5-28.35 GHz), however these operations are on a secondary basis with respect to existing and future LMDS links.

5.4.3 FSS on ESOMPs

ECC Decision ECC/DEC/(13)01 provides an harmonized regulatory framework for ESOMPs [304]. The main elements are summarized here:

- ESOMPS shall be operated within CEPT in the bands identified for uncoordinated Earth Stations, as provided in ECC/DEC/(05)01;

- the technical requirements applying to FSS Earth stations, as identified in section 5.4.2.3, also apply to ESOMPs;
- in the bands identified for FS use ("Ter" bands) on the territory of all CEPT administrations, and in the band labelled "sat*" (28.8365-29.9485 MHz) in administrations implementing FS in this band, the following limitations apply:
  - aircraft mounted ESOMPs shall respect the following PFD (Power Flux Density) mask over the territory of countries implementing FS:

-124.7	$0° \leq \delta \leq 0.01°$
$-120.9 + 1.9 \log_{10}(\delta)$	$0.01° < \delta \leq 0.3°$
$-116.2 + 11.0 \log_{10}(\delta)$	$0.3° < \delta \leq 1.0°$
$-116.2 + 18.0 \log_{10}(\delta)$	$1.0° < \delta \leq 2.0°$
$-117.9 + 23.7 \log_{10}(\delta)$	$2.0° < \delta \leq 8.0°$
–96.5	$8.0° < \delta \leq 90.0°$

    where δ is the angle of arrival at the Earth's surface (degrees).

    These PFD values are expressed in $dBW/m^2/(14\ MHz)$;
  - ship-mounted shall not produce an PFD in excess of -109.0 dBW/m^2 in a reference bandwidth of 14.0 MHz at a height of 20.0 m above mean sea level at the low-water mark of the territory of the administrations concerned. Propagation losses to assess this value assumes a percentage of time of 0.007%;
  - the values in the 2 above bullets can be exceeded over the territory of administrations which so agrees.

The ESOMP decision also places requirements on administrations to provide information to the European Communications Office (ECO) with respect to the following aspects:

- whether frequencies within 28.8365-28.9485 GHz are designated for ESOMP operations, or not, within their territory;
- the necessity for ESOMPs operating on the Earth surface in the vicinity of airfields to be coordinated.

In addition, ECC Decision ECC/DEC/(13)01 [304] aims to provide technical conditions to allow ESOMPs to operate in the parts of the range 27.5-29.5 GHz available for uncoordinated FSS Earth stations and in the band 29.5-30.0 GHz. Although the frequency arrangements in the range 27.5-29.5 GHz are in principle harmonized in CEPT through this Decision, there may be cases where a band available for uncoordinated FSS in one country is used for FS systems in a neighbouring country. This could occur, for example, in the band 28.8365-28.9485 GHz, which is designated for uncoordinated FSS Earth stations, but is also used for terrestrial services in some CEPT countries.

In the case of land based ESOMPs operating in the bands available for uncoordinated FSS Earth stations, there is no change to the current interference environment since ESOMPs may operate in any location, just like uncoordinated FSS Earth stations.

In the case of ESOMPs mounted on aircraft, additional regulatory provisions are required, since the geometry of the interference environment is different. An ESOMP mounted on an aircraft and operating in the territory of one country could cause interference to terrestrial systems operating in a neighbouring country even when the separation distance is significantly larger than would be the case for an uncoordinated FSS Earth station on land. Consequently, this Decision introduces PFD thresholds (see 3rd bullet above) for ESOMPs mounted on aircraft that apply to the territory of administrations that operate terrestrial systems in the same bands as those used by the aircraft-mounted ESOMPs.

Also, in the case of ESOMPs mounted on vessels, the interference environment is also different to that for land based ESOMPs. In particular, ESOMPs on vessels could operate in international waters (typically beyond 12 nautical miles from the coast). Hence, it is necessary to ensure that terrestrial systems deployed in the band 27.5-29.5 GHz are also adequately protected from interference from these terminals. Consequently, this Decision applies a PFD threshold (see 3rd bullet above) to ESOMPs on vessels. This threshold applies at the low-water mark of any affected country in any part of the band 27.5-29.5 GHz designated for use by terrestrial systems in that country.

To comply with the PFD values applicable to ESOMPs on aircraft and vessels, any ESOMP operating in the range 27.5-29.5 GHz must monitor its location and have control over other characteristics such as equivalent isotropic radiated power (EIRP) and antenna pointing direction. This function may be accomplished by the ESOMP Network Control Facility (NCF), which shall have the possibility of reducing the terminal EIRP, or even ceasing transmission.

5.5 Scenario D Regulatory Context

Scenario D addresses Cognitive Radio GSO Satellite in Ku-band in both downlink and uplink [10.7 – 12.75 GHz, 12.75 – 13.25 GHz, and 13.75 – 14.5 GHz]. Specifically:

a. Cognitive GSO satellite terminals reusing frequency bands of other incumbent GSO satellite systems in D1/D2;

b. GSO FSS cognitive satellite terminals reusing frequency bands of FS links in D1/D2;

c. Support of GSO satellite terminals on mobile platforms in D1/D2.

Where:

- D1: Ku-band downlink in the 10.7 - 12.75 GHz band;
- D2: Ku-band uplink in the 12.75 – 13.25 GHz and 13.75 - 14.5 GHz band.

5.5.1 Scenario D1

Scenario D1 concerns the satellite downlink allocations in the range 10.7-12.75 GHz. It aims at investigating the possible use of cognitive satellite user terminals with very low directivity opportunistically receiving in this band.

5.5.1.1 ECA and ITU-R Tables of Allocations in this frequency band

The following diagrams summarize the frequency allocations in the 10.7-12.75 GHz frequency range.

Table 19 - ECA Frequency Allocation in the 10.7-12.75 GHz band (Source: [424])

RR Region 1 Allocation and RR footnotes applicable to CEPT	*European Common Allocation*	*ECC/ERC harmonisation measure*	*Applications*	*European footnotes*	*Standard*	*Notes*
10.7 - 11.7 GHz						
FIXED	FIXED	ECC/DEC/(05)11	AES		EN 302 186	
FIXED-SATELLITE (S/E) 5.441 5.484A (E/S) 5.484	FIXED-SATELLITE (S/E) 5.441 5.484A (E/S) 5.484	ERC/DEC/(00)08 ERC/REC 12-06	Fixed		EN 302 217	Limited to high capacity fixed links
MOBILE except aeronautical mobile	MOBILE except aeronautical mobile					
	Mobile-satellite (S/E)	ECC/DEC/(05)10 ECC/DEC/(05)11 ERC/DEC/(00)08	FSS Earth stations		EN 301 427 EN 301 428 EN 301 430 EN 301 360 EN 301 459 EN 302 340 EN 302 448	Within the band 10.7-10.95/11.2-11.45 GHz in accordance with App 30B of RR SIT/SUT - EUTELTRACS - VSAT
		ECC/DEC/(06)03	HEST		EN 301 428 EN 301 459	
		ECC/DEC/(06)02	LEST		EN 301 428 EN 301 459	
			-		EN 302 977	Vehicle-mounted Earth stations
11.7 - 12.5 GHz						
BROADCASTING	BROADCASTING-SATELLITE 5.492	ERC/DEC/(00)08	Broadcasting-satellite receivers		EN 301 459 EN 301 360 EN 302 340 EN 302 448	In accordance with App 30 of RR. SIT within the band 12.4 - 12.5 GHz
BROADCASTING-SATELLITE 5.492	FIXED					
FIXED	MOBILE except aeronautical mobile	ECC/DEC/(06)03	HEST			
MOBILE except aeronautical mobile						
5.487	5.487	ECC/DEC/(06)02	LEST	EU28		
5.487A	5.487A		-		EN 302 977	Vehicle-mounted Earth stations
12.5 - 12.75 GHz						
FIXED-SATELLITE (S/E) 5.484A (E/S)	FIXED-SATELLITE (S/E) 5.484A (E/S)	ECC/DEC/(05)11	AES		EN 302 186	
5.494 5.495 5.496	5.496	ECC/DEC/(05)10 ECC/DEC/(05)11	FSS Earth stations		EN 301 427 EN 301 428 EN 301 430 EN 301 360 EN 302 186 EN 301 459 EN 302 340 EN 302 448	Priority for civil networks. Low density carriers, including VSATs and digital SNG are encouraged to use this band VSAT - SIT/SUT
		ECC/DEC/(06)03	HEST		EN 301 428 EN 301 459	
		ECC/DEC/(06)02	LEST		EN 301 428 EN 301 459	
			-		EN 302 977	Vehicle-mounted Earth stations

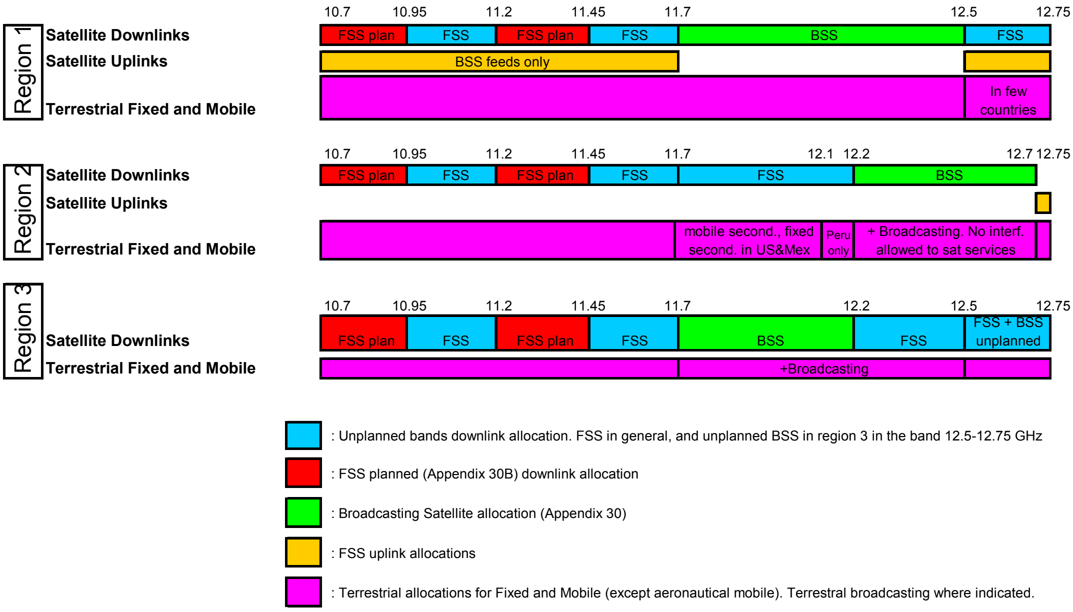


Figure 30 - Allocation summary in Ku downlink bands 10.7-12.75 GHz (Source: TAS-F)

In the band 12.5-12.75 GHz, in which the downlink band is mainly used for Ku-band VSAT services in Europe, the countries of Regions 1 and 3 in which Fixed and Mobile (except aeronautical mobile) services are allocated on a primary basis are as follows:

Figure 31 - Countries with Terrestrial allocation to Fixed and Mobile in 12.5-12.75 GHz

It should be noted that, in addition, in France, Greece, Monaco, Montenegro, Uganda, Romania, Tanzania, and Tunisia the band 12.5-12.75 GHz is also allocated to the Fixed and Mobile services (except aeronautical mobile) on a secondary basis.

5.5.1.2 Regulations applicable to incumbent services and actual use

Satellite downlinks

5.5.1.2..1 Power limits

In order to protect the Fixed Service, the power flux density (PFD) provided in Table 20 applies to geostationary satellites.

Table 20 - PFD Limitations to GSO satellites in 10.7-12.75 GHz band

5.5.1.2..1.1.1 Band / Region	**5.5.1.2..1.1.2 Limit (according to elevation δ)**			**5.5.1.2..1.1.3 Regulatory provision**
	δ < 5°	5° < δ < 25°	δ > 25°	
10.7-11.7 GHz	–150	–150 + 0.5(δ – 5)	–140	RR Article 21 – Table 21-4
12.2-12.75 GHz in Region 3 12.5-12.75 GHz (Region 1 countries listed in Nos. **5.494** and **5.496**)	–148	–148 + 0.5(δ – 5)	–138	RR Article 21 – Table 21-4
11.7-12.5 GHz in Region 1 12.2-12.7 GHz in Region 2 11.7-12.2 GHz in Region 3	–148	–148 + 0.5(δ – 5)	–138	RR Appendix 30 – Annex 1 §4

These limits are expressed in dBW/m²/4kHz[17].

Footnote 5.494 lists the following countries in Region 1 for which the band 12.5-12.75 GHz is also allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis: Algeria, Angola, Saudi Arabia, Bahrain, Cameroon, the Central African Rep., Congo (Rep. of the), Côte d'Ivoire, Djibouti, Egypt, the United Arab Emirates, Eritrea, Ethiopia, Gabon, Ghana, Guinea, Iraq,

[17] References are contained in the Radio Regulations in Article 21 and/or Appendix 30, Annex 1.

Israel, Jordan, Kuwait, Lebanon, Libya, Madagascar, Mali, Morocco, Mongolia, Nigeria, Oman, Qatar, the Syrian Arab Republic, the Dem. Rep. of the Congo, Somalia, Sudan, South Sudan, Chad, Togo, and Yemen.

Footnote 5.496 also lists the countries in Region 1 for which the band 12.5-12.75 GHz is also allocated to the fixed and mobile, except aeronautical mobile, services on a primary basis, but with the limit that stations of the FSS shall respect the power flux limits indicated in Table 21-4 of Article 21 of the Radio Regulation. These countries are Austria, Azerbaijan, Kyrgyzstan, and Turkmenistan. It is also indicated the station of the FS or MS shall not cause harmful interferences to FSS stations in other countries outside those four.

It also to be noted the footnote 5.494 has been modified during the last World Radio Conference (2012). Some countries have asked to be removed or added from the footnote.

From this table, it should be noted that only the bands 11.7-12.2 GHz in Region 2, and 12.5-12.75 GHz in Region 1 (except countries identified in the map in Figure 31) are exempt from PFD limitations.

For a geostationary satellite located at a range of 36000 km, these PFD limits corresponds to an equivalent EIRP of about 61 dBW/36 MHz. In practice, Ku-band FSS geostationary satellites operate at EIRP levels around 50 to 54 dBW/36 MHz, and up to about 60dBW/36MHz for broadcasting satellites.

5.5.1.2..2 Coordination procedures

As regards satellite coordination, incoming satellite systems have to apply coordination procedures laid down in:

- Article 9 and 11 of the radio regulations for the unplanned FSS bands. These procedures implement a first come – first served principle, by which new systems protect systems that have already engaged the procedure;
- Appendix 30 of the Radio Regulations for the BSS planned bands;
- Appendix 30B of the Radio Regulations for the FSS planned bands.

In the planned bands, the national orbit/spectrum resources set aside for each ITU administration must be protected by new systems. In addition, systems additional to national planned systems coordinate among themselves on a first-come first-served basis.

5.5.1.2..3 Typical uses

CEPT

Within CEPT the whole Ku downlink band is used extensively for DTH (Direct-to-home) applications. DTH dish size in Europe is typically of 60 cm, being limited by inter-system coordination between adjacent satellites. Outside the BSS portion, VSAT services are also provided. In this case satellite downlinks may be addressing either user terminals, or gateway stations. VSAT typical size is 1 m or even less (*e.g.*, Astra2Connect antennas).

The band 12.5-12.75 GHz is extensively used for VSAT terminal reception. In Europe, Ku-band satellites are usually spaced by 3°.

US

In US, unlike Europe, the use of the band is very heterogeneous across the Ku downlink band.

The band 11.7-12.2 GHz is massively used by VSAT applications. This band is the core for ubiquitous deployment of Earth stations, because of the absence of terrestrial services. Other applications exist such as DTH, trunking, and cable head-end feed.

The two sub-bands 10.95-11.2 GHz and 11.45-11.7 GHz are shared with terrestrial fixed service. FSS downlinks in this band are mainly used for international services (*i.e.*, links which one termination point is outside the US) because of a regulation restricting use of this band to international, intercontinental systems.

The BSS band (12.2-12.7 GHz) is exclusively used for TV reception, called DBS in US. The wide orbital spacing among DBS satellites enables reception by smaller dishes (45 cm). There is also a co-primary FS allocation in this band for a service known as Multichannel Video and Data Distribution Service (MVDDS). Under U.S. regulations, MVDDS deployments must protect pre-existing DBS deployments.

In the US, FSS satellites are typically spaced about 2° apart by regulation. BSS satellites are spaced by 9°, although the possibility of reduced spacing is being contemplated.

Brazil

In Brazil, the band 10.7-12.2 GHz is used for DTH, while the 11.7-12.2 GHz portion is used mainly for VSAT services.

The 12.2-12.7 GHz band has recently been opened by ANATEL for use by the BSS.

In Brazil, the orbital spacing between FSS Ku-band satellites is 2°.

Satellite uplinks

There is no known use of satellite uplinks in this band.

Fixed Services

With respect to the Fixed Service in CEPT, the ECC Report 173 [287] provides comprehensive information on deployment in Europe as of approximately the end of 2010.

Europe

About 9300 PtP links are in service in this range, allocated many years ago to PtP links[18]. In the 10.7 – 12.5 GHz band, some PMP base stations are reported, mainly in Hungary (about 150 base stations in total). 95% percentile of hop lengths indicated as "typical" is 40 km (33 km for those indicated as "minimum").

The majority of applications consist of high capacity links, individually licensed, forming part of telecommunication and broadcasting infrastructure networks.

Frequency usage refers to CEPT ERC/REC 12-06 with few national plans. Channel arrangements for the fixed service in this band as given by the ITU-R Recommendation F.387 are also considered.

Many countries anticipate an increase in the use of this band during the next years (10-30% increase) and in one country (Italy) it appears to be already congested. The situation is overall stable over time, as reported in Figure 32. It has to be noted that, due to satellite sharing problems, some countries have stopped the introduction of new links in this band (see ERC/DEC/(00)08).

[18] Note that Figure 32 shows less than 9,300 links. This is because it considers only 19 countries which provided inputs as reported in [287], whereas 9,300 refers to all CEPT countries, i.e. more than 40 countries.

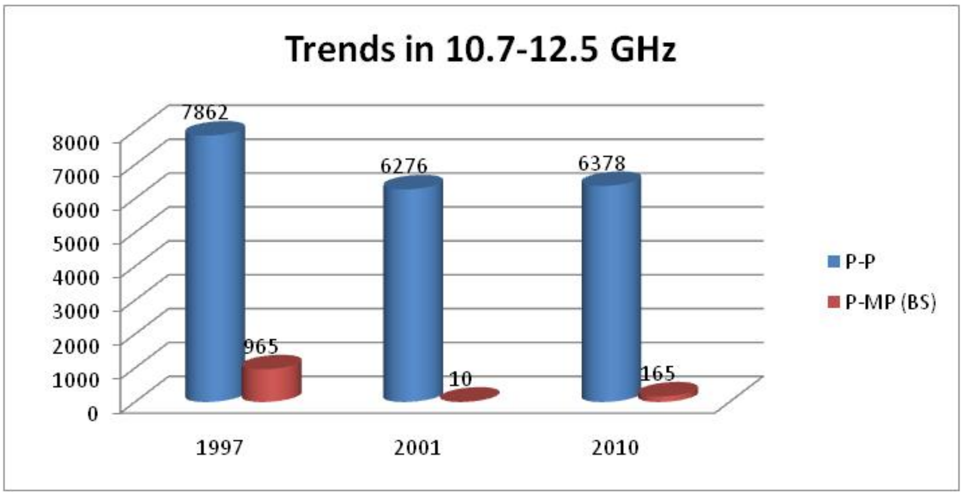


Figure 32 - Trend for the PtP and PMP links in the band 10.7-12.5 GHz in the 19 CEPT countries available for comparison (Source: [287])

The situation appears different in the band 10.7-11.7 GHz compared to the band 11.7-12.5 GHz:

- **10.7-11.7 GHz:** There are approximately 9,300 links within CEPT, the vast majority for point to point applications, and very few for point-to-multipoint applications. 95% of these links are concentrated in 10 countries (among the 31 CEPT member countries that responded to the CEPT study): Czech Rep., France, Greece, Hungary, Ireland, Italy, Norway, Poland, Portugal, and Russia.

  The Czech Republic, Italy, and Russia alone gather 60% of all links in CEPT in this band.

- **11.7-12.5 GHz:** There are only about 260 FS links in this band in Europe, 55% of them being located in Hungary for Point-to-multipoint applications. The remaining is scattered in Slovenia, Serbia, Bosnia Herzegovina, Italy, Cyprus, and Czech Republic. These include MVDDS applications using the FS allocation on a secondary basis.

  With respect to the 12.5-12.75 GHz frequency band, there is no significant FS deployment in this band in Europe.

<u>**US**</u>

There is a significant deployment of Fixed Service in the band 10.7-11.7 GHz over the US territory. The “international-only” restriction that applies to FSS in this band was intended to limit FSS deployment and therefore the coordination burdens on FS deployments in the band.

The ITU table of allocations shows that in North America (Mexico, US) the Fixed Service is secondary compared to FSS in the band 11.7-12.2 GHz. Therefore no significant FS roll-out is expected in that band. A similar situation applies in the band 12.2-12.7 GHz, where BSS is afforded a priority status. As noted above, however, there is a co-primary FS allocation for MVDDS in the United States. This spectrum has been auctioned in 2004 and 2005, but deployment has been limited to date. One of the U.S. DBS companies has acquired the majority of the MVDDS spectrum in the U.S.

In the 12.7-12.75 GHz band there are allocations to Fixed Service for various applications: TV Broadcast Auxiliary, Cable TV Relay, Fixed Microwave (see US table of frequency allocation [332]).

5.5.2 Scenario D2

The scenario D2 concerns the satellite uplink allocations in the ranges 12.75-13.5 GHz and 13.75 - 14.5 GHz. It aims at investigating the possible use of cognitive user transmit terminals in these bands with very low directivity.

5.5.2.1 ECA and ITU-R Tables of Allocations in this frequency band

The following diagrams summarize the frequency allocations in the 12.75-13.5 GHz and 13.75 - 14.5 GHz frequency ranges of interest in scenario D2.

Table 21 - ECA Frequency Allocation Table for the 12.75-14.5 GHz band (Source: [424])

RR Region 1 Allocation and RR footnotes applicable to CEPT	*European Common Allocation*	*ECC/ERC harmonisation measure*	*Applications*	*European footnotes*	*Standard*	*Notes*
12.75 - 13.25 GHz						
FIXED	FIXED	ERC/REC 12-02	Fixed		EN 302 217	
FIXED-SATELLITE (E/S) 5.441	FIXED-SATELLITE (E/S) 5.441		FSS Earth stations		EN 301 430	
MOBILE						
Space research (deep space) (S/E)						
13.75 - 14 GHz						
FIXED-SATELLITE (E/S) 5.484A	FIXED-SATELLITE (E/S) 5.484A		-			Data relay satellites
RADIOLOCATION	RADIOLOCATION		Defence systems			Military radars
Earth exploration-satellite	Space research					
Space research			FSS Earth stations		EN 301 430	
Standard frequency and time signal-satellite (E/S)			Maritime radar			Navigation radars, ship berthing radars
5.499	5.502 EU2		Passive sensors (satellite)			Future VLBI measurements
5.500	5.503 EU26					
5.501		ERC/REC 70-03	Radiodetermination applications		EN 300 440	Within the band 13.4-14.0 GHz
5.502						
5.503						
14 - 14.25 GHz						
FIXED-SATELLITE (E/S) 5.457A 5.457B 5.484A 5.506 5.506B	FIXED-SATELLITE (E/S) 5.457A 5.457B 5.484A 5.506 5.506B	ECC/DEC/(05)11	AES		EN 302 186	
RADIONAVIGATION 5.504	Space research	ECC/DEC/(05)10	ESV		EN 302 340	
Space research	Mobile-satellite (E/S) 5.504B 5.504C 5.506A	ECC/DEC/(06)03	HEST		EN 301 428	
Mobile-satellite (E/S) 5.504B 5.504C 5.506A		ECC/DEC/(06)02	LEST		EN 301 428	
5.504A	5.504		MSS Earth stations		EN 301 427 EN 302 977	Priority for civil networks
		ERC/REC 13-03	VSAT		EN 301 430 EN 301 428	Low density carriers, including VSATs and digital SNG, are encouraged to use this band
			-		EN 302 448	Tracking Earth stations on trains, vehicle-mounted Earth stations
14.25 - 14.3 GHz						
FIXED-SATELLITE (E/S) 5.457A 5.457B 5.484A 5.506 5.506B	FIXED-SATELLITE (E/S) 5.457A 5.457B 5.484A 5.506 5.506B	ECC/DEC/(05)11	AES		EN 302 186	
RADIONAVIGATION 5.504	Mobile-satellite (E/S) 5.504B 5.506A 5.508A	ECC/DEC/(05)10	ESV		EN 302 340	
Mobile-satellite (E/S) 5.504B 5.506A 5.508A	Space research		MSS Earth stations		EN 301 427 EN 302 977	Priority for civil networks
Space research		ERC/REC 13-03	VSAT		EN 301 428 EN 301 430	SNG
5.504A	5.504		-			Vehicle-mounted Earth stations
5.508						
14.3 - 14.4 GHz						
FIXED	FIXED-SATELLITE (E/S) 5.457A 5.484A 5.506	ECC/DEC/(05)11	AES		EN 302 186	
FIXED-SATELLITE (E/S) 5.457A 5.457B 5.484A 5.506 5.506B	Mobile-satellite (E/S) 5.504B 5.506A 5.509A	ECC/DEC/(05)10	ESV		EN 302 340	
Mobile except aeronautical mobile			FSS Earth stations		EN 302 340	Fixed links to be coordinated with Fixed Satellite Services on a national basis
Mobile-satellite (E/S) 5.504B 5.506A 5.509A			MSS Earth stations		EN 301 427 EN 302 977	Priority for civil networks
Radionavigation-satellite 5.504A		ERC/REC 13-03	VSAT		EN 301 428 EN 301 430	SNG
			-			Vehicle-mounted Earth stations

14.4 - 14.47 GHz

FIXED	FIXED-SATELLITE (E/S) 5.457A 5.484A 5.506	ECC/DEC/(05)11	AES	EN 302 186	
FIXED-SATELLITE (E/S) 5.457A 5.457B 5.484A 5.506 5.506B	Mobile-satellite (E/S) 5.504B 5.506A 5.509A	ECC/DEC/(05)10	ESV	EN 302 340	
MOBILE except aeronautical mobile			FSS Earth stations	EN 302 340	Fixed links to be coordinated with Fixed Satellite Services on a national basis
Mobile-satellite (E/S) 5.504B 5.506A 5.509A					
Radionavigation-satellite 5.504A	5.504A		MSS Earth stations	EN 301 427 EN 302 977	Priority for civil networks
		ERC/REC 13-03	VSAT	EN 301 428 EN 301 430	SNG
			-		Vehicle-mounted Earth stations

4.47 - 14.5 GHz

FIXED	FIXED-SATELLITE (E/S) 5.457A 5.484A 5.506	ECC/DEC/(05)11	AES	EN 302 186	
FIXED-SATELLITE (E/S) 5.457A 5.457B 5.484A 5.506 5.506B	Mobile-satellite (E/S) 5.504B 5.506A 5.509A	ECC/DEC/(05)10	ESV	EN 302 340	
MOBILE except aeronautical mobile			FSS Earth stations	EN 302 340	Fixed links to be coordinated with Fixed Satellite Service on a national basis
Mobile-satellite (E/S) 5.504B 5.506A 5.509A	Radio astronomy		MSS Earth stations	EN 301 427 EN 302 977	Priority for civil networks
Radio astronomy			Radio astronomy		Spectral line observations, VLBI
5.149	5.149				
5.504A	5.504A				
		ERC/REC 13-03	VSAT	EN 301 428	SNG
			-		Vehicle-mounted Earth stations

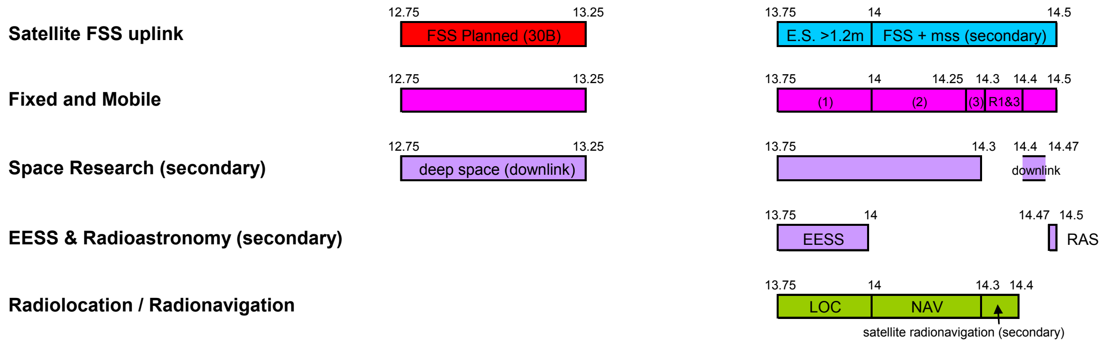


Figure 33 - Frequency allocations in 12.75-14.5 GHz band

In the band 13.75-14.3 GHz, the allocation to the Fixed and Mobile Service exists in some countries. These countries within ITU Regions 1 and 3 are identified in the maps shown below:

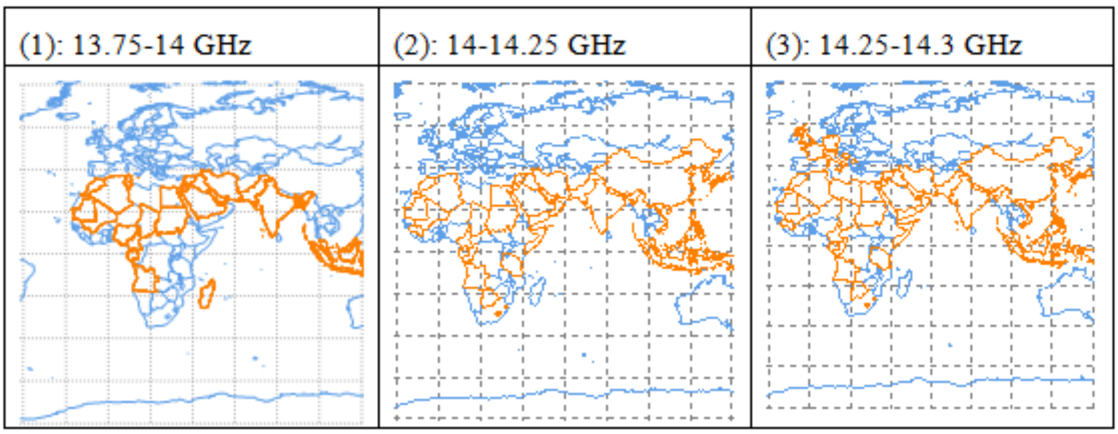


Figure 34 - Countries with FS allocation in 13.75-14.3 GHz band

In the 14.3-14.4 GHz band, the allocation to the Fixed and Mobile service is valid in Regions 1 and 3, and worldwide in the 12.75-13.25 GHz and 14.4-14.5 GHz bands.

5.5.2.2 Regulations applicable to incumbent service and actual use

Satellite uplinks

5.5.2.2..1 Inter-system coordination aspects

With respect to satellite coordination, new systems have to apply coordination procedures laid down in:

- Article 9 and 11 of the radio regulations for the unplanned FSS bands (13.75-14.5 GHz). These procedures implement a first-come first-served principle, by which new systems protect systems that have had already engaged the procedure;
- Appendix 30B of the Radio Regulations for the FSS planned bands (12.75-13.25 GHz).

In the planned bands, the national orbit/spectrum resources set aside for each ITU administration must be protected by new systems. In addition, new systems in the planned bands coordinate among themselves on a first-come first-served basis.

5.5.2.2..2 Technical limits applying to Earth stations

The following mandatory off-axis EIRP limitations apply (RR Article 22 "Space Services") in the bands 12.75-13.25 GHz and 13.75-14.5 GHz:

Off-axis EIRP (dBW/40kHz):

- $3° \leq \varphi \leq 7°$: 42 - 25 Log(φ)
- $7° < \varphi \leq 9.2°$: 21
- $9.2° < \varphi \leq 48°$: 45 – 25 Log(φ)
- $48° < \varphi \leq 180°$: 3

Moreover, ITU RR Footnote 5.502 specified the following rules for the 13.75-14.0 GHz band:

- in the 13.75-14 GHz band, the Earth station of a geostationary fixed-satellite service network shall have a minimum antenna diameter of 1.2 m and an Earth station of a non-geostationary fixed-satellite service system shall have a minimum antenna diameter of 4.5 m. In addition, the EIRP, averaged over one second, radiated by a station in the radiolocation or radionavigation services shall not exceed 59 dBW for elevation angles above 2° and 65 dBW at lower angles. Before an administration brings into use an Earth station in a geostationary-satellite network in the fixed-satellite service in this band with an antenna size smaller than 4.5 m, it shall ensure that the power flux-density produced by this Earth station does not exceed:
    - -115 dB(W/(m^2 * 10 MHz)) for more than 1% of the time produced at 36 m above sea level at the low water mark, as officially recognized by the coastal State;
    - -115 dB(W/(m^2 * 10 MHz)) for more than 1% of the time produced 3 m above ground at the border of the territory of an administration deploying or planning to deploy land mobile radars in this band, unless prior agreement has been obtained.
- For Earth stations within the fixed-satellite service having an antenna diameter greater than or equal to 4.5 m, the EIRP of any emission should be at least 68 dBW and should not exceed 85 dBW. (WRC-03).

The ITU-R Recommendation S.524-9 specifies the following EIRP limits for Earth stations in general (*i.e.*, hubs, VSATs, etc) in the bands 12.75-13.25 GHz and 13.75-14 GHz:

Off-axis EIRP (dBW/40kHz):

- $2.5° \leq \varphi \leq 7°$: 39 - 25 Log(φ)
- $7° < \varphi \leq 9.2°$: 18
- $9.2° < \varphi \leq 48°$: 42 – 25 Log(φ)
- $48° < \varphi \leq 180°$: 0

In addition, the Recommendation S.728-1 specifies for VSATs only the following off-axis limits:

Off-axis EIRP (dBW/40kHz):

- $2° \leq \varphi \leq 7°$: 33 - 25 Log(φ)
- $7° < \varphi \leq 9.2°$: 12
- $9.2° < \varphi \leq 48°$: 36 – 25 Log(φ)
- $48° < \varphi \leq 180°$: -6

5.5.2.2..3 Technical limits applying to ESOMPs

Specific limitations for stations on board vessels (ESVs)

Specific limits apply for ESVs (ITU-R Resolution 902 (WRC-03) [334]) operating in the 14-14.5 GHz frequency range and near the coastal area of countries listed in that Resolution.

Off-axis EIRP (dBW/40kHz):

- $2° \leq \varphi \leq 7°$: 33 - 25 Log(φ)
- $7° < \varphi \leq 9.2°$: 12
- $9.2° < \varphi \leq 48°$: 36 – 25 Log(φ)
- $48° < \varphi \leq 180°$: -6

Other limits:

- Minimal Diameter = 1.2 m (0.6 m if agreement of the coastal administration)
- EIRP Max towards horizon: 12.5 dBW/MHz and 16.3 dBW
- Coordination Distance: 125 km from coastline. Below that distance, a coordination agreement is required with the concerned country.

These off-axis limits for ESVs are similar to those defined in ITU-R Recommendation S.728-1 for VSATs, and in ETSI standards.

It should be noted that the off-axis EIRP requirements applicable in US under FCC regulation for VSAT routine licensing are about 8 dB more stringent than the above requirements.

Specific limitations for stations on board aircrafts (AES)

In order to protect terrestrial systems operating in the band 14-14.5 GHz, the Recommendation ITU-R M.1643 defines power flux density limits on ground generated by aircraft-mounted Earth stations, as a function of the elevation θ:

- -132 + 0.5 · θ dB(W/(m2 · MHz)) for θ ≤ 40°
- -112 dB(W/(m2 · MHz)) for 40 < θ ≤ 90°

From this mask, the EIRP density limits of aircraft mounted terminals can be derived as follows (cf Annex 2 of Recommendation ITU-R M.1643):

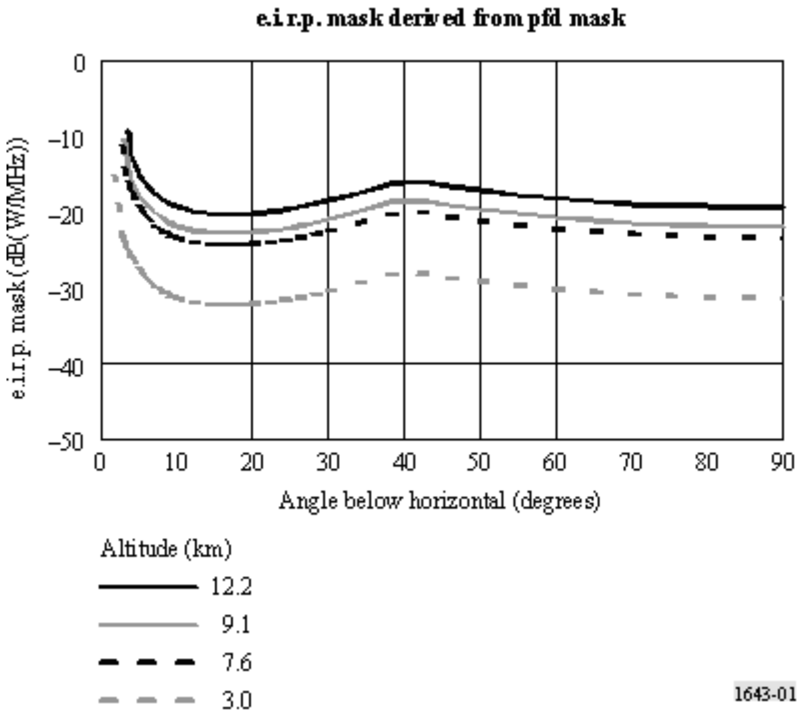


Figure 35 - EIRP mask of aircraft mounted terminals in 14-14.5 GHz band for countries with FS allocations (Source: Annex 2 of Rec. ITU-R M.1643)

This mask applies on the territory of countries having allocations for the fixed service, and in certain portions of the 14-14.5 GHz band.

Fixed Services

<u>Band 12.75-13.25 GHz</u>

In the CEPT, ECC Report 173 provides the following information [287]:

About 57600 PtP links are in operation in this range. 95% percentile of hop length indicated as “typical” is 25 km (11 km for those indicated as “minimum”).

The major utilization is for medium-high capacity links, individually licensed, most of them belonging to fixed, mobile and broadcast infrastructure.

The frequency usage refers to CEPT ERC/REC 12-02.

Regarding the usage, several countries indicate that they expect a moderate increase in coming years (5-30% increase). Nevertheless congested situations are reported by many administrations. The comparison chart shows a continuous increase trend since 1997, as illustrated in the figure below.

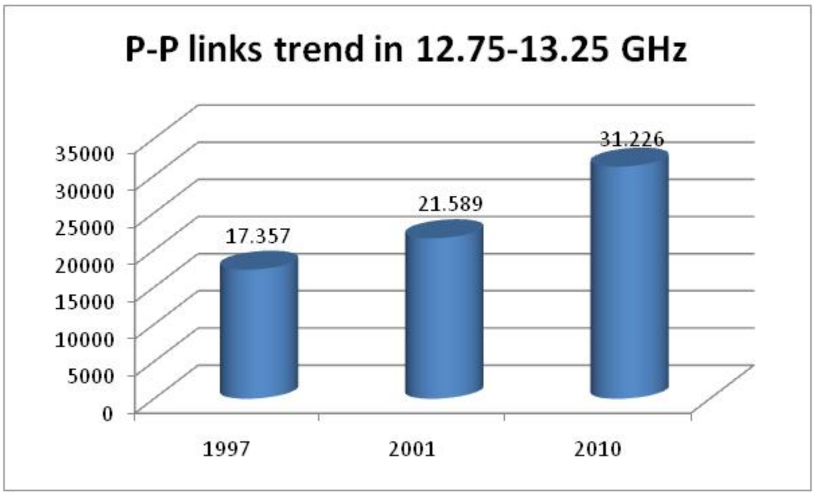


Figure 36 - Trend for the PtP links in the band 12.75-13.25 GHz in the 19 CEPT countries available for comparison (Source: [287])

Unlike in 10.7-11.7 GHz where the majority of links is concentrated in some countries, the 13 GHz band shows a very widespread development throughout Europe.

In the US, the 12.75-13.25 GHz band is used by the Fixed Service for several applications, including fixed microwave links, Cable TV relay and TV Broadcast Auxiliary service.

<u>Band 14-14.5 GHz</u>

With reference to ECC Report 173 [287], about 1500 PtP links have been declared in the 14.25-14.5 GHz band. The use of this band by the FS is limited to a few countries in the CEPT (Cyprus, France, Italy, UK, and the Russian Federation). In the UK and France the 14.25-14.5 GHz band is closed to new fixed links. In 2011, around 300 existing links were still in use in each country.

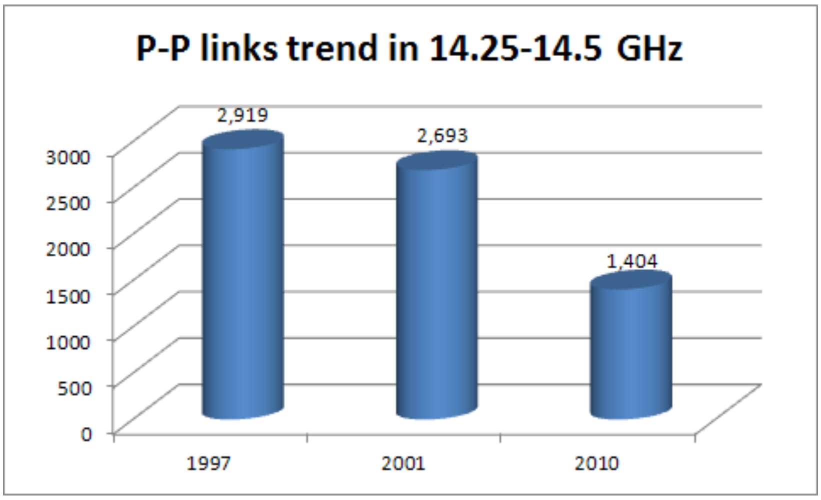


Figure 37 - Trend for the PtP links in the band 14.25-14.5 GHz in the 19 CEPT countries available for comparison (Source: [287])

There are no reported links in Europe in the band 14-14.25 GHz.

Space Research Service

5.5.2.2..4 Deep Space secondary downlinks in the band 12.75-13.25 GHz

Deep space Earth stations receive communications from space probes located beyond 2 x 10^6 km from the Earth.

Deep space systems are described in Recommendation ITU-R SA.1014. There are few deep space sites, which typically employ very large Earth stations (diameter about 70m) able to receive very weak signals form space probes.

As described in Recommendation ITU-R SA.1014, deep-space systems employ primarily allocations in the 2 GHz, 8 GHz and 30 GHz range. It seems that the 13 GHz band is not used in practice.

5.5.2.2..5 Space Research allocation in the band 13.75-14.5 GHz

In the 13.75-14 GHz band, RR footnote 5.503 affords specific protection to Space Research service in the band 13.77-13.78 GHz for Space Research space stations brought in service prior to 31 January 1992.

The Space Frequency Coordination Group (SFCG) is a frequency management forum that gathers Space Agencies for managing the use of the space science spectrum. The SFCG publishes a handbook, which is a useful source of information for space science applications [337]. The Recommendation SFCG 12-2 "USE OF THE 14.0-15.35 GHz AND 16.6-17.1 GHz BANDS FOR SPACE RESEARCH, CATEGORY A", recommends that the 14.0-15.35 GHz band be used for space-to-Earth transmissions of Space Research Category A missions.

Therefore the Space Research secondary allocation above 14 GHz should only be used for downlinks, and for non-deep space applications (Category A). No operational satellite with a mission in this service in the range 14-14.5 GHz has been identified, while some are operating above 14.5 GHz.

Earth Exploration Satellite Service (EESS)

This EESS allocation is a legacy from a former primary allocation. Nowadays, all the Ku-band EESS systems have been migrated to the lower 13.25-13.75 GHz range.

ITU-R Resolution 152 (WRC-12) recognizes that the 13.25-13.75 GHz band has been allocated to the EESS (active) on a primary basis [429]. It also recognizes that EESS (active) satellites with three types of active sensor in 13.25-13.75 GHz – scatterometers, altimeters and precipitation radars – have been operating in this band for many years. The remote sensing systems of EESS (active) are used in backscatter echomode to monitor weather, water and climate change and similar emergencies, with the aim of preventing natural disasters, which could suffer from interference resulting from FSS (uplink). It also recognizes that, although EESS (active) satellites are currently operated by only a limited number of countries, measurements are performed worldwide and the remote sensing data and related analyses are distributed and used globally, and are performed for the benefit of the whole international community. Moreover, it recognizes that the EESS (active) systems are crucial for the protection of human life and natural resources. It is necessary to ensure that the EESS (active) systems shall be protected without any undue constraints to their operations in the 13.25-13.75 GHz band.

Radioastronomy

The Handbook of the Committee on Radio Astronomy Frequencies (CRAF) [338] identifies that the 14.47-14.5 GHz band is used by the Radio Astronomy Service (RAS) in Europe on a secondary basis in Germany, UK, and Russia. Moreover, it states that radio astronomy stations on the territory of France, Italy, Spain, and the UK that are operating in the 14.47-14.50 GHz band are explicitly protected from interference from the MSS operating in the 14.0-14.5 GHz band.

On a national basis, an administration may implement restrictions to transmitters potentially operating in the vicinity of such stations.

Radiolocation and Radionavigation

5.5.2.2..6 Radiolocation in the 13.75-14 GHz band

In Europe (European Common Allocation table), this allocation is used for maritime radars, and defence radars, which characteristics are described in ITU-R Recommendation M.1644.Radionavigation in the 14-14.3 GHz band:

In the European common allocation table, there is no mention about the use of this service.

5.5.2.2..7 Satellite Radionavigation (secondary) in the 14.3-14.4 GHz band

There is no known use of this band by satellite radionavigation.

5.6 Scenario E Regulatory Context

Scenario E addresses Cognitive Radio GSO Satellite downlink in C-band [3.4 – 3.8 GHz]. Specifically:

a. FSS cognitive satellite terminals reusing frequency bands of FS[19] links;

b. Support of satellite terminals on mobile platforms.

5.6.1 ECA and ITU-R Table of Allocations in this frequency band

This scenario addresses the 3.4-3.8 GHz frequency range within C-band.

The allocation of services in this frequency range as defined by CEPT and ITU is as per the following tables.

Table 22 - ECA Table of Allocations in 3.4-3.8 GHz band (Source: [424])

RR Region 1 Allocation and RR footnotes applicable to CEPT	*European Common Allocation*	*ECC/ERC harmonisation measure*	*Applications*	*European footnotes*	*Standard*	*Notes*
3400 - 3500 MHz						
FIXED	FIXED		Amateur	EU17	EN 301 783	Within the band 3400-3410 MHz
FIXED-SATELLITE (S/E)	FIXED-SATELLITE (S/E)					
Mobile 5.430A Radiolocation	MOBILE 5.430A Amateur	ECC/DEC/(07)02 ECC/REC/(04)05 ERC/REC 14-03	BWA		EN 302 217 EN 302 326 EN 302 623 EN 302 774	Within the band 3400-3800 MHz
5.431	Radiolocation		FSS Earth stations		EN 301 443	
			PMSE		EN 302 064	For coordinated SAB/SAP applications for occasional use. In some countries the mobile service may be on secondary basis
			Radiolocation (civil)			Upper limit for airborne radars is 3410 MHz
		ECC/DEC/(06)04 ECC/REC/(11)09 ECC/REC/(11)10	UWB applications		EN 302 065	Generic UWB Location Tracking Type 2 (LT2) Location Application for Emergency Services (LAES)
		ECC/DEC/(11)06	MFCN			Within the band 3400-3800 MHz

[19] When referring to FS, terrestrial PtP and PMP BFWA services are considered.

3500 - 3600 MHz					
FIXED FIXED-SATELLITE (S/E)	FIXED FIXED-SATELLITE (S/E)	ECC/DEC/(07)02 ECC/REC/(04)05 ERC/REC 14-03	BWA	EN 302 217 EN 302 326 EN 302 623 EN 302 774	Within the band 3400-3800 MHz
Mobile 5.430A	MOBILE 5.430A				
Radiolocation			FSS Earth stations	EN 301 443	
			PMSE	EN 302 064	For coordinated SAB/SAP applications for occasional use. In some countries the mobile service may be on secondary basis
		ECC/DEC/(06)04 ECC/REC/(11)09 ECC/REC/(11)10	UWB applications	EN 302 065	Generic UWB Location Tracking Type 2 (LT2) Location Application for Emergency Services (LAES)
		ECC/DEC/(11)06	MFCN		Within the band 3400-3800 MHz
3600 - 3800 MHz					
FIXED	FIXED		-		In some countries the mobile service may be on secondary basis
FIXED-SATELLITE (S/E) Mobile	FIXED-SATELLITE (S/E) MOBILE	ECC/DEC/(07)02 ECC/REC/(04)05	BWA	EN 302 217 EN 302 326 EN 302 623 EN 302 774	Within the band 3400-3800 MHz
		ECC/DEC/(05)09	FSS Earth stations	EN 301 443 EN 301 447	Priority for civil networks
		ERC/REC 12-08	Fixed	EN 302 217	Medium/high capacity fixed
		ECC/DEC/(06)04 ECC/REC/(11)09 ECC/REC/(11)10	UWB applications	EN 302 065	Generic UWB Location Tracking Type 2 (LT2) Location Application for Emergency Services (LAES)
		ECC/DEC/(11)06	MFCN		Within the band 3400-3800 MHz

Table 23 - ITU-R Table of Allocations in 3.4-3.8 GHz band

Region 1	Region 2	Region 3
3.4 – 3.6 FIXED FIXED-SATELLITE (S/E) Mobile 5.430A Radiolocation **3.6 – 3.8** FIXED FIXED SATELLITE (Space-Earth) Mobile	**3.4 – 3.5** FIXED FIXED SATELITE (space-Earth) Amateur Mobile 5.431A Radiolocation **3.5- 3.7** FIXED FIXED SATELLITE (Space-Earth) MOBILE, except aeronautical mobile Radiolocation 5.433	**3.4 – 3.5** FIXED FIXED-SATELLITE (S/E) Amateur Mobile 5.432B Radiolocation 5.433 5.282 5.432 5.432A **3.5 – 3.6** FIXED FIXED SATELLITE (Space-Earth) MOBILE, except aeronautical mobile 5.433A Radiolocation 5.433 **3.6 – 3.7** FIXED FIXED SATELLITE (Space-Earth)

	3.7 – 3.8 FIXED FIXED SATELLITE (Space-Earth) MOBILE, except aeronautical mobile	MOBILE, except aeronautical mobile Radiolocation5.433 5.435 **3.7 – 3.8** FIXED FIXED SATELLITE (Space-Earth) MOBILE, except aeronautical mobile
Main Sharing Usage		
Region 1	**Region 2**	**Region 3**
FSS (space-Earth) FS	FSS (space-Earth) FS	FSS (space-Earth) FS

Since WRC-07, the 3400-3600 MHz band has been identified for International Mobile Telecommunications (IMT) or Mobile in all EU countries and almost all CEPT member countries. The term IMT covers IMT-2000 and IMT-Advanced systems.

At the ITU–level Recommendation ITU-R M.1036 on frequency arrangements for implementation of the terrestrial component of IMT has been revised to include, among others, the European arrangement(s) for the 3400-3600 MHz band.

By the beginning of 2012, the ITU-R agreed on the IMT-Advanced technologies in cooperation with standardisation organizations, paving the way for future mobile broadband usage going beyond IMT-2000 [410].

5.6.2 EU regulatory framework in this frequency band

European Commission Decision 2008/411/EC [279] aims at harmonizing, without prejudice to the protection and continued operation of other existing use in this band, the conditions for the availability and efficient use of the 3400-3800 MHz band for fixed and mobile terrestrial systems capable of providing electronic communications services.

The Decision sets the following conditions:

- no later than six months after entry into force of the Decision Member States were required to designate and make available, on a non-exclusive basis, the 3400 - 3600 MHz band for terrestrial electronic communications networks, in compliance with the parameters set out in the Annex to the Decision;

- by 1 January 2012 Member States were required to designate and subsequently make available, on a non-exclusive basis, the 3600-3800 MHz band for terrestrial electronic communications networks.

In the Decision Annex, the following parameters are defined for fixed and nomadic deployments:

A) LIMITS FOR IN-BLOCK EMISSIONS

Table 1

E.i.r.p. spectral density limits for fixed and nomadic deployments between 3 400 and 3 800 MHz

Station type	Maximum e.i.r.p. spectral density (dBm/MHz) (including tolerances and automatic transmitter power control (ATPC) range)
Central station (and repeater station downlinks)	+ 53 (1)
Terminal station outdoor (and repeater station uplinks)	+ 50
Terminal station (indoor)	+ 42

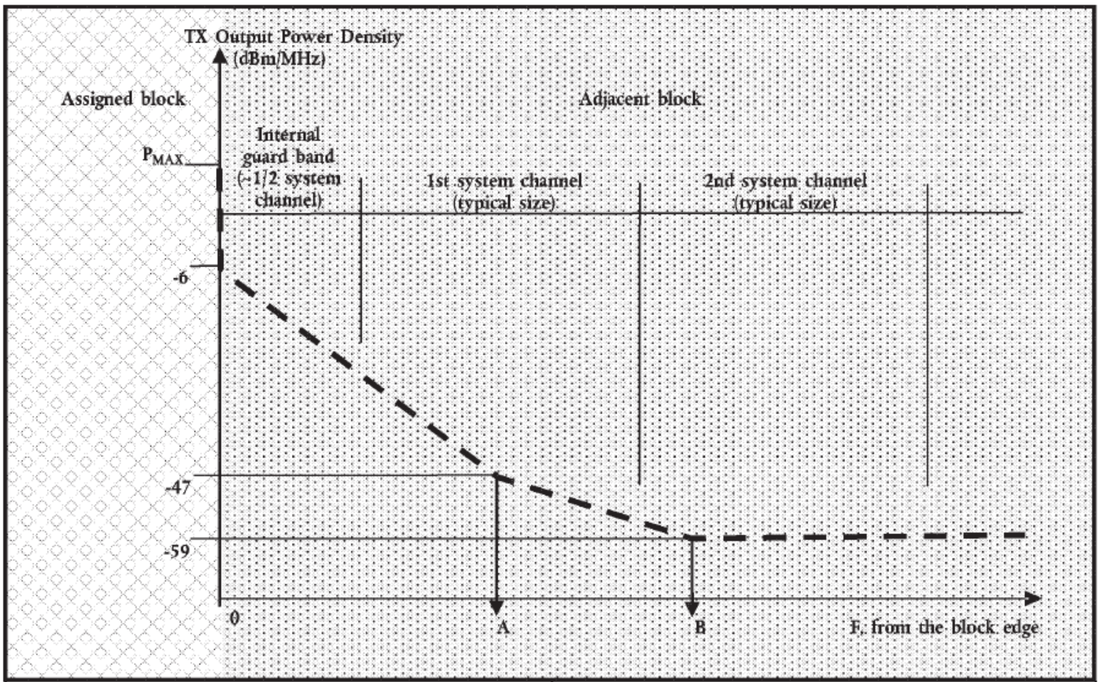
(1) The central station e.i.r.p. spectral density value given in the table is considered suitable for conventional 90 degrees sectorial antennas.

Figure 38 - EIRP spectral density limits for fixed and nomadic deployments in 3400 – 3800 MHz band (Source: [279])

B) LIMITS FOR OUT-OF-BLOCK EMISSIONS (BLOCK EDGE MASK FOR CENTRAL STATIONS)

Figure

Central station out-of-block emissions



Frequency offset	Definition (% of the size of the assigned block)
A	20 %
B	35 %
NB: The percentages given in the 'Definition' column refer to the smaller of adjacent blocks, if blocks are of unequal size.	

Table

Tabular description of central station block edge mask

Frequency offset	Central station transmitter output power density limits (dBm/MHz)
In-band (within assigned block)	See Tables 1 and 2
ΔF = 0	– 6
0<ΔF<A	– 6 – 41· (ΔF/A)
A	– 47
A<ΔF<B	– 47 – 12· ((ΔF – A)/(B – A))
ΔF≥B	– 59

Figure 39 - Block-Edge Masks for Central Stations in 3400 – 3800 MHz band (Source: [279])

5.6.2.1 CEPT Context

On 29 March 2012, the European Commission issued a Mandate to CEPT to determine technical conditions regarding spectrum harmonization for terrestrial wireless systems in the 3400-3800 MHz frequency band [411]. CEPT was directed to review and amend the technical conditions for the harmonized use of that band in order to adapt them to the latest developments in technology by preserving flexibility of use in line with the Wireless Access Policy for Electronic Communications Services (WAPECS) approach, including updating of the Block Edge Mask (BEM) and introducing harmonized frequency arrangements.

CEPT was mandated to undertake the following tasks:

- "Assess and justify any need to revise the common minimal (least restrictive) technical conditions, including BEM, which underlie the harmonized use of in the 3400-3800 MHz frequency band in the EU and, if necessary, identify modified conditions in view of accommodating developments in wireless broadband access technology in particular larger bandwidths. These conditions should be sufficient to avoid interference, facilitate cross-border coordination, and ensure co-existence with other existing systems and services in the same band and adjacent bands."
- "Assess and justify any need to introduce channelling arrangements in addition to (1) and, if necessary, develop a harmonized solution that is sufficiently precise for the development of EU-wide equipment."

CEPT in turn developed a roadmap to structure the work in response to this mandate to address the following issues:

- assess and justify any need to revise the common minimal (least restrictive) technical conditions including BEM;
- identify modified conditions in view of accommodating developments in wireless broadband access technology in particular larger bandwidths;
- assess and justify any need to introduce channelling arrangements;
- if necessary, develop a harmonized solution that is sufficiently precise for the development of EU-wide equipment.

Any harmonized frequency arrangements for the 3400-3800 MHz band had to facilitate high data rate mobile/fixed communications networks including IMT services supported by larger channel bandwidths as an evolution to the existing framework without the consequential requirement for a replacement of systems based on the existing regulatory framework. It was aiming at providing the basis to the mobile industry and administrations to respond to the growth of mobile broadband and technological developments for wider channel bandwidths and increased data rates.

The ECO (formerly ERO) carried out a survey in 2008 (ECC PT1(09)109R1), which found diverse implementation of BFWA within 3400-3800 MHz in CEPT countries, including some IMT systems [438]. This implementation is reflected in various licensing approaches (national, regional) and various frequency blocks choices (different portions of the 3400-3800 MHz). Moreover, this survey showed that paired blocks were used or planned to be used in TDD mode in some countries.

CEPT developed ECC/DEC/(11)06 on harmonized frequency arrangements for mobile/fixed communications networks operating in the 3400-3600 MHz and 3600-3800 MHz bands. In so far as is practicable, the frequency arrangements in ECC/DEC/(11)06 were intended to be technology neutral and capable of facilitating competitive provision of services using a range of technologies and modes (fixed, nomadic, and mobile) with sufficient flexibility to accommodate current wireless broadband services deployed in the band.

When developing these channelling arrangements, ECC considered the following CEPT regulatory framework that is in force for BFWA system in the 3400-3800 MHz band:

- the ECC/REC/(04)05 that offers guidelines for accommodation and assignment of multipoint BFWA systems in the frequency bands 3400-3600 MHz and 3600-3800 MHz;
- the ECC/DEC/(07)02 on availability of frequency bands between 3400-3800 MHz for the harmonized implementation of Broadband Wireless Access systems (BWA).

5.6.2.2 FS Deployment Data in Europe

The following figure describes the expected trends on the use of the 3.4-4.2 GHz band (note that only the 3.4-3.8 GHz sub-band is of interest here), as anticipated by the ECC Report 173, for the 19 countries whose information was made available to CEPT [287].

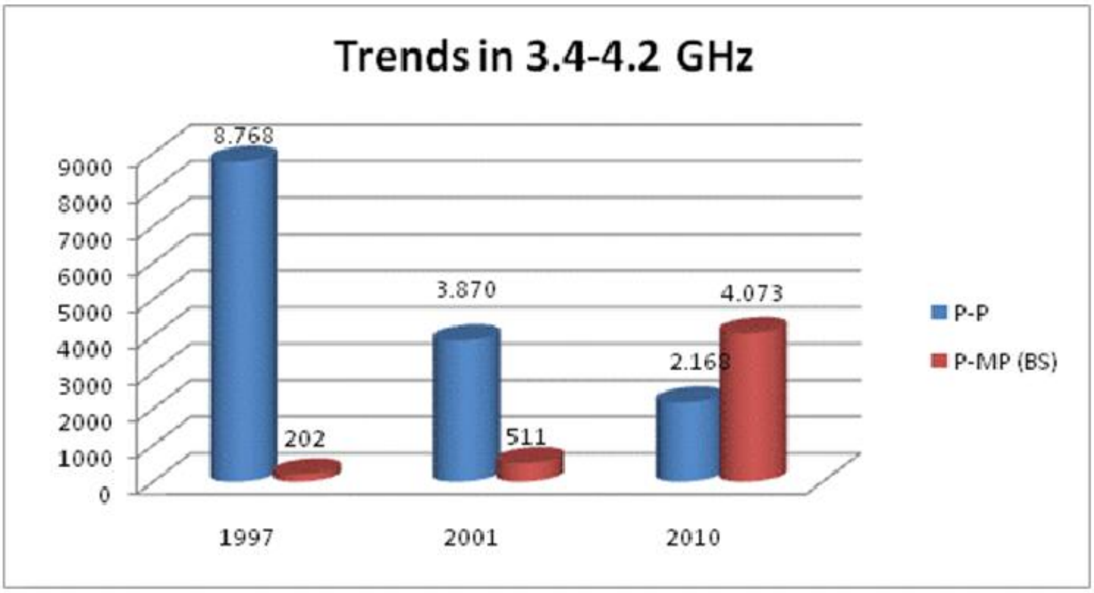


Figure 40 - Trend for the PtP and PMP (in this case only Base Stations are counted) links in the band 3.4-4.2 GHz (Source: [287])

5.6.3 FSS on ESOMPs

Under ITU Resolution 902 (WRC-03) [334] and through recommendations set in the CEPT Report 91 [430] on the compatibility of Earth stations on board vessels transmitting within the gaps in the CEPT Fixed Service channel plan for the lower 6 GHz band (5 925-6 425 MHz), decisions for operation of Earth stations on mobile platforms were developed for the C-band, particularly in the range 5925-6425 MHz.

It should be noted that the approach proposed in the CEPT Report 91 [430] in general complies with the terms of ITU Resolution 902 (WRC-03) [334], but only for those administrations that accept the terms of the report (see Clause 4, Annex 1, Res. 902). However administrations are under no obligation to accept the terms of the CEPT report and may continue to require compliance with the more restrictive limitations given in the resolution. It was made known during approval of the CEPT Report 91 [430] that some CEPT administrations do not intend accepting the proposed measures and will continue using the original provisions of ITU Resolution 902 (WRC-03) [334].

In particular, when considering the protection of primary Fixed Service systems in the lower 6 GHz band (5925-6425 MHz), administrations, if so they wish, have the sovereign right to retain the limits on ESV operation given in ITU Resolution 902 (WRC-03) [334], as expressed in the following extract from its Annex 1, item 10:

"*When ESVs operating beyond the territorial sea but within the minimum distance (300 km from the coastline) fail to comply with the terms required by the concerned administration pursuant to items 2 and 4, then that administration may:*

- *request the ESV to comply with such terms or cease operation immediately; or*
- *request the licensing administration to require such compliance or immediate cessation of the operation.*"

For the given frequency range of interest in this scenario (3.4-3.8 GHz), ITU Resolution 902 (WRC-03) considers that ESVs are currently operating through fixed-satellite service networks in the bands 3700-3800 MHz and also notes that that ESVs may be assigned frequencies to operate in FSS networks in the bands 3700-3800 MHz pursuant to No. 4.4 of the Radio Regulations and shall not claim protection from, nor cause harmful interference to, other services having allocations in these bands [334].

5.7 Scenario F Regulatory Context

Scenario F addresses Cognitive Radio GSO Satellite uplink/downlink in S-band [1980–2010 MHz and 2170–2200 MHz]. Specifically:

a. Cognitive hybrid satellite/terrestrial broadcast terminals using frequency bands of F1/F2;
b. Cognitive terrestrial terminals using frequency bands of F1/F2.

Where:

- F1: S-band uplink 1980–2010 MHz;
- F2: S-band downlink 2170–2200 MHz.

In this portion of the spectrum, hybrid satellite-terrestrial networks with mobile user terminals are deployed utilizing potentially different broadcast and interactive technologies in the space and terrestrial segment. The incumbent of the integrated network is the satellite operation together with the integrated complementary terrestrial network. The complementary terrestrial CR link may be able to dynamically adapt its forward and return link to the changing interference scenario.

5.7.1 ECA and ITU-R Tables of Allocations in this frequency band

The allocation of services in the studied frequency ranges is as per the following tables.

Table 24 - ECA frequency allocation tables for the 1980-2010 and 2170-2200 MHz bands (Source: [424])

RR Region 1 Allocation and RR footnotes applicable to CEPT	*European Common Allocation*	*ECC/ERC harmonisation measure*	*Applications*	*European footnotes*	*Standard*	*Notes*
1980 - 2010 MHz						
FIXED	MOBILE		-			This band can also be used by fixed service on a national basis
MOBILE MOBILE-SATELLITE (E/S) 5.351A	MOBILE-SATELLITE (E/S) 5.351A Fixed		IMT			Within CEPT, this band is identified for IMT. This includes IMT-2000 and IMT-Advanced
5.388 5.389A	5.388 5.389A					
5.389B 5.389F		ECC/DEC/(06)09 ECC/DEC/(06)10 ECC/DEC/(07)04 ECC/DEC/(07)05	MSS Earth stations		EN 301 442 EN 301 473 EN 302 574	The mobile satellite systems using this band may incorporate a CGC

2170 - 2200 MHz					
FIXED	MOBILE		-		This band can also be used by fixed service on a national basis
MOBILE	MOBILE-SATELLITE (S/E) 5.351A				
MOBILE-SATELLITE (S/E) 5.351A	Fixed		IMT-2000 satellite component		Within CEPT, this band is identified for IMT.This includes IMT-2000 and IMT-Advanced
5.388 5.389A	5.388 5.389A				
5.389F		ECC/DEC/(06)09 ECC/DEC/(06)10 ECC/DEC/(07)04 ECC/DEC/(07)05 ECC/REC/(10)01	MSS Earth stations	EN 301 442 EN 301 473 EN 302 574	The mobile satellite systems using this band may incorporate a Complementary Ground Component (CGC)

Table 25 - ITU-R Table of Allocations in 1980-2010 MHz and 2170-2200 MHz bands

Region 1	Region 2	Region 3
1980 – 2010 MHz FIXED MOBILE MOBILE SATELLITE (Earth-space 5.351A 5.388 5.389A 5.389B 5.389F		
2170 – 2200 MHz FIXED MOBILE MOBILE SATELLITE (Earth-space 5.351A 5.388 5.389A 5.389F		

ITU Resolution 212 indicates that that the availability of the satellite component of IMT in the 1980-2010 MHz and 2170-2200 MHz bands simultaneously with the terrestrial component of IMT would improve the overall implementation and the attractiveness of IMT.

The European Union has established a regulatory framework assigning 2x15 MHz to both Solaris Mobile Ltd and Inmarsat. This legal framework, which is legally binding on the Member States of the European Union, enables each operator to deploy complementary ground component (CGC) networks as an integral part of its satellite network anywhere within its satellite footprint and anywhere within its assigned frequency band.

The EU rules also state specifically that sharing is not possible between MSS and FS unless the latter are integrated into the MSS system.

In all three ITU Regions 1, 2 and 3, the frequency 1980-2010 MHz and 2170-2200 MHz bands have co-primary allocations for Mobile Services (MS), Fixed Services (FS), Mobile Satellite Services (MSS).

The UK administration has filed Request for Coordination notices with the ITU on Inmarsat's behalf for the following three orbital locations: 8.5E, 31E, and 61.5E covering the 1980-2010 MHz and 2170-2200 MHz bands. The regulatory deadline for bringing these filings into use is 8 February 2017.

The French administration has notified, on behalf of Solaris Mobile, bringing into use of satellite filings 3GSAT-G17R and F-SAT-S-E-10E for the provision of Mobile Satellite Services in the full 2x30 MHz. The satellite network filing 3GSAT-G17R has the highest ITU priority. Both filings have completed ITU coordination over the 27 Member States of the European Union (EU) and CEPT. The filings are subject to the ITU assignment lifetimes of 30 years. National authorizations are required to provide service within individual countries.

The ITU-R approved in 2011 the inclusion of Solaris Mobile's system in the ITU-R Recommendation and Report identifying the 2 GHz MSS band (and L-band) as the preferred harmonized frequency bands for Public Protection and Disaster Relief services provided by satellite in the following items:

- Recommendation ITU-R M.1854 on the "Use of mobile-satellite service (MSS) in disaster response and relief."
- Report ITU-R M.2149 on the "Use and examples of mobile-satellite service systems for relief operation in the event of natural disasters and similar emergencies."

5.7.2 EU regulatory framework in this frequency band

The EU Commission adopted Decision 2007/98/EC [8] in February 2007 on the harmonized use of radio spectrum in the 2 GHz frequency bands for the implementation of systems providing Mobile Satellite Services (MSS).

In June 2008 the European Parliament and Council adopted Decision 626/2008/EC [42], which provides a selection and authorization process for the award of the designated spectrum to MSS operators (*i.e.*, satellite operators), and for a harmonized approach to authorization and deployment of MSS systems in European Union Member States.

On 14 May 2009, both Solaris Mobile Ltd. and Inmarsat plc. received confirmation from the European Commission of the assignment of 2 x 15 MHz of spectrum each within the 2 GHz Band across Europe [44]. This provided both applicants with the obligation to provide MSS, and the right to deploy CGC in all EU Member States within the 2x15 MHz assigned to each of them.

Finally, the Commission Decision on the modalities for a coordinated application of the rules on enforcement with regard to MSS, was adopted in 2011 [45]. This Decision sets out a process to be followed when a Member State finds that an authorized operator does not comply with one or more of the common conditions as outlined in Decision 626/2008/EC on the selection and authorization of systems providing mobile satellite services.

5.7.2.1 CEPT Harmonization

The ECC Decision ECC/DEC/(06)09 [282] provided for the designation and the conditions of use of the 1980-2010 and 2170-2200 MHz bands by systems in the mobile satellite service including those supplemented by a CGC. The Decision includes the requirement for mobile satellite systems operating in this frequency band to ensure compatibility with terrestrial systems operating in the mobile service in the adjacent bands operating in bands below 1980 MHz and between 2010-2170 MHz.

The ECC Recommendation ECC/REC/(10)01 [286] provides guidelines that Member States should use to ensure the compatibility between CGC in the 2170-2200 MHz band and a number of Earth stations listed in the Recommendation used by the Earth Satellite Service, Space Research Service, or Space Operation Service operating in the 2200-2290 MHz band. The Recommendation requires Member States to coordinate CGC operating in the 2170-2200 MHz band and operating within a specific radius / distance from the specific Earth stations listed.

ECC Report 197 addresses the issue of compatibility between MSS terminals in the 2 GHz MSS band (without CGC) and terrestrial UMTS in adjacent or nearby bands provisionally concludes that [400] [20]:

[20] Further information can be found in the statistical analysis results presented in pages 29 and 30 of [400].

- there are potential interference issues when an MSS User Terminal (UT) transmitting to the satellite is in the vicinity of a base station or a UT of an ECN network;
- deterministic results show that when an MSS UT is near to a victim ECN BS, in the absence of any mitigation technique, the interference caused is above the recommended protection criterion based on I/N. Nevertheless, it should also be taken into account that ECN networks are built with more than one base station. Table 21 of ECC report 197 shows, in some cases, a range of distances in which interference would be caused to the victim ECN BS; in those cases, the lower distance may mean that the interferer is pointing towards another base station;
- the deterministic study of micro- and pico- base stations reveal that the minimum distance that gives protection from interference is between 200 meters and 1400 meters for a micro base station and between 100 meters and 600 meters for a pico base station. In most cases these distances exceeds the normal cell radius of the (pico or micro) base station;
- as a consequence of these deterministic results, a statistical analysis was also performed as complementary analysis. A statistical analysis of interference into micro and pico base stations has not been performed in this study due to the current limitations of the SEAMCAT tool in modelling networks composed of different type of cells in a single simulation. Statistical analysis has however been performed with the SEAMCAT tool for studying the interference effects into ECN macro base stations and ECN UT;
- the report takes and uses the criteria for assessment of the statistical results; MSS terminal interference to the UMTS network is considered sufficiently low provided that the capacity loss is no more than 5% on average over the different snapshots.

5.7.3 National Authorizations

Only the selection of the operators providing systems of mobile satellite services has been made at European level. Operators will be authorized by each Member State, subject to a number of harmonized authorization conditions.

According to a report for the European Commission [401], as of the end of December 2010, authorization structures for MSS were said to be in place in 21 Member States; 5 Member States said such structures were not in place; and 1 Member State did not provide information. However, a subsequent report indicated that by the end of December 2011, authorization structures for MSS were said to be in place in all but one Member State.

The approaches that Member States have taken towards authorization of the MSS component of 2 GHz MSS networks vary considerably. Numerous models are applied to MSS authorizations:

- twelve Member States apply either a license exemption or general authorization for the MSS component. One Member State NRA concluded that it could not legally grant a general authorization to specific identified applicants. One of these twelve Member States has actually issued a general authorization although its rules may technically not be in place (IE);
- nine Member States require an individual right of use for the MSS component;
- six Member States require an individual right of use for a consolidated/integrated MSS and CGC network. Member States define this integrated right of use in different ways, however, as shown by the contrast between ES and PT, which both issue what they call an integrated right of use. In ES, the single right of use covers the MSS component and all CGCs, with a single

fee. In PT, the single right of use covers the MSS component, but there is an additional (very large) fee for each CGC added to the network;

- some Member States have granted temporary, testing or trial authorizations (for example, BE, FR, IT, LU) for the development of the service;
- some Member States have included the two selected operators in their national table of allocations (DK, FI, PL);
- one Member State reported that authorization of broadcast services over the MSS network could require additional rounds of authorization from regional authorities (BE).

5.8 Scenario G Regulatory Context

Scenario G addresses sharing between cognitive NGSO FSS systems and incumbent FS terrestrial systems operating in Ka-band, where the cognitive satellite terminals could dynamically control the interference caused to incumbent terrestrial stations. Both downlink [17.7-19.7 GHz] and uplink [27.8285-28.4445 GHz and 28.9485-29.4525 GHz] frequency bands are considered. In this respect, relevant ECC Decisions are:

- ECC/DEC/(00)07: giving guidance on the use of the 17.7-19.7 GHz band by FSS and FS;
- ECC/DEC/(05)01: providing a segmentation between FS and FSS stations in the frequency band of 27.5-29.5 GHz;
- ECC/DEC/(13)01: addressing the harmonized use of ESOMPs operating within the given frequency bands.

In particular, ECC/DEC/(00)07 decision stipulates that stations of the FSS can be deployed anywhere, but without right of protection from interference generated by FS radio stations. Cognitive Radio techniques could significantly increase the spectrum usage allocated to FSS by enabling access to frequency spectrum in the vicinity of terrestrial transmitters. Cognitive Radio techniques could act as a dynamic and flexible protection of FSS downlink from FS interference. The downlink part of this scenario can be seen as an extension of the FSS exclusive frequency band 19.7-20.2 GHz by adding significant user capacity in the 17.7-19.7 GHz bandwidth.

In addition, ECC/DEC/(05)01 designates the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz bands for the use of FS systems and stipulates that CEPT administrations shall not authorise the deployment of uncoordinated FSS Earth stations in the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz bands.

CoRaSat WP2 is investigating whether CR techniques could help to solve these specific sharing scenarios. In this respect, the following aspects of the scenario are investigated:

a. NGSO FSS cognitive satellite terminals using frequency bands shared with FS links with priority protection in G1/G2;
b. NGSO FSS cognitive satellite terminals onboard mobile platforms using frequency bands shared with FS links with priority protection in G1 (downlink only).

Where:

- G1: Ka-band downlink in the 17.7-19.7 GHz band;
- G2: Ka-band uplink in the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz bands.

5.8.1 ECA and ITU-R Tables of Allocations in this frequency band

The allocation of services in the studied frequency ranges is as per the following tables:

Table 26 - ECA Table of Allocations in 17.7 – 19.7 and 27.5 – 29.5 GHz bands (Source: [424])

RR Region 1 Allocation and RR footnotes applicable to CEPT	*European Common Allocation*	*ECC/ERC harmonisation measure*	*Applications*	*European footnotes*	*Standard*	*Notes*
17.7 - 18.1 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516	FIXED-SATELLITE (S/E) 5.484A (E/S) 5.516		Feeder Links			Feeder links for the BSS service. Appendix 30A of RR
MOBILE			FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
18.1 - 18.3 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A (E/S) 5.520	FIXED-SATELLITE (S/E) 5.484A	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
			Feeder links			Feeder links for the BSS service.
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE	METEOROLOGICAL-SATELLITE (S/E)		WeatherSatellites			
5.519 5.521	5.519					
18.3 - 18.4 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A (E/S) 5.520	FIXED-SATELLITE (S/E) 5.484A (E/S) 5.520	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks'
			Feeder links			Feeder links for the BSS service
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE 5.519 5.521	METEOROLOGICAL SATELLITE (S/E) 5.519					
18.4 - 18.6 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.484A	FIXED-SATELLITE (S/E) 5.484A	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
MOBILE		ECC/DEC/(13)01	ESOMPs		EN 303 978	
18.6 - 18.8 GHz						
EARTH EXPLORATION-SATELLITE (passive)	EARTH EXPLORATION-SATELLITE (passive)					
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.522B	FIXED-SATELLITE (S/E) 5.522B	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
MOBILE except aeronautical mobile						
Space research (passive)	5.522A		Passive sensors (satellite)			Surface emmissivity, snow, sea, ice and precipitation
5.522A 5.522C						
18.8 - 19.3 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) 5.523A	FIXED-SATELLITE (S/E) 5.523A	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated earth stations. Priority for civil networks
MOBILE		ECC/DEC/(13)01	ESOMPs		EN 303 978	
19.3 - 19.7 GHz						
FIXED	FIXED	ERC/DEC/(00)07 ERC/REC 12-03	Fixed		EN 302 217	
FIXED-SATELLITE (S/E) (E/S) 5.523B 5.523C 5.523D 5.523E	FIXED-SATELLITE (S/E) (E/S) 5.523B 5.523C 5.523D 5.523E	ERC/DEC/(00)07	FSS Earth stations		EN 301 360 EN 301 459	To coordinated Earth stations. Priority for civil networks
MOBILE		ECC/DEC/(13)01	ESOMPs		EN 303 978	
19.7 - 20.1 GHz						
FIXED-SATELLITE (S/E) 5.484A 5.516B	FIXED-SATELLITE (S/E) 5.484A 5.516B		MSS Earth stations		EN 301 459 EN 301 360	For uncoordinated Earth stations SUT
		ECC/DEC/(13)01	ESOMPs		EN 303 978	
Mobile-satellite (S/E)	Mobile-satellite (S/E)	ECC/DEC/(06)03	HEST		EN 301 459 EN 301 360	

27.5 - 28.5 GHz

FIXED 5.537A	FIXED		Feeder links		Feeder links to be used for Broadcasting satellites (HDTV) 27.5-29.5 GHz
FIXED-SATELLITE (E/S) 5.484A 5.516B 5.539	FIXED-SATELLITE (E/S) 5.484A 5.516B 5.539	ECC/DEC/(13)01	ESOMPs	EN 303 978	
MOBILE		ECC/DEC/(05)01 T/R 13-02	Fixed	EN 302 217	For frequency arrangement between FS and FSS see ECC/DEC/(05)01
5.538 5.540	5.538 5.540	ECC/DEC/(05)01	FSS Earth stations	EN 301 360	The Earth-to-Space direction for uncoordinated Earth stations within the band 27.5-27.8285 GHz. The Space-to-Earth direction is limited to beacons for uplink power control 27.5-27.501 GHz
		ECC/REC/(11)01 ECC/DEC/(05)01	BFWA	EN 302 326	CRS paired with 28.5-29.5 GHz for FDD systems. The Earth-to-Space direction for uncoordinated Earth stations within the band 27.5-27.8285 GHz. The Space-to-Earth direction is limited to beacons for uplink power control 27.5-27.501 GHz

28.5 - 29.1 GHz

FIXED	FIXED		Feeder links		Feeder links to be used for Broadcasting satellites (HDTV) 27.5-29.5 GHz
FIXED-SATELLITE (E/S) 5.484A 5.516B 5.523A 5.539	FIXED-SATELLITE (E/S) 5.484A 5.516B 5.523A 5.539				
MOBILE Earth exploration-satellite (E/S) 5.541	Earth exploration-satellite (E/S) 5.541	ECC/DEC/(05)01 T/R 13-02	Fixed	EN 302 217	For frequency arrangement between FS and FSS see ECC/DEC/(05)01
5.540		ECC/DEC/(05)01	FSS Earth stations	EN 301 360	Uncoordinated Earth stations within the band 28.4445-28.8365 GHz
		ECC/DEC/(13)01	ESOMPs	EN 303 978	
		ECC/REC/(11)01 ECC/DEC/(05)01	BFWA	EN 302 326	TS paired with 27.5-28.5 GHz for FDD systems. Uncoordinated Earth stations within the band 28.4445-28.8365 GHz

29.1 - 29.5 GHz

FIXED	FIXED		Feeder links		Feeder links to be used for Broadcasting satellites (HDTV) 27.5-29.5 GHz
FIXED-SATELLITE (E/S) 5.516B 5.523C 5.523E 5.535A 5.539 5.541A	FIXED-SATELLITE (E/S) 5.516B 5.523C 5.523E 5.535A 5.539 5.541A	ECC/DEC/(13)01	ESOMPs	EN 303 978	
MOBILE		ECC/DEC/(05)01 T/R 13-02	Fixed	EN 302 217	Within the band 29.0605-29.4525 GHz
Earth exploration-satellite (E/S) 5.541	Earth exploration-satellite (E/S) 5.541	ECC/DEC/(05)01	FSS Earth stations	EN 301 360	Uncoordinated Earth stations within the band 29.4525-29.5 GHz
5.540	5.540	ECC/REC/(11)01 ECC/DEC/(05)01	BFWA	EN 302 326	TS paired with 27.5-28.5 GHz for FDD systems. Uncoordinated Earth stations within the band 29.4525-29.5 GHz

Table 27 - ITU-R Table of Allocations in 17.7 – 19.7 and 27.5 – 29.5 GHz bands

Region 1	Region 2	Region 3
17.7 – 18.1 FIXED FIXED SATELLITE (Space-Earth) 5.484A (Earth-space) 5.516 MOBILE	**17.7 – 17.8** FIXED FIXED SATELLITE (Space-Earth) 5.517 (Earth-space) 5.516 BROADCASTING SATELLITE Mobile 5.518 5.515 5.517 **17.8 – 18.1** FIXED FIXED SATELLITE (Space-Earth) 5.484A (Earth-space) 5.516 MOBILE 5.519	**17.7 – 18.1** FIXED FIXED SATELLITE (Space-Earth) 5.484A (Earth-space) 5.516 MOBILE

<table>
<tr><td colspan="3">18.1 – 18.4
FIXED
FIXED SATELLITE (Space-Earth) 5.484A 5.516B
(Earth-space) 5.520
MOBILE
5.519 5.521</td></tr>
<tr><td colspan="3">18.4 – 18.6
FIXED
FIXED SATELLITE (Space-Earth) 5.484A 5.516B
MOBILE</td></tr>
<tr><td>18.6 – 18.8
EARTH RESEARCH SATELLITE
FIXED
FIXED SATELLITE (space-Earth)
5.522B
MOBILE, except aeronautical mobile
Space research
5.522A 5.522C</td><td>18.6 – 18.8
EARTH RESEARCH SATELLITE
FIXED
FIXED SATELLITE (space-Earth)
5.516B 5.522BB
MOBILE, except aeronautical mobile
SPACE RESEARCH
5.522A</td><td>18.6 – 18.8
EARTH RESEARCH SATELLITE
FIXED
FIXED SATELLITE (space-Earth)
5.522B
MOBILE, except aeronautical mobile
Space research
5.522A</td></tr>
<tr><td colspan="3">18.8 – 19.3
FIXED
FIXED SATELLITE (space-Earth) 5.516B 5.523A
MOBILE</td></tr>
<tr><td colspan="3">19.3 – 19.7
FIXED
FIXED SATELLITE (space-Earth) (Earth-space)
5.523B 5.523C 5.523D 5.523E
MOBILE</td></tr>
</table>

27.5 -28.5 FIXED 5.537A FIXED SATELLITE (Earth-space) 5.5484A 5.516B 5.539 MOBILE 5.538 5.540
28.5 – 29.1 FIXED FIXED SATELLITE (Earth-space) 5.5484A 5.516B 5.523A 5.539 MOBILE Earth research Satellite (Earth-space) 5.541 5.540
29.1 – 29.5 FIXED FIXED SATELLITE SERVICE (Earth-space) 5.516B 5.523C 5.523E 5.535A 5.539 5.541A MOBILE Earth Exploration by satellite (Earth-space) 5.541 5.540

5.8.2 Regulatory Status in this Frequency Band

Relevant ECC Decisions in this frequency band are:

- ECC/DEC/(00)07: giving guidance on the use of the 17.7-19.7 GHz band by FSS and FS;
- ECC/DEC/(05)01: providing a segmentation between FS and FSS stations in the frequency band of 27.5-29.5 GHz;
- ECC/DEC/(13)01: addressing the harmonized use of ESOMPs operating within the given frequency bands.

In particular, ECC/DEC/(00)07 decision stipulates that stations of the FSS can be deployed anywhere, but without right of protection from interference generated by FS radio stations. Cognitive Radio techniques could significantly increase the spectrum usage allocated to FSS by enabling access to frequency spectrum in the vicinity of terrestrial transmitters. Cognitive Radio techniques could act as a dynamic and flexible protection of FSS downlink from FS interference. The downlink part of this scenario can be seen as an extension of the FSS exclusive frequency band 19.7-20.2 GHz by adding significant user capacity in the 17.7-19.7 GHz bandwidth.

In addition, ECC/DEC/(05)01 designates the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz bands for the use of FS systems and stipulates that CEPT administrations shall not authorise the deployment of uncoordinated FSS Earth stations in the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz bands.

Thus, of specific relevance to this scenario are:

a. NGSO FSS cognitive satellite terminals using frequency bands shared with FS links with priority protection in G1/G2.

Where:

- G1: Ka-band downlink in the 17.7-19.7 GHz band;
- G2: Ka-band uplink in the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz bands.

In this way, the bands where only coordinated Earth stations can be used today are investigated, *i.e.*, bands shared with FS.

Further details on the Decision ECC/DEC/(00)07 on the use of the 17.7-19.7 GHz downlink band by FSS and FS, and on the Decision ECC/DEC/(05)01 on the use of the 27.5-29.5 uplink band (including, specifically, the 27.8285-28.4445 GHz and 28.9485-29.4525 GHz ranges) by FSS and FS, can be found in Sections 5.3.2 and 5.4.2, respectively.

5.8.3 FSS on ESOMPs

ECC Decision ECC/DEC/(13)01 [304] addresses the harmonized use of Earth Stations On Mobile Platforms (ESOMPs) which operate within the 17.3-20.2 GHz (space-to-Earth) and 27.5-30.0 GHz (Earth-to-space) frequency bands.

Of specific relevance to this scenario are the following aspects:

a. NGSO FSS cognitive satellite terminals onboard mobile platforms using frequency bands shared with FS links with priority protection in G1 (downlink only).

Where:

- G1: Ka-band downlink in the 17.7-19.7 GHz band.

That is, the downlink bands for ESOMPs are investigated. It does not really make sense to have the uplink investigated as well because either ESOMPs are authorized in bands where there is no FS, or ESOMPs are not authorized in bands where there is FS.

The analysis conducted in Section 5.3.3 above for Scenario B is also applicable here.

5.9 Overview of CR Projects Addressing Regulatory Aspects

In the companion CoRaSat deliverables D2.2 [441] and D2.6 [442], ongoing and past Cognitive Radio projects are reviewed in detail from the technology point of view. These include relevant EU, ESA, and National CR projects, including:

- EU projects in CR context: ABSOLUTE, ACROPOLIS, ARAGORN, C2POWER, COGEU, COST IC0902, CREW, CROWN, CRS-i, E3, FARAMIR, OneFIT, PHYDYAS, QoSMOS, QUASAR, ROCKET, SACRA, SAPHYRE, SENDORA.
- ESA projects in CR context: ACROSS, ESA-1-5800.
- National projects in CR context: CO2SAT, SALICE, SPECTRA, LICORNE.

Most of these projects address technological aspects and do not elaborate relevant regulatory issues. Moreover, as these projects mainly focus on terrestrial CR technologies, no CR project providing significant information on satellite regulation was found.

To complement the presented regulatory context review, this Section considers only the limited subset of CR projects which have emphasized relevant regulatory aspects (see Table 28).

Table 28 - Reviewed CR Projects with focus on Regulatory Aspects

Project Acronym	Full title	Funding Programme	Funding Scheme	Timeframe	Reference
ACROPOLIS	Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum	EC FP7 ICT	NoE	Oct 2010–Sep 2013	[394]
E3	End-to-End Efficiency	EC FP7 ICT	IP	Jan 2008 – Dec 2009	[391]
OneFIT	Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future InterneT	EC FP7 ICT	STREP	Jul 2010 – Dec 2012	[392]
QoSMOS	Quality of Service and MObility driven cognitive radio Systems	EC FP7 ICT	IP	Jan 2010 – Dec 2012	[393]
ESA_1-5800	The Changing Regulatory and Evolutionary Environment and its Impact on the Satellite Communication Business	ESA ARTES	ARTES 1 Study	2008 - 2010	[383]

5.9.1 ACROPOLIS

ACROPOLIS analyses the complexity of implementation of the cognitive radio techniques in practical terms. The deployment of CR and Dynamic Spectrum Access (DSA) presents many challenges at the regulatory, market and technical level. It identifies the challenges and describes how they are being addressed by the main regulatory and standardisation entities. The relevance of the challenges depends on the use cases where CR concepts could be applied.

The following regulatory challenges were identified by ACROPOLIS [396]:

- Appropriate regulations for various operational scenarios: the regulatory process for CR is significantly more complex than conventional radio communication services and is dependent on the specific business scenarios. A significant trade-off is between avoiding the risk of wireless interference to incumbent users (due to constraints on CR emissions, which are too loose) and not hampering the commercial success of CR (due to constraints which are too restrictive).
- Certification and protection against mis-behavior: in comparison with conventional wireless communications systems, which are designed to operate in specific frequency bands, CR equipment is theoretically able to transmit in a wide range of frequencies. As a consequence, there is an increased risk of wireless interference, which can be both intentional (for example, malicious devices) or unintentional, whereby a radio is inadvertently unable to detect the incumbent usage of a frequency channel (for example, because of shadowing effects or hidden-node problem). CR devices clearly present new challenges from a certification point of view in comparison to conventional devices.
- Complex spectrum trading schemes: CRs provide the possibility of spectrum trading, whereby bands can be temporarily re-allocated from a provider to another. The implementation of spectrum trading can be quite complex from the regulatory point of view.
- Complex international framework: the introduction of new radio communication services often requires a complex and lengthy coordination process among international, European and national spectrum regulators. Regulators and manufacturers must also address cross-border issues for CR devices moving from one spectrum regulatory area to another.
- Lack of flexibility of existing licensing schemes: lack of flexibility in some existing licenses, because of existing regional or international agreements or because the license has prescribed specific technical conditions.
- Lack of precise data for spectrum utilization: even if various measurement campaigns have been performed in various parts of the world, there is a lack of clear consensus on the available spectrum, which can be exploited by CR devices through opportunistic access.

Further information is available on the project website [394] as well as on the recently published paper [396].

5.9.2 E3

In the regulatory context, E3 identified and developed a strategy to achieve most impact in the development of the ITU-R WRC-11 agenda item 1.19. Moreover, towards a future regulatory framework allowing a more dynamic and flexible allocation of spectrum resources as well as towards a new approach towards equipment certification and licensing, National as well as Europe-wide and worldwide regulation authorities and standardisation organisations were acquainted with a mindset towards the requirements and needs of a future regulation system.

Further information is available on the project website: [391].

5.9.3 OneFIT

Regarding regulatory bodies, OneFIT targeted European regulation authorities (one of which being a consortium member) but also wider initiatives and events of the ECO (European Communications Office) and other international bodies (*e.g.*, ITU) to which many of the OneFIT members had good relations. Work and outcomes were used to inform the regulation authorities about the technological options and aim to lead to the rules for a more dynamic and flexible allocation of spectrum resources, as well as to corresponding rules towards certification and licensing of (opportunistically behaving) equipment.

Further information is available on the project website: [392].

5.9.4 QoSMOS

With respect to regulation, QoSMOS observed activities in FCC, CEPT, ITU-R, and OFCOM. QoSMOS provided no direct contribution to these bodies but it had an intensive dialog with regulators involved in the External Advisory Board (EAB) to ensure that QoSMOS results were known by the regulators and that actual information from the relevant regulatory bodies could been taken into account for the work in QoSMOS. The regular interaction with these organisations helped to place QoSMOS results in the relevant national as well international bodies (such as CEPT, ITU, and Wireless Innovation Forum).

On the policy development, the regulatory framework at that time did not allow the implementation of deployment scenarios as anticipated in QoSMOS. Changes to regulatory regimes were under way in terms of market liberalisation and introduction of more operational flexibility, but there was a long way to go before opportunistic or cognitive radio could be used as new media access mechanism and the next big step in this direction was about to be taken at WRC-11. To be able to fully exploit the technologies and deployment scenarios anticipated in QoSMOS, the consortium realised the need to involve regulation bodies as well as organisations such as standardisation bodies, fora or lobbying groups into the discussions and planning of the project directions. In this respect, the EAB discussed on a regular basis QoSMOS outputs and research directions (see, *e.g.*, OFCOM’s perspective on the challenges for TVWS radio systems using geo-location databases [393]).

Further information is available on the project website: [393].

5.9.5 “ESA _1-5800”: The Changing Regulatory and Evolutionary Environment and its impact on the Satellite Communication Business

This study, titled “The Changing Regulatory and Evolutionary Environment and its impact on the Satellite Communication Business” [383], investigated eight selected topics concerning frequency spectrum regulations reflecting their potential impact on the satellite communication business in a changing regulatory and evolutionary environment.

Since the first auctions for frequency spectrum in the late 1990s, the commercial value of frequency spectrum has increased rapidly, resulting in a fast growing pressure on sharing frequency bands allocated to satellite communications with mobile and fixed radio services. This has been due to fact that fast growing economies in many countries implement more and more communication networks but also due to the fast growing demand for broadband access quality and broadband mobile services.

The decisions taken at WRC-07 already showed a high demand for the terrestrial broadband mobile radio services and this trend is dramatically increasing. Given the project timeframe (2008-2010), the scope of its work comprised topics on satellite communication related to WRC-12 and CEPT as follows:

- TOPIC#1: Fact finding of currently existing frequency spectrum resources allocated to the Mobile (MSS), Fixed (FSS), and Broadcasting (BSS) satellite services as given by the ITU Radio Regulations (Edition 2008), i.e. including decisions taken by WRC-07;

- TOPIC#2: Investigations on convergence of mobile and fixed services and their potential regulatory impacts and consequences on future radio regulations in support of WRC-12 Agenda Item 1.2;
- TOPIC#3: Support on the analysis of use of frequency spectrum in the 21 GHz range for future concepts of BSS (WRC-12 Agenda Item 1.13);
- TOPIC#4: Investigations of SDR technologies and CRS concepts enabling flexible spectrum management scenarios and their impact on future radio regulations in support of WRC-12 Agenda item 1.19;
- TOPIC#5: Support and analysis of the ITU-R studies for sharing with other radio services in the context of WRC-12 Agenda Item 1.25 to consider additional allocations the MSS;
- TOPIC#6: Analysis the consequences of the use of Broadband Wireless Access (BWA) systems authorised by the European Commission by for operations in the FSS C-band 3.4-3.8 GHz, in line with EC decision 411/2008/EC;
- TOPIC#7: Scenarios and sharing conditions for the operation of Complementary Ground Component (CGC) as complement to MSS provisioning in the 1.6/1.5 GHz MSS bands;
- TOPIC#8: Analysis on the current and future use of Ka-band spectrum for SatCom in the CEPT region.

6 Cognitive Radio Standardisation Activities

6.1 Overview of Cognitive Radio Standardisation Context

An important and essential aspect in the commercial feasibility and deployment of the DSA/CR concept is its standardisation. The existing standards relevant for Cognitive Radio have been mainly addressing terrestrial communications. The most important standardisation initiatives to date have been brought forward by the Institute of Electrical and Electronics Engineers (IEEE). Nevertheless, other international standardisation organizations or industry associations such as the International Telecommunication Union (ITU), the European Telecommunications Standards Institute (ETSI), the 3rd Generation Partnership Project (3GPP), the Wireless Innovation Forum (formerly known as SDR Forum), and the European association for standardizing information and communication systems (ECMA international) have been or are working in the development of DSA/CR standards as well [339].

Table 29 below provides an overview of the main standardisation activities on CR to date.

Table 29 - Overview of main standardisation activities on CR.

Body	Branch	Group	Standard	Description
IEEE	802	802.11	802.11af	TV White Spaces Operation
			802.11h	Spectrum and Transmit Power Management Extensions in the 5 GHz Band in Europe
			802.11y	3650-3700 MHz Operation in USA
		802.15	802.15.2	Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Band
		802.16	802.16a	Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11 GHz
			802.16h	Improved Coexistence Mechanisms for License-Exempt Operation
			802.16m	Air Interface for Fixed and Mobile Broadband Wireless Access Systems
			802.16.2	Recommended Practice for Local and metropolitan area networks - Coexistence of Fixed Broadband Wireless Access Systems
		802.19	802.19	Coexistence between wireless standards of unlicensed devices
		802.22	802.22	Cognitive Wireless Regional Area Networks for operation in TV bands
			802.22a	Enhanced Management Information Base and Management and Control Plane Interfaces and Procedures
			802.22b	Enhancements for Broadband Services and Monitoring Applications
			802.22.1	Enhanced Interference Protection of the Licensed Devices
			802.22.2	Recommended Practice for Installation and Deployment of 802.22 Systems

	DySPAN	1900	1900.1	Definitions and Concepts for Dynamic Spectrum Access: Terminology and Concepts for Next Generation Radio Systems and Spectrum Management
			1900.1a	Addition of New Terms and Associated Definitions
			1900.2	Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence between Radio Systems
			1900.3	Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules
			1900.4	Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks
			1900.4a	Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands
			1900.4.1	Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks
			1900.5	Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications
			1900.5a	Interface Description between Policy Architecture Components
			1900.5.1	Vendor-Independent Policy Language for Managing the Functionality and Behavior of Dynamic Spectrum Access Networks
			1900.6	Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems
			1900.6a	Procedures, Protocols and Data Archive Enhanced Interfaces
			1900.7	Radio Interface for White Space Dynamic Spectrum Access Radio Systems Supporting Fixed and Mobile Operation
ITU	ITU-R	WP 1B	SM.2152	Definitions of SDR and CRS
			1B/267-E	Draft CPM text on WRC-12 agenda item 1.19
		WP 5A	M.2225	Cognitive radio systems in the land mobile service
		WP 5D	M.2242	Cognitive radio systems specific for IMT systems
ETSI	RRS	WG1 & WG3	TR 102 838	Summary of feasibility studies and potential standardisation topics
			TR 102 684	Feasibility Study on Control Channels for Cognitive Radio Systems
			TR 103 067	Feasibility study on Radio Frequency (RF) performances for Cognitive Radio Systems operating in UHF TV band White Spaces
			TR 101 571	Feasibility study for coexistence between Cognitive Radio Systems operating in white spaces of the 470 – 790 MHz band and services delivered by existing RF Cable Networks operating in fixed wires

			TR 102 682	Functional Architecture (FA) for the Management and Control of Reconfigurable Radio Systems
			TR 102 683	Cognitive Pilot Channel
			TR 102 907	Use Cases for Operation in White Space Frequency Bands
			TR 102 908	Coexistence Architecture for Cognitive Radio Networks on White Space Frequency Bands
			TR 102 946	System requirements for Operation in UHF TV Band White Spaces
3GPP	–	–	TS 23.402 TS 24.302 TS 24.312	Access Network Discovery and Selection Function
WINNF	–	–	SDRF-06-R-0011	SDRF Cognitive Radio Definitions
			SDRF-06-P-0009	Cognitive Radio Definitions and Nomenclature
			WINNF-11-R-0001	Comments on the Wireless Innovation Forum to the FCC
			SDRF-07-P-0019	Use Cases for Cognitive Applications in Public Safety Communications Systems - Volume 1: Review of the 7 July Bombing of the London Underground
			WINNF-09-P-0015	Use Cases for Cognitive Applications in Public Safety Communications Systems - Volume 2: Explosion at a chemical plant
			WINNF-09-P-0012	Quantifying the Benefits of Cognitive Radio
			WINNF-12-P-0003	TD-LTE in White Space
			WINNF-10-S-0007	Description of the Cognitive Radio Ontology
ECMA	TC48	TGI	ECMA-392	MAC and PHY for operation in TV white space
IETF	–	PAWS	PAWS	Protocol to Access White Space Database
DARPA	–	–	–	neXt Generation Communications (XG) program

6.2 IEEE

The most popular standards on CR are the IEEE 802.22 standard for Wireless Regional Area Network (WRAN) using white spaces in the TV frequency spectrum and the IEEE 1900 series of standards in the area of dynamic spectrum management [340] developed by the Dynamic Spectrum Access Networks (DySPAN) Standards Committee (SC), formerly known as Standards Coordinating Committee 41 (SCC41), and even earlier IEEE P1900 Standards Committee. However, there are several other, lesser known, related activities within IEEE as well. Many other completed IEEE 802 standards already include CR-like capabilities or related building blocks that evolved from coexistence activities [341]. The following sections provide an overview of IEEE standardisation activities.

6.2.1 IEEE 802.22

IEEE 802.22 is the first worldwide standard based on the CR technology [342], [343], [344]. The most prominent target application of IEEE 802.22 is wireless broadband access in rural and remote areas, with performance comparable to those of existing fixed broadband access technologies serving urban and suburban areas. This technology is especially useful for serving less densely populated areas, such as rural areas and developing countries where most vacant TV channels can be found [345].

The standard defines the physical (PHY) and MAC layers of a CR-based air interface [346], [347] for use by license-exempt devices on a non-interfering basis in spectrum allocated to the TV broadcast service. IEEE 802.22 incorporates advanced cognitive radio capabilities including dynamic spectrum access, incumbent database access, accurate geolocation techniques, spectrum sensing, regulatory domain dependent policies, spectrum etiquette, and coexistence for optimal use of the available spectrum.

The standard considers the utilization of VHF and UHF TV bands for two main reasons, namely the favorable propagation characteristics of the lower frequency bands allocated to the TV service and the consequent larger coverage areas, and the considerable amount of available TV white space [348], [349], [350]. The 802.22 project initially identified the North American frequency range of operation between 54 and 862 MHz, which was extended between 47 and 910 MHz in order to meet additional international regulatory requirements. Since there is no worldwide uniformity in channelization for TV services, the standard also accommodates the various international TV channel bandwidths of 6, 7, and 8 MHz. The 802.22 system defines a fixed Point-To-Multipoint (PTM) architecture where each Base Station (BS) communicates with up to 255 associated stations, referred to as Customer Premises Equipments (CPEs), by means of time division multiplexing in the DownStream (DS) direction (BS to CPE) and a demand assigned Time Division Multiple Access (TDMA) scheme in the UpStream (US) direction (CPE to BS). The specified BS coverage range is 30 km (with some additions to support 100 km under favorable propagation conditions) and targets peak throughput rates at the edge of the coverage area of 1.5 Mbps per user in DS and 384 kbps in US.

The scope of IEEE 802.22 is the PHY and MAC layers:

- *PHY layer [351]:* at the PHY layer, a Spectrum Sensing Function (SSF) and a geo-location function are defined. These provide necessary functionality to support the cognitive capabilities of the system. Spectrum sensing analyzes the signals in the interested channels to identify which channels are occupied by licensed transmission. In IEEE 802.22, both the BS and CPE should have spectrum sensing capability to detect the three different licensed transmissions: analog television, digital television, and potential licensed low-power auxiliary devices such as wireless microphones. It is worth noting that in February 2011 the Federal Communications Commission (FCC) decided to remove spectrum sensing requirements and use TV white space data bases to identify unused TV channels.
- *MAC layer [352]:* at the MAC layer, a function called Spectrum Manager (SM) is defined. The SM is a cognitive function only available at the BS. It uses the inputs from the spectrum sensing function, geolocation and the incumbent database to determine the TV channel for the WRAN cell and the EIRP limits on the specific WRAN devices. This entity is conceptually located at the MAC sublayer in the BS, and works closely with the data path MAC to communicate with the CPE. The SM interfaces with the physical layer management entity (PLME) to control the local sensing and geo-location functions, and with the station management entity (SME) to access the incumbent database and for any local override. The SM needs to take various steps to declare that a channel may be used for operation.

IEEE 802.22 was published as an official IEEE Standard on July 1, 2011. Various amendments and extensions to the original IEEE 802.22-2011 standard have appeared.

- *IEEE 802.22a:* the IEEE 802.22a amendment, which is expected to be completed in December 2013, defines a new clause for Management and Control Plane Interfaces and Procedures to the existing IEEE 802.22-2011 standard. The Management Information Base (MIB) structure enhancements include changes to comply with the ASN.1 format and support for the new clause. Some modifications to the existing clause on Primitives for Cognitive Radio Capabilities were defined to align it with the content in the MIB clause.
- *IEEE 802.22b:* in March 2012, the IEEE announced the approval of the IEEE 802.22b Amendment Project for Enhanced Broadband Services and Monitoring Applications. This amendment enhances the capabilities of the IEEE 802.22 standard in order to accommodate a wide variety of applications using cognitive radio technology in TVWS. These applications include long range and regional area smart grid, critical infrastructure monitoring, triple play services like providing voice, video and data, backhaul for broadband access, offloading cellular telephony traffic, regional area public safety and homeland security networks, emergency broadband services, monitoring rain forests, monitoring livestock, and border protection, etc.
- *IEEE 802.22.1:* IEEE 802.22.1, published in November 1st 2010, is a standard developed to enhance harmful interference protection for low power licensed devices operating in TV bands. To protect the wireless microphones operating in TV bands, the IEEE 802.22.1 subgroup standardized the use of a beacon signal. WRAN devices must be able to sense the 802.22.1 beacon, which is used to signal and advertise the presence of wireless microphones. The beacon symbol contains information about the location of these microphones, and a signature and certificate to prove that it is legitimate and that protection is needed.
- *IEEE 802.22.2:* IEEE 802.22.2 is a standard for recommended practice for the installation and deployment of IEEE 802.22 systems.

In addition to the definition of the PHY and MAC layers of the system, the IEEE 802.22 standard also includes two security sub-layers that target non-cognitive as well as cognitive functionality of the system and the interactions between the two [412], [413]:

- the security sub-layer 1 provides subscribers with authentication, or confidentiality for user data and MAC management messages transmitted across the broadband wireless network. It does this by applying cryptographic transforms to MAC data units carried across connections between CPE and BS;
- the security sub-layer 2 validates the availability of spectrum for the incumbent and the cognitive users by employing mechanisms such as distributed sensing and decision making. This includes authentication of the incumbent sensing information to avoid Denial of Service (DoS) attacks, authentication of the IEEE 802.22.1 beacon frame utilizing the security features that are already embedded in it, authentication of the geolocation and co-existence information, etc.

The security sub-layers employ an authenticated client/server key management protocol in which the BS operator controls distribution of keying material to client CPE. This material is used to protect MAC management messages, and may be optionally used to protect user data. The basic security mechanisms are strengthened by adding EAP-based CPE device-authentication to the key management protocol. In addition, these security sublayers provide operators with strong protection from theft of service.

6.2.2 IEEE 1900

This series of standards is developed by the IEEE DySPAN-SC, whose scope includes the following:

- dynamic spectrum access radio systems and networks with the focus on improved use of spectrum;
- new techniques and methods of dynamic spectrum access including the management of radio transmission interference;
- coordination of wireless technologies including network management and information sharing amongst networks deploying different wireless technologies.

The IEEE 1900 series concentrates on the development of architectural concepts and specifications for policy-based network management with dynamic spectrum access in a heterogeneous wireless access network composed of incompatible wireless technologies, for example, 3rd/4th Generation (3G/4G), WiFi and WiMAX.

The series is composed of seven standards (IEEE 1900.1 to IEEE 1900.7):

- *IEEE 1900.1: Definitions and Concepts for Dynamic Spectrum Access: Terminology and Concepts for Next Generation Radio Systems and Spectrum Management* (September 2008). This standard provides definitions and explanations of key concepts in the fields of spectrum management, cognitive radio, policy-defined radio, adaptive radio, software-defined radio, and related technologies. The document goes beyond simple, short definitions by providing amplifying text that explains these terms in the context of the technologies that use them. The document also describes how these technologies interrelate and create new capabilities while at the same time providing mechanisms supportive of new spectrum management paradigms such as dynamic spectrum access.

  From February 2011, the Working Group works on a new amendment project IEEE 1900.1a for the "Addition of New Terms and Associated Definitions."
- *IEEE 1900.2: Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence between Radio Systems* (July 2008). This recommended practice provides guidance for the analysis of coexistence and interference between various radio services. In particular, this recommended practice provides technical guidelines for analyzing the potential for coexistence or in contrast interference between radio systems operating in the same frequency band or between different frequency bands.
- *IEEE 1900.3: Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules*. The main purpose of this initiative was to provide recommended practices to help assure compliance with requirements for spectrum use by using formal mathematical concepts and methods. The methods developed by the IEEE 1900.3 Working Group were aimed at providing an initial evaluation to be used before hardware testing and supporting the evaluation being developed in 1900.2. This recommended practice provided guidance for validity analysis of proposed SDR terminal software prior to programming and activation of an SDR terminal or SDR components, and on how to estimate the conformance with relevant specifications of software intended for deployment into a SDR terminal. The recommended practices were developed to support quality control and testing. The goal of this

effort was to assure that SDR software can be deployed with high confidence that it will operate within prescribed regulatory and operational limits. This guideline applies to wireless network operators and terminal equipment manufacturers to help them define test guidelines that conform to SDR technologies, as described in 1900.1, to be licensed by regulatory authorities. IEEE 1900.3 WG was disbanded.

- IEEE 1900.4: *Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks* (February 2009). The purpose of 1900.4 is to address radio resource management, reconfiguration management in composite wireless networks comprising multiple radio access technologies. It addresses the optimization of resources in both fixed and dynamic spectrum access contexts. The 1900.4 standard defines a policy-based management framework for decision making.

  From April 2009, the IEEE 1900.4 Working Group works on two projects: (i) IEEE 1900.4a Amendment for Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands, and (ii) IEEE 1900.4.1 Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks.

- IEEE 1900.5: *Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications* (January 2012). IEEE 1900.5 standard defines a vendor-independent set of policy-based control architectures and corresponding policy language requirements for managing the functionality and behavior of dynamic spectrum access networks. The purpose of this standard is to define policy language and associated architecture requirements for interoperable, vendor-independent control of Dynamic Spectrum Access functionality and behavior in radio systems and wireless networks. This standard will also define the relationship of policy language and architecture to the needs of at least the following constituencies: the regulator, the operator, the user, and the network equipment manufacturer.

  The Working Group is now working in the IEEE 1900.5a amendment defining the interface description between policy architecture components, and the IEEE 1900.5.1 standard, which defines a vendor-independent policy language for managing the functionality and behavior of dynamic spectrum access networks based on the language requirements defined in the IEEE 1900.5 standard.

- IEEE 1900.6: *Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems* (April 2011). The interfaces and data structures required for exchanging sensing-related information in order to increase interoperability between sensors and their clients developed by different manufacturers are defined in this standard. The logical interface and supporting data structures are defined abstractly without constraining the sensing technology, client design, or data link between sensor and client. The entities involved and parameters exchanged in this process. It further elaborates on the service access points, service primitives, as well as generic procedures used to realize this information exchange, are defined by this standard.

  From June 2006, the Working Group works on the IEEE 1900.6a amendment, which defines Procedures, Protocols and Data Archive Enhanced Interfaces. This amendment adds procedures, protocols and message format specifications for the exchange of sensing related data, control data and configuration data between spectrum sensors and their clients. In addition, it adds specifications for the exchange of sensing related and other relevant data and specifies related interfaces between the data archive and other data sources. This amendment provides specifications to allow integrating 1900.6 based distributed sensing systems into existing and future dynamic spectrum access radio communication systems. It enables existing legacy systems to benefit so as to widen the potential adoption of the IEEE 1900.6 interface as an add-on to these systems and to claim standard conformance for an implementation of the interface. In addition it facilitates sharing of spectrum sensing data and other relevant data among 1900.6 based entities and external data archives.

- *IEEE 1900.7: Radio Interface for White Space Dynamic Spectrum Access Radio Systems Supporting Fixed and Mobile Operation*. This standard specifies a radio interface including MAC sublayer(s) and PHY layer(s) of white space dynamic spectrum access radio systems supporting fixed and mobile operation in white space frequency bands, while avoiding causing harmful interference to incumbent users in these frequency bands. The standard provides means to support P1900.4a for white space management and P1900.6 to obtain and exchange sensing related information (spectrum sensing and geolocation information).

In addition to the work by the IEEE DySPAN-SC on the 1900 series, a new Study Group on Dynamic Spectrum Access in Vehicular Environments (DSA-VE) was created within IEEE DySPAN-SC in July 2011 to evaluate the need for DSA standardisation in this area and provide all the information needed to prepare a decision on the creation of a new working group.

6.2.3 Other IEEE standards

Other IEEE standardisation activities have been initiated to address:

- *Coexistence issues among various systems*. Within IEEE, an area known as coexistence, which is indirectly related to cognitive radio, has been considered for many years. Many radios must include an ability to coexist with other radios using different protocols in the same bands. This is particularly true in unlicensed bands where a wide variety of unrelated protocols are applied, including such IEEE standards as IEEE 802.11, IEEE 802.15, and IEEE 802.16. In particular, techniques such as dynamic frequency selection (DFS) and power control (PC) were developed and standardized to deal with coexistence issues. The coexistence techniques developed and being developed for these bands are similar to those for CR.
- *Make amendments to existing standards with the aim of supporting coexistence with license-exempt devices*. After the opening of the TV spectrum for flexible spectrum usage by other systems, various IEEE groups started to make amendments to their established standards for supporting the operation in TVWS.

For instance, several amendments have been made to the PHY and MAC layers of the IEEE 802.11 standard to support channel access and coexistence in TV white spaces. Some examples include the introduction of new functionalities such as sensing of other transmitters (IEEE 802.11af, also known as Wi-Fi 2.0, White-Fi or "Wi-Fi on steroids" [353], [354]), Transmit Power Control (TPC) and DFS (IEEE 802.11h), and some extensions thereof (IEEE 802.11y). Similarly, the IEEE 802.16h amendment develops improved mechanisms to enable coexistence among license-exempt systems based on the IEEE 802.16 standard, and to facilitate the coexistence of such systems with incumbent users [355]. IEEE 802.19 deals with coexistence issues between unlicensed wireless networks, such as IEEE 802.11/15/16/22. The focus of the IEEE 802.19 standard is on the development of technology-independent methods for supporting coexistence among potentially dissimilar networks that will operate in a common TV white space channel.

A detailed description of other IEEE standardisation activities related with CR is provided below:

- ***IEEE 802.11af.*** *TV White Spaces Operation.* This amendment defines modifications to both the 802.11 PHY and the 802.11 MAC Layer, to meet the legal requirements for channel access and coexistence in the TV White Space, including for example spectrum sensing functionalities.
- ***IEEE 802.11h.*** *Spectrum and Transmit Power Management Extensions in the 5 GHz Band in Europe.* This amendment to IEEE 802.11 standard provides mechanisms for DFS and TPC that may be used to satisfy regulatory requirements for operation in the 5 GHz band in Europe. It was originally designed to address European regulations but is now applicable in many other regulatory domains. This amendment solves problems like interference with satellites and radar using the same 5 GHz frequency band. DFS ensures that channels containing radar are avoided by an Access Point (AP) and energy is spread across the band to reduce interference to satellites. TPC ensures that the average power is less than the regulatory maximum to reduce interference to satellites.
- ***IEEE 802.11y.*** *3650-3700 MHz Operation in USA*. This amendment to the 802.11 standard enables high-powered data transfer equipment to operate on a co-primary basis in the 3650–3700 MHz band in the U.S. It standardizes the mechanisms required to allow shared 802.11 operations with other users and includes new mechanisms. In particular, IEEE 802.11y adds three new concepts to the IEEE 802.11 based standard: (i) Contention Based Protocol (CBP) with enhancements to the carrier sensing and energy detection mechanisms of 802.11; (ii) Extended Channel Switch Announcement (ECSA), which provides a mechanism for an access point to notify the stations connected to it of its intention to change channels or to change channel bandwidth; and (iii) Dependent Station Enablement (DSE), a mechanism by which an operator extends and retracts permission to license exempt devices to use licensed radio spectrum. While the scope of 802.11y was limited to operation in the 3650-3700 MHz band in the US, care was taken so that, if the light licensing concept was well received, it would not be necessary to start a task group process in order for 802.11y devices to operate in other countries or in other frequency bands. As a result, lightly licensed 802.11 devices will be able to operate in any 5, 10, or 20 MHz channel that regulators make available by simply adding entries to the country and regulatory information tables in Annex I and J of 802.11.
- ***IEEE 802.15.2.*** *Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Band.* This standard provides recommended practices for coexistence of IEEE 802.15 Wireless Personal Area Networks (WPAN) and IEEE 802.11 Wireless Local Area Networks (WLAN) operating in unlicensed frequency bands. IEEE 802.15.2 defines a coexistence model to quantify the mutual interference of a WLAN and a WPAN as well as a set of Coexistence Mechanisms to facilitate coexistence of WLAN and WPAN devices.
- ***IEEE 802.16a.*** *Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11 GHz.* This amendment to the 802.16 standard expands its scope by extending the Wireless MAN air interface to address operational frequencies from 2-11 GHz. This amendment added DFS and TPC techniques. The standard includes an Annex (B.2) that discusses coexistence in license-exempt bands and provides interference analysis.

- ***IEEE 802.16h.*** *Improved Coexistence Mechanisms for License-Exempt Operation.* This amendment to the 802.16 standard specifies improved mechanisms (as policies and medium access control enhancements) to enable coexistence among license-exempt systems based on IEEE standard 802.16 and to facilitate the coexistence of such systems with incumbent users. Through reducing the potential interference caused by such systems sharing the same frequency bands, it targets improved user service experience and increased robustness and efficiency of the spectrum use. A mechanism called Cognitive Radio Signaling is introduced to help co-channel 802.16 base stations to mitigate interference.
- ***IEEE 802.16m.*** *Air Interface for Fixed and Mobile Broadband Wireless Access Systems.* This amendment to the 802.16 standard provides an advanced air interface for operation in licensed bands, which includes cognitive technology. This amendment meets the cellular layer requirements of IMT-advanced next-generation mobile networks while providing continuing support for legacy WirelessMAN-OFDMA equipment.
- ***IEEE 802.16.2.*** *Recommended Practice for Local and metropolitan area networks - Coexistence of Fixed Broadband Wireless Access Systems.* This was one of the first coexistence standards, which specifies a recommended practice providing guidelines for minimizing interference in BFWA systems. It addresses pertinent coexistence issues and recommends engineering practices, as well as provides guidance for the system design, deployment, coordination, and frequency usage.
- ***IEEE 802.19.*** *Coexistence between wireless standards of unlicensed devices.* Many of the IEEE 802 wireless networks use unlicensed spectrum, which leads to the issue of coexistence of different wireless networks within the the same location. To this end, the IEEE 802.19 Wireless Coexistence Working Group was created in order to deal with coexistence issues between unlicensed wireless networks, such as IEEE 802.11, IEEE 802.15, IEEE 802.16 and IEEE 802.22. The focus of the IEEE 802.19 standard is on the development of technology-independent methods for supporting coexistence among potentially dissimilar networks that will operate in a common spectrum.

6.3 ITU

The work on Cognitive Radio Systems (CRS) is done in several study groups in ITU-R:

- *Study Group 1: Spectrum Management.* Studies on SDR and CRS were initiated at the WRC-07 through Resolution 956 (WRC-07): "Regulatory measures and their relevance to enable the introduction of software-defined radio and cognitive radio systems." The task of conducting the necessary studies was assigned to the Study Group 1 (SG 1), Working Part 1B (WP 1B) "Spectrum management methodologies and economic strategies," which has studied the item.
- *Study Group 5: Terrestrial Services.* The study of various technical aspects was also assigned after WRC-07. Working Party 5A (WP 5A) "Land mobile service above 30 MHz (excluding IMT); wireless access in the fixed service; amateur and amateur-satellite services" developed a new ITU-R report on "Cognitive radio systems in the land mobile service" including descriptions of applications of cognitive radio systems and possible deployment scenarios. The work on CRS in SG 5 is also involving WP 5D "IMT Systems" with work on another ITU-R report on "Cognitive Radio Systems Specific to IMT Systems."

The ITU-R WP1B activity on CRS has developed two documents related to CRS.

1. Definitions of SDR and CRS [357]. Here, under the framework of WRC-12 agenda item 1.19, ITU-R WP1B has developed definitions of SDR and CRS to assist in the conduct of studies, to make clear the distinctions between SDR and CRS technologies, and to provide common understanding and facilitate their use in an unambiguous way in ongoing work by the ITU-R.
2. Draft CPM text on WRC-12 agenda item 1.19 [358]. The following key elements can be identified in the draft.
    a. **CRS deployment scenarios.** Four deployment scenarios identified:
        i. Use of CRS to guide reconfiguration of connections between terminals and multiple radio systems.
        ii. Use of CRS by an operator of a communication system to improve the management of its assigned spectrum resources.
        iii. Use of CRS as an enabler of cooperative spectrum access.
        iv. Use of CRS as an enabler of opportunistic spectrum access.
    b. **CRS challenges and opportunities.** The introduction and operation of stations using CRS technologies in systems of any radiocommunication service should not impose any additional constraints to other services sharing the band.
    c. **CRS capabilities and their applicability to facilitate coexistence in shared bands.** ITU-R identified: i) spectrum sensing; ii) positioning (geo-location); iii) access to information on the spectrum usage, local regulatory requirements, and policies; and iv) capabilities to adjust operational parameters.
    d. **Relationship between SDR and CRS.** SDR is recognized as an enabling technology for CRS. SDR does not require characteristics of CRS for operation. In addition, SDR and CRS are at different phases of development, *i.e.*, SDR have already been utilized and CRS are now being researched.
    e. **Analysis of the results of studies.** Potential benefits of CRS to various radiocommunication services is recognized. Further studies of CRS are needed, especially on dynamic and/or opportunistic spectrum access. The study also concluded that there is no need for modification of Radio Regulations for the introduction of CRS technology.
    f. **Methods to satisfy the agenda item.** Two methods are proposed to satisfy the agenda item: i) no change to the Radio Regulations; and ii) add a WRC Resolution providing guidance for further studies and guidance for the use of CRS and no other changes to the Radio Regulations.

WP5A has developed a report on “Cognitive radio systems in the land mobile service” [359]. This report focuses on technical aspects of CRS. The following key elements can be identified in the report:

1. **Technical Characteristics and Capabilities.** The following key capabilities of the CRS are underlined in its definition.
    a. **Capability to obtain knowledge.** The following key components are included:
        i. CRS operational radio environment: current status of spectrum usage, indication of available radio systems and their assigned frequency bands, coverage areas of these radio systems and interference levels.

ii. CRS operational geographical environment: positions of radios which are components of CRS and other radio systems, orientation of antennas of radios of CRS and other radio systems, distribution of users in the geographic area of CRS.

iii. Internal state of CRS: configuration of CRS (e.g., frequency bands and protocols used by its radios), traffic load distribution, transmission power values.

iv. Established policies: frequency bands allowed to be used by CRS under certain conditions, rules that CRS shall follow to avoid causing harmful interference.

v. Usage patterns: collect behavior of CRS, other radio systems and users.

vi. Users' needs: user preferences or policies. Examples of user preferences are request for high bandwidth, low delay, fast download time, and low cost.

In order to obtain knowledge, CRS can use various approaches, including: Collection information form component radio systems, geo-location, spectrum sensing, white space data base access, access to Cognitive Pilot Channel.

b. **Capability to adjust operational parameters and protocols.** Such adjustment consists of two stages: making decision and reconfiguration.

c. **Capability to learn.** Learn from the results of its actions in order to further improve its performance.

2. **Operational techniques.** Many technologies have contributed to the CRS concept. Among them are the following key technologies.

    a. **Distributed decision making.** Refers to the architecture of the management system inside the CRS responsible for making decisions on which parameters and protocols need to be adjusted, when, and how. Such management system will also control the process of obtaining knowledge.

    b. **Cognitive Pilot Channel.** Already described in the ETSI description.

    c. **White space access.** Refers to the spectrum usage scenario where the radio regulations allows the CRS to access temporary unused spectrum in the frequency bands allocated to another radio system.

    d. **White space data base access and spectrum sensing.** White space database is the database that contains information on incumbent systems operation in a particular frequency band or channels in particular locations.

    e. **Software Defined Radio**

WP5D has developed a report on "Cognitive radio systems specific for International Mobile Telecommunication Systems" [360]. This report focuses on technical aspects of CRS. The following key elements can be identified in the report:

1. **Scenarios of cognitive radio systems specific for IMT systems.** Possible scenarios of application include:

    a. Update of a network for optimized radio resource usage.

  b. Upgrade of an existing radio interface or a network with a new radio interface.
  c. In-band coverage/capacity improvement by relays.
  d. Self-configuration and self-optimization of femtocells.
  e. Multi-modes coexistence and simultaneous transmission.
2. **Determination of the IMT spectrum usage,** including considerations on:
  a. Measurement collection system for determination of spectrum state.
  b. Additional methods for determination of spectrum state.
  c. Spectrum quality evaluation.
  d. Spectrum balancing.
3. **Impacts of cognitive radio systems specific for IMT systems,** taking into account:
  a. CRS approaches applicable to IMT.
  b. Cognitive networks for IMT systems.
  c. Additional aspects and technical challenges of CRS technology in IMT networks.
  d. Spectrum refarming in IMT networks.
  e. Intra-operator based radio resource optimization.
4. **Performance of IMT systems with CRS capability,** considering:
  a. Potential benefits of using CRS technology in IMT systems:
    i. Overall spectrum efficiency and capacity improvement.
    ii. Radio resources utilization flexibility.
    iii. Interference mitigation.
  b. Potential implications of using CRS technology in IMT systems:
    i. Signalling overhead in CRS.
    ii. Increase of the system complexity.
    iii. Increase of the control/user plane latency.
  c. **Key performance indicators for CRS technology in IMT systems.**

As the most relevant outcome of the ITU R studies regarding cognitive radio, the WRC-12 agreed on a Resolution for the deployment and use of stations used for DSA including those implementing CRS [405]. The WRC-12 considered that a cognitive radio system is defined as a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained (Report ITU-R SM.2152). It further resolved:

- that any radio station used for dynamic spectrum access including those implementing CRS within any radiocommunication service shall operate in accordance with the provisions of the Radio Regulations applicable for that specific service in the related frequency band;

- to urge administrations when authorizing operation of stations used for dynamic spectrum access including those implementing CRS within a service, to take measures to avoid harmful interference in bands shared with radiocommunication services with equal or higher status, such as space services (space-to-Earth), radiodetermination service, passive services (radio astronomy, Earth exploration-satellite service and space research service) and safety services;
- that the use of stations for dynamic spectrum access including those implementing CRS shall be avoided in the bands included in the frequency allotment plans [such as Appendices 17, 18, 25, 26, and 27].

6.4 ETSI

The ETSI organization is divided into four workgroups. Each workgroup has a dedicated task to study different aspects of a CRS. These are: General System Overview, Enabling Technologies to support a CRS (Functional Architecture (FA) together with a Cognitive Pilot Channel (CPC)), Software Defined Radio (which is the software that implements and enables the CRS technologies), and Security. The main focus of our are the results of WG2.
The CPC is a channel between the network operator and the terminal that conveys the necessary information to a mobile device (MD) for enabling its cognitive radio features.
The FA activity is about designing a platform architecture for future MD that enable the CR principle. It defines what kind of function blocks a MD needs in order to have CR capabilities.

ETSI Board created a Technical Committee for Reconfigurable Radio Systems (RRS) in January 2008. The main purpose of this Technical Committee was to study the feasibility and take the responsibility of standardisation activities related to RRS including SDR and CR. To this end the ETSI RRS TC collects and defines the related RSS requirements from relevant stakeholders; and it also identifies gaps, where existing ETSI standards do not fulfill the requirements, and suggests further standardisation activities to fill those gaps.

The RSS Technical Committee is structured into four Working Groups:

- *WG1 focuses on "System Aspects"* and develops proposals from a system aspects point of view for a common framework in TC RRS with the aims to guarantee coherence among the different TC RRS WGs and to avoid overlapping and gaps between related activities. WG1 has conducted feasibility studies on CRS concept and potential regulatory aspects of CRS and SDR.
- *WG2 focuses on "Radio Equipment Architecture"* and proposes common reference architectures for SDR/CR radio equipment (mobile handset devices, radio base stations, etc.), related interfaces, etc. The base stations related work is currently in an early stage, whereas the current work focus in mobile devices mainly on SDR related interface standardisation between distinct stakeholder domains, such as SDR chipset vendors and mobile devices manufacturers. In the context of this SDR mobile devices framework, a reference architecture has been derived which outlines the relevant interfaces and concerned building blocks. However, this envisaged architecture is not meant to be normative.
- *WG3 focuses on "Cognitive Management and Control."* The group collects and defines the system functionalities for Reconfigurable Radio Systems that are related to the Spectrum Management and Joint Radio Resource Management across heterogeneous access technologies. Furthermore, the group has developed a Functional Architecture for the Management and Control for Reconfigurable Radio Systems as well as a report on the Cognitive Pilot Channel (CPC) as an enabler to support the management of the RRS.

- *WG4 focuses on "Public Safety"* and collects and defines the related RRS requirements from relevant stakeholders in the Public Safety and Defense domain. The group defines the system aspects for the applications of RRS in Public Safety and Defense.

In October 2009, ETSI's RRS Technical Committee released a series of Technical Reports [361], [362], [363], [364] that examine the standardisation needs and opportunities. The reports summarize the feasibility studies carried out by the committee and present the recommended topics for standardisation. Following the completion of the feasibility studies, RRS has standardized a Functional Architecture for Reconfigurable Radio Systems [365], and some of its elements such as the CPC [366] (see D2.6 [442] for more details on the CPC concept), mostly bearing in mind TV whitespace scenarios [367], [368], [369].

6.4.1 Standardisation Activities related to CoRaSat Scenario F

In 2010 three ETSI Standards have been developed and approved. The three standards are part of a multi-part deliverable covering the Harmonised Standard for satellite Earth stations for MSS operating in the 1980 MHz (Earth to space) and 2170 MHz (space to Earth) frequency bands.

1. EN 302 574-1: Complementary Ground Component (CGC) for wideband systems
2. EN 302 574-2: User Equipment for wideband systems
3. EN 302 574-3: User Equipment for narrowband systems

Although these standards do not address CR per se, they are outlined here for the sake of completeness.

6.4.1.1 EN 302 574-1: CGC for wideband systems

The standard applies to CGC radio equipment type deployed in Mobile Satellite Services systems with the following characteristics:

- the CGCs may have both transmit and receive capabilities and are part of a hybrid Satellite /terrestrial network;
- the CGCs operate with an assigned channel signal bandwidth (CBw) of 1 MHz or greater;
- the CGC may be local coverage, medium coverage or wide coverage ground components;
- the CGCs may be an element in a multi-mode base station. It may consist of a number of modules with associated connections, or may be a self-contained single unit.

Within the technical requirement specifications, the parameters covered include: i) a spectrum emission mask; ii) adjacent channel leakage power ratio; iii) transmitter spurious emissions; iv) CGC maximum output power; v) transmit inter modulation; vi) receiver spurious emissions; vii) blocking characteristics; viii) receiver inter-modulation characteristics; and ix) receiver adjacent selectivity.

6.4.1.2 EN 302 574-2: User Equipment for wideband systems

The standard applies to User Equipment (UE) radio equipment type, with the following characteristics:

- UE have transmit and receive capabilities and operate in a hybrid Satellite/terrestrial network;
- the satellite component is based on GSO;
- the UE operates with an assigned channel signal bandwidth of 1 MHz or greater;

- the UE may be handset, handheld, portable, vehicle mounted, host connected, semi-fixed or fixed equipment, or may be an element in a multi-mode terminal. It may consist of a number of modules with associated connections and user inter-face, or may be a self-contained single unit

Within the technical requirement specifications, the parameters covered include: i) control and monitoring functions; ii) maximum output power; iii) spectrum emissions mask; iv) transmitter spurious emissions; v) maximum output power; vi) adjacent channel leakage power ratio; vii) out of synchronization handling of output power; viii) receiver adjacent channel selectivity; ix) blocking characteristics; x) receiver spurious response; xi) receiver intermodulation characteristics; and xii) receiver spurious emissions.

6.4.1.3 EN 302 574-3: User Equipment for narrowband systems

The standard applies to User Equipment (UE) with the following characteristics:

- UE with both transmit and receive capabilities and operate in a Geostationary satellite network;
- UE operating with an assigned channel signal bandwidth (CBw) small than 1MHz;
- UE may be handset, handheld, portable, vehicle mounted, host connected, semi-fixed or fixed equipment, or may be an element in a multi-mode terminal. It may consist of a number of modules with associated connections and user interface, or may be a self-contained single unit.

Within the technical requirement specifications, the parameters covered include: i) unwanted emission outside the band 1980 MHz to 2100 MHz; ii) unwanted emissions within this band; iii) unwanted emissions in carrier-off state; iv) UE control and monitoring functions; and v) loss of signal handling of output power.

6.5 3GPP

3GPP (3rd Generation Partnership Project) is a union of 6 standard development organizations in telecommunications. The Four Technical Specification Groups (TSG) in 3GPP are Radio Access Networks (RAN), Service & Systems Aspects (SA), Core Network & Terminals (CT) and GSM EDGE Radio Access Networks (GERAN).

Each of the four TSGs has a set of Working Groups, which meet regularly four to six times a year. Each TSG has its own quarterly Plenary meeting where the work from its WGs is presented for information, discussion and approval. Each TSG has a particular area of responsibility for the Reports and Specifications within its own Terms of Reference (Details available in the Specification Groups pages).

Physical layer research is performed within the TSGs GERAN and RAN group. The RAN group performs Phy layer research through its WG1. The latest release by the RAN WG1 is about Universal Mobile Telecommunications System (UMTS). The techniques investigated here are about Multiple Access (where DS-CDMA is used), Channel Coding and Interleaving, Modulation and Spreading, Physical Layer Procedures (power control, cell search, etc.), Physical Layer Measurements and Relationship of the physical layer functions. Hence, this is not directly about Cognitive Radio, but rather classical terrestrial communication systems.

Several technical studies are being carried out at the moment on how CR principles and techniques can be introduced into 3GPP mobile communication systems (i.e., mainly LTE). However, no standardized solutions are available to date. Nevertheless, 3GPP LTE standards already include some CR-like capabilities that are worth mentioning, in particular, the Access Network Discovery and Selection Function (ANDSF) [370],[371],[372]. The scope of the ANDSF as defined in 3GPP is to support multi-access network scenarios with intersystem-mobility between 3GPP-networks (such as GSM, EDGE, UMTS, HSPA or LTE) and non-3GPP networks (*e.g.*, WiMAX or WLAN). The ANDSF is an entity within an Evolved Packet Core (EPC) of the System Architecture Evolution (SAE) for 3GPP compliant mobile networks. The purpose of the ANDSF is to provide CR capabilities by assisting the User Equipment (UE) to discover non-3GPP access networks that can be used for data communications in addition to 3GPP access networks, performing inter-system handovers, and providing the UE with rules policing the connection to these networks.

6.6 Wireless Innovation Forum

The Wireless Innovation Forum (WINNF) is a non-profit "mutual benefit corporation" dedicated driving technology innovation in commercial, civil, and defense communications around the world. Forum members bring experience in Software Defined Radio, Cognitive Radio and Dynamic Spectrum Access, technologies in diverse markets and at all levels of the wireless value chain to address emerging wireless communications requirements. The Forum acts as a venue for its members to collaborate to achieve these objectives.

The Wireless Innovation Forum was founded in 1996 originally as "The Modular Multifunction Information Transfer System Forum," renamed in 1998 to "The Software Defined Radio Forum," and renamed in 2009 to "The Wireless Innovation Forum" reflecting the fact that many of the projects undertaken by its members had moved beyond SDR to include Cognitive Radio, Systems of Systems, Ad-Hoc Networks, and Dynamic Spectrum Access Technologies.

The documents produced under the framework of the Wireless Innovation Forum can be classified into 3 different types:

- *Recommendations:* Documents provided by the Forum to other organizations, such as the ITU, FCC or the JPEO, to provide guidelines or opinions.
- *Reports:* Used by the Forum to formally present the current state of some relevant topic with the Software Defined Radio community (regulations, markets, business, etc.).
- *Specifications:* Documents designed to provide a WINNF-supported definition of a specific architectural element or interface within a software defined radio system.

The following documents produced by the Wireless Innovation Forum are worth mentioning:

- *Recommendation SDRF-06-R-0011, "SDRF Cognitive Radio Definitions," November 2007.* This document is intended to communicate a set of definitions in the area of Software Defined Radio and Cognitive Radio. These definitions are developed to communicate to practitioners in the field the approach of the Forum to these technologies.
- *Report SDRF-06-P-0009, "Cognitive Radio Definitions and Nomenclature," September 2008.* This document identifies many different aspects of cognitive radio and places them into a coherent framework. The purpose of this document is to identify components and collect working definitions for many of the technologies and techniques related to cognitive radios as

they are used within the Wireless Innovation Forum's Cognitive Radio Working Group and across the wireless marketplace.

- *Recommendation WINNF-11-R-0001, "Comments of the Wireless Innovation Forum to the FCC," February 2011.* This document is a response to a Notice of Inquiry (NOI) from the FCC[21] seeking comment on a variety of ways in which DSA radios and techniques can promote more intensive and efficient use of the radio spectrum [395]. The document discusses the benefits of DSA and CR technologies, the potential of cognitive market mechanisms together with DSA to increase efficiency, access and value, the application of DSA/CR techniques in public safety as well as several aspects of policy radios, security and testbeds.
- *Report SDRF-07-P-0019, "Use Cases for Cognitive Applications in Public Safety Communications Systems - Volume 1: Review of the 7 July Bombing of the London Underground," November 2007.* This report is the first in a planned series of reports to develop concepts for the application of cognitive radio technology to enhance the communications capabilities of public safety first responders. The methodology for developing cognitive use cases is based on an analysis of response to actual or hypothesized events. This report is an analysis of the events of July 7, 2005, a terrorist attack involving coordinated explosions of bombs in and around the London Underground. This analysis is not an evaluation of that response, but instead uses the lessons learned from real events and the observed response to envision how evolving cognitive technology could enhance the ability of responders in the future to communicate more effectively and efficiently than available technology allowed. Based on the analysis, the report concludes that development of cognitive capabilities has potential to dramatically increase the ability of incident commanders. Four examples of how cognitive radio technology could be utilized in such situations (defined as cognitive use cases) are identified and described in this report: i) Network extension for coverage and reachback; ii) Dynamic access of spectrum; iii) Dynamic prioritization; and iv) Dynamic network configuration to include non-first responders. The cognitive radio functional capabilities, regulatory implications, and policy and procedure implications for each use case are analyzed as well.
- *Report WINNF-09-P-0015, "Use Cases for Cognitive Applications in Public Safety Communications Systems Volume 2," January 2010.* This report is the second in a series of reports to develop concepts for the application of cognitive radio technology to enhance the communications capabilities of public safety first responders, highlighting how such capabilities, residing in radios or implemented in a network, can improve the communications of public safety first responders. This report outlines a hypothetical scenario of a major explosion at a chemical plant in a mid-sized metropolitan area. The scenario was developed with input from public safety practitioners, communications system engineers, and radio developers. It provides the basis (events, activities, and timelines) required in analyzing the impact of cognitive-based radio and network functions on first responder communications and mission effectiveness. Based on the analysis, the report concludes that the utilization of cognitive radio functions can dramatically increase the ability of Incident Commanders to meet their mission objectives. The report provides eight examples (defined as use cases) of how cognitive radio or network technology could be utilized, and explains in detail the

[21] Note that, in response to this FCC NOI, the the Satellite Industry Association (SIA) opposed the use of DSA techniques by terrestrial services in satellite bands [414],[415].

technical, regulatory, and operational procedure developments required to make these capabilities available for public safety use.

- *Report WINNF-09-P-0012, "Quantifying the Benefits of Cognitive Radio," December 2010.* This document reports the results of an extensive survey performed by the Cognitive Radio Work Group (CRWG) of the Forum on open and public CR literature. The intent was to document the "hard numbers" that researchers and developers had reported to date so researchers and developers can better assess the value proposition of CR. The document also reviews how CR could help address the needs of commercial, public safety, and military users.
- *Report WINNF-12-P-0003, "TD-LTE in White Space," June 2012.* This document reports the results of an extensive research project performed by the members of the Wireless Innovation Forum on exploiting the use of White Space spectrum for deploying TD-LTE on a no-interference-no-protection basis. The intent of this report is to document the impact of introducing TD-LTE to neighbouring systems, the corresponding interference mitigation methodologies and also business possibilities.
- *Specification WINNF-10-S-0007, "Description of the Cognitive Radio Ontology," September 2010.* The Cognitive Radio Ontology is an important part of the Modelling Language for Mobility (MLM) project undertaken by the MLM Working Group of Wireless Innovation Forum. The MLM project focuses on the signaling between advanced radio systems to support next generation features of vertical and horizontal mobility, spectrum awareness, dynamic spectrum adaption, waveform optimization, capabilities and feature exchanges. This document presents the Cognitive Radio Ontology.

6.7 ECMA

ECMA International is an industry association founded in 1961 and dedicated to the standardisation of Information and Communication Technology (ICT) and Consumer Electronics (CE). In December 2009, ECMA released ECMA-392, the first DSA/CR standard for personal/portable devices operating in TV white space [373], [374]. The standard specifies the PHY and MAC layers of a DSA/CR system with flexible network formation, mechanisms for protection of incumbent users, adaptation to different regulatory requirements and support for real-time multimedia traffic. In addition to PHY and MAC layers, ECMA-392 also includes specifications for MUX sub-layer for higher layer protocols. Optional security protection is also included in the specifications. The ECMA-392 standard is envisaged to enable new applications such as in-home high-definition video streaming and interactive TV broadcasting services.

6.8 IETF

In 2011, and after the decision of the Federal Communications Commission (FCC) to remove spectrum sensing requirements and use TV white space data bases to identify unused TV channels instead, the Internet Engineering Task Force (IETF) joined the standardisation efforts on DSA/CR by creating a Working Group to develop a Protocol to Access White Space (PAWS) databases.

The objecives of this WG are:

- standardize a mechanism for discovering a white space database;
- standardize a mechanism for accessing a white space database;
- standardize query and response formats to be carried over the database access method;

- ensure that the discovery mechanism, database access method and query response formats have appropriate security levels in place.

The first draft of the PAWS protocol was released in 2011 [375], [376], and latest additions have been included in late 2012 and early 2013 [377], [378].

6.9 DARPA

In 2005, Shared Spectrum Company was awarded the prime contract for Phase III of the neXt Generation Communications (XG) program funded by the Department of Defense's (DoD) Defense Advanced Research Projects Agency (DARPA) and managed by the Air Force Research Laboratory (AFRL). The XG Program is developing technology and system concepts for military radios to dynamically access spectrum in order to establish and maintain communications. The goal is to demonstrate the ability to access 10 times more spectrum with near-zero setup time; simplify RF spectrum planning, management and coordination; and automatically de-conflict operational spectrum usage. XG technology assesses the spectrum environment and dynamically uses spectrum across frequency, space and time. XG is designed to be successful in the face of jammers and without harmful interference to commercial, public service, and military communications systems. XG is transitioning to the Army to solve spectrum challenges in-theater.

7 CONCLUSIONS

7.1 Conclusions on Technology Framework

Based on the findings of Chapter 4 and further details in D2.6 **[442]**, this section presents a summary of the considered techniques per scenario. Subsequently, it comments on the satellite-specific impairments and interference types which may affect each scenario. Finally, conclusive remarks are noted in order to provide technological guidelines for future tasks.

The following table is a summary of the identified technologies and priorities to be reviewed for the different scenarios considered. This is the result of qualitative evaluation of available techniques based on abstract system models defined by the considered scenarios. The quantitative analysis will be conducted as part of WP3.

Table 30 - Summary of CR Techniques Gap Analysis

CoRaSat Scenario	Category of CR Technique	CR Technique	PROs	CONs
A	*Underlay*	• Beamforming • Exclusion Zone	• Efficient, easy adaptation • Simpler deployment	• Complexity • Adaptation protocols needed
	Interweave	• Angular domain • Polarization domain	• Information in databases	• Advanced front-end, protocols • Database security and integrity
	Overlay	• -	• -	• Large delay, difficult to recover incumbent messages
B	*Underlay*	• Beamforming • Exclusion Zone	• Efficient, easy adaptation • Simpler deployment	• Complexity • Adaptation protocols needed
	Interweave	• Database/sensing combination	• Easy adaptation, information in databases	• Advanced front-end, sensing protocols, complexity • Database security and integrity
	Overlay	• -	• -	• Large delay, difficult to get incumbent messages
C	*Underlay*	• Beamforming • Exclusion Zone	• Efficient, easy adaptation • Simpler deployment	• Complexity • Adaptation protocols needed

	Interweave	• Database/sensing combination	• Easy adaptation, information in databases	• Advanced front-end, sensing protocols, complexity • Database security and integrity
	Overlay	• -	• No delays	• Dedicated antenna to get incumbent messages
D	*Underlay*	• Beamforming (FL) • Exclusion Zone (FL) • Interference Alignment (RL) • Precoding (RL)	• Efficient, easy adaptation • Simpler deployment Testo	• Complexity • Adaptation protocols needed
	Interweave	• Blind wideband sensing	• Efficient, not depending on a priori information	• Complexity
	Overlay	• Terminal-centric • Gateway-centric	• No overhead • Network-wide knowledge	• More than 2 RX, limited knowledge • Overhead, delay
E	*Underlay*	• Beamforming at the cognitive receiver	• Efficient, easy adaptation • Simple deployment	• Complexity
	Interweave	• Database/sensing combination	• Easy adaptation • Information in databases	• Advanced front-end, protocols, complexity • Database security and integrity
	Overlay	• -	• -	• Relay not practical • Complexity
F	*Underlay*	• Beamforming • Exclusion Zone	• Efficient, easy adaptation • Simpler deployment	• Complexity • Adaptation protocols needed
	Interweave	• Database/sensing combination	• Easy adaptation, information in databases	• Advanced front-end, protocols, complexity • Database security and integrity
	Overlay	• Terminal-centric • Gateway-centric	• No overhead • Network-wide knowledge	• More than 2 RX, limited knowledge

				• Overhead, delay
G	*Underlay*	• Beamforming • Exclusion Zone	• Efficient, easy adaptation • Simpler deployment	• Complexity • Adaptation protocols needed
	Interweave	• Database/sensing combination	• Easy adaptation, information in databases	• Advanced front-end, sensing protocols, complexity • Database security and integrity
	Overlay	• -	• -	• Large delay, difficult to get incumbent messages

Table 32 below highlights satellite-system impairments which may jeopardise the application of cognitive radio techniques to the considered scenarios. Table 33 below summarizes the interference types identified for each scenario. It should be noted that this is a preliminary study and the detailed impact of these impairments will be evaluated in the context of WP3.

Table 31 - Satellite Scenario Impairments

Scenario	Impairment	Possible Effect
A	• propagation models (line of sight, directivity, polarization, correlated areas) • round-trip delay • feeder link characteristics	• increased interference in low elevation angles • high switch-off delay • increased interference due to high power transmission
B	• wide beam coverage • system architecture • propagation models (line of sight, directivity, polarization, correlated areas) • round-trip delay • power imbalance between satellite terrestrial signal levels	• downlink interference affects a large geographical area • increased interference in low elevation angles • high switch-off delay • increased interference near incumbent
C	• wide beam coverage • system architecture • propagation models (line of sight, directivity, polarization, correlated areas)	• aggregated interference from multiple incumbent • increased interference in low elevation angles • increased interference due to high power transmission
D	• system architecture • propagation models (line of sight, directivity,	• real time information needed • depolarization increases interference

	polarization, correlated areas) • round-trip delay, • wide beam coverage • gateway characteristics	• high switch-off delay • downlink interference affects a large geographical area • increased complexity
E	• propagation models (line of sight, directivity, polarization, correlated areas) • power imbalance between satellite terrestrial signal levels	• increased interference in low elevation angles • increased interference from terrestrial
F	• system architecture • propagation models (line of sight, directivity, polarization, correlated areas) • round-trip delay • receiver characteristics (non linearity, dynamic, sensitivity, antenna directivity, etc.)	• complexity due to coordination in hybrid systems • increased interference due to low frequency • high switch-off delay • complexity for dual reception in hybrid systems
G	• wide beam coverage • system architecture • propagation models (line of sight, directivity, polarization, correlated areas, NGSO satellite mobility) • round-trip delay (DL) • power imbalance between satellite terrestrial signal levels (DL)	• downlink interference affects a large geographical area (DL) • high switch-off delay (DL) • increased interference near incumbent (DL) • aggregated interference from multiple incumbent (UL) • increased interference due to high power transmission (UL) • increased interference in low elevation angles • time variant interference

Table 32 - Satellite Scenario Interference Types

Scenario	Interference Type
A	GSO BSS feeder link ground station →GSO FSS
B	FS →GSO FSS
C	GSO FSS uplink → FS
D	Among GSO FSS terminals
E	Terrestrial Gateway I → Satellite Ground station C (strong interference) Satellite C → Terrestrial Gateway I (weak interference)
F	Among terminals
G	FS → NGSO FSS (DL) NGSO FSS uplink → FS (UL)

Based on the above observations from technological viewpoint, it can be concluded that all three CR technique groups are potentially applicable to scenarios C, D, F and G. Scenarios A and B are not supportable with overlay as it is not feasible. For Scenario E overlay concepts may not be applicable as relay is unlikely to function correctly.

Regarding the considered scenarios, interference types and satellite-specific impairments were identified for each case. It can be concluded that there is a number of challenges that have to be addressed in order to apply the techniques developed in terrestrial context for satellite scenarios. According to this qualitative analysis, the importance of each challenge is determined based on the considered scenario (frequency range/system architecture), the transmission direction (uplink/downlink) and the type of interference. These challenges are going to be taken into account in Task 2.4 which will determine the selected scenarios based on business, regulatory and technological criteria. For the selected scenarios, the effect of these challenges will be quantified in Task 3.2 "Technology Analysis and Mapping", whereas new designs or adjustments will be proposed in Task 3.3 "Technology Adaptation and Design".

7.2 Conclusions on Regulatory Framework

Based on the findings of Chapters 5 and [441], here below is a summary of the regulatory analysis conducted for each identified CoRaSat scenario.

Table 33 - Summary of Regulatory Analysis for CoRaSat Scenarios

Scenario	Context	Sharing Type	CR Regulatory Barriers	Potential CR Regulatory Benefits	Impact to Current Regulatory Framework
A	Ka-band 17.3-17.7 GHz GSO DL	Inter-system • BSS GSO Feeder Links (Incumbent) vs. GSO FSS (Cognitive)	• Database Security (Confidentiality, Integrity, Availability) • Certification Equipment • Spectrum Trading • Less mature regulatory framework in developing countries. • Deployment data accuracy and availability	• CR improve sharing of frequencies between FSS and BSS feeder links	• Reasonable modifications to current regulatory framework required

B	Ka-band 17.7-19.7 GHz GSO DL	Inter-system • FS (Incumbent) vs. GSO FSS (Cognitive)	• Database Security (Confidentiality, Integrity, Availability) • Certification Equipment • Spectrum Trading • Less mature regulatory framework in developing countries. • FS deployment data accuracy and availability • Growing number of FS links • Increased FS lobbying	• CR could allow deployment of FSS terminals in frequency bands usually used for gateways	• Reasonable modifications to current regulatory framework required • EU regulation encourages implementati on of mitigation techniques for either FS or FSS systems
C	Ka-band 27.5-29.5 GHz GSO UL	Inter-system • FS (Incumbent) vs. GSO FSS (Cognitive)	• Database Security (Confidentiality, Integrity, Availability) • Certification Equipment • Spectrum Trading • International Aspects (developed vs. developing countries) • FS deployment data accuracy and availability • Current EU or National regulation forbids FSS operations of uncoordinated terminals in large parts of the band	• CR could permit FSS to use the FS spectrum without interference to FS systems	• Significant modifications to current regulatory framework required for large parts of the band

D	Ku-band 10.7-12.75 GHz (DL) 12.75-13.25 GHz (UL), 13.75-14.5 GHz (UL) GSO	Inter-system • Dual Satellite (GSO FSS/BSS vs. GSO FSS/BSS) • FS (Incumbent) vs. GSO FSS (Cognitive)	• Database Security (Confidentiality, Integrity, Availability) • Certification Equipment • Spectrum Trading • Less mature regulatory framework in developing countries. • FS deployment data accuracy and availability • Current EU or National regulations forbids FSS operations of uncoordinated terminals in large parts of the uplink band	• CR not anticipated to bring any added value in dual-satellite GSO FSS scenario, neither in DL nor in UL cases. • CR could permit GSO FSS to better use the spectrum where massive FS deployment exists under specific conditions in UL scenario	• Reasonable modifications to current regulatory framework required in DL bands • Significant modifications required in most of the UL bands

E	C-band 3.4-3.8 GHz (DL) GSO	Inter-system • FS (Incumbent) vs. GSO FSS (Cognitive)	• Database Security (Confidentiality, Integrity, Availability) • Certification Equipment • Spectrum Trading • Less mature regulatory framework in developing countries. • Significant interference issues due to FS proliferation • Large separation distances between FS and FSS stations, which would highly increase OPEX for both FS and FSS operators • Potential massive deployment of MS rendering database CR more difficult, due to mobility issues and data accuracy	• No or limited CR benefits anticipated • Compared to existing interference mitigation approaches, CR not expected to provide additional benefits for FSS	• Significant modifications to current regulatory framework required to be able to use CR (especially, at international level)
F	S-band 1980-2010 MHz (UL) 2170-2200 MHz (DL) GSO	Intra-system • Hybrid Satellite/Terrestrial • Incumbent: Satellite with integrated CGC	• No regulatory barriers foreseen for this intra-system sharing scenario. • Existing solutions already identified / available / ongoing.	• CR anticipated to increase system throughput, considering optimized intra-system terrestrial and satellite propagation conditions	• Minor to no modifications to current regulatory framework required

G	Ka-band 17.8-19.7 GHz (DL) 27.8285-28.4445 GHz (UL), and 28.9485-29.4525 GHz (UL) NGSO	Inter-system • FS (Incumbent) vs. NGSO FSS (Cognitive)	• Database Security (Confidentiality, Integrity, Availability) • Certification Equipment • Spectrum Trading • Less mature regulatory framework in developing countries. • FS deployment data accuracy and availability • Current EU or National regulation forbids FSS operations of uncoordinated terminals in large parts of the uplink band	• CR could optimize the FS vs. NGSO FSS frequency usage in DL scenario where FSS is unprotected (17.7-19.7 GHz)	• Reasonable modifications to current regulatory framework required in DL bands • Significant modifications required for most of the UL bands • EU regulation encourages implementati on of mitigation techniques for either FS or FSS systems

Based on the regulatory analysis conducted in the previous chapters on the potential of CR applicability to SatCom, the summary of findings for each frequency band of interest is as follows:

- <u>Summary of findings on Ka-Band</u>

  For the different scenarios considered (A, B, C, and G), Cognitive Radio has a good potential to improve sharing between the incumbent systems and cognitive satellite systems, particularly in the sharing scenarios between FS (Incumbent) vs. FSS (Cognitive). Reasonable modifications to the current regulatory framework are expected to be needed for scenarios A, B, and G for the downlink frequency band while significant modifications may be needed for scenario C and for scenario G for the uplink frequency bands.

- <u>Summary of findings on Ku-Band</u>

  For the different cases considered in scenario D, sharing may be improved by the use of Cognitive Radio for only one of them, in the uplink direction of sharing between FS (Incumbent) vs. GSO FSS (Cognitive). Reasonable modifications to the current regulatory framework are expected to be needed for the downlink frequency bands while significant modifications may be needed for the uplink frequency bands.

- <u>Summary of findings on C-Band</u>

It is not expected that Cognitive Radio will improve sharing for scenario E. Significant modifications to the current regulatory framework are expected to be needed in order to benefit from Cognitive Radio techniques, in particular at international level.

- Summary of findings on S-Band

  It is expected that Cognitive Radio will improve sharing for scenario F. In addition, minor or no modifications to the current regulatory framework are expected to be needed.

To this end, consolidating the overall results, the following scenarios present higher attractiveness from the regulatory point of view to improve sharing conditions:

- Ka-band:
  - Scenario A: GSO BSS Feeder Links (Incumbent) vs. GSO FSS (Cognitive) Sharing, 17.3-17.7 GHz, DL;
  - Scenario B: FS (Incumbent) vs. GSO FSS (Cognitive) Sharing, 17.7-19.7 GHz, DL;
  - Scenario G: FS (Incumbent) vs. NGSO FSS (Cognitive) Sharing, 17.7-19.7 GHz, DL.
- S-band:
  - Scenario F: Intra-System Sharing (Hybrid Satellite/Terrestrial), 1980-2010 MHz (UL) and 2170-2200 MHz (DL).

7.3 Conclusions on Standardisation Framework

Despite the number of initiatives and activities carried out so far, standardisation of Cognitive Radio systems constitutes an exciting challenge still requiring more effort. Cognitive Radio standardisation activities so far have been focusing on terrestrial communications. They have been carried out so far in a rather uncoordinated manner by a wide variety of organizations (IEEE, ITU, ETSI, 3GPP, Wireless Innovation Forum, ECMA, IETF, DARPA) working independently on different heterogeneous standards and initiatives. This drawback has already been identified by the CRS-i (Cognitive Radio Standardisation-initiative) FP7 Coordination Action (see deliverable D2.2 [441] and project website [295]), which is aimed at facilitating and easing cooperation and coordination of standardisation activities between current as well as future FP7 European projects on Cognitive Radio systems and ICT standards organizations. However, some kind of coordination among standardisation organizations is still required in order to join efforts and prevent standardisation organizations from working independently on standards with the same scope.

In addition to that, different countries have different spectrum regulations. While this appears to be reasonable as a result of different social and economic environments, this situation complicates the standardisation of Cognitive Radio systems and the development of worldwide standards. Moreover, most of the existing standards related to the Cognitive Radio technologies have been specifically devised and elaborated for (or bearing in mind) terrestrial systems (in particular, the exploitation of TV White Spaces), with little or no consideration of SatCom scenarios. This situation claims for a revision of the existing Cognitive Radio standards and/or the development of new standards particularly for those scenarios where Cognitive Radio over SatCom could bring-in potential benefits and improve the spectrum sharing conditions between cognitive satellite systems and incumbent systems.

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9 DEFINITION, SYMBOLS, AND ABBREVIATIONS

2G	Second Generation Mobile Communication
3G	Third Generation Mobile Communication
3GPP	Third Generation Partnership Project
4G	Fourth Generation Mobile Communication
A2C	Astra2Connect
a.k.a.	also known as
AES	Aircraft Earth Station
ANDSF	Access Network Discovery and Selection Function
AP	Access Point
ARCEP	French Regulatory Authority
ASA	Authorized Shared (or Spectrum) Access
ATPC	Automatic Transmission Power Control
BEM	Block Edge Mask
BFWA	Broadband Fixed Wireless Access
BS	Base Station
BSM	Broadband Satellite Multimedia
BSO	Beneficial Sharing Opportunity
BSS	Broadcast Satellite System
BWA	Broadband Wireless Access
CBw	Channel BandWidth
CENELEC	Centre for Electro Technical Standards
CEPT	European Conference on Posts and Telecommunications
CGC	Complementary Ground Component
CBP	Contention Based Protocol
CPC	Cognitive Pilot Channel
CPE	Customer Premises Equipment
CR	Cognitive Radio
CRAF	Committee on Radio Astronomy Frequencies
CRS	Cognitive Radio System
DARPA	Defense Advanced Research Projects Agency
DBS	Direct Broadcast Satellite
DCA	Dynamic Channel Assignment
DEC	CEPT Decision
DFS	Dynamic Frequency Selection
DOW	Description of Work
DS	Down-Stream
DSA	Dynamic Spectrum Assignment
DSE	Dependent Station Enablement
DTH	Direct-To-Home
DVB	Digital Video Broadcasting
DVB-H	DVB Handheld
DVB-NGH	DVB Next Generation Handheld
DVB-RCS	DVB with Return Channel via Satellite
DVB-S	DVB via Satellite
DVB-S2	DVB via Satellite version 2
DVB-T	DVB Terrestrial
DVB-T2	DVB Terrestrial version 2
DySPAN	Dynamic Spectrum Access Networks

EBU	European Broadcasting Union
EC	European Commission
ECC	European Communications Committee
ECO	European Communications Office
EDA	European Digital Agenda
EDGE	Enhanced Data rates for Global Evolution
EIRP	Equivalent Isotropically Radiated Power
EPC	Evolved Packet Core
ERO	European Radiocommunications Office (now ECO)
E/S	Earth Station
ESOMP	Earth Station on Mobile Platform
ESV	Earth Station on board Vessel
ETSI	European Telecommunications Standards Institute
EU	European Union
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network (a.k.a. LTE)
FA	Functional Architecture
FCC	Federal Communications Commission
FM	Frequency Management
FM44	Project Team Frequency Management 44 of the CEPT
FP7	7th Framework Programme
FS	Fixed Service
FSS	Fixed Satellite Service
FWA	Fixed Wireless Access
FWS	Fixed Wireless System
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
GSO	Geostationary Orbit
HDFS	High Density Fixed Service
HDFSS	High Density Fixed Satellite Service
HSPA	High Speed Packet Access
IMT	International Mobile Telecommunications
ITU	International Telecommunications Union
ITU-R	Radiocommunications Sector of the ITU
JTG	Joint Task Group
LAN	Local Area Network
LE	License-Exempt
LMCS	Local Multipoint Communication Service
LMDS	Local Multipoint Distribution Service
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium Access Control
MFCN	Mobile/Fixed Communication Network
MLM	Modelling Language for Mobility
MSS	Mobile Satellite Service
MVDDS	Multichannel Video and Data Distribution Service
NRA	National Regulatory Authority

NCC	Network Control Centre
NCF	Network Control Facility
NGSO	Non Geostationary Orbit
NOI	Notice of Inquiry
O3b	Other 3 billion (people)
OFCOM	UK regulator for communications
PAWS	Protocol to Access White Space
PC	Power Control
PFD	Power Flux Density
PLME	Physical Layer Management Entity
PMP	Point to Multipoint
PtP	Point to Point
QoS	Quality of Service
QoE	Quality of Experience
R&D	Research and Development
RAN	Radio Access Network
RAS	Radio Access and Spectrum
RAS	Radio Astronomy Service
RCS	Return Channel via Satellite
RCST	RCS Terminal
RLAN	Radio Local Area Network
RLC	Radio Link Control
ROES	Receive Only Earth Stations
RR	Radio Regulation
RRS	Reconfigurable Radio System
RSPG	Radio Spectrum Policy Group
RSPP	Radio Spectrum Policy Programme
SC	Standards Committee
SDR	Software Defined Radio
SFCG	Space Frequency Coordination Group
SIA	Satellite Industry Association
SIN	Satellite Interactive Network
SM	Spectrum Manager
SME	Station Management Entity
SoA	State of the Art
SRD	Short Range Device
SSF	Spectrum Sensing Function
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TPC	Transmit Power Control
TV	Television
TVRO	TV Receive-Only
TVWS	TV White Spaces
VSAT	Very Small Aperture Terminal
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
US	Up-Stream (or United States – depending on context)
UTRAN	UMTS Terrestrial Radio Access Network

WAPECs	Wireless Access Policy for Electronic Communications Services
WG	Working Group
WG SE	Working Group Spectrum Engineering of the CEPT
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WINNF	Wireless Innovation Forum
WLAN	Wireless Local Area Network
WP	Work Package
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
WSD	White Space Device
WSDB	White Space Database
XG	neXt Generation communications (DARPA program)

10 Document History

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1	0	18/10/2013	First Release to the European Commission	SES

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Appendix A: Recommendation ITU-R F.699-7*

Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to about 70 GHz

(Question ITU-R 110/9)

(1990-1992-1994-1995-1997-2000-2004-2006)

Scope

This Recommendation provides reference radiation patterns for, and information on, fixed wireless system antennas in the frequency range from 100 MHz to about 70 GHz. This information may be used in coordination studies and interference assessments when particular information concerning the FWS antenna is not available.

The ITU Radiocommunication Assembly,

considering

a) that, for coordination studies and for the assessment of mutual interference between fixed wireless systems (FWS) and between stations of such systems and Earth stations of space radiocommunication services sharing the same frequency band, it may be necessary to use reference radiation patterns for FWS antennas;

b) that, for the above studies, radiation patterns based on the level exceeded by a small percentage of the side-lobe peaks may be appropriate;

c) that the side-lobe patterns of antennas of different sizes are strongly influenced by the ratio of the antenna diameter to the operating wavelength;

d) that reference radiation patterns are required for the case where information concerning the antenna diameter is not available;

e) that, at large angles, the likelihood of local ground reflections must be considered;

f) that the use of antennas with the best available radiation patterns, noting Report ITU-R. F.2059, will lead to the most efficient use of the radio-frequency spectrum,

recommends

1 that, in the absence of particular information concerning the radiation pattern of the FWS antenna involved (see Note 1), the reference radiation pattern as stated below should be used for:

1.1 interference assessment between FWS;

1.2 coordination studies and interference assessment between FWS stations and stations in space radiocommunication services sharing the same frequency band;

* This Recommendation should be brought to the attention of Radiocommunication Study Groups 4, 6, 7, and 8.

2 that the following reference radiation pattern should be adopted for frequencies in the range 100 MHz to about 70 GHz;

2.1 for frequencies in the range 1 GHz to about 70 GHz, in cases where the ratio between the antenna diameter and the wavelength is greater than 100, the following equations should be used (see Notes 6 and 7):

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2 \qquad 0° < \varphi < \varphi_m$$

$$G(\varphi) = G_1 \qquad \varphi_m \leq \varphi < \varphi_r$$

$$G(\varphi) = 32 - 25 \log \varphi \qquad \varphi_r \leq \varphi < 48°$$

$$G(\varphi) = -10 \qquad 48° \leq \varphi \leq 180°$$

where the following parameters are used:

- $G(\varphi)$: gain relative to an isotropic antenna
- φ: off-axis angle (degrees)
- D: antenna diameter; λ: wavelength — expressed in the same units
- G_1: gain of the first side-lobe $= 2 + 15 \log \frac{D}{\lambda}$
- $\varphi_m = \frac{20\lambda}{D} \sqrt{G_{max} - G_1}$ degrees
- $\varphi_r = 15.85 \left(\frac{D}{\lambda} \right)^{-0.6}$ degrees

2.2 for frequencies in the range 1 GHz to about 70 GHz, in cases where the ratio between the antenna diameter and the wavelength is less than or equal to 100 the following equations should be used (see Notes 6 and 7):

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2 \qquad 0° < \varphi < \varphi_m$$

$$G(\varphi) = G_1 \qquad \varphi_m \leq \varphi < 100 \frac{\lambda}{D}$$

$$G(\varphi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \varphi \qquad 100 \frac{\lambda}{D} \leq \varphi < 48°$$

$$G(\varphi) = 10 - 10 \log \frac{D}{\lambda} \qquad 48° \leq \varphi \leq 180°$$

2.3 for frequencies in the range 100 MHz to less than 1 GHz, in cases where the ratio between the antenna diameter and the wavelength is greater than 0.63 (G_{max} is greater than 3.7 dBi), the following equations should be used:

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2 \qquad 0° < \varphi < \varphi_m$$

$$G(\varphi) = G_1 \qquad \varphi_m \leq \varphi < 100 \frac{\lambda}{D}$$

$$G(\varphi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \varphi \qquad 100 \frac{\lambda}{D} \leq \varphi < \varphi_s$$

$$G(\varphi) = -2 - 5 \log \frac{D}{\lambda} \qquad \varphi_s \leq \varphi \leq 180°$$

where:

- $\varphi_s = 144.5 \left(\frac{D}{\lambda} \right)^{-0.2}$

3 that in cases where only the maximum antenna gain is known, D/λ may be estimated from the following expression:

$$20 \log \frac{D}{\lambda} \approx G_{max} - 7.7$$

where G_{max} is the main lobe antenna gain (dBi);

4 that in cases where only the beamwidths of the antenna are known:

4.1 D/λ (expressed in the same unit) may be estimated approximately by the following expression:

$$D/\lambda \approx 70 / \theta$$

where θ is the beamwidth (–3 dB) (degrees);

4.2 given θ, G_{max} may be estimated approximately by:

$$G_{max} \text{ (dBi)} \approx 44.5 - 20 \log \theta$$

5 that administrations submit measured radiation patterns or specifications to allow new and improved reference radiation patterns for use in coordination studies and interference assessment to be developed and proposed (see Appendix 1 of Annex 1);

6 that Annex 1 should be referred to for additional information concerning reference radiation patterns for FWS antennas;

7 that for the detailed calculation of interference levels on interference paths it is necessary to consider the cross-polar response of the victim and interfering system antennas;

7.1 that for the calculation in *recommends* 7, including the component of signal radiated on the intended polarity by the transmitting antenna and the co-polar response of the victim receive antenna to the component of signal radiated on the unintended polarity by the transmitting antenna, the following equation may be used:

$$G_t(\varphi_t)+G_r(\varphi_r)=10\cdot\log\left(10^{\frac{G_{tH}(\varphi_t)+G_{rV}(\varphi_r)}{10}}+10^{\frac{G_{tV}(\varphi_t)+G_{rH}(\varphi_r)}{10}}\right) \quad \text{dBi}$$

where the following parameters refer to antenna gain (dBi):

- $G_t(\varphi_t)$: transmit antenna effective gain in the direction of the victim antenna
- $G_r(\varphi_r)$: receive antenna effective gain in the direction of the interfering antenna
- $G_{tH}(\varphi_t)$: horizontally polarized gain component of the transmit antenna
- $G_{rV}(\varphi_r)$: vertically polarized gain component of the receive antenna
- $G_{tV}(\varphi_t)$: vertically polarized gain component of the transmit antenna
- $G_{rH}(\varphi_r)$: horizontally polarized gain component of the receive antenna.

φ_t and φ_r are the angles between the direction of main beam and direction towards victim and transmitting antenna respectively.

Further information and numerical examples on using the equation above is given in Annex 2.

8 that the following Notes should be regarded as part of this Recommendation.

NOTE 1 – It is essential that every effort be made to utilize the actual antenna pattern in coordination studies and interference assessment.

NOTE 2 – It should be noted that the radiation pattern of an actual antenna may be worse than the reference radiation pattern over a certain range of angles (see Note 3). Therefore, the reference radiation pattern in this Recommendation should not be interpreted as establishing the maximum limit for radiation patterns of existing or planned FWS antennas. Noting that for certification purpose, administrations may adopt standards, usually based on statistical measurements of real antennas, which may represent different values for the side-lobe radiation pattern levels.

NOTE 3 – The reference radiation pattern should be used with caution over the range of angles for which the particular feed system may give rise to relatively high levels of spill-over.

NOTE 4 – The reference pattern in § 2 is only applicable for one polarization (horizontal or vertical). Reference patterns for two polarizations (horizontal and vertical) are under study.

NOTE 5 – The reference radiation pattern included in this Recommendation is only for antennas which are rotationally symmetrical. The reference radiation pattern for antennas with asymmetrical apertures and for non-aperture FWS antennas in the frequency range from 100 MHz to 1 GHz requires further study. For such antennas, the above reference patterns may be considered to be provisionally valid. In this case, the D/λ value computed from G_{max} is an equivalent D/λ and not the actual D/λ.

NOTE 6 – Mathematical models of average radiation patterns for use in certain coordination studies and interference assessment are given in Recommendation ITU-R F.1245.

NOTE 7 – Reference radiation patterns of omnidirectional and sectoral antennas in point-to-multipoint systems are given in Recommendation ITU-R F.1336.

NOTE 8 – Further study is required to ensure that reference radiation patterns continue to develop to take account of advances in antenna design.

NOTE 9 – While generally applicable, the reference pattern in *recommends* 2 does not suitably model some practical fixed service antennas and it should be treated with caution over a range of angles from 5° to 70° (see also Notes 2 and 3).

Annex I - Reference radiation patterns for FWS antennas

1 Introduction

For the study of frequency sharing between FWS and the FSS or of the possibility of frequency reuse in a FWS network, it is often necessary to use a reference diagram, because the actual radiation pattern of the antennas is not always accurately known or gives too many details. The reference pattern should therefore represent the side-lobe envelope in a simplified fashion.

The reference radiation pattern to be selected may, however, vary according to the use for which it is intended.

In general, the reference radiation patterns in the main text of this Recommendation shall be used.

2 Uses of reference radiation patterns

The two main uses of reference radiation patterns are the following:

2.1 Preliminary studies within the coordination area

In the determination of the coordination area around an Earth station, FWS station antennas are assumed to point directly at the Earth station. However, in most cases there will be some angular discrimination. The use of a simple reference radiation diagram makes it possible to eliminate from further consideration FWS stations situated in the coordination area but not likely to produce interference.

This diagram, must, of necessity, be conservative to prevent the elimination of critical contributing sources of interference. The precise calculation of the interference level of course, requires more accurate information on the antenna diagram.

2.2 Frequency reuse in a fixed wireless network

In a fixed wireless network, the same frequency may be used many times, either on sections sufficiently distant from each other or on sections starting from the same station and lying in different directions, or on the same section using cross-polarization.

In the last two cases, the performance of the antenna is of great importance and a fairly precise reference radiation pattern must be used for the network project; this pattern may be less simple than that considered in § 2.1, recognizing that economic efficiencies need to be taken into account, administrations may wish to encourage the use of high performance antenna types in high spectrum use areas.

3 Results of measurements on the antennas of fixed wireless links

Measurements with numerous antennas provide adequate confirmation of the reference radiation patterns in the main text of this Recommendation at least up to a value of D/λ of approximately 130. However, the following points must be borne in mind:

3.1 Some antennas of relatively old designs have less satisfactory performance characteristics than more recent models. The existence of such medium performance antennas should be taken into account for frequency sharing.

3.2 The above computation is based on the assumption that the antennas operate in free-space conditions. The performance characteristics of antennas installed in the field may, however, be slightly less satisfactory owing to reflection from neighbouring obstacles or from other antennas installed on the same mast.

4 Radiation patterns of high performance antennas

High performance antennas contribute greatly to the increase of nodal capacity in FWS. For the horn-reflector antennas, which were developed to comply with the requirements of terrestrial FWS in dense networks, the reference diagram above may be regarded as valid only in the horizontal plane. For planes away from the horizontal significant sensitivity variations are displayed.

Figure 1 gives an example for the radiation diagram of a specific but widely-used pyramidal horn reflector antenna. Radiation envelope contours are plotted (in dB below the main beam) in a coordinate system using angles φ and θ (the center of the spherical coordinate system being the centre of the antenna aperture). The strong departure from the rotational symmetry assumed in the reference radiation patterns in *recommends* 2 of this Recommendation is due to:

- the spill-over lobe around $\varphi = +90°$ and $60° < \theta < 80°$;
- the weather cover lobe around $\varphi = -90°$ and $50° < \theta < 90°$.

The spill-over lobe is a consequence of wave diffraction at the upper lip of the aperture caused by direct rays emanating from the pyramidal horn section. This effect is pronounced only for vertical polarization. The weather cover lobe is due to reflection of energy by the tilted plastic weather cover back onto the parabolic surface which then re-directs most of the energy downward over the lower lip of the aperture. This phenomenon is polarization and frequency insensitive.

An offset-reflector type antenna shows sharp directivity especially in the horizontal plane. Figure 42 illustrates examples of the radiation patterns of the offset-reflector antenna together with an example of the pyramidal horn-reflector antenna read from Figure 41.

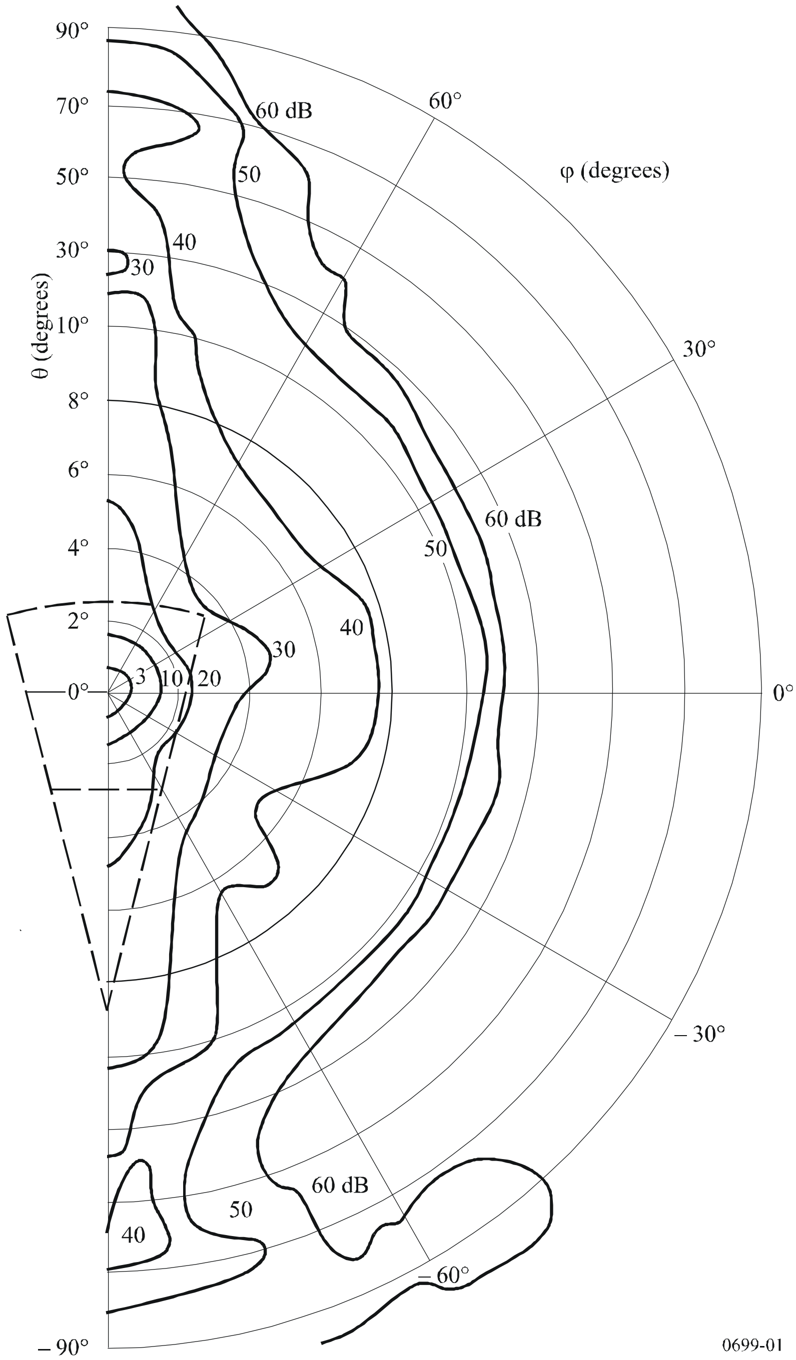

Figure 41 - Three-dimensional radiation pattern for a pyramidal horn-reflector antenna at 3.9 GHz and vertical polarization (note scale change at θ=10°)

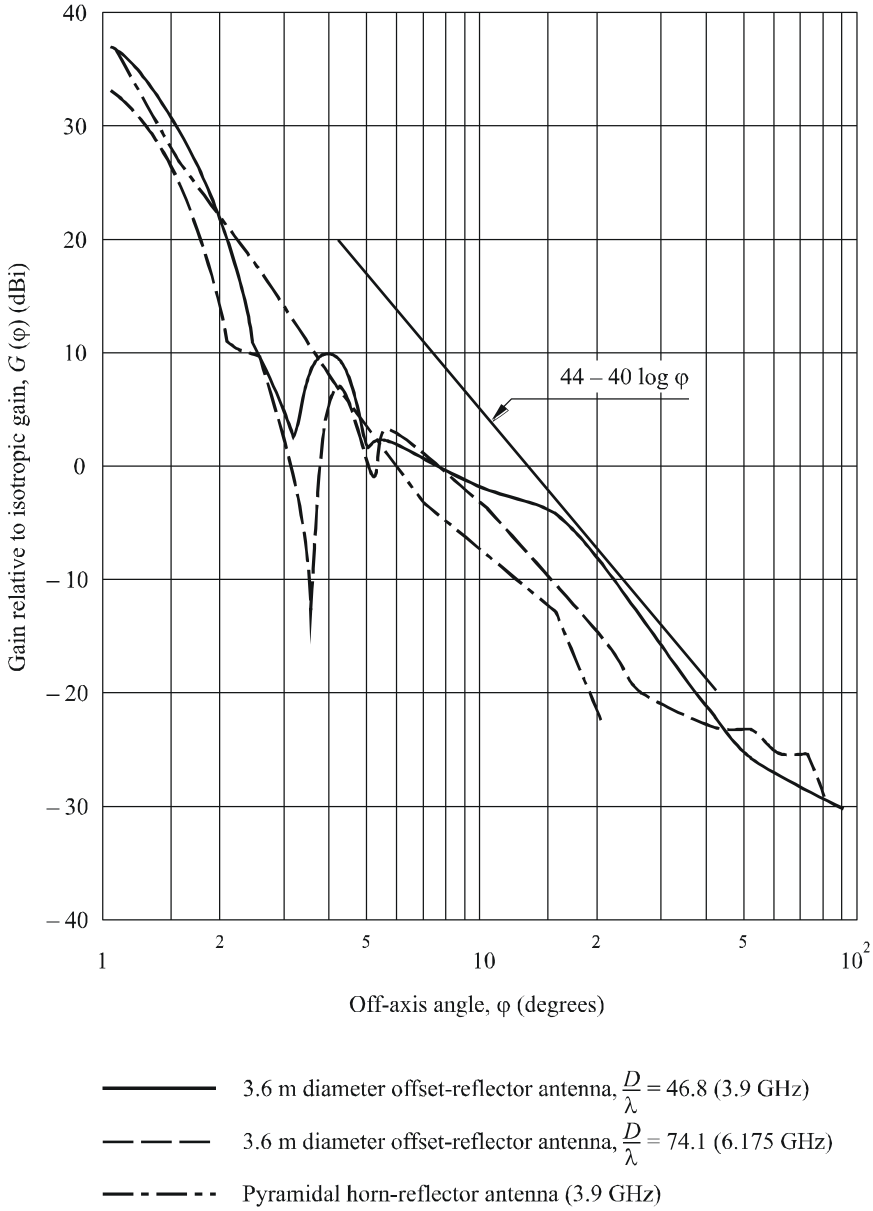

Figure 42 - The radiation pattern of high performance antennas

For horn reflector antennas and for offset antennas with a very low illumination on the edge of the reflector, the following formula may be provisionally used as a reference radiation pattern in the horizontal plane:

$$G = 88 - 30 \log \frac{D}{\lambda} - 40 \log \varphi \qquad (1)$$

This formula is valid outside the main lobe for φ up to about 90°. However, when the illumination on the edge of the reflector is not very low, the level of side-lobes in certain directions may be higher than that given by equation (1).

Appendix 1 to Annex I - Measured patterns for use in the further development of this Recommendation

1 Introduction

There is a continuing need to review and update the reference radiation patterns contained in this Recommendation. As the frequency bands being used for FWS extend beyond 70 GHz, there is a need to widen the scope of these reference radiation patterns above 70 GHz. To assist with the above, this Appendix contains comparisons of some practical antenna pattern envelopes and radiation patterns with the corresponding reference patterns derived from this Recommendation and Recommendation ITU-R F.1245.

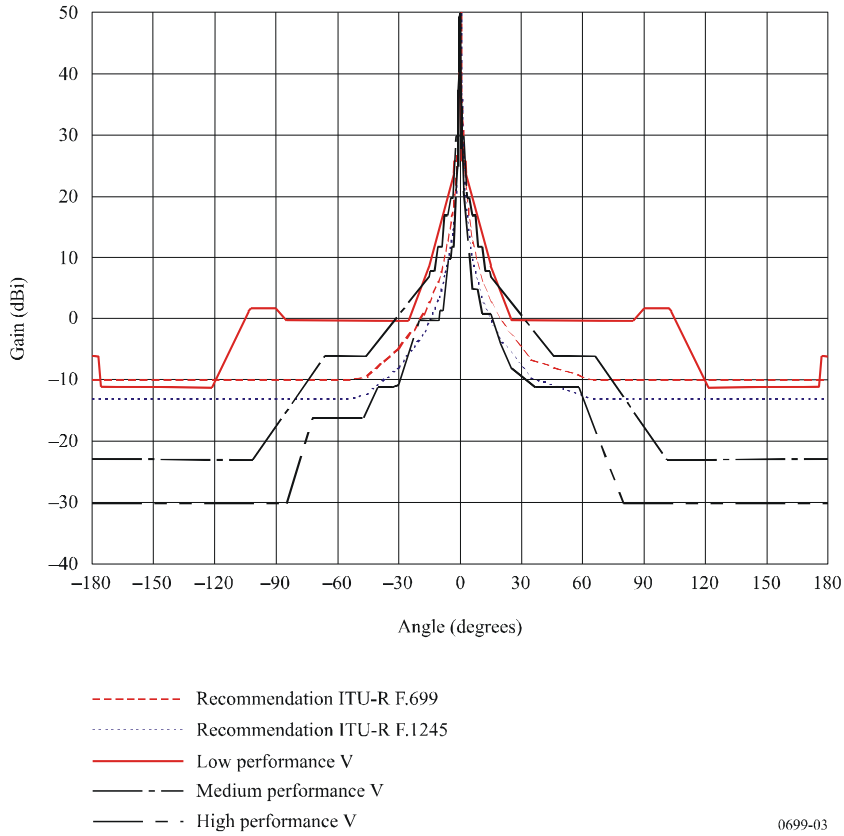

Figure 43 - 10.7 GHz point-to-point (P-P) antenna of 3 m diameter (D/λ=114; gain=49.8 dBi) (H: horizontal polarization, V: vertical polarization)

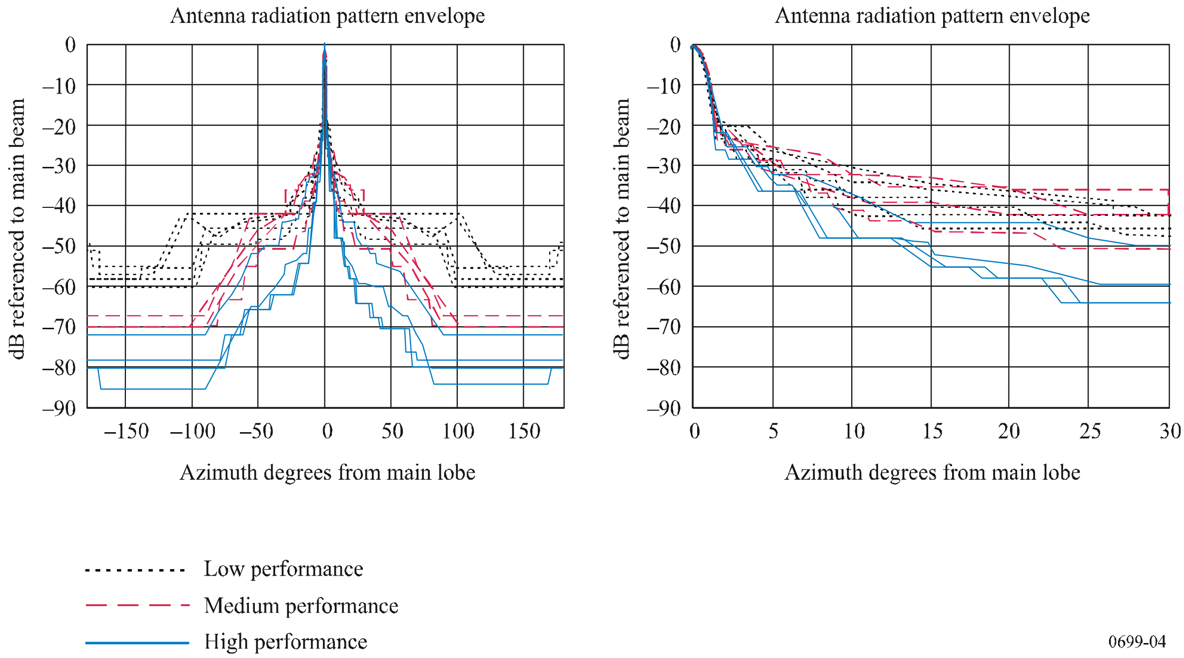

Figure 44 - Patterns for a sample of production antennas (1.8 m diameter, horizontal polarization, 10.7 GHz)

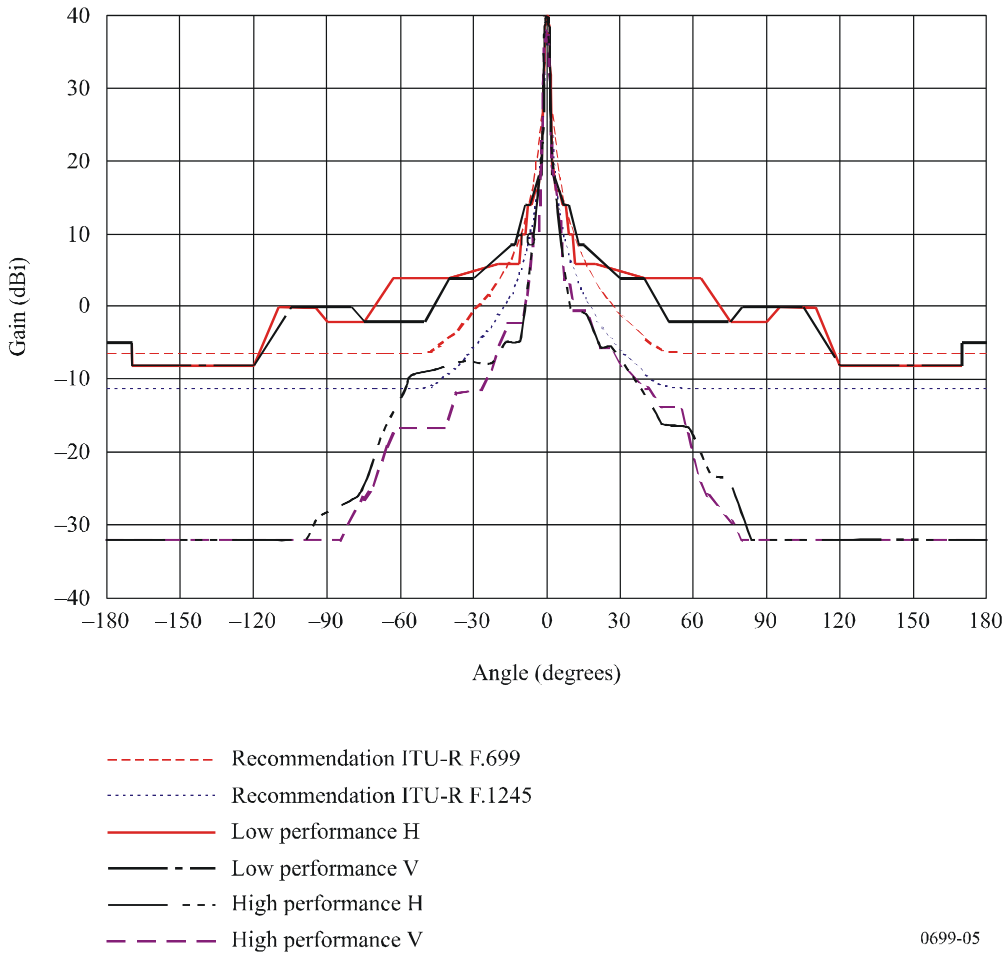

Figure 45 - 10.7 GHz point-to-point (P-P) antenna of 1.2 m diameter (D/λ=43; gain=39.9 dBi) (H: horizontal polarization, V: vertical polarization)

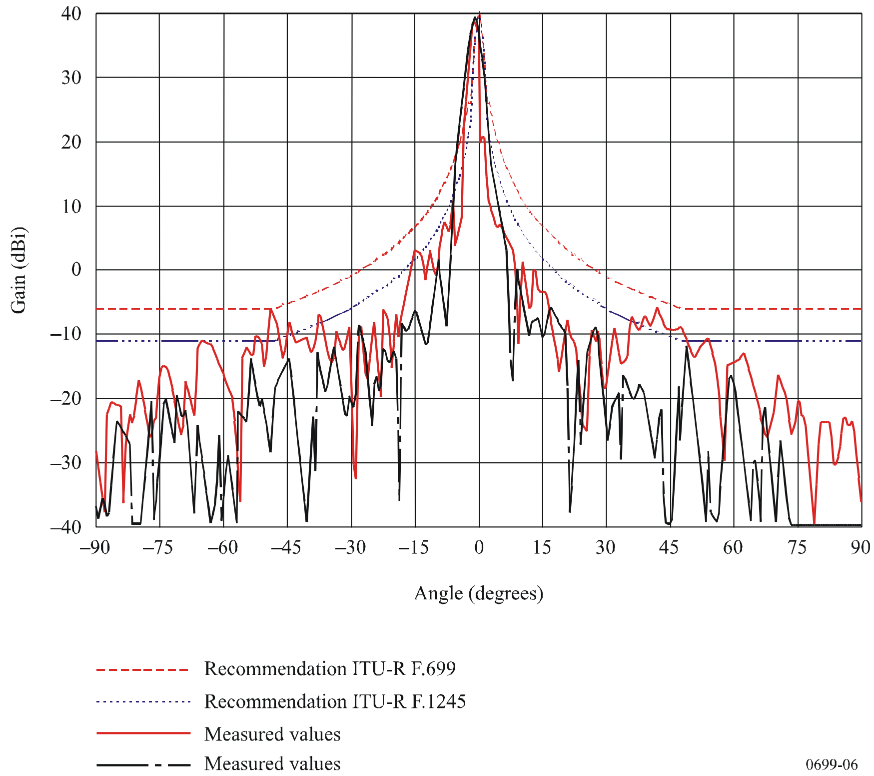

Figure 46 - 21 GHz lens horn P-P antenna of 50 cm diameter (D/λ=37; gain=40 dBi)

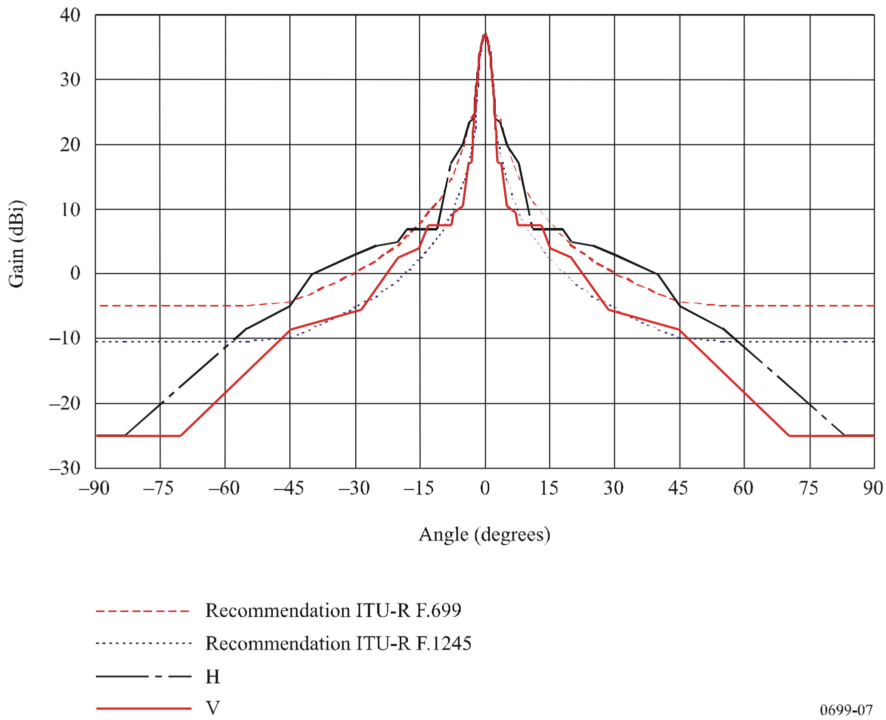

Figure 47 - 31 GHz P-P antenna of 0.3 m diameter (D/λ=32; gain=36.9 dBi) (H: horizontal polarization, V: vertical polarization)

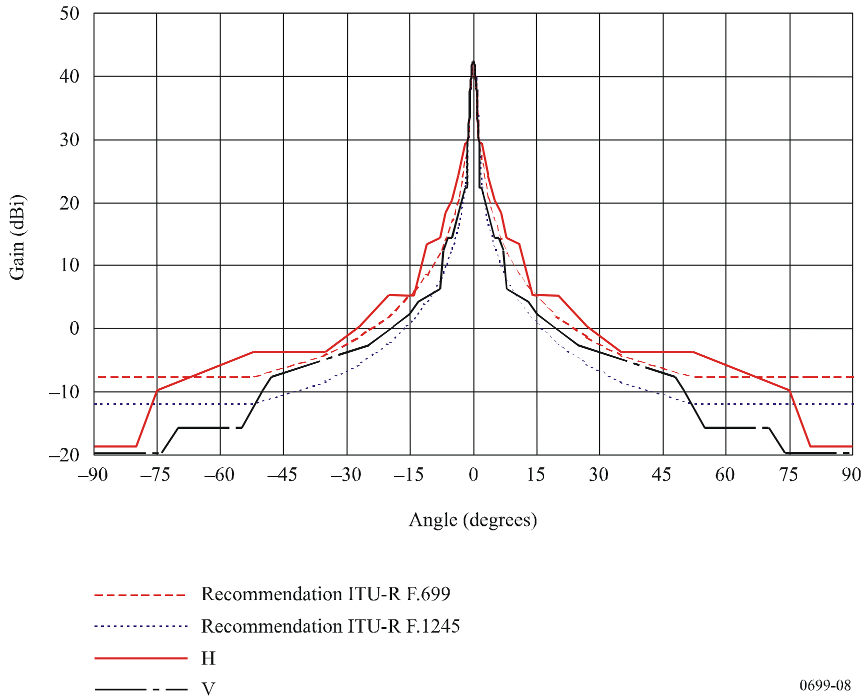

Figure 48 - 55 GHz P-P antenna of 0.3 m diameter (D/λ=57; gain=42.4 dBi) (H: horizontal polarization, V: vertical polarization)

Annex II - Details on the application of *recommends* 7

1 Introduction

Some figures and numerical examples are given with the aim to support the designations used in the equation of *recommends* 7.1.

An alternative equation (see § 4) can be used if relative antenna gains data are given.

In the case of a mutual gain calculation between co-polar antennas the alternative equation shall be used (see § 5).

2 Situation

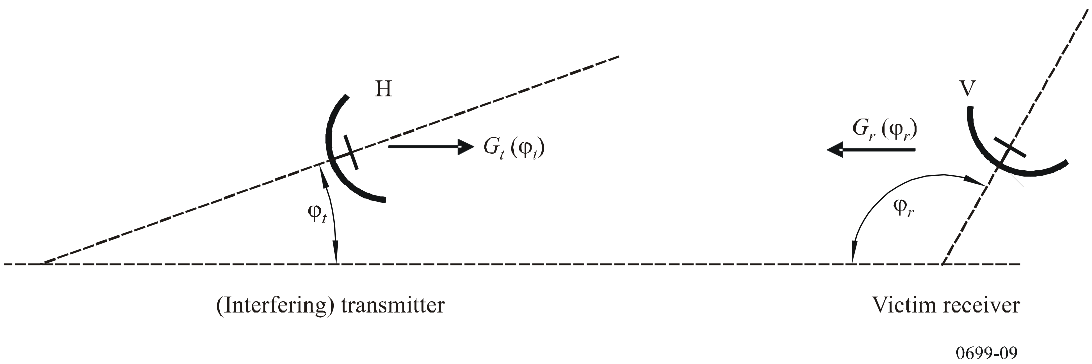

Figure 49 - Generic example of mutual situation and orientation of transmitting antenna and victim receiving antenna

3 The numerical example

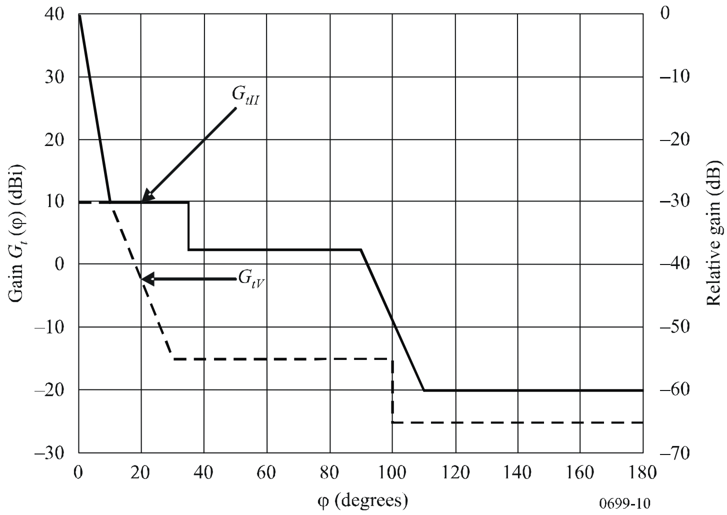

Figure 50 - Example of transmitter antenna mask for co- and cross-polarization

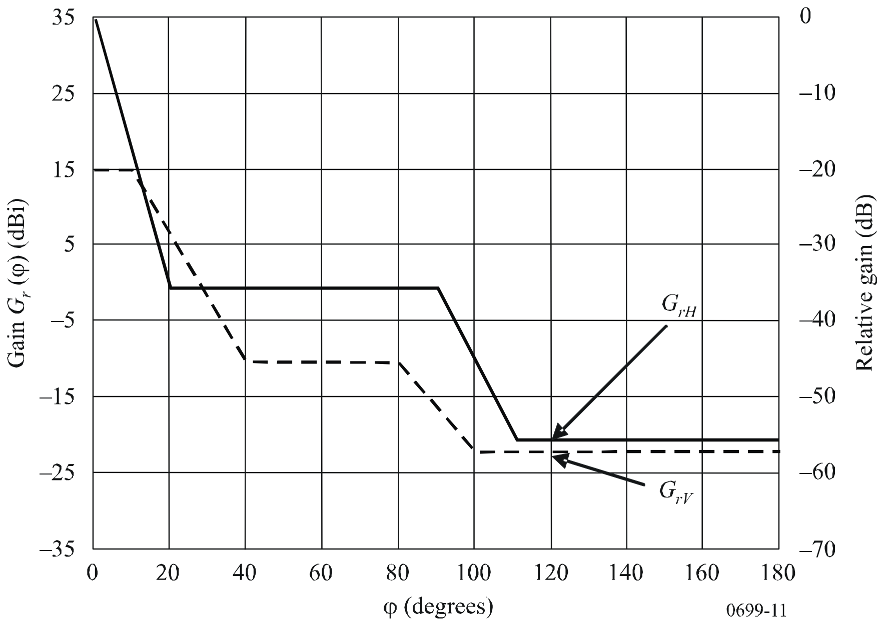

Figure 51 - Example of receiver antenna mask for co- and cross-polarization

The example for cross-polarized antennas is given below. The following values can be obtained from the Figure 49Figure 50Figure 51:

- $\varphi_t =$ 20°
- $\varphi_r =$ 120°
- $G_{tH}(\varphi_t)$ =10 dBi
- $G_{rV}(\varphi_r)$ =–22 dBi
- $G_{tV}(\varphi_t)$ =–2 dBi
- $G_{rH}(\varphi_r)$ =–20 dBi

Using these values in the equation gives us the following result: $G_t(20°) + G_r(120°) = –11.6$ dBi.

Due to the reciprocity theorem the result of a mutual gain calculation is the same if the transmitter and receiver antennas are exchanged.

4 Alternative equation for cross-polarized case

In the case that G_{tmax}, G_{rmax} and relative gain of sideband lobes are given (as shown in the right side scale in Figs. 10 and 11), equation (2) is applicable:

$$G_t(\varphi_t) + G_r(\varphi_r) = G_{tmax} + G_{rmax} + 10 \cdot \log\left(10^{\frac{G_{tH}(\varphi_t)+G_{rV}(\varphi_r)}{10}} + 10^{\frac{G_{tV}(\varphi_t)+G_{rH}(\varphi_r)}{10}}\right) \quad \text{dBi} \qquad (2)$$

In equation (2) G_{tmax}, G_{rmax} and the result are given in dBi, but the side lobes' relative gain in dB.

5 Alternative equation for co-polarized case

If both antennas are co-polar the values should be changed accordingly and the equation will become:

$$G_t(\varphi_t) + G_r(\varphi_r) = 10 \cdot \log\left(10^{\frac{G_{tH}(\varphi_t)+G_{rH}(\varphi_r)}{10}} + 10^{\frac{G_{tV}(\varphi_t)+G_{rV}(\varphi_r)}{10}}\right) \quad \text{dBi} \qquad (3)$$

The numerical example gives, in the co-polar case, a common gain of –9.8 dBi with the same antennas as used above (Figure 50Figure 51).

APPENDIX B: OVERVIEW OF COGNITIVE RADIO PROJECTS

This section reviews the research projects that are relevant to CoRaSat and discusses the main aspects, problems, and outcomes that are of particular interest and applicability for the CoRaSat project.

Table 34 provides a list of the projects overviewed in this section.

Note that the bulk of this overview concerns terrestrial communications, with far less work specifically directed to the impact of CR on satellite communications.

Moreover, it is important to highlight that the overview presented in this section does not reflect the position of the CoRaSat consortium but the position of the various consortia whose projects are described hereinafter.

Table 34 - Overview of CR related projects

Acronym	Full title	Funding Scheme[22]	Timeline
EC PROJECTS			
ABSOLUTE	Aerial Base Stations with Opportunistic Links for Unexpected & Temporary Events	IP	Oct 2012–Sep 2015
ACROPOLIS	Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum	NoE	Oct 2010–Sep 2013
ARAGORN	Adaptive Reconfigurable Access and Generic Interfaces for Optimisation in Radio Networks	STREP	Jan 2008–Aug 2010
C2POWER	Cognitive Radio and Cooperative Strategies for POWER saving in multi-standard wireless devices	STREP	Jan 2010–Dec 2012
COGEU	COGnitive radio systems for efficient sharing of TV white spaces in European context	STREP	Jan 2010–Dec 2012
COST IC0902	Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks	COST Action	Dec 2009–Dec 2013
COST IC0905 TERRA	Techno-Economic Regulatory Framework for Radio Spectrum Access for Cognitive Radio (CR)/Software Defined Radio (SDR)	COST Action	May 2010 – May 2014
CREW	Cognitive Radio Experimentation World	IP	Oct 2010–Sep 2015
CROWN	Cognitive Radio Oriented Wireless Networks	STREP-FET	May 2009–Apr 2012
CRS-i	Cognitive Radio Standardization-initiative	CSA	Nov 2012–Oct 2015
E3	End-to-End Efficiency	IP	Jan 2008–Dec 2009
FARAMIR	Flexible and spectrum-Aware Radio Access through Measurements and modelling In cognitive Radio systems	STREP	Jan 2010–Jun 2012
MONET	Mechanisms for Optimization of hybrid ad-hoc networks and satellite NETworks	STREP	Jan 2010–Jun 2012
OneFIT	Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future InterneT	STREP	Jul 2010–Dec 2012
PHYDYAS	PHYsical layer for DYnamic Spectrum Access and cognitive radio	STREP	Jan 2008–Jun 2010
QoSMOS	Quality of Service and MObility driven cognitive radio Systems	IP	Jan 2010–Dec 2012

[22] *IP: Integrated Project, NoE: Network of Excellence, STReP: Specific Targeted Research Project, CSA: Coordination and Support Action, FET: Future and Emerging Technologies, COST: Cooperation in Science and Technology, ARTES: Advanced Research in Telecommunications Systems.*

QUASAR	QUantitative Assessment of Secondary Spectrum Access	STREP	Jan 2010–Jun 2012
ROCKET	Reconfigurable OFDMA-based Cooperative Networks Enabled by Agile Spectrum Use	STREP	Jan 2008–Dec 2009
SACRA	Spectrum and energy efficiency through multi-band Cognitive Radio	STREP	Jan 2010–Dec 2012
SAPHYRE	Sharing Physical Resources – Mechanisms and Implementations for Wireless Networks	STREP	Jan 2010–Mar 2013
SENDORA	Sensor Network for Dynamic and Cognitive Radio Access	STREP	Jan 2008–Dec 2010

ESA PROJECTS			
ACROSS	Applicability of Cognitive Radio (CR) to Satellite Systems	ARTES 1	Apr 2010 – July 2012
ESA ITT A07284			Start: July 2013
ESA_1-5800	The Changing Regulatory and Evolutionary Environment and its Impact on the Satellite Communication Business	ARTES 1	2008-2010
NATIONAL PROJECTS			
CO2SAT	Cooperative and Cognitive Architectures for Satellite Networks	Luxembourg	Jan 2011--Dec 2013
CORE+	Cognitive radio trial environment+	Finland	Jan 2013 - Dec 2014
SALICE	Satellite-Assisted LocalIzation and Communication systems for Emergency services	Italy	Oct 2008--Oct 2010
SPECTRA	Spectrum and Energy Efficiency Through Multiband Cognitive Radio	Spain	Sept 2010 – Aug 2014
LICoRNe	Leveraging Insurance for services providers cohabitation over Cognitive Radio Networks	France	Dec 2010 – Dec 2013

B.1 EC Projects

B.1.1 ABSOLUTE

Consortium: Thales Communications and Security, Gennevilliers, France; France Telecom - Orange SA, France; Triagnosys GmbH, Wessling, Germany; German Aerospace Center, Munich, Germany; Create-Net Research Center, Trento, Italy; The University of York, U.K.; Fraunhofer Heinrich Hertz Institute, Berlin, Germany; EUTELSAT SA, Paris, France; University of Duisburg-Essen, Germany; Allsopp Helikited Limited, U.K.; Advanten, France; Mira Telecom, Romania; British Association of Public Safety Officials, U.K.; Agence Nationale des Fréquences, France; RMIT University, Melbourne, Australia; Josef Stefan Institute, Slovenia; Nomor Research GmbH, Germany.

ABSOLUTE (Aerial Base Stations with Opportunistic Links for Unexpected & Temporary Events) is a new FP7 ICT Call 8 Integrated Project (IP), which was kicked-off on October 1, 2012. It aims to design and validate an innovative rapidly deployable future network architecture which is resilient and capable of providing broadband multi-service, secure, and dependable connectivity for large coverage areas affected by large scale unexpected events (or disasters) leading to the partial or complete unavailability of the terrestrial communication infrastructure or for temporary events leading to the demand for very high throughput and augmented network capacity. The project will demonstrate the high capacity, low-latency, and coverage capabilities of LTE-A solutions adapted for broadband emergency communications within disaster relief scenarios through flexible base stations embedded on-board aerial platforms and terrestrial land mobile stations.

The ultimate goal in ABSOLUTE is to provide reference implementations for interoperable and backward compatible solution, and relevant regulatory and standardization efforts, enabling quick adoption of 4G communication technologies to remarkably improve the disaster recovery and crisis management preparedness of all relevant public safety and security stakeholders in Europe and worldwide. The functional elements and the respective network architecture enhancements will be based on the user/stakeholder requirements analysis and will also be based on the European positioning for Broadband spectrum strategy for public safety and technology evolution with standardization feedback for the harmonization of PPDR (Public Protection for Disaster Relief) and Broadband PPDR services. The design and development of the standalone and autonomous 4G eNodeBs in ABSOLUTE will clearly have an impact for the public safety communications landscape and in particular towards faster adoption and maturity of LTE-A based systems for mission critical deployments.

In response to the requirement to deploy flexible and rapidly deployable resilient network infrastructures in emergency, disaster or any related tremendous unexpected events, the main goal of ABSOLUTE is to design and validate an innovative holistic network architecture ensuring dependable communication services based on the following main features:

- rapid deployment, flexibility, scalability, and seamless reconfigurability;
- provision of broadband services;
- resilience, availability, and security;
- integration of LTE-A with advanced satellite communications and current public safety networks (TETRA).

ABSOLUTE objectives will be achieved through the opportunistic combination of aerial, terrestrial, and satellite communication links with the aim to maximize network availability and allow a rapid and incremental network deployment. This seamlessly reconfigurable and highly scalable network environment will also embed adequate levels of mobility support and energy efficiency.

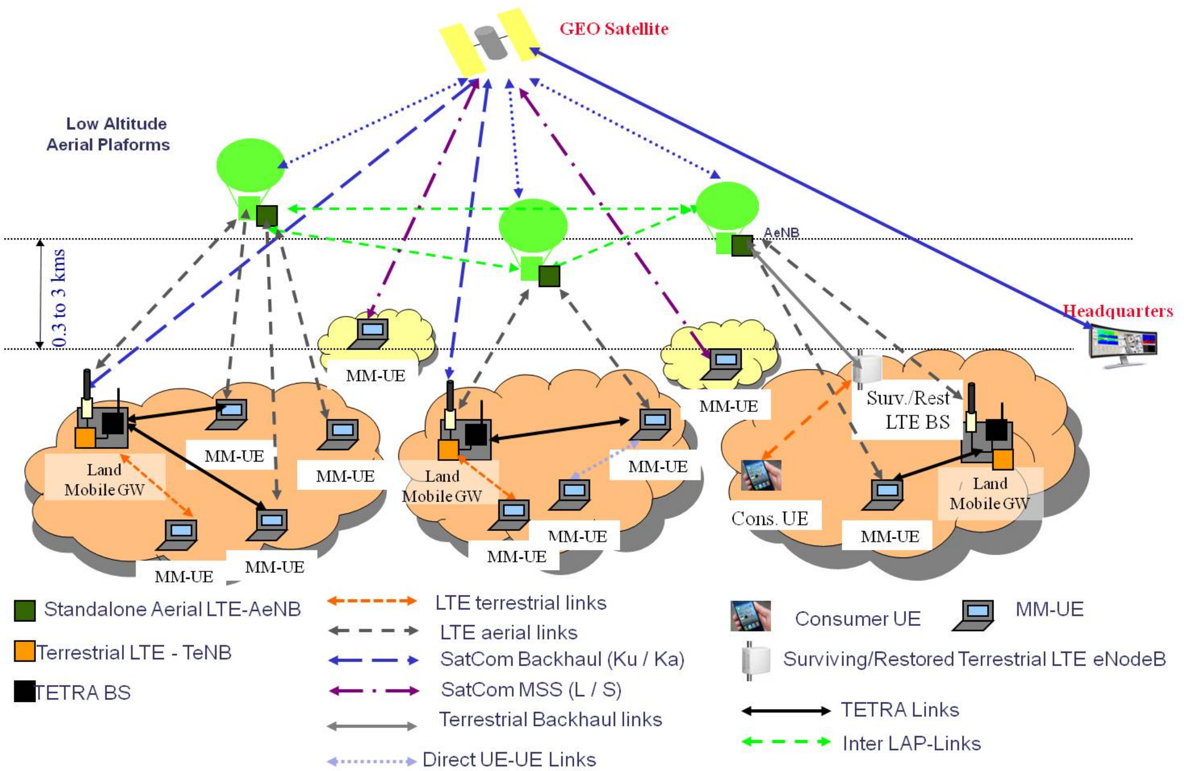

Figure 52 - ABSOLUTE Architecture

The ABSOLUTE architecture is based on the following elements, which will be designed and implemented in the project:

- low altitude Aerial LTE-A Base Stations (AeNodeB), embedded in Low Altitude Platforms (LAPs) providing high data rates and coverage over large areas;
- portable Land Mobile LTE-A Base Stations (TeNodeB) interoperable with conventional PPDR systems (TETRA base stations) and sensor networks (sensor gateways), enabling dedicated coverage and broadband satellite backhauling capabilities in Ka-band;
- advanced multimode LTE-A Professional terminals (multimode-user equipments or MM-UE) enabling direct mode LTE communications (LTE D2D) and direct messaging services via S-band satellite when outside of TeNodeB or AeNodeB coverage.

Figure 52 depicts the different network elements and communication links enabling the overall ABSOLUTE ecosystem.

In relation to CoRaSat, ABSOLUTE addresses mobile terrestrial, aerial, and satellite communication technologies. In particular, SatCom is mainly used for Ku-/Ka-band backhauling services as well as for L-/S-band mobile satellite services. On cognitive radio aspects, ABSOLUTE investigates – among others – cognitive radio techniques for dynamic spectrum access and management for seamless network re-configurability and scalability, and opportunistic networking techniques for improved communication robustness, system availability and link resilience. As such, Cognitive and Context Aware communications and network management solutions for public safety communications are part of the project targeted results. For the time being, due to the recent KO of the project, no further public information on specific cognitive radio technologies to be pursued in the ABSOLUTE project is currently available. The ABSOLUTE project will be regularly monitored and specific relevant issues on Cognitive Radio will be taken into account in CoRaSat.

B.1.2 ACROPOLIS

Consortium: King's College London; RWTH Aachen University; University of Rome "La Sapienza"; Institute of Accelerating Systems and Applications; Technical University of Dresden; University of Piraeus Research Center; Wroclaw Research Center EIT+; KTH Royal Institute of Technology; SS. Cyril and Methodius University in Skopje; Centre Tecnologic de Telecomunicacions de Catalunya; Joint Research Center (JRC), European Commission; Poznan University of Technology; University of Surrey; Eurecom; University of Leeds; EADS Innovation Works.

ACROPOLIS (Advanced coexistence technologies for radio optimization in licensed and unlicensed spectrum) is an FP7 Network of Excellence (NoE) specifically designed to foster cooperation among experts, share expertise and harmonize research in the area of wireless cognitive and cooperative communications in order to support advanced coexistence technologies for radio resource usage optimization and provide improved system capacity, spectrum usage efficiency and energy efficiency, enhanced wireless connectivity coverage, and the ability to support novel and interesting wireless communications applications and use cases. The purpose of ACROPOLIS is to link experts from around Europe working on coexistence technologies such as spectrum sharing and cognitive radio, specifically considering the intersection of cognitive radio, opportunistic spectrum access, flexible radios, and self-organizing networks. Such coexistence technologies within ACROPOLIS are aimed towards the optimization of radio spectrum usage.

ACROPOLIS targets three classes of applications:

- Cognitive Radio Systems and other spectrum sharing paradigms (dynamic spectrum allocation, opportunistic spectrum allocation, secondary market mechanism, etc.);
- self-organizing networks, including cognitive wireless network architectures;

- legacy network optimization based on novel approaches.

Some of the research challenges in cognitive radio and networking addressed in ACROPOLIS include:

- database-enabled cognitive radio;
- cognitive radio femtocells;
- cognitive radio for home networking;
- spectrum awareness for cognitive radio (*e.g.*, spectrum sensing approaches);
- neighbourhood and network awareness for cooperative and cognitive networks;
- learning mechanisms and knowledge management solutions;
- decision making algorithms and decision execution solutions;
- conformance monitoring, assessment and security issues;
- economic models for cognitive radio and dynamic spectrum access;
- learning and knowledge management, policy-construction and decision making issues;
- novel applications and use-cases for cognitive radio and networking;
- platforms for experimentation of cognitive radio technologies.

In relation to CoRaSat, ACROPOLIS addresses cognitive radio and spectrum sharing approaches, and investigates their associated problems and techniques. While ACROPOLIS focuses on an exclusively terrestrial domain, the outcomes and solutions provided in the area of cognitive radio networking and dynamic/flexible spectrum sharing are relevant to CoRaSat and, as such, will be taken into account.

B.1.3 ARAGORN

Consortium: RWTH Aachen University; ST Microelectronics, Italy; European Microsoft Innovation Center; Toshiba Europe; University College London; Consorzio Ferrara Ricerche; University SS. Cyril and Methodius, Skopje; Huawei Technologies Sweden AB.

The ARAGORN (Adaptive Reconfigurable Access and Generic Interfaces for Optimisation in Radio Networks) project explored and developed enabling technologies to facilitate the application of machine intelligence and adaptive communications technologies in the optimization of resource usage in wireless networks. Most particularly, the project explored the application of methods originating from the artificial intelligence community in order to increase the efficiency and system performance of the present day and future systems following the cognitive radios and networks paradigm. The technology developed addressed the issue of increased system complexity of reconfigurable and software radio based devices, enabling co-operation between smart objects.

The ARAGORN project developed a Cognitive Resource Manager (CRM) that aims to ensure that efficient use is made of both node-local and shared resources in a collaborative wireless system. These include, for example, local energy consumption and shared use of available bandwidth. In order to achieve this, ARAGORN developed a range of standardized interfaces through which the CRM is able to both obtain information from and update the configuration of each layer of the protocol stack, including at the application layer. Given this, the CRM seeks to optimize cross-layer and inter-node performance using multi-dimensional optimization algorithms from the machine learning and artificial intelligence domains. The project developed and combined the CRM and related software modules with reconfigurable radio front-end and software techniques to demonstrate that a cognitive radio system works efficiently under realistic conditions.

In contrast to other cognitive radio research, the ARAGORN project did not focus on dynamic spectrum access networks but aimed at adding real cognition to mobile devices, enabling them to take reasonable decisions autonomously, and demonstrated the feasibility of such cognitive radio devices in realistic conditions by means of a hardware/software prototype. While the main focus of CoRaSat is on flexible/dynamic sharing of spectrum, this will certainly be made feasible by devices implementing cognitive radio functionalities. As such, the outcomes of the ARAGORN project are of certain interest and applicability to CoRaSat and will be taken into account in the project where applicable.

B.1.4 C2POWER

Consortium: Instituto de Telecomunicacoes; Cea-Leti; Portugal Telecom Inovacao; University of Surrey; Center for Research and Telecomm. Experimentation for Networked Communities; Sigint Solutions Ltd.; **Wroclawskie Centrum Badan EIT+ SP ZO.O; EADS Defence and Security Systems**; VEEBEAM; **LANTIQ Deutschland GmbH**.

The main objective of the C2POWER (Cognitive Radio and Cooperative Strategies for POWER saving in multi-standard wireless devices) project was to research, develop and demonstrate energy saving technologies for multi-standard wireless mobile devices, exploiting the combination of cognitive radio and cooperative strategies while still enabling the required performance in terms of data rate and Quality of Service (QoS)to support active applications.

To avoid the foreseen 4G "energy trap", C2POWER investigated, developed and demonstrated how cognition and cooperative strategies can be extended to decrease the overall energy consumption of mobile devices while still enabling the required performance in terms of QoS. In particular, two complementary techniques to increase power efficiency at the wireless interface of handsets were investigated:

- cooperative power saving strategies between neighbouring nodes using low power short range communications;
- cognitive handover mechanisms to select the Radio Access Technology (RAT) that has the lowest energy demand in heterogeneous environments.

At the technical level, the main goals of C2POWER were:

- investigate how context information can be used by cooperative strategies to achieve power efficiency at the wireless interface of mobile devices and save battery lifetime;
- investigate and demonstrate the potential of cooperative techniques based on advanced short range communications for the goal of power/battery lifetime saving of mobile wireless devices;
- investigate and demonstrate minimum energy consumption handover procedures and policies between heterogeneous technologies and associated trade-offsin realistic scenarios;
- investigate, design, and demonstrate energy efficient reconfigurable multi-standard transceivers (BB and RF) able to switch from one standard to another according to a power saving strategy.

The main techniques addressed by the project were:

- context awareness and signalling for power saving strategies: investigation and implementation of energy efficient network and node discovery modules;
- energy-efficient reconfigurable radio transceivers: to investigate and implement a transceiver platform that is multi-standard in nature, flexible and energy efficient;

- cooperative short range communications for power saving: to investigate and implement energy efficient algorithms/protocols for short-range communications that include: i) cooperation protocols based on utility functions; ii) routing; and iii) cooperative relaying;
- energy-efficient cognitive handovers procedures and policies: to investigate and implement energy efficient cognitive handover algorithms (including femtocells) and the validation framework.

The focus of C2POWER was mainly in energy saving technologies for wireless mobile devices (paying attention to the wireless transmission and reception process without considering any power issues at the other components of mobile phones such as display, memory, camera, etc.), exploiting the combination of cognitive radio and cooperative strategies. While C2POWER considered cognitive radio techniques for energy saving in wireless mobile devices, the focus of CoRaSat is on the application of cognitive radio techniques for spectrum sharing (in SatCom scenarios). However, both benefits of cognitive radio techniques (*i.e.*, energy saving and spectrum efficiency) are not mutually exclusive and may be obtained simultaneously. Moreover, energy saving in battery-powered elements is also a concern in SatComs, and there is no doubt that SatCom systems would benefit of cognitive radio approaches that not only enable dynamic sharing of the spectrum but also allow energy saving. As such, the activities of C2POWER are relevant to CoRaSat and will be taken into account.

B.1.5 COGEU

Consortium: Instituto de Telecomunicações, Portugal; Thales, France; Portugal Telecom Inovação; Trinity College Dublin; University of the Aegean, Greece; Sigint Solutions Ltd., Cyprus; Poznan University of Technology, Poland; Institut für Rundfunktechnik, Germany; Rohde & Schwarz, Germany; Towercom a. s., Slovakia.

The COGEU (COGnitive radio systems for efficient sharing of TV white spaces in European context) project was aimed at taking advantage of the TV digital switch-over (or analog switch-off) by developing cognitive radio systems that leverage the favorable propagation characteristics of the TVWS through the introduction and promotion of real-time secondary spectrum trading and the creation of new spectrum commons regime. COGEU also defined new methodologies for TVWS equipment certification and compliance addressing coexistence with the DVB-T/H European standard.

At the technical level, the main goals of COGEU were to:

- design, implement and demonstrate enabling technologies based on cognitive radio to support mobile applications over TVWS for spectrum sharing business models;
- quantify the impact of TVWS devices on DVB-T receivers and define methodologies for TVWS equipment certifications and compliance in the European regulatory context.

COGEU considered a centralized topology with a spectrum broker trading with players as illustrated in the figure below. The spectrum broker controls the amount of bandwidth and power assigned to each user in order to keep the desired QoS and interference below the regulatory limits. In the COGEU reference model, the centralized Broker is an intermediary between the geolocation database (spectrum information supplier) and players that negotiate spectrum on behalf of spectrum users.

To fulfill the goals of COGEU and enable the efficient exploitation of TVWS in the European context, the project explored scenarios and business/market models, researched on enabling technologies (secondary spectrum trading mechanisms, spectrum sensing algorithms to detect DVB devices and wireless microphones, geolocation databases for cognitive access, interference measurements, coexistence approaches between TVWS cognitive devices, DVB and wireless microphones, dynamic radio resource management and protocols with context awareness) and developed a spectrum trading demonstrator for selected scenarios.

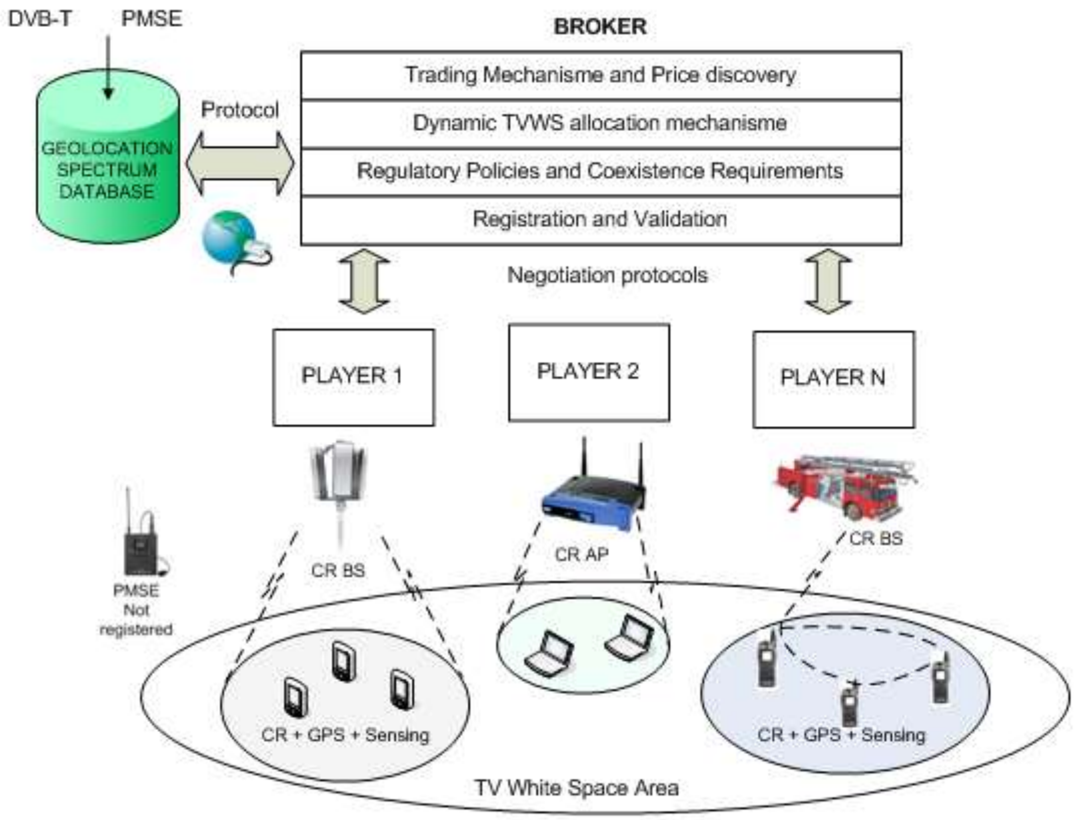

Figure 53 - COGEU reference model.

CoRaSat focus is on spectrum sharing in SatCom bands, where the possible spectrum sharing scenarios may differ considerably from the scenarios found in terrestrial systems that access TVWS opportunistically. However, many of the enabling technologies researched in COGEU are key ingredients to be researched and developed in CoRaSat, and the potential applicability of the solutions developed in COGEU (in the framework of terrestrial exploitation of TVWS) to SatCom scenarios is an interesting aspect to be considered and analyzed.

B.1.6 COST IC0902

Consortium: There are currently 196 researchers from almost 30 different countries involved in COST Action IC0902.

The main objective of the COST Action IC0902 (Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks) is to integrate the cognitive concept across all layers of communication systems, resulting in the definition of a European platform for cognitive radio and networks.

The Action proposes coordinated research in the field of cognitive radio and networks. The cognitive concept applies to coexistence between heterogeneous wireless networks that share the electromagnetic spectrum for maximum efficiency in resource management. Several efforts are currently in place in European research centers and consortia to introduce cognitive mechanisms at different layers of the communications protocol stack. This Action goes beyond the above trend by integrating the cognitive concept across all layers of system architecture, in view of joint optimization of link adaptation based on spectrum sensing, resource allocation, and selection between multiple networks, including underlay technologies.

The cross-layer approach will provide a new perspective in the design of cognitive systems, based on a global optimization process that integrates existing cognitive radio projects, thanks to the merge of a wide-range of expertise, from hardware to applications, provided by over 30 academic and industrial partners.

The final result will be the definition of a European platform for cognitive radio and networks. To reach this goal, algorithms and protocols for all layers of the communications stack will be designed, and a set of standard interfaces as well as a common reference language for interaction between cognitive network nodes will be defined.

Research activities are organized in Working Groups (WG) that map five Technical Challenges:

- *WG1 - Definition of cognitive algorithms for adaptation and configuration of a single link according to the status of external environment*. WG1 addresses all aspects related to single link adaptation, such as spectrum sensing, measurement and shaping, and interference suppression.

- *WG2 - Definition of cooperation-based cognitive algorithms, that take advantage of information exchange at a local level*. WG2 focus on the definition of cognitive mechanisms taking advantage of cooperation of devices in spatial proximity.

- *WG3 - Definition of network-wide mechanisms for enabling the cognitive approach*. WG3 places a particular focus on the extension of cognition from the single network device to the whole network.

- *WG4 - Definition of mechanisms for intersystem coexistence and cooperation*. WG4 addresses intersystem cooperation and coexistence under both technical and standardization/regulation points of view. Given the strong importance of regulation and standardization, this Working Group also acts as a gathering point for the organization and coordination of contributions to regulation and standardization bodies from partners of the Action.

- *WG5 - Definition of a cross-layer cognitive engine*. WG5 focuses on the introduction of cognition in devices above the network layer, exploring the definition of a cross-layer cognitive engine. The Working Group takes advantage of the results obtained in the other Working Groups in order to identify the main capabilities required for the cross-layer engine to enable an effective use of available information and device characteristics, such as the presence of multiple wireless interfaces, when available, while taking into account application requirements.

Special Interest Groups (SIGs) address research issues that span across different Working Groups:

- *SIG1 - Information representation languages*. The SIG involves experts of traditionally distant fields (radio, computer science, artificial intelligence). This topic is instrumental for both intra-device cognitive entities, and intra and inter-network cognitive protocols. This SIG investigates innovative solutions in the definition of representation languages by taking advantage of synergies between experts working on different topics in different WGs.

- *SIG2 - Learning and artificial intelligence*. The SIG allows experts to work together and possibly generate new knowledge towards the application of machine learning and artificial intelligence to the conception of the cognitive platform.

- *SIG3 - Mobility management for cognitive wireless networks*. The SIG allows experts to conceive models that are adequate to specific network typologies, and analyze techniques related to the topology control in cognitive mobile radio networks. SIG3 is intended to deal with all aspects related to mobility in the design and performance evaluation of solutions, algorithms and protocols for cognitive networks.

- *SIG4 – Positioning*. The SIG4 focuses on the different aspects of "Positioning" in cognitive radio networks. SIG4 allows experts to work together and investigate innovative techniques to address jointly the Technical Challenges from the different WGs under a common umbrella by capitalizing cognitive radio networks by positioning information and attaining positioning information in a cognitive radio network.

The IC0902 action started on December 2009 and will end in December 2013. During this time, more members, both European and international, have joined and are currently following the workshops. Currently, there are representatives from the following COST countries:

Belgium, Bosnia and Herzegovina, Croatia, Cyprus, Czech Republic, Denmark, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Ireland, Israel, Italy, Latvia, Norway, Poland, Portugal, Romania, Serbia, Slovenia, Spain, Sweden, Turkey, United Kingdom, Luxembourg and the following non COST partners: United States of America, Joint Research Center (Ispra), China, Canada, and Australia.

In relation to CoRaSat, this COST action is of relevance and its past, current and future development will be monitored by the consortium.

B.1.7 COST IC0905 TERRA

Consortium: Very big (>20 countries):

http://w3.cost.esf.org/index.php?id=177&action_number=IC0905

COST IC0905 TERRA (Techno-Economic Regulatory Framework for Radio Spectrum Access for Cognitive Radio (CR)/Software Defined Radio (SDR)) is one of the European networking activities within the framework of COST - European Cooperation in Science and Technology. This project was launched in May 2010 and will run until May 2014. The concept behind this action is to establish a multi-disciplinary European forum focused on coordinating techno-economic studies for the development of a harmonized European regulatory framework in order to facilitate the advancement and broad commercial deployment of CR/SDR systems. This action aims to focus on results and experiences from national and international research initiatives and early standard-setting activities by recommending sound regulatory policies. The main objective of this action is to develop a comprehensive techno-economic regulatory framework of radio spectrum access rules for CR/SDR, catering for envisaged CR/SDR deployment scenarios and fostering the development of the wireless industries and consumer interests at large. To achieve the above objective, this action focusses on research into development of plausible deployment scenarios for CR/SDR based on results of current and future technological research and development activities and research into what regulations would be technically feasible. Furthermore, it also focusses on research into what regulatory regime would be economically attractive, and research into the overall impact assessment and societal benefits of the developed regulatory scenarios.

This action consists of 4 working groups (WGs) and 2 special interest groups (SIGs):

- WG1 *"CR/SDR deployment scenarios"* has the objective of developing an inventory of deployment scenarios for CR/SDR as well as devising modelling methods to describe the intra-system links of functioning of CR/SDR in the given deployment scenario.

- WG2 *"CR/SDR co-existence studies"* is working with the identified CR/SDR deployment scenarios to devise and carry out the technical co-existence studies that would result in identification of essential technical rules/conditions for CR/SDR.
- WG3 *"Economic aspects of CR/SDR regulation"* focuses on evaluating the economic aspects of the developed CR/SDR regulations considering both the attractiveness of rules suggested by studies in WG1 and WG2 and the development of any new regulatory paradigms based on economic policies.
- WG4 *"Impact assessment of CR/SDR regulation"* works on carrying out impact assessment for identified combinations of techno-economic sets of CR/SDR deployment rules with the aim of identifying the most attractive combinations to form the basis for the ultimate CR/SDR regulatory framework.
- The goal of the Special Interest Group on "Energy Efficiency considerations in CR/SDR regulatory options" (SIG-EE) is to investigate various aspects of energy efficiency in CR/SDR taking into account of not only technical but also economic and regulatory issues. In particular, the ways of energy management and their influence on the deployment scenarios and devised modelling methods considered in WG1 will be investigated. Furthermore, impact of energy-utilization in the assumed co-existence studies will be examined. Finally, economic and regulatory aspects related to energy-saving in the CR/SDR will be devised.
- The goal of the Special Interest Group on "Pluralistic Licensing" (SIG-PL) is to investigate and develop concepts around pluralistic licensing, the award of licenses under the implicit assumption that opportunistic spectrum access will be allowed in associated spectrum. The goal of another Special Interest Group on "ISM Advanced" is to investigate and develop the concept of ISM advanced band i.e., possible conversion of one or a part of traditional ISM bands, such as well-known 2.4 GHz band, into CR-friendly spectrum access framework that would retain the original flexibility of ISM band while giving it new possibilities as a testing ground for more powerful wireless technologies.

B.1.8 CREW

Consortium: iMinds; imec; CTVR; Technische Universität Berlin; Technische Universität Dresden; Thales Communications & Security France; EADS; Jožef Stefan Institute.

The main target of the CREW (Cognitive Radio Experimentation World) project is to establish an open federated test platform, which facilitates experimentally-driven research on advanced spectrum sensing, cognitive radio and cognitive networking strategies in view of horizontal and vertical spectrum sharing in licensed and unlicensed bands. The CREW platform incorporates 5 individual wireless testbeds incorporating diverse wireless technologies (heterogeneous ISM, heterogeneous licensed, cellular, wireless sensor, heterogeneous outdoor) augmented with State-of-the-Art cognitive sensing platforms. In particular, CREW federates (see Figure below): a software defined radio testbed at Trinity College Dublin, a heterogeneous ISM wireless testbed at iMinds (formerly known as IBBT), a sensor network testbed at TU Berlin, outdoor heterogeneous ISM/TVWS at Josef Stefan Institute, spectrum sensing platform developed at imec, and an LTE testbed at TU Dresden. At later stages of the project, the federation welcomed additional partners to conduct experiments on the federated testbeds and/or integrate their own cognitive radio platforms or cognitive software solutions in the existing testbeds.

The CREW federated platform is designed to support the following functionalities:

- a common portal with a comprehensive description of the functionalities of the federated testbed and clear guidelines on how to access and use the federated testbed;
- the ability to "mix and match" different aspects of different testbeds to help explore as wide a range of usage scenarios as possible;
- a benchmarking framework, enabling experiments under controlled/reproducible test conditions, offering universal and automated procedures for experiments and performance evaluation, allowing a fair comparison between different cognitive radio and cognitive networking concepts or between subsequent developments;
- realistic data sets to be made available to the research community (as training data);
- performance evaluation of external hardware under controlled test conditions.

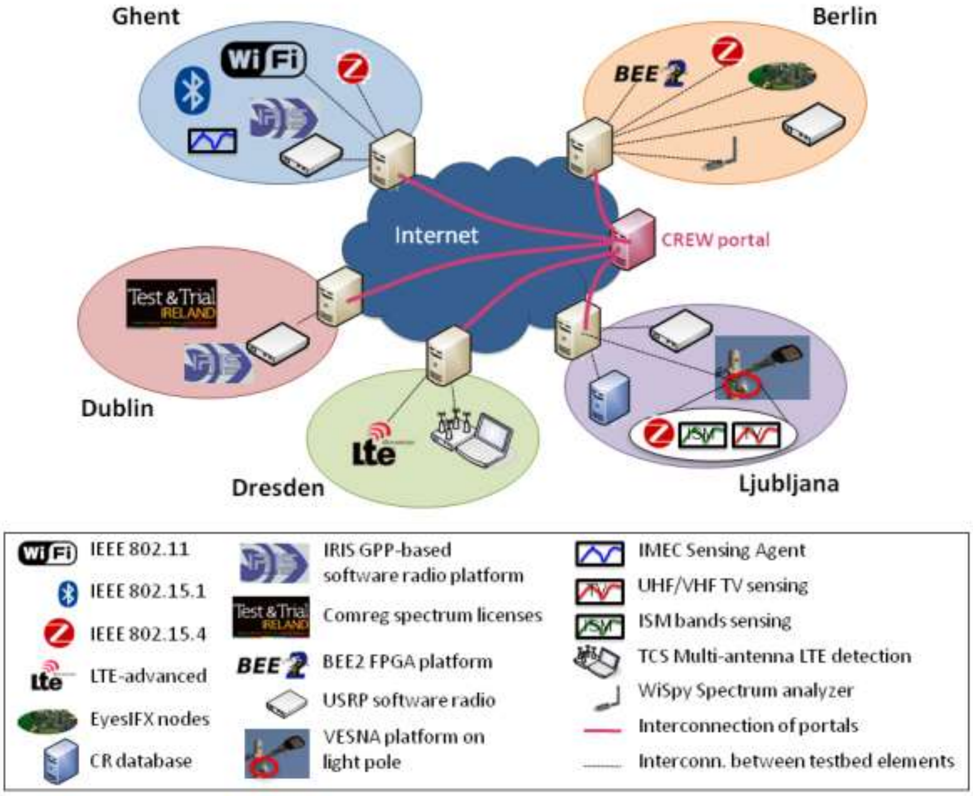

Figure 54 - CREW architecture.

The CREW platform offers 3 modes of operation:

- *Mode 1: Individual CREW testbed usage*. This mode offers the common CREW portal with clear and uniform information about access and usage of each testbed, usage scenarios, feedback on user experience & results.
- *Mode 2: Single CREW heterogeneous testbed usage*. This mode allows physically hosting of nodes from one testbed in another, hence creating new nodes from combinations of CREW hardware/software components.
- *Mode 3: Multiple sequential CREW testbed usage*. This mode enables the capturing of data/behaviours from one CREW testbed and replay for emulation or post-processing purposes on a second CREW testbed.

The CREW facilities and federation allows the experimental validation of cognitive radio & cognitive networking concepts for the following usage scenarios:

- *Context awareness for cognitive networking*, focusing on spectrum sensing in unlicensed (ISM) and licensed bands (TV white spaces, cellular systems).
- *Robust cognitive networks*, focusing on applications that require robust communications though avoiding harmful interference and using frequency agility to improve communication quality.
- *Horizontal resource sharing in the ISM band*, focusing on algorithms, protocols and networking architectures for coexistence of and cooperation between independent heterogeneous network technologies.
- *Cooperation in heterogeneous networks in TV bands*, focusing on new ideas for opportunistic spectrum access to underutilized licensed TV bands.
- *Cognitive systems and cellular networks*, focusing on the impact of dynamic spectrum access by cognitive users on LTE cellular incumbent systems.

The CREW testbed integrates experimentation platforms for terrestrial communication systems operating in terrestrial bands. On the other hand, CoRaSat's interest is in the dynamic exploitation of satellite bands by both satellite and terrestrial systems. However, since one important objective of CoRaSat is to provide a proof-of-concept implementation of cognitive radio techniques in SatComs, the lessons learnt from the implementation and development of the CREW platform will be an important input to be taken into account when building the CoRaSat test platform and demonstrator.

B.1.9 CROWN

Consortium: Queens University Belfast; Athens Information Technology, Greece; EURECOM, France; Darmstadt University of Technology, Germany; Infineon, France; QinetiQ, UK; Office of Communications, UK; Institute for Inforcomm Research (I2R), Singapore.

The CROWN (Cognitive Radio Oriented Wireless Networks) project was funded under the FP7 Future Enabling Technologies (FET) programme, which embraces research initiatives that are classified as high technical risk but with high potential reward. The main aim of CROWN was to understand the technical issues of cognitive radios through a proof-of-concept demonstrator, working towards the realistic implementation of cognitive radios for better, more spectrally and financially efficient wireless communications. The fundamental objective of the CROWN project was to address some important challenges of cognitive radio networks that prevent them from wide adoption, as well as to expand the cognitive radio concept to include useful novel cognitive radio paradigms and solutions. In particular, the main core challenges that the project addressed were: i) the problem of distributed interference awareness; and ii) the problem of communicating over as many as possible concurrent channels in the same communication spectrum with minimal mutual interference, enabled by smart antenna systems. These have been major showstoppers for cognitive radio, resulting in a low confidence that such unlicensed systems can indeed operate in a transparent way avoiding interference with each other as well as licensed systems.

The specific objectives of the project are listed below:

- the theoretical analysis of spectral efficiency in cognitive radio networks;
- the development of "distributed ambient interference sensing" techniques;
- The development of "spatially & spectrally aware" cognitive radio transmission techniques.
- the development of a new cognitive radio hardware/software communication platform.

These problems were addressed by a combination of distributed intelligence (via MAC protocol) and advanced signal processing, including interference detection and smart antenna processing, tailored to the network architecture at hand. To validate these techniques, the project analyzed information-theoretic benchmarks for the maximum spectrum efficiency bounds and developed an experimental platform (consisting of configurable hardware components with various signal processing and distributed MAC capabilities), where the developed cognitive radio techniques were tested.

In relation to CoRaSat, CROWN addressed important problems of cognitive radio that are inherently relevant to CoRaSat, such as spectrum/interference awareness methods, spectrum sharing solutions and the prototyping/validation of practical solutions for cognitive radio systems. The outcomes of the project related to cognitive radio networking and dynamic/flexible spectrum sharing are relevant to CoRaSat, as well as the lessons learnt from the implementation and development of a hardware/software platform for cognitive radio communications.

B.1.10 CRS-i

Consortium: Instituto de Telecomunicacoes; Cea-Leti; University of Surrey; Nokia Siemens Networks; NEC; iMinds.

The scope of the CRS-i (Cognitive Radio Standardization-initiative) FP7 Coordination Action is to coordinate and support existing and future projects and to facilitate the exploitation of their results by strengthening their momentum and impact on cognitive radio standardization. The main objective of CRS-i is to stimulate, facilitate and ease cooperation and exchange between current as well as future FP7 research projects on cognitive radio systems and ICT standards organizations.

To date, there are only few standards that may be used as benchmark for the type approval or the certification of the operation of cognitive radio equipment and they are rather incomplete and fairly fragmented. Notably, there are a range of standards in the IEEE 802 family, in the DySPAN 1900.x family and significant efforts by the IETF PAWS and the ETSI RRS working group, in particular in the TV White Space domain. Standardization is only a side aspect in research projects, yet most related FP7 projects do participate in and contribute to standardization bodies. However, all projects face the fact that it is difficult to achieve impact during the rather short life time of an FP7 project. In particular, standardization in cognitive radio is a process with low speed reaction because of many conflicting spectrum requirements and regulatory implications.

In this context, the main objective of CRS-i is to coordinate and support existing and future FP7 projects and to facilitate the exploitation of their results by establishing a concentrated approach to cognitive radio systems standardization. CRS-i has the following three specific objectives:

- *Offer a consultancy service on standardization to FP7 projects addressing Cognitive Radio, Dynamic Spectrum Access and Coexistence issues as a tool to facilitate the pull through the standards processes*. It is the aim of CRS-i to proactively suggest potential convergence points between FP7 projects with potential for standardization, avoiding effort fragmentation. The consultancy service will identify and concentrate on the most promising standard developments and standardization groups, and will make the research projects aware about forthcoming standardization opportunities.
- *Extend and coordinate standardization activities of the Call 4 & Call 5 projects beyond the projects lifetime, namely FP7 COGEU, FP7 QoSMOS, FP7 SACRA and FP7 OneFIT*. Standardization is a process with low speed reaction and does need more continuous engagement than 36-month projects can provide. Projects face the fact that it is difficult to achieve impact during the rather short (typically 2-3 years) lifetime of an FP7 project. CRS-i

will allocate extra resources to extend standardization activities of the FP7 projects QoSMOS, COGEU, SACRA and OneFIT after the end of these projects (December 2012).

- *Reinforce the collaboration of FP7 projects with USA and Japan's "cognitive radio stakeholders" with the potential of achieving mass market and economy of scale*. Japan and USA are leading the standardization activities on cognitive radio, driving the development of the IEEE 802.xx and IEEE 1900.x families. A strategic objective of CRS-i is to reinforce the collaboration of FP7 projects with USA and Japan's "cognitive radio stakeholders" and ensure that Europe will be able to turn the research outcomes into standard compliant products. To this end, CRS-i will establish and International Advisory Board (EU, USA and Japan). CRS-i will identify gaps, where the existing cognitive radio standards do not fulfill the European requirements, and suggest further standardization activities to fill those gaps.

It is the aim of CRS-i to help move from a fragmented contribution situation to an organized and efficient joint effort aiming at increasing the impact of EU projects on cognitive radio standardization. The overall CRS-i process is illustrated and summarized in the Figure below.

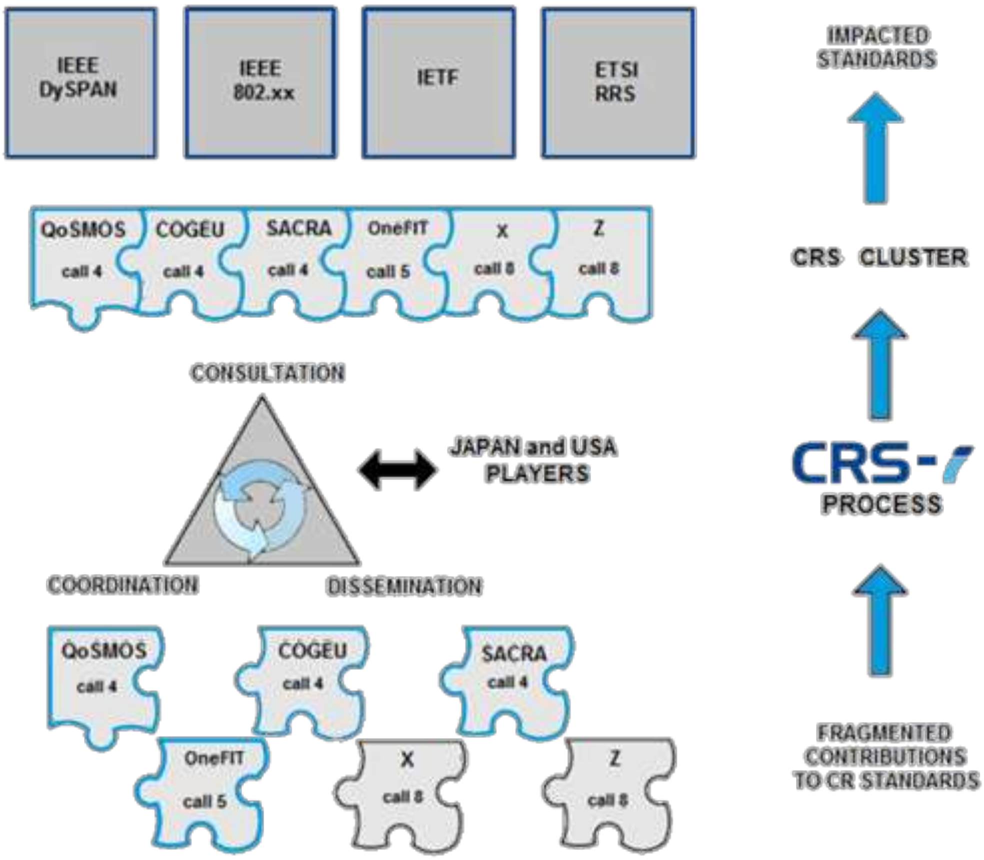

Figure 55 - CRS-i approach.

The CRS-i initiative is organized into four Work Packages (WPs). The objectives of each WP provide a good illustration of how CRS-i can help and benefit the standardization impact of ongoing FP7 EU projects, as it is the case of CoRaSat:

- WP1: Project Management.
- WP2: Standardization consultancy service.
    - Create a CRS-cluster and the legal basis for communication with the CRS-i.
    - Offer a coherent consultancy service for cognitive radio standardization to any related FP7 project.

  - Provide to FP7 cognitive radio projects state-of-the-art information on standards available or under development.
  - Drive the formation of new standardization proposals that address the missing research priorities in a coordinated manner.
- WP3: Coordination of FP7 projects contributions to cognitive radio standards.
  - Extend standardization activities of QoSMOS, COGEU, SACRA and OneFIT beyond projects life time in a coordinated manner.
  - Derive a coherent standardization approach exploiting results from FP7 projects on cognitive radio and dynamic spectrum access, avoid fragmentation of standardization efforts through specific task forces.
  - Strengthen the position of FP7 projects in standardization efforts on cognitive radio at a global level and to facilitate the pull through of European project outcomes.
  - Monitor and assessment of contributions to standards via CRS-i.
- WP4: Dissemination.
  - Organize workshops on global cognitive radio standardization and regulation.
  - Reinforce the collaboration of FP7 projects with US and Japan's "cognitive radio stakeholders" through an International Advisory Board.
  - Facilitate the creation of a common vision and priorities in cognitive radio systems beyond the boundaries of Europe.

Of special interest to ongoing EU projects, as it is the case of CoRaSat, is the CRS-i consultancy service. The objective of the CRS-i consultancy service is to strengthen the position of FP7 projects in standardization bodies related to cognitive radio at a global level, and to facilitate the pull through of European project outcomes. The overall idea and information flow of the standardization consultancy service proposed by the CRS-i is showed in Figure 56.

The standardization consultancy process is structured into the following phases:

1. In order to initiate the process of sharing information between the CRS-cluster projects and the coordination action CRS-i, is important to establish from the beginning of this action the necessary legal framework to address confidentiality between FP7 projects and the CRS-i coordination action.
2. The CRS-i, in interaction with the CRS-cluster will understand the standardization target and potential of each project on the cognitive radio area and derive a coherent standardization plan for each research project. Meanwhile, the CRS-i will pro-actively investigate and seek opportunities for contributions to standards that potentially match the projects objectives. Issues that need to be addressed by the research projects in this phase are:
   a. What to standardize?
   b. Choosing the right standards body.
   c. Getting the timing right.
   d. Funding for membership, travel and time.
   e. Which partners participate?
   f. IPR ownership, or who can contribute what?

3. FP7 projects (or the project partner responsible for the standardization activities), based on their own standardization plans and research results, will submit draft proposals to be analysed by the CRS-i consultancy service. This is done in a voluntary basis.
4. The CRS-i consultancy service will provide recommendations in order to increase the likelihood of acceptance by the target standardization bodies, e.g., appropriate time window and best location to standardize a specific R&D result, editorial revision, etc. The CRS-i will pro-actively suggest potential convergence points between FP7 projects with potential for standardization, avoiding effort fragmentation and unnecessary competition between projects and between standardization groups. Also, task forces can be built up to create sufficient momentum for successfully introducing new technical ideas into standardization or to initiate the foundation of a new Work Item or Working Group in standardization if needed.
5. The FP7 project will revise the draft proposal taking into consideration the CRS-i recommendations or ask for further advice. Finally the project (or the project partner responsible for the standardization activities) will submit the contribution to the target standardization working group.
6. Taking advantage of the deep involvement of the CRS-i partners on the global cognitive radio standards, they will follow and support the contribution through the standardization process providing continue feedback to the FP7 R&D projects. A mix of support from different types of organizations can be seen as a stronger endorsement of the EU project proposals.

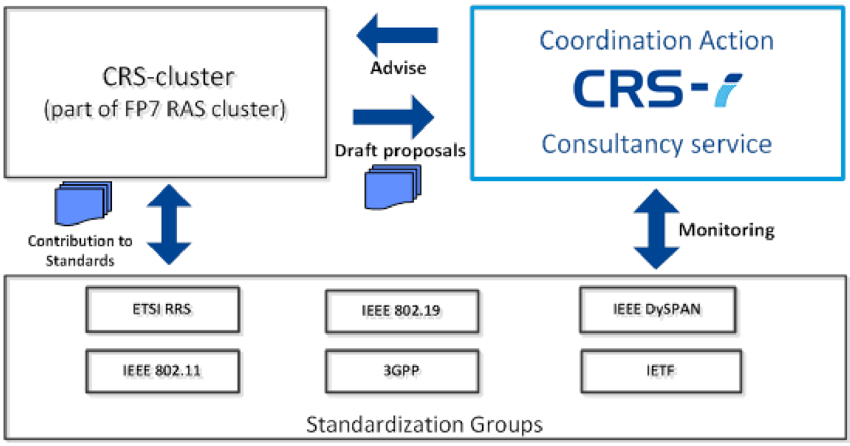

Figure 56 - CRS-i consultancy service.

The action plan of the CRS-i consultancy service is summarized in the following points:

- derivation of a plan for interfacing with standards organizations at the beginning of the new project's activities. This plan will help the project to synchronize with relevant ongoing standardization processes, and start the process of building the consensus required in order to achieve the project goals;
- selection of suitable standardization Working Groups for each research project;
- advice about the best time-window for an effective standardization impact and the requested standardization procedure;
- dissemination of Call for contributions among CRS-i cluster projects;
- setting up of a dialogue within the CRS-i cluster concerning potential synergies and common interests across projects in standardization bodies;

- follow-up standardization contributions resulting from project work and consultancy interaction.

Any EU project interested in the CRS-i consultancy service can contact the CRS-i initiative through the project's web site at http://www.ict-crsi.eu/index.php/contact-us.

The CRS-i initiative has a great potential to increase the impact of CoRaSat solutions and outcomes on standardization bodies and thus facilitate the deployment of CoRaSat techniques and solutions in cognitive radio-enabled SatCom systems. Therefore, the development of CRS-i and its activities will be closely followed and monitored by CoRaSat.

B.1.11 E3

Consortium: Alcatel-Lucent Deutschland AG; Agence Nationale des Fréquences; Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen (BNetZA); Beijing University of Posts and Telecommunications; Deutsche Telekom AG; Ericsson AB; Fraunhofer-Gesellschaft zur Foerderung der angewandten Forschung e.V.; France Telecom; IDATE; NEC technologies UK; Nokia Corporation; Office of Communications; Radio Communications Agency Netherlands; Thales Communications S.A.; Telefónica Investigación y Desarrollo S.A. Unipersonal; Telecom Italia S.p.A.; University of Surrey; Toshiba Research Europe Ltd (TREL); National and Kapodistrian University of Athens; Universitat Politecnica de Catalunya; University of Piraeus Research Center; Vrije Universiteit Brussel; Motorola SAS.

The E^3 (End-to-End Efficiency) project was aimed at integrating cognitive wireless systems in the Beyond 3G (B3G) world, evolving current heterogeneous wireless system infrastructures into an integrated, scalable, and efficiently managed B3G cognitive system framework. The key objective of the E^3 project was to design, develop, prototype and showcase solutions to guarantee interoperability, flexibility and scalability between existing legacy, and future wireless systems, manage the overall system complexity, and ensure convergence across access technologies, business domains, regulatory domains and geographical regions. E^3 was aimed at ensuring seamless access to both applications and services as well as exploitation of the full diversity of corresponding heterogeneous systems, in order to offer an extensive set of operational choices to the users (*e.g.*, seamless experience), application and service providers (*e.g.*, fast deployment of enhanced features and services in reduced time frames), operators (*e.g.*, network management, operation and maintenance), manufacturers (*e.g.*, wider market and migration to new standards) and regulators (*e.g.*, increasing spectrum efficiency). E^3 addressed the optimization of the use of radio resources and spectrum, following cognitive radio and cognitive network paradigms (autonomic management, learning, experience, knowledge as well as context, profiles, policies). Relying on the results on reconfigurable equipment of the IST E^2R project, E^3 extended the corresponding concepts towards the design of a wireless cognitive radio system, conceived on a fully cognitive system basis, where network entities are able to self-adapt to a dynamically changing context (user traffic demands, etc.). The E^3 concept is illustrated in the Figure below.

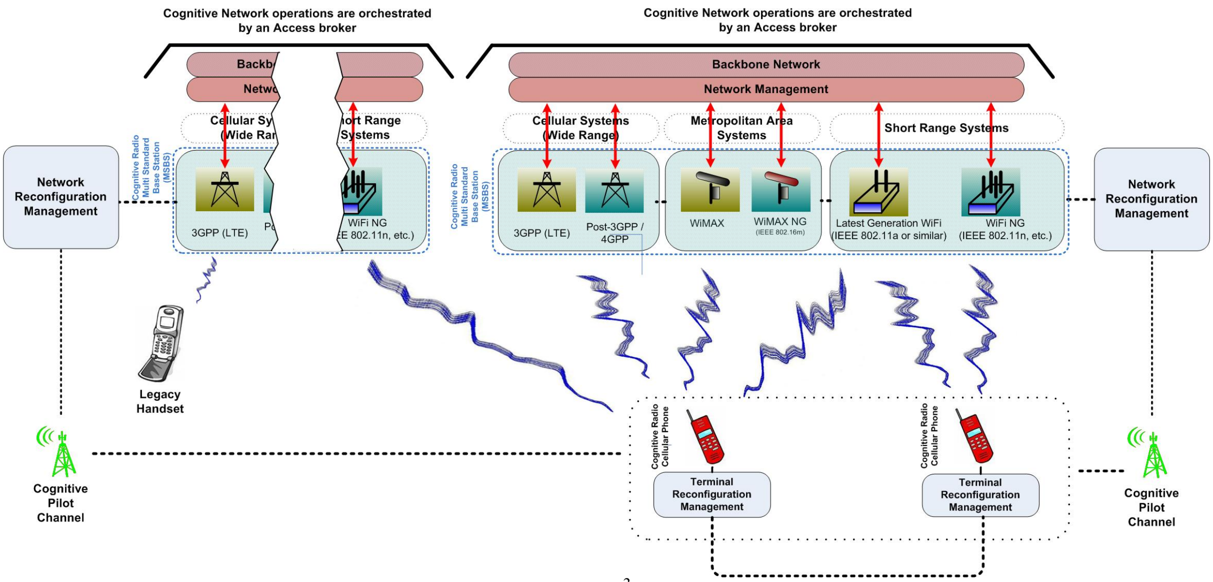

Figure 57 - E^3 concept.

To overcome the complexity of such a communication environment, E^3 set out four main objectives:

- *Design of a Cognitive Radio System exploiting the capabilities of reconfigurable networks and self-adaptation to a dynamically changing environment*. In order to minimize the reconfiguration overhead, to maximize the reactivity of network entities to any context change in a dynamic scenario and to control the calculation complexity distribution, both edges of the network and user devices are fed with context information by suitable enablers which are introduced in the project, such as a physical and/or logical Cognitive Pilot Channel (CPC), etc. Based on this knowledge, the network entities perform the link optimization in a distributed way - either fully autonomously or subject to network constraints which may be imposed in a collaborative optimization process with the goal to improve the reliability and convergence characteristics.
- *Enable a gradual, non-disruptive evolution of existing wireless networks in accordance to user requirements*. In particular, the system capacity and QoS provision is updated based on a by-need basis building on an existing deployment. The vision of ubiquitous high-speed networks is possible to become reality in a short- to mid-term perspective by exploitation of simultaneous legacy Radio Access Technology (RAT) links in mobile terminals. This approach can be enriched by future ultra-high throughput standards, representing new bricks in the heterogeneous landscape,
- *Define means to increase the efficiency of wireless network operations, in particular by optimally exploiting the full diversity of the heterogeneous radio eco-space*, both from the operators and users perspectives. In order to ensure flexible and spectrum efficient radio access, radio network parameters have to be adapted in an either network-terminal collaborative or autonomous manner with respect to changing customer behavior in order to offer optimal network performance. A key objective of the flexible and efficient use of spectrum is the provision of broadband access in rural areas.
- *Increase system management efficiency for network operation and (re-) configuration building on cognitive system and distributed self-organization principles*. Corresponding architectural designs and algorithms were proposed and assessed, specifically targeting collaborative distributed optimization of operational parameters as well as fully autonomous functions. The efficient provision of context information for distributed parameterization was also addressed.

The main technical research challenges addressed by E^3 are listed below:

- *Elaboration of a Technical Use Case Portfolio*. Reference use cases need to be defined for the context of the targeted heterogeneous and cognitive wireless system framework. Use cases were proposed covering the heterogeneity on the network side including multiple cellular, metropolitan area and short-range radio access systems as well as a heterogeneous multi-device context on the user side. The proposed use cases cover highly dynamic scenarios in which the user device constantly updates the link parameters combined with the interruption of the existing and the initiation of new links within single and multiple operator contexts.
- *Construction of an Architectural Framework*. A unique and generic architectural framework was proposed, which is network- and equipment-agnostic and is mapped onto existing/future network topologies. The framework supports both the Telecom Functions (system operations that ensure proper communication sessions control) and the O&M Functions (system operations that ensure proper behavior of the system elements) in the context of wireless reconfigurable/cognitive systems. This cognitive network architecture/framework provides a homogenized approach of the system architecture and forms a basis for the functionalities, capabilities and algorithmic solutions developed in the project.
- *Convergence of Wireless Systems*. In the context of a heavily heterogeneous, cognitive wireless systems landscape, the convergence of independently managed radio access systems towards an efficient and integrated framework is a key challenge. E^3 defined the concept of Cognitive Pilot Channel (CPC), and analyzed its logical and physical characteristics (e.g., protocols/frequency/bandwidth) as an enabler for helping the terminal to discover the spectrum allocation and to develop cognition enabling schemes for reconfigurable/cognitive systems focusing on spectrum-sensing and information provision mechanisms. The CPC concept can be used to address the hidden-node problem as well.
- *Specification of the Autonomic and Self-x related Concepts*. E^3 incorporated autonomic and self-x concepts into a System Architecture (SA) framework. The developed SA integrates self-managed and self-organizing systems governance in terms of reacting to changes of its environment in a dynamic and efficient way. Collaborative or autonomous distributed decision-making based approaches can be employed under such SA framework, considering both single- and multi-operator scenarios.
- *Optimization of Spectrum and Radio Resources following Cognitive Network Paradigms*. In the framework of a highly dynamic, heterogeneous wireless system, E^3 proposed spectrum and radio resource selection schemes envisaged to be efficient in terms of: a) high reactivity to any context change, b) low parameterization overhead, in particular from the network onto the user terminals, and c) distribution of computational optimization complexity of the various network entities. The corresponding approaches were studied from a collaborative (network-terminal) perspective as well as from an autonomous perspective, where edges of the network and user equipment entities perform non-collaborative decisions.
- *Provision for Enablers for Reconfigurable and Cognitive Systems*. Beyond the provision of a physical and/or logical CPC, spectrum-sensing approaches from both a network centric and distributed point of view were addressed in E^3 as well. The idea of this approach is to enable edges of the network as well as user terminals to identify independently available systems, either in a collaborative single-operator or non-collaborative multiple-operator scenario. For this purpose, algorithmic studies were performed with the goal of identifying available resources and access schemes in a distributed way.

These challenges were addressed considering two main approaches:

- *Collaboration in Semi-Distributed Resource Management*. Multi-standard base-stations are expected to be a key element in the future deployment of cognitive, heterogeneous wireless systems. The network operator will thus be able to dynamically adapt the spectrum occupation strategy and the choice of the suitable Radio Access Technologies (RATs) depending on the current context. On the other hand, the user terminals have to adapt their respective radio resource usage strategies depending on a time-variant network side configuration. E^3 developed solutions taking into account the specificities of heavily heterogeneous systems, which are based on collaborative and autonomous distributed decision-making principles.

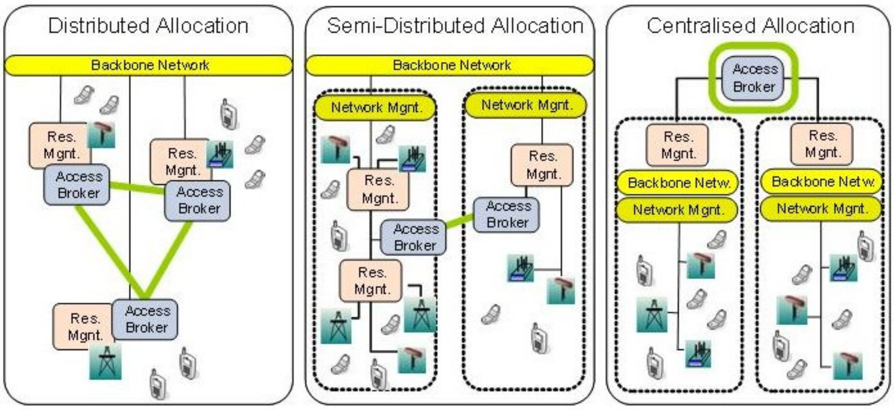

Figure 58 - E^3 Centralized and distributed management.

- *Autonomous Cognitive Radio Schemes*. While collaborative distributed decision-making requires some interactions between the network and its edges and/or the network and user terminals, any autonomous approach is supposed to perform its decisions unilaterally. In this context, two target areas are identified: a) the edges of the network adapting autonomously to the time-variant needs of the system from a network perspective, and b) the terminals (e.g., operating in a multi-operator domain) which are able to select link providers in a non-collaborative way and exchange context information mutually with neighbouring entities.

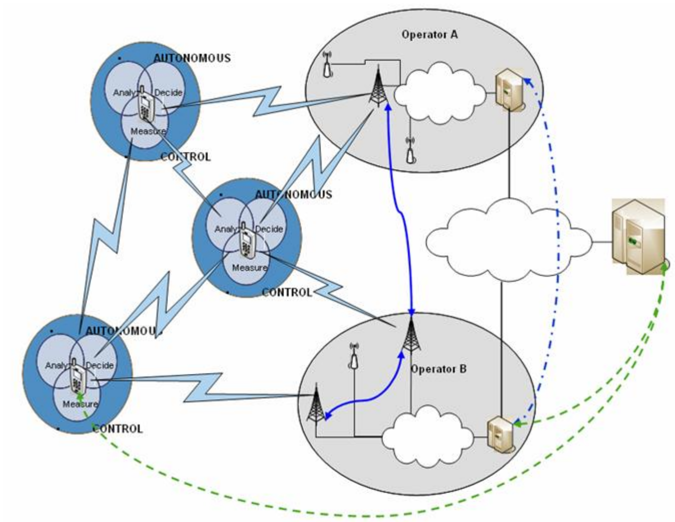

Figure 59 - E^3 Autonomous operation of system nodes.

The main contributions and technical outcomes of E^3 can be summarized as follows:

1. Business Models:

- Market assessment and business models for the introduction of cognitive systems to the B3G world.

2. Architecture of Cognitive Systems:
    - Functional Architecture (FA)/System Architecture (SA) for the introduction of cognitive systems to the B3G world.
    - Assessment framework for cognitive systems.
3. Collaborative Algorithms:
    - Self-x techniques for the optimization of radio access networks.
    - Dynamic spectrum management exploiting cognition techniques.
    - Joint Radio Resource Management (JRRM) enhanced with cognition techniques.
4. Autonomous Algorithms:
    - Functionality for creating awareness.
    - Functionalities for autonomous distributed control.
    - Functionalities for awareness signalling.
5. Enablers:
    - Cognitive Pilot channel (CPC).
    - Spectrum Sensing.
    - Cognitive Control Radio.
6. Prototyping:
    - The E3 prototyping environment.
    - Demonstration Scenarios:
        i. Knowledge-based management of reconfigurable B3G infrastructures.
        ii. Self-optimization of cognitive devices.
        iii. DSNPM-assisted femtocell reconfiguration.
        iv. Demonstration of self-x functionalities.
        v. GSM based CPC Demonstration.

In relation to CoRaSat, E^3 addressed cognitive radio and spectrum sharing approaches, and investigated their associated problems and techniques. While E^3 focused on an exclusively terrestrial domain, many of the enabling technologies proposed and researched in the context of E^3 are key ingredients to be studied and further analyzed in CoRaSat for the SatCom domain. The potential applicability of the solutions developed in E^3 (*e.g.*, self-organization and optimization, dynamic/flexible spectrum access, joint radio resource management, and awareness mechanisms such as spectrum sensing, the CPC concept or cognitive control radio) to SatCom scenarios is an interesting aspect to be analyzed and will be considered in the context of CoRaSat.

B.1.12 FARAMIR

Consortium: RWTH Aachen University; Interuniversitair Micro-Electronica Centrum VZW; Universitat Politècnica de Catalunya; Huawei Technologies Sweden AB; Toshiba Europe; Institute of Accelerating Systems and Applications; Thales Communications SA; University Ss. Cyril & Methodius, Skopje; France Telecom; Bundesnetzagentur.

The goal of the FARAMIR (Flexible and spectrum-Aware Radio Access through Measurements and modelling In cognitive Radio systems) project was to research and develop techniques for increasing the radio environmental and spectral awareness of future wireless systems. The project addressed this by developing a reference architecture and implementation for Radio Environment Maps (REMs), which are essentially knowledge bases in which cognitive radios store and access information on the environment and other wireless systems. New spectrum sensing technologies and algorithms were also developed, including novel radio neighbourhood mapping techniques for characterizing interference sources. These technologies were then applied for resource management decisions in a variety of wireless network types. The project also carried out extensive spectrum measurements to improve the understanding of usage of spectrum in Europe, both in different countries and in different socio-economic environments, and developed spectrum occupancy models to be exploited in the analysis, design and simulation of cognitive radio networks and their associated techniques and algorithms.

The main objectives pursued by the FARAMIR project were:

- *To develop a comprehensive technology chain and show how radio environmental information can be measured, collected, and represented efficiently employing Radio Environmental Map (REM) techniques*. FARAMIR developed reference architecture and functional entities, as well as parts of a context-sensitive Radio Resource Manager (RRM) in order to demonstrate its capability to optimize heterogeneous networks.
- *To conduct spectrum occupancy measurements in several European sites with different equipment and frequency bands to provide real-world data for the spectrum occupancy modelling community*. This data is shared openly and transparently with other technical communities and available online. The data provide an objective, scientific basis for the quantifiable debate on the availability of "free spectrum", and was also exploited in the project to develop spectrum occupancy models for the analysis, design and simulation of cognitive radio systems.
- *To develop necessary data models, software and protocol frameworks for exchanging spectrum data, and study the trade-offs between exchanging a large amount of data and possible errors in the data modelling*. FARAMIR took into account different scenarios and architectures, such as operator centric, distributed and heterogeneous systems. The right amount of sampling and data exchange was analyzed in this scenario, considering new concepts such as Value of Perfect Information (VPI) to quantify the benefits of REM-data measurements for RRM optimization.
- *To develop radio resource management concepts to increase operational efficiency of both legacy and future networks*. RRM solutions were developed in FARAMIR by exploiting the available radio environmental information, obtained by means of measurement-based modelling and optimization methods, including machine-learning based optimizers.

In relation to CoRaSat, FARAMIR addressed cognitive radio and spectrum sharing approaches, and investigated their associated problems and techniques. While FARAMIR focused on an exclusively terrestrial domain, many of the enabling technologies proposed and researched in the context of FARAMIR are key ingredients to be studied and further analyzed in CoRaSat for the SatCom domain.

The potential applicability of the solutions developed in FARAMIR (e.g., spectrum awareness maps such as spectrum sensing, radio environment maps, radio neighbourhood mapping techniques, or cognitive RRM techniques exploiting environmental awareness) to SatCom scenarios is an interesting aspect to be analyzed and will be considered in the context of CoRaSat.

B.1.13 MONET

Consortium: Tekever (PT), CRAT (IT), University of Surrey (UK), ISDEFE (ES), ASTRIUM S.A.S. (FR), Slovenian Administration for Civil Protection and Disaster Relief (SI).

MONET (Mechanisms for Optimization of hybrid ad-hoc networks and satellite NETworks) was an FP7 ICT Call 5 Collaborative project that aimed to guarantee the connectivity among all the actors in the emergency areas: 1) by establishing ad-hoc networks among the users when they are in the same area; 2) by connecting teams located in different areas by means of satellite links, and by connecting all the units with the CPs (Command Posts) and the CPs with the BO (Back Office) by means of satellite links. MONET scenarios that use hybrid nodes (terrestrial and satellite nodes) are shown in Figure 60 and Figure 61 below. The movement of nodes that form a mobile ad-hoc network makes it likely that some partitions may occur in the wireless network without connectivity among them. Both geostationary/non-geostationary satellites have been envisaged as a “range extension” network. The first step in understanding such hybrid networks and associated challenges is the perception of the possible applications and uses for these types of networks.

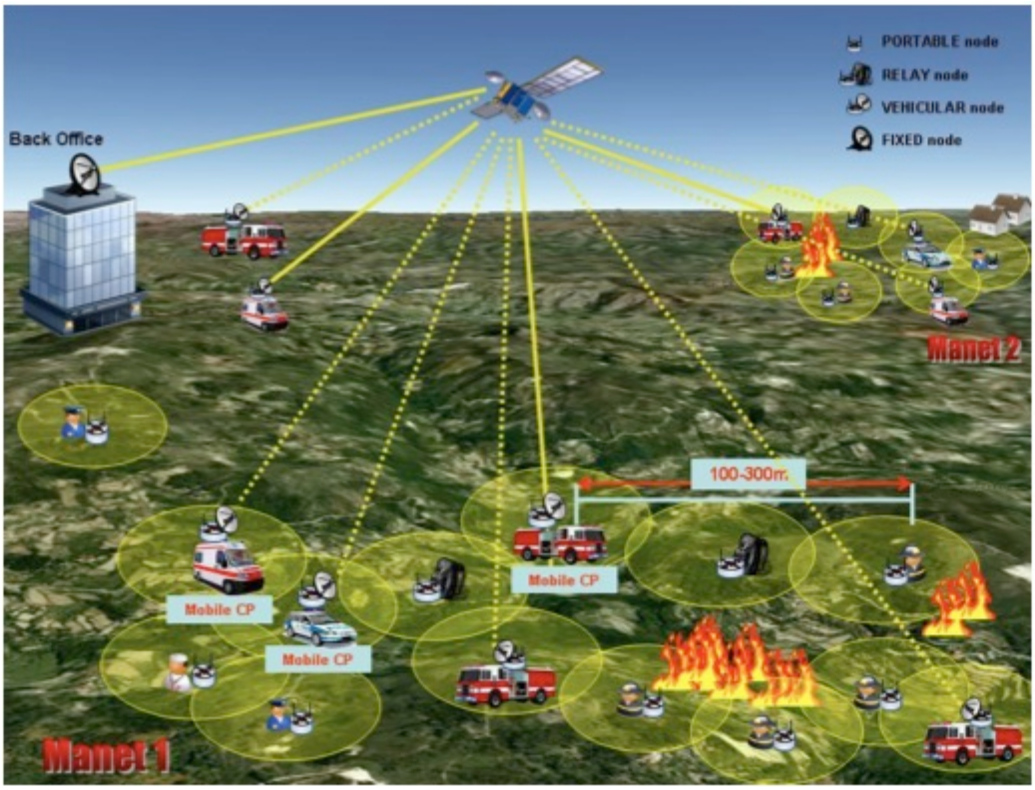

Figure 60 - MONET Forest Fire Emergency Scenario

This was achieved through the study of a set of scenarios and development of a concept of operations for the network (WP2). Next, in order to understand the complexity of these heterogeneous, dynamic and distributed environments, the MONET team investigated protocol, functional and network architectures using complementary top-down and bottom-up approaches (WP3). The most promising investigated mechanisms and solutions (WP4) were developed (WP5), implemented (WP6) and subsequently validated through a field exercise representing a real life application (WP7) in Spain. All information is available at the web site http://monet.tekever.com.

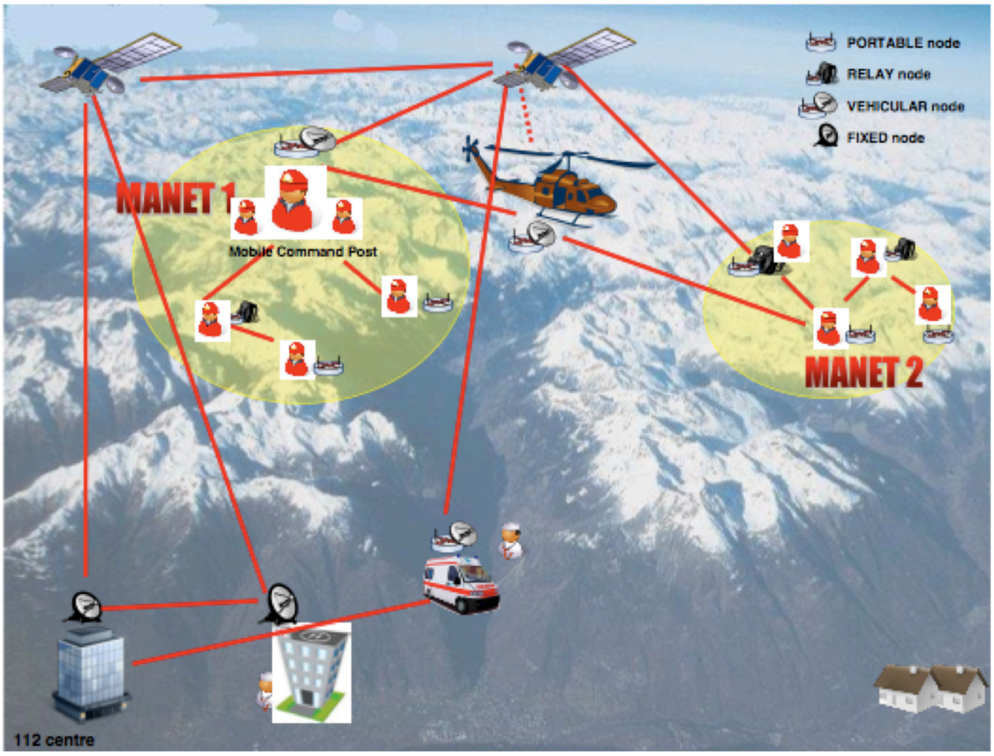

Figure 61 - MONET Mountain Rescue Emergency Scenario

B.1.14 OneFIT

Consortium: University of Piraeus Research Center; Alcatel-Lucent Bell-Labs Deutschland; Telefonica Investigacion y Desarrollo S.A. Unipersonal; Thales Communications and Security; Intel Mobile Communications; NEC Technologies UK; VTT Technical Research Centre of Finland; EIT+ Wroclaw Research Centre; University of Surrey; Universitat Politecnica de Catalunya; La Citadelle Inzenjering; Bundesnetzagentur fur Elektrizitat, Gas, Telekommunikation, Post und Eisenbahnen.

The OneFIT (Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future InterneT) project was aimed at developing and validating the vision of opportunistic networks that are managed, and coordinated with the infrastructure, by advanced cognitive systems. The aim was to enhanced wireless service provision and extended access capabilities for the Future Internet, through higher resource utilization, lower costs, and management decisions with a larger "green" footprint.

The main requirements defining the Future Internet provided the motivation for the project:

- demand for new applications/services and expanded use of wireless;
- support for diversified applications/services;
- need for increased efficiency in resource provisioning and utilization.

In order to achieve this main objective, the project addressed various technical challenges, related to the detailed objectives of the project:

- _Elaborate on business and application provision scenarios, derive requirements and technical challenges, and provide validation criteria_ (in terms of higher resource utilization, "green" footprint, and lower costs) that will drive the adoption of opportunistic networks and respective cognitive management systems in the Future Internet era.

- *Design the functional and system architecture that will address the requirements and the technical challenges*. A functional architecture was derived by identifying the required functionality for addressing the requirements, and by attributing the identified functionality to the CMON (Cognitive Management system for the Opportunistic Network) and CSCI (Cognitive management System for the Coordination of the Infrastructure) entities. The system architecture was derived by finding a deployment of the CMON/CSCI functionality to the nodes of the opportunistic network and to the elements of the infrastructure.
- *Develop the appropriate "Control Channels for the Cooperation of the Cognitive Management Systems" (C4MS)*. This involves the definition of information, signalling flows and protocols for supporting the cooperation between the CMONs, and the CMONs and CSCIs, in the realization of the management tasks: suitability determination, creation, maintenance, and handling of forced terminations. The control channels are enablers for exchanging information and knowledge on the context encountered, the profiles of users/ applications/ devices/ elements, the policies that should be applied, and the decisions reached. The basis for this is the CPC and CCR concepts, which were integrated and evolved.
- *Develop the appropriate algorithms for enabling the opportunistic network functionalities*: Cognitive systems for Managing the Opportunistic Network (CMON) and Cognitive management Systems for Coordinating the Infrastructure (CSCI). This means the realization of the CMON and CSCI functionality, in order to support the management tasks of suitability determination, creation, maintenance, and handling of forced terminations.
- *Realize the necessary validation activities for providing evidence on the efficiency of opportunistic networks and cognitive management systems for application provision in the Future Internet era*. Validation work in OneFIT consisted of experiments that involve social-networking and prosumer (derives from the combination of "producer" and "consumer") applications/services/micro-services, the cognitive management systems and their control channels, and hardware testbeds.

The solution developed in OneFIT (see Figure 9) comprises the following elements:

- *Opportunistic networks*, which are operator-governed, temporary, coordinated extensions of the infrastructure. They are dynamically created, through operator spectrum, policies, information and knowledge, in places and at the time they are needed to deliver multimedia flows to mobile users, in a most efficient manner (with respect to the targets outlined above). They can comprise network elements of the infrastructure, and terminals/devices potentially organized in an infrastructureless manner. Opportunistic networks can be characterized by the following features:
    - they are governed by operators through the provision of resources (e.g., spectrum available) and policies, as well as context/profile information and knowledge, which is exploited for their creation/maintenance;
    - they are extensions of the infrastructure that comprises various devices and terminals (envisaged in the Future Internet), potentially organized in an infrastructure-less mode, as well as elements of the infrastructure;
    - they exist temporarily for the time frame necessary to support particular applications (requested in specific location and time). Applications can be related to the social networking and prosumer (derives from the combination of "producer" and

"consumer") concepts as well as to the support of an enterprise (in a particular area and time interval) for developing and delivering products or digital services;

- at the lower layers, the operator designates the spectrum used for the communication of the nodes of the opportunistic network (*i.e.*, the spectrum derives through coordination with the infrastructure). In this respect, in principle, the bands are licensed (even though the use of license–exempt bands is not prohibited);
- the network layer capitalizes on context-, policy-, profile-, and knowledge-awareness to optimize routing and service/content delivery.

As shown in Figure 62, an opportunistic network may include cellular Base Stations (BSs), offering macrocell (macroBS), microcell, picocell, or femtocell (femtoBS) coverage, as well as WiFi access points (APs), mostly connected through wireline networks. The devices included in an opportunistic network can be mobile phones, personal computers, cameras, etc.

- *Cognitive management systems*. Two types of systems were envisaged called "Cognitive systems for Managing the Opportunistic Network" (CMONs) and "Cognitive management Systems for Coordinating the Infrastructure" (CSCIs). A fundamental idea of the OneFIT concept is to provide the means to facilitate close cooperation between the infrastructure and the opportunistic networks. Such collaboration is essential for ensuring viability, deployment and value creation for all the stakeholders. OneFIT applies, through the CMONs and the CSCIs, cognitive techniques for the management of the opportunistic networks and for coordinating the infrastructure, which leads to robustness and dependability. The approach capitalizes on the self-management features and also on the learning capabilities that must be intrinsic to cognitive systems. A cognitive management system hosts and implements capabilities for:
  - context acquisition and reasoning, profile management, and policy-awareness;
  - the cooperation with other cognitive management systems, through the exchange of profiles, policies, and context information;
  - building and sharing knowledge, which, in principle, refers to the situations (contexts) typically encountered, the policies applied, the optimization decisions taken, and the resulting efficiency achieved;
  - decision-making through cross-layer optimization functionality that takes into account the context of an operation, the profiles, the policies (potentially, of various business level stakeholders), and the acquired knowledge and experience.

The operational context describes aspects like: (i) the geo-area and time period in question, (ii) applications requested, (iii) mobility levels, (iv) radio quality, and (v) element or device status. The profile component provides information on the capabilities of devices and infrastructure-elements, the characteristics of applications, and the requirements and preferences of users. The policies provide rules for context handling, in terms of objectives to be achieved, strategies to be used for the optimization, and constraints to be respected.

CMONs and CSCIs will have functionality and collaborate for performing the following tasks:

- Determination of the suitability of the opportunistic network approach. This includes node/infrastructure discovery, identification of candidate nodes, identification and generation of spectrum opportunities from the infrastructure side, interference coordination through the exploitation of results from off-line studies.

  - Opportunistic network creation. This includes the selection of the optimal, feasible configuration of the opportunistic networks. A configuration includes the selection of participant nodes, spectrum and routing pattern.
  - Opportunistic network maintenance. This involves QoS control (monitoring and corrective actions) of the data and control flows served by the opportunistic network, and the realization of reconfiguration actions in the case of alterations in the node status, and the spectrum and routing conditions.
  - Handling of forced terminations of the opportunistic network. This means to try to preserve the provision of applications as much as possible, even when the opportunistic network has to be terminated before the data session ends.

- *Control Channels for the Cooperation of the Cognitive Management Systems (C4MS)*. The exchange of information and knowledge between the CMONs and CSCIs relies on control channels (information, signalling flows and protocols) that are built through the integration and evolution of two control concepts: the cognitive pilot channel (CPC) and the cognitive control radio (CCR). The CPC is a (logical and optionally in part a physical) channel, which provides information from the network to the terminals, e.g., on frequency bands, available Radio Access Technologies, and spectrum usage policies. Therefore, the CPC is the basis for the coordination between infrastructure and opportunistic networks, i.e., the communication between CSCIs and CMONs. The CCR is a channel for the peer-to-peer exchange of cognition related information between heterogeneous network nodes (e.g., between terminals). Therefore, it is the basis for the exchange of information/knowledge between the nodes of the opportunistic network, i.e., the communication between CMONs. OneFIT integrated and evolved the two concepts to obtain the C4MS. Evolutions involved the specification of supplementary information, signalling flows and protocols (data/packet structures and exchange strategies) required for the support of the tasks suitability determination, creation, maintenance, and forced termination handling.

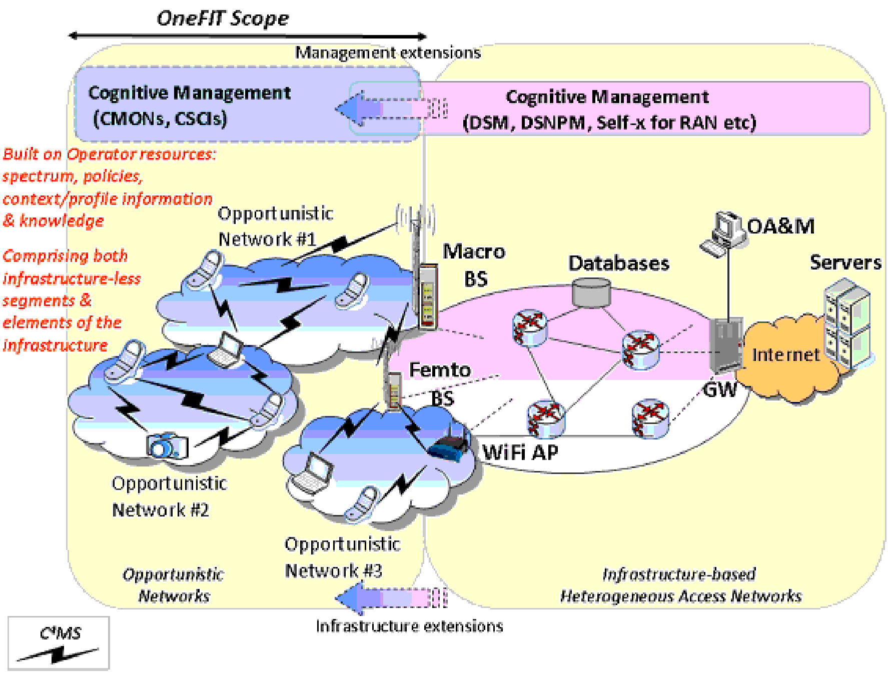

Figure 62 - OneFIT solution.

The solution developed in OneFIT was envisaged to enable efficient business and service offerings in the following scenarios:

- *Scenario 1: "Opportunistic coverage extension"* describes a situation in which a device cannot connect to the network operator's infrastructure, due to lack of coverage or a mismatch in the radio access technologies. The proposed solution includes one or more additional connected users that, by creating an opportunistic network, establish a link between the initial device and the infrastructure, and act as a data relay for this link.
- *Scenario 2: "Opportunistic capacity extension"* depicts a situation in which a device cannot access the operator's infrastructure due to the congestion of the available resources at the serving access node. The proposed solution proposes the redirection of the access route through an opportunistic network that avoids the congested network segment.
- *Scenario 3: "Infrastructure supported opportunistic ad-hoc networking"* shows the creation of an infrastructure-less opportunistic network between two or more devices for the local exchange of information (e.g. peer-to-peer communications, home networking, location-based service providing, etc.). The infrastructure governs the creation of the opportunistic network and benefits from the local traffic offloading, as well as on new opportunities for service providing.
- *Scenario 4: "Opportunistic traffic aggregation in the radio access network"* describes the usage of a local opportunistic network among several devices, in order to share a reduced number of infrastructure links towards a remote service-providing server or database. This situation allows some degree of traffic aggregation and caching that is useful to improve the overall network performance.
- *Scenario 5: "Opportunistic resource aggregation in the backhaul network"* depicts how opportunistic networks can be used to aggregate both backhaul bandwidth and processing/storage resources on access nodes. In this case, the opportunistic network is created over access points rather than user terminals, thus offering a new focus on system performance improvement.

In relation to CoRaSat, OneFIT addressed cognitive radio and spectrum sharing approaches, and investigated their associated problems and techniques. While OneFIT focused on an exclusively terrestrial domain, many of the enabling technologies proposed and researched in the context of OneFIT have potential for their application in the SatCom domain. The potential applicability of the solutions developed in OneFIT (e.g., temporary opportunistic networks/links, cognitive management systems and specified means to exchange and distribute information such as the C4MS) to SatCom scenarios is an interesting aspect to be analyzed and will be considered in the context of CoRaSat.

B.1.15 PHYDYAS

Consortium: **Conservatoire National des Arts et Métiers, France; Technishe Universität München, Germany; Tampere University of Technology, Finland; Université Catholique de Louvain, Belgium; SINTEF - Trondheim, Norway; Centre Tecnologic de Telecomunicacions de Catalunya, Spain; Research Academic Computer Technology Institute, Greece; University of Napoli Federico II, Italy; CEA-LETI Grenoble, France; Agilent-Belgium; Alcatel-Lucent Swindon, UK; Alcatel-Lucent Deutschland; COMSIS-Paris, France.**

The main objective of the PHYDYAS (Physical Layer for Dynamic Spectrum Access and Cognitive Radio) project was to develop an advanced physical layer for future radio systems (based on dynamic spectrum access and cognitive radio), exploiting a filter bank-based multicarrier technique, with enhanced efficiency and flexibility in the spectrum exploitation so that it can meet the needs and requirements of cognitive radio systems.

PHYDYAS was motivated by the fact that a new physical layer is needed for the new concepts of dynamic access spectrum management and cognitive radio. The requirements of high data rates and flexible spectrum allocation are met by multicarrier techniques, which can approach the theoretical capacity limits in communications. The scheme frequently used, i.e., Orthogonal Frequency Division Multiplexing (OFDM), is a block processing technique, which lacks flexibility and has poor spectral resolution. In contrast, a Filter Bank MultiCarrier (FBMC) technique offers high spectrum resolution and can provide independent sub-channels, while maintaining or enhancing the high data rate capability. FBMC has the potential to fulfill the requirements for future flexible/dynamic spectrum access approaches based on cognitive radio.

Based on this foundation, the project developed a set of algorithms for: (i) single and multi-antenna terminals, (ii), scalability and adaptability, and (iii) multiple access, and investigated the impact of such techniques on cognitive radio. The project included theoretical developments to complete the existing knowledge (exploiting existing results and algorithms, particularly those from the OFDM area), the design and integration of efficient algorithms, and the realization of a demonstrator. The three main research areas addressed by the project included:

- *Signal processing.* Solutions were proposed for:
    - Fast scalable synchronization and initialization.
    - Transmit and receive processing (single antenna).
    - MIMO transmit and receive processing.
    - Prototype filter and filter bank structure.
- *Communications.* Solutions were proposed for:
    - Dynamic access and cross layer aspects.
    - Backward compatibility with OFDM.
    - Radio scene spectrum analysis and cognitive radio.
- *Design and realization of a hardware/software demonstrator.* The tasks included the:
    - Development and integration of a simulation package.
    - Implementation of a laboratory setup with real-time channel emulation and performance measurement.
    - Evaluation of the radio scene analysis functionality.

In relation to CoRaSat, PHYDYAS addressed physical layer concepts and ideas that are not exclusive of the terrestrial domain and therefore may offer the possibility of a direct application to the SatComs framework with (presumably) little modifications. The outcomes of the PHYDYAS project, especially in the signal processing and communications areas, but also in the development of a demonstrator, are relevant to CoRaSat and will therefore be taken into account.

B.1.16 QoSMOS

Consortium: British Telecommunications; Alcatel-Lucent Germany; Agilent Technologies; Budapest University of Technology and Economics; Commissariat à l'Energie Atomique; Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.; Instituto de Telecomunições; NEC

Technologies (UK) Ltd; Telenor ASA; Thales Communications SA; TST Sistemas SA; Technische Universität Dresden; University of Oulu (Oulun Yliopisto); University of Surrey; NEC Corporation.

The main objective of QoSMOS (Quality of Service and MObility driven cognitive radio Systems) was to develop a framework for cognitive radio systems capable to provide QoS guarantees under user mobility, and to develop and prove critical technologies to improve the utilization of the radio spectrum, consistent with co-existence with other services and opening up of the mobile broadband value chain. To this end, the QoSMOS project developed a flexible system concept/architecture along with the algorithms, methods and solutions associated to each of its architectural components. The developed architecture is flexible enough to be mapped to a number of scenarios of practical interest, all of them in the terrestrial domain.

The architecture developed in QoSMOS is illustrated in Figure 63. The main distinguishing feature of the QoSMOS system concept is the definition of two cognitive managers (CM), which operate on different timescales and amounts of radio/spectrum resource. The spectrum manager (CM-SM) is centralized and operates on a longer timescale. The CM-SM acquires the relevant context information (from different sources such as the spectrum sensing module, SS, spectrum regulations and operator policies from appropriate repositories, along with feedback from the other CM), and based on this information builds a spectrum portfolio of the resources available in a particular region, which condenses all the above information for further use by other entities. The resource manager (CM-RM) is distributed and operates on a shorter timescale, allocating lower amounts of spectrum to individual wireless streams from the spectrum portfolio, also based on a set of rules. The main user of the spectrum portfolio is the CM-RM, which is in charge of provision of data service to upper layers (user application) using the spectrum opportunities and rules indicated by the portfolio and in accordance with service requirements. The CM-RM also provides the functionalities needed to implement incumbent protection, relying on a close cooperation with the CM-SM, which in turn implements incumbent protection on a spectrum management level. This split of responsibility between CM-SM and CM-RM adds flexibility for the allocation of spectrum. Feedback flows between both cognitive managers in order to allow an efficient operation and exploitation of the spectrum.

Besides these two cognitive managers, the QoSMOS system concept defines other modules, which are summarized in the following. The “Spectrum Sensing” entity is responsible for controlling the sensing process by interacting with the sensor, for making decision based in sensing measurements, and to report the sensing measurements back to the requesting cognitive management entities. SS is in charge of providing up-to-date environment information by means of sensing the surrounding radio environment. The “Transceiver” entity is in charge of implementing spectrum-efficient and flexible transmission and reception techniques that enable an efficient exploitation of (possibly heterogeneous) spectrum opportunities, minimizing interference to the incumbent system and at a reasonable implementation complexity. The transceiver is able to perform synchronized data transmission and to provide unidirectional or bidirectional dedicated broadcast and multicast channels on different spectrum band operated by the supported heterogeneous radio access technologies. Additionally, it provides CM-RM with measurement reports and transceiver capabilities (i.e., capabilities to transmit and receive data). The “Common Portfolio Repository” entity is used to store the spectrum portfolio and to exchange context information among network entities. The information includes available frequency bands and spectrum usage policies. The “Global & Local Regulations Policy Databases" entity is used to provide regulatory information for spectrum assignment (licensee status, usage requirements). The "Adaptation Layer" entity provides a seamless and RAT-agnostic communication between some of the different functional entities. This mainly applies to the communication in heterogeneous configurations to facilitate the data exchange between different network elements. The adaptation layer provides a unique communication interface among the QoSMOS entities that enables an easy way to exchange of information and signalling, abstracting the heterogeneity of different communication technologies. The "User Application" entity represents any application running on a user terminal providing a service to an end-user, and requiring access to the network. The user application should be able to express its requirements in terms of QoS for the CM-RMs to decide on admitting or refusing the associated service. The "Network Coordination" entity has the overall responsibility of the configuration of an operator's infrastructure network. It includes part of the mobility management, and monitors the overall performance of the networks under its control to eventually decide on the reconfiguration of network segments.

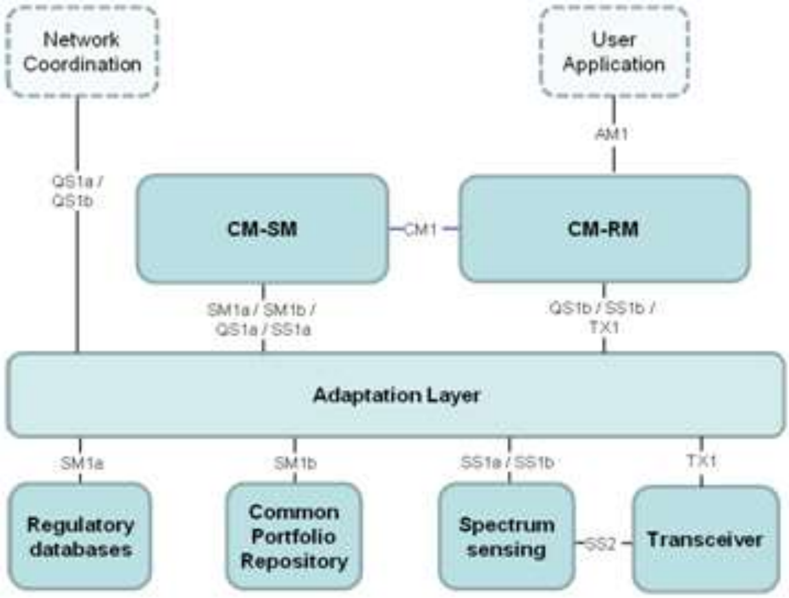

Figure 63 - QoSMOS reference model.

The QoSMOS architecture was designed bearing in mind the principles of flexibility and adaptability to various real scenarios of practical interest. The project identified six main scenarios of interest:

- *Dynamic backhaul*. This scenario involves wireless backhaul connections from access networks and remote terminals to a core network. The nodes that provide the backhaul can be relays as well as aggregators of traffic. The terminals at the access side of the network and the backhaul nodes themselves could be fixed, nomadic or mobile, so the nodes must be dynamic in how they provide a backhaul link. One example of a dynamic backhaul scenario is an emergency scenario. This emergency scenario could be a car crash. From the scene of the accident communications devices for the fire, police, and highway services need to communicate back to the rest of their team. The relays may be permanent fixtures along the roadside or temporary relays/aggregators can be deployed quickly from the nearest core network access point to the scene of the accident. Another example of a dynamic backhaul scenario is for fixed relays/aggregators that provide wireless backhaul using opportunistic access. This opportunistic access can make this solution more cost effective than alternative wireless backhaul solutions that involve paying for spectrum licenses.

- *Cellular extension in TVWS*. In this scenario, mobile networks (*e.g.*, LTE) utilize whitespace spectrum in addition to their own licensed spectrum. This additional spectrum allows for mobile operators to gain additional bandwidths to benefit the user. A mobile operator normally operates the cellular system using their licensed bands, namely base stations in the incumbent protected area using only the assigned licensed bands. On the other hand, base stations located far away from the incumbent protected area will opportunistically utilize the same spectrum band as the incumbent protected area for expanding their operational bands in addition to their licensed band without causing harmful interference to the incumbent systems. In the case of multiple operators, such opportunistically utilized spectrum is shared among them. The sharing mechanisms and management are taken by a spectrum manager with a spectrum database. The opportunistic use of spectrum could be used to enhance the coverage or capacity for a mobile operator. These represent long range and short range requirements respectively. The suitability of a spectrum band for this scenario therefore depends on whether it is to be used for coverage enhancement or capacity enhancement.

- *Rural broadband*. This scenario involves the provision of wireless Internet connectivity to homes in rural locations through a base station. This scenario has high QoS requirements, to accommodate the range of Internet usage that domestic customers require, but has a very low mobility requirement (as the locations of homes are fixed). For this system to be deployable in all rural areas it should have frequency flexibility, which is why a QoSMOS solution can be successful. The topology for a rural broadband deployment is point-to-multipoint. The homes will act as remote terminals at the user end while the base station will act as the access point providing Internet connectivity. The homes are likely to have antennas on the outside of the home. By having the antennas on the outside of homes propagation loss is reduced resulting in potential benefits such as lower power consumption, greater range and the ability to use cheaper (less sensitive) equipment. This scenario is expected to use low frequency spectrum bands that are available for opportunistic access. The low frequency of the band is desirable due to the improved propagation characteristics. The stakeholders in this scenario are mainly the network operator and the service provider. This scenario could be the most economically viable way to provide Internet access to rural locations that currently either do not have a fixed line broadband connection, or only have a low data rate broadband connection. The link length is expected to vary from 1-10km. There is no actual limit on the minimum distance. The limit on maximum distance is dependent on the transmit powers allowed, the frequency being used and the terrain. A typical example of how rural broadband connectivity might be implemented is to use TVWS spectrum to connect an isolated village that has little or no Internet connectivity and it is not cost effective to deploy a fixed line solution. The use of TVWS is a suitable spectrum band due to its favorable propagation properties as well as the fact that it is currently being opened up for opportunistic access.

- *Cognitive ad hoc network*. The ad hoc network scenario typically includes properties of high dynamics and different nodes and terminals. The nodes of an ad hoc network will typically be user terminals with added functionality for, *e.g.*, relaying, or store-and-forward. An example is an emergency ad hoc network, such as an emergency situation with several actors (police, paramedics and fire fighters). They will typically have two needs: One is to communicate efficiently between one another; the other is to establish a connection to a rescue co-ordination center. This use will typically have high requirements on quick establishment and reliable communication. Another example is a network established for a business meeting to, *e.g.*, exchange documents and other information. Dependent on the type of event, such a network may be partly pre-planned before the actual event. The requirements on quick setup may, in this case, be relaxed.

- *Direct terminal-to-terminal communication in cellular systems*. In an infrastructure-based network, all of the traffic from a mobile terminal to another mobile terminal goes through the central controller such a base station or access point. This is always true, regardless of the relative position of the two corresponding devices. For direct terminal-to-terminal (T2T) communication in an infrastructure-based network, the mobile terminals communicate directly, with no data traffic going through the base station. However, the system management in this scenario is still kept within the cellular network rather than in the terminals themselves. This is the main difference from the ad hoc scenario. A scenario in which direct terminal-to-terminal communication is beneficial is, for example, a call between close-by colleagues in an office environment.

- *Cognitive femtocell.* The femtocell scenario describes a user situation with low mobility, but high demands on throughput and QoS. It may also be described as a “hot spot” scenario. Femtocells are always connected to an infrastructure. In conventional terminology, femtocells are small base stations connected to a cellular core network via a fixed infrastructure but here we also include Wi-Fi type access points connected in infrastructure mode. The topology is thus a star-type. Femtocell hot spots are typically used as domestic wireless broadband solutions and public hot spots in e.g. commuter areas, cafés and similar. Both indoor and outdoor deployment is possible. The cognitive femtocell scenario will typically comprise two main node types: a base station or access point, and the user terminals. The access point, or “femtocell” node, must have gateway functionality and access control mechanisms. The terminal will typically be smart phones and multi-media lap-tops, but we cannot exclude simpler voice-only terminals and even sensor nodes. An Example of the scenario is a private wireless access solution of the same type as Wi-Fi is used today. This typically comprises single femtocells with access control. Another example is in public hot spots, where several femtocells comprise a larger coverage area. Access may be open for all users in the area or limited on a commercial basis. One further example is the use of indoor femtocells to provide outdoor coverage in e.g. urban/suburban streets. This can be similar to services and coverage based on sharing access points.

These six scenarios can be grouped under two generic groups that relate to the expected transmission ranges. The first group embraces longer-range scenarios (rural broadband, dynamic backhaul and cellular extension in TVWS), while the second group includes shorter-range scenarios (terminal-to-terminal communication in cellular systems, cognitive femtocell and cognitive ad hoc network). Furthermore, three of them are purely cellular (cellular extension in TVWS, cognitive femtocell and terminal-to-terminal communication in cellular systems), two purely not (cognitive ad hoc network and rural broadband) and one is covering both areas (dynamic backhaul). Figure 64 shows the mapping of these scenarios to cellular/non-cellular and long/short range.

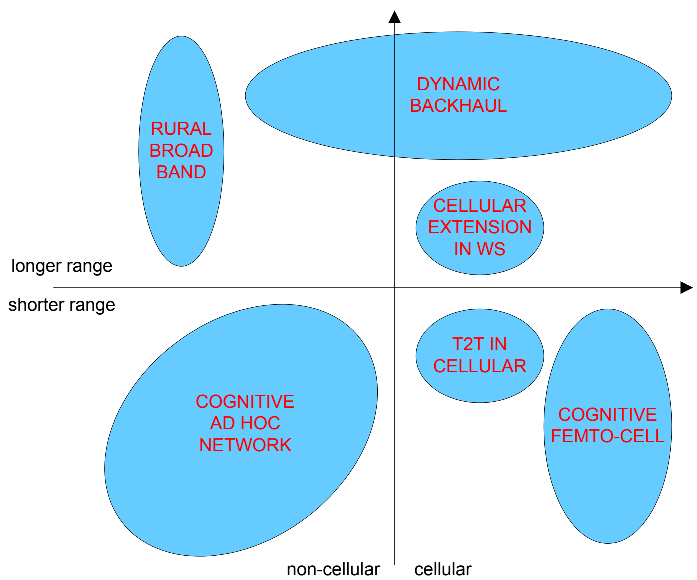

Figure 64 - QoSMOS scenarios.

Relying on the QoSMOS architecture, and bearing in mind the considered application scenarios and uses cases, the QoSMOS project developed solutions for the specific architectural elements of the QoSMOS system concept as well as solutions involving the system concept as a whole, including:

- *Spectrum micro-trading*. Spectrum trading is a tool to increase overall spectrum utilization and to open up opportunities for businesses to get access to desired spectrum. Regulatory rules for spectrum trading have been implemented in some countries for some spectrum bands, for instance in the UK and US. However, the current spectrum trading regimes usually require long times to execute a trade, hence limiting the flexibility over short time scales. Spectrum micro-trading is a concept to enable trading of spectrum at the micro scale in three dimensions: on the micro-spatial, micro-temporal and micro-frequency scale. QoSMOS defined an ecosystem for spectrum micro-trading involving spectrum traders, spectrum brokers, spectrum databases, wireless sensor networks, and spectrum regulators.
- *Radio environment mapping and sensing*:
    - *Modelling of the radio environment*. QoSMOS proposed a Measurement, Modelling and Emulation (MME) framework in order to enable cognitive radio systems to obtain awareness of their surrounding radio environment by performing measurements of the spectral activity, modelling the observed spectral activity and finally emulating the radio scene.
    - *Framework for radio context acquisition*. QoSMOS developed an architectural framework for implementing sensing functionalities and a protocol stack for exchanging sensing information. Based on the system reference model shown in Figure 63, a specific model for the sensing was extracted, which incorporates the basic functionalities and builds a framework for all the activities related to sensing. The model also highlights the different interfaces needed to communicate with other system blocks and with other sensing blocks.
    - *Algorithms for radio context acquisition*. This ranges from classical radio context acquisition (i.e., local sensing) to disseminated sensing with exchange of collaboratively or cooperatively collected context data. QoSMOS proposed new spectrum sensing solutions, namely: (i) hybrid detection, which consists in mixing energy detection and cyclostationary feature detection, (ii) improved energy detection with background process for noise estimation, (iii) antenna processing based on smart antenna techniques, (iv) improved energy detection for particular signal formats (e.g., PMSE devices), and (v) spectrum sensing based on statistical tests from the statistical test theory (Anderson-Darling and Kolmogorov-Smirnov).
- *Physical layer architecture*:
    - *Transceiver reference model*. QoSMOS developed a transceiver reference model for cognitive radio systems based on the overall QoSMOS architectural model shown in Figure 63.
    - *Flexible physical techniques for exploitation of TVWS*. This includes modifications to the conventional OFDM(A) schemes retaining as much compatibility with legacy waveforms as possible, but also other more general modulation schemes with better characteristics, identifying appropriate modulation schemes for specific scenarios and proposing adaptations of the transmission parameters. Some examples of solutions developed in this group include windowed OFDM, interference avoidance by a

combined time and frequency domain processing, Generalized Frequency Division Multiplexing (GFDM) and Filter Bank Multi Carrier (FBMC) techniques.

- *QoS and mobility solutions*:
    - *QoS and mobility framework*. QoSMOS developed a framework to provide QoS guarantees in a wide variety of cognitive radio networks under the presence of mobile terminals, considering not only the physical mobility of the terminals but also the spectrum mobility (when the spectrum used for opportunistic communications is pre-empted upon appearance of incumbent users, the opportunistic user must vacate the resources and the service needs to be promptly handed over to another available spectrum portion).
    - *Spectrum and radio resource management algorithms*. Bearing in mind the reference architectural model presented above, the QoSMOS project developed algorithms for the CM-SM and CM-RM entities (*i.e.*, spectrum and resource management algorithms), for the specific project scenarios, including resource allocation, resource exploitation, access control, mobility control, and environment cognition.
- *Proof-of-concept demonstrations*, with practical implementations of an incumbent scene emulator and spectrum sensing engine, a flexible transceiver for cognitive radio systems operating opportunistically, distributed/collaborative sensing approaches, and an integrated proof-of-concept including the main players in a QoSMOS cognitive radio scenario.

In relation to CoRaSat, QoSMOS addressed the key issues and elements in the design of a cognitive radio system operating opportunistically in an underused spectrum band. The QoSMOS system concept was developed from a general point of view, thus leading to a general and flexible architectural design. However, the flexibility and applicability of such architecture was assessed by mapping the developed reference model to the centralized/distributed network elements that can be found in various terrestrial communication systems (scenarios). However, the flexibility of the QoSMOS architecture, already shown by its mapping to a number of heterogeneous (terrestrial) scenarios, suggests the possibility to reuse the concepts and ideas of the QoSMOS system concept in the design of a similar flexible architecture for SatCom systems, which might potentially be mapped and implemented in the various scenarios considered in CoRaSat. In this task, the concepts and ideas developed in QoSMOS can serve as useful inputs to be taken into account in CoRaSat.

B.1.17 QUASAR

Consortium: Aalto University; BNetzA; British Telecommunications plc; Ericsson AB; FICORA; KTH Royal Institute of Technology; Ofcom; PTS; RWTH Aachen University; Ss Cyril and Methodius University (UKIM) Skopje; Yonsei University.

The overall objective of the QUASAR (Quantitative Assessment of Secondary Spectrum Access) project was to remove the “hype” from Cognitive Radio and Dynamic Spectrum Access discussion and replace that with clearly justified facts and quantified spectrum opportunity models that can be used to make real business and deployment decisions. The QUASAR project was aimed at bridging this gap between the claims made in conventional cognitive radio research and practical implementation by assessing and quantifying the “real-world” benefits of secondary (opportunistic) access to incumbent (licensed) spectrum. The analysis was based on two key features of cognitive radio: the ability of the secondary users to discover the opportunity to use the spectrum, and assessing the electro-magnetic impact of secondary user transmissions on incumbent system (receivers). Novel approaches were proposed beyond the traditional notion of detecting “spectrum holes,” treating spectrum opportunity discovery as a data fusion problem, as well as new schemes that cope interference from multiple uncoordinated secondary users.

More specifically, the objectives of the QUASAR project can be summarized as follows:

- *Investigate the impact of opportunistic spectrum access on incumbent system performance, especially as a function of incumbent system receiver requirements*. This work was done by taking into account not only in-channel, but also adjacent channel and electro-magnetic interference problems. The work considered both short-term impact on existing equipment and long-term possibilities to improve resilience of incumbent systems.

- *Move the community from "detecting spectrum holes" to the regime of "discovering 'real' spectrum opportunities."* A novel approach employed by the project was to go beyond relying on simple signal processing and detection, and treat the spectrum discovery problem as a data fusion problem. The project considered the modelling and decision problem in the context where information is collected from multiple different sources that include spectrum detection, databases, location context etc. The goal was to provide a full data fusion model and spectrum discovery framework for the community, which was pursued by providing methodologies and an assessment tools.

- *Develop detailed methods to assess the impact of multiple secondary users*. The provision of commercial services based on broadband wireless access will inevitably involve situations with multiple competing or cooperating secondary users, who might use heterogeneous access technologies. QUASAR considered a quantitative analysis on the impact of such situations on incumbent users, providing also insights into the performance degradation of secondary users as a function of the number of secondary users, thus providing a quantitative understanding of the achievable service levels using secondary access.

- *Multi-parameter and utility based assessment of value of spectrum (opportunities)*. The project developed a methodology to model the value of spectrum and measure the efficiency of systems based on utilities. Beyond the simplistic capacity and bit/s/Hz assessments, the project provided a more holistic and balanced viewpoint and methodology taking into account different parameters such as coverage, "user perceived quality", operational costs, etc.

- *Provide detailed roadmaps and guidelines on how to apply and analyze new opportunistic spectrum access business models*. A comprehensive analysis of the techno-economic environment from multiple viewpoints was performed and used to develop understandable and applicable what-if scenarios and models, which can be used by decision managers within different stakeholder organizations to make reasoned decisions on exploitation.

- *Provide specific and reasoned proposals to go beyond the current regulatory framework and to cover the whole value-chain inspiring interaction between all stakeholders and regulators*. QUASAR aimed at removing uncertainties in undefined cognitive radio terminology, models and value propositions.

The QUASAR project defined models, scenarios, and performance measures, on which a number of secondary spectrum access regimes were proposed and studied in the project. The project analysed the business impact of the proposed schemes as well as their regulatory feasibility. Three key issues in the technical feasibility and performance of the proposed schemes are:

- The concept of spectrum opportunity discovery and the performance of secondary access with respect to various methods to determine the possibility to fit the secondary link into the spectrum, space and time constraints given by the incumbent users.

- The impact of the performance of the incumbent system, in particular the capabilities of the incumbent receivers to withstand secondary interference, both co-channel and in adjacent channels, considering current incumbent systems (ignorant of potential secondary use) as well as future systems, designed to withstand various amounts of secondary interference.
- The real impact of secondary multi-access, *i.e.*, when several secondary users access the spectrum in a cooperative or non-cooperative way (as opposed to the conventional approach of most previous studies, which analyze the behaviour of a single secondary user accessing the incumbent spectrum).

Besides analyzing the feasibility of the various proposed secondary access regimes, the project provided performance evaluation models and tools. These methodologies and tools were integrated into a toolbox for quantitative assessment of the spectrum availability and achievable performance of secondary access. This assessment was performed both with respect to traditional capacity measures as well as using user utility base performance measures.

In relation to CoRaSat, QUASAR addressed cognitive radio and spectrum sharing approaches, and proposed new points of view and approaches on practical issues of real cognitive radio systems, as discussed above. These contributions are clearly relevant to the objectives of the CoRaSat project and, as such, will be taken into account in the developed of the technical activities of CoRaSat.

B.1.18 ROCKET

Consortium: Universitat Politècnica de Catalunya (UPC); Motorola Labs; Aachen University (RWTH); Commissariat a l'énergie atomique (CEA); Intracom S.A.; University of Surrey (UNIS); Czech Technical University (CTU); Gowex; Dune S.L.R.; Thales.

The ROCKET (Reconfigurable OFDMA-based Cooperative Networks Enabled by Agile Spectrum Use) project was aimed at providing a ubiquitous wireless solution to reach bit rates higher than 100Mbps with peak throughputs higher than 1Gbps, based on reconfigurable Orthogonal Frequency Division Multiplexing Access (OFDMA) cooperative networks enabled by agile spectrum use. While increasing peak rates is a natural must-do for new standards, the philosophy of ROCKET was that providing homogeneous high rate coverage is equally important as it guarantees a constant user experience over the whole served area and is the key enabler to a higher average spectral efficiency of the system. In line with this principle, the project addressed two questions which are at the core of future IMT-advanced system design: i) how to increase the bandwidth and make the whole system benefit from it?; and ii) How to increase system spectral efficiency and provide ubiquitous high-rate coverage?

These questions were addressed by devising methods for improved spectrum management through opportunistic spectrum usage, advanced multi-user cooperative transmission, collaborative inter-cell operation, and ultra-efficient MAC design. A prototyping platform accommodating PHY, MAC and Networking functionality was used to prove the computational feasibility of key MAC and cooperation concepts.

In particular, the main two questions addressed by the project lead to the following solutions:

- How to enlarge the bandwidth and make the whole system benefit from it?
    - *Operation on wider channels*. The maximum channel bandwidth is 20 MHz in IEEE802.16e, although WiMAX profiles are currently defined only up to 10 MHz. For such bandwidths and for the usual link budgets, an increase in the available bandwidth translates into a proportional increase in offered bit rate. It is also well known that system capacity can be further enhanced with the use of MIMO techniques

in highly dispersive environments, but these are not efficient in dealing with path loss and shadowing. Results have shown how cooperative relaying can exploit wideband short-range links to create Virtual Antenna Arrays, thus also increasing the throughput in remote areas. Taking this into account, ROCKET investigated how the whole system may benefit from wideband links.

  - *Opportunistic spectrum usage*. Allocating one wide block of contiguous spectrum for incumbent use by one given system may not always be feasible. In this case, it may be necessary to explore and exploit the locally available spectrum, after ensuring that incumbent systems operation is not disturbed and possibly applying coexistence and radio resource sharing mechanisms. In this context, ROCKET investigated and studied technologies for the opportunistic usage of spectrum.
  - *Scattered multi-band operation*. Some devices may be able to operate simultaneously in multiple-bands. As an example, a fixed infrastructure relay may be equipped with an air interface at typical cellular frequencies (1 to 3 GHz) for communication with the Subscriber/Mobile Stations, and a higher frequency air interface (*e.g.*, 5 GHz or higher) for communication with the base station or other relays. ROCKET investigated how this multi-band capability impacts the system behaviour and performance.

- How to enhance system spectral efficiency and provide ubiquitous high-rate coverage?
  - *Advanced cooperative transmission and reception techniques*. Conventional and cooperative relays can be deployed for coverage extension and spectral efficiency increase, and benefits can be obtained by using simple relay terminals especially at cell edge and in shadowed areas. ROCKET investigated cooperation at the PHY and MAC levels, which can all further improve system spectral efficiency, aimed at providing a more homogeneous experienced quality in the cell for a given deployment of base stations. In this sense, the project studied: i) improved single-user and multiuser cooperative techniques (*e.g.*, closed-loop techniques exploiting different levels of channel state information at the source and relay terminals, new protocols that use multiple relays, joint scheduling of UL and DL transmissions, etc.); ii) base stations and relay stations cooperative transmissions (cooperation can be extended to multiple base stations with relays potentially attached to different base stations, which can achieve very high uplink spectral efficiency gains at cell edge by cooperatively decoding the signal received on 3 (or more) base stations connected by high-speed fibre backhaul); and iii) joint multiple cooperative links (including interference cancellation techniques implemented in the transmitter and in the receiver).
  - *Base stations and relay stations coordination*. In this line, the project studied: i) dynamic radio resource reuse taking into account the existence of relays and their cooperation capabilities (which enables the application of low frequency reuse factors and hence the increase of the spectral efficiency); ii) cluster-based link adaptation (aimed at combining cluster-based power allocation with both cell-based modulation and coding algorithms and cooperation protocol); and iii) optimal route selection in multi-hop and cooperative communication (including multiple parallel relays, more than 2-hop paths, relay-to-relay transmission and cooperation).
  - *Ultra-Efficient MAC layer*. In this line, the project studied solutions for: i) overhead reduction (a good trade-off must be found between exploiting the degrees of freedom offered by the PHY layer versus controlling the MAC overhead); and ii)

reconfigurable MAC (since the system will be able to operate at different central frequencies, in different bandwidths, some MAC parameters will have to be adapted dynamically).

- *Adaptive schemes and resource allocation*. Several adaptive resource allocation and scheduling algorithms such as integrated bit, power and sub-carrier allocation, or user grouping for SDMA scheduling were investigated in ROCKET, taking into account that the additional degrees of freedom introduced with multi-user cooperative transmissions require the design low-complexity algorithms in order to allocate the radio resource, schedule mixed QoS users, and allocate the resource according to criteria such that the benefits of the PHY layer are realized.

From the above discussion it is clear that the two main questions addressed by the ROCKET project are also of paramount importance to the SatCom scenarios. The solutions contributed by the ROCKET project in order to address these problems are thus relevant to the objectives of the CoRaSat project and will therefore be taken into account in the definition of adequate solutions for SatCom scenarios.

B.1.19 SACRA

Consortium: Thales Communications (FR); NEC Technologies (UK); VTT (FI); Institut Telecom (FR); Fraunhofer IIS (DE); EURECOM (FR); DICE(AT); University of Athens (GR); Infineon (FR)

The aim of the SACRA (Spectrum and energy efficiency through multi-band cognitive radio) project was to design, develop and implement a multi-band cognitive radio technology for future broadband communication devices, capable to perform an optimal joint resource allocation on two separate frequency bands of the radio spectrum as illustrated in the Figure below. The objective of the project was to be able to distribute the user data flows in an optimal way, based on measurements of radio spectrum occupancy and other inputs of interest, and implement an advanced hardware platform supporting such cognitive operation. SACRA addressed jointly these different aspects in one project to guarantee a coherent system approach, towards a target scenario of interest defined at the beginning of the study. The main contribution of the SACRA project was therefore the combination of innovative approaches on radio frequency front-end and base band components design with new cognitive radio algorithms integrated into a single demonstrator platform. The main goal of SACRA was the development of this demonstrator to validate the complementary enabling techniques designed for cognitive systems to increase the system gain (throughput/power compromise), especially for IMT-advanced target, by means of a platform including wideband RF power efficient solutions for multi-band communications and spectrally efficient radio resource management.

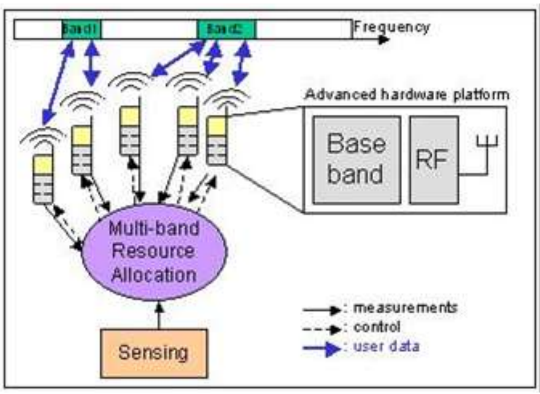

Figure 65 - SACRA concept.

In order to accomplish this objective, the SACRA project first defined a target scenario for the study, including the specification of global system requirements (architecture, target figures, characteristics) and the definition of working assumptions, parameters and hypothesis. Based on this common framework, different enabling techniques were studied and new solutions were proposed, including:

- Sensing and access techniques as well as space-time frequency polarization coding schemes.
- Radio resource management, interference management and allocation techniques for multi-band operation.
- Design of antenna and radio frequency parts: integrated RF receiver front-end and versatile ADC, compact multi-band dual polarized multiple antennas, architecture for an integrated RF transmitter, DAC and power amplifier pre-distortion.
- Flexible base band design by providing a framework for embedded software design and validation.

All these studies and the corresponding solutions were integrated in a compound system on a single platform.

The problem addressed in the SACRA project is an important problem of practical significance in cognitive radio systems and, as such, is relevant to CoRaSat. The ability of accessing simultaneously two separate frequency bands in an opportunistic manner can bring significant spectrum efficiency improvements as well as performance improvements to the secondary network.

B.1.20 SAPHYRE

Consortium: Technische Universität Dresden (DE); Alcatel-Lucent Deutschland AG (DE); Consorzio Ferrara Ricerche (IT); EURECOM (FR); Fraunhofer Institut für Telekommunikation (DE); Linköpings Universitet (SE); Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (NL); Technische Universität Ilmenau (DE); Wrocławskie Centrum Badań EIT+ Sp. z o.o. (PL)

The objective of the SAPHYRE (Sharing Physical Resources – Mechanisms and Implementations for Wireless Networks) project was to demonstrate how equal-priority resource sharing in wireless networks improves spectral efficiency, enhances coverage, increases user satisfaction, leads to increased revenue for operators, and decreases capital and operating expenditures. SAPHYRE was aimed at developing new approaches to make better use of the spectrum resources that are available for mobile communication services. Development focused on principles and enabling technologies for resource sharing in wireless networks, specifically for the sharing of spectrum and infrastructure.

The vision of SAPHYRE was to:

- Show how voluntary sharing of physical and infrastructure resources enables a fundamental, order-of-magnitude-gain in the efficiency of spectrum utilization.
- Develop the enabling technology that facilitates such voluntary sharing.
- Determine the key features of a regulatory framework that underpins and promotes such voluntary sharing.

SAPHYRE's main objectives can be conceptually described as:

- Analyze and develop new self-organizing physical layer resource (spectrum, spatial coexistence) sharing models by a generalized cross-layer and cross-disciplinary approach.

- Propose and analyze efficient co-ordination mechanisms that require only small intervention (to counteract selfish, malicious users). In particular in sharing scenarios, incentive based design was applied in order to reduce regulatory complexity.
- Develop a framework for infrastructure sharing to support quality of service with sufficiently wide carrier bandwidths and competition between different operators.
- Develop modern and novel physical layer techniques, including MIMO, SDMA, multi-hop, relay co-operative transmission, with the potential to lead to high spectral efficiency.

In relation to CoRaSat, the SAPHYRE project addressed the spectrum sharing problem in cognitive radio networks, which is the main focus of CoRaSat, and investigated their associated problems and techniques. Some of the enabling technologies proposed and researched in the context of SAPHYRE may find a field of application in SatCom scenarios and are therefore relevant to CoRaSat.

B.1.21 SENDORA

Consortium: Eurecom; KTH Royal Institute of Technology; Linkoping University; NTNU; University of Rome "Sapienza"; Telenor; Thales; Aalto University; University of Valencia.

The SENDORA (Sensor Network for Dynamic and Cognitive Radio Access) project developed a new approach for cognitive radio called "sensor network aided cognitive radio" in which a sensor network assists the cognitive radio actuation by monitoring the spectrum use. The capability to detect spectrum holes (*i.e.*, spectrum opportunities) without interfering with the incumbent network currently accessing the spectrum is a major difficulty faced by cognitive radio systems. The innovative concept proposed by the SENDORA project consisted in deploying a sensor network to solve this issue. SENDORA developed innovative techniques based on sensor networks to support the coexistence of licensed and unlicensed wireless users in a same area.

The SENDORA project targeted three major objectives:

- The identification and analysis of the business scenarios of the Wireless Sensor Network (WSN) aided Cognitive Radio technology.
- The definition and simulation of the WSN aided opportunistic access and dynamic resource allocation strategies for cognitive radios, which first requires a detailed work on the enabling techniques
- The design of a flexible and reconfigurable architecture, and a demonstration through a proof-of-concept of the WSN aided Cognitive Radio technology

To address these objectives, the SENDORA project addressed many different advanced techniques. This concept is a system approach that involves a set of advanced wireless communications techniques including spectrum sensing, interference management, cognitive radio reconfiguration management, cooperative communications, end-to-end protocol design, and cross-layer optimization. All these enabling techniques together form a compound system able to improve the spectrum use in a significant way, and as such, are relevant to the objectives of CoRaSat.

B.2 ESA Projects

B.2.1 ACROSS

Consortium: VTT Technical Research Centre (FI), Elektrobit Wireless Communications Ltd. (FI)

This section provides information on the ACROSS (Applicability of Cognitive Radio to Satellite Systems) project, funded by ESA under the ARTES 1 Programme.

B.2.1.1 Objectives

This project aimed at studying the applicability of Cognitive Radio (CR) technologies to satellite communications networks. The study was focused on the following aspects:

- performing a State-of-the-Art for CR/Flexible Spectrum Management (FSM)/Dynamic Spectrum Access (DSA) technologies both in Europe and worldwide, covering the different concepts, test bed implementations and possible deployments;
- investigation of the benefits of CR/FSM/DSA technology usage in satellite communication networks and analysis of the trade-offs between these technologies and the satellite networks specificities;
- investigation of the potential scenarios for the applicability of CR/FSM/DSA technology in satellite communication networks;
- proposal of the technology development roadmaps and usage guidelines.

B.2.1.2 Features

A broad State-of-the-Art review on cognitive radio systems, channel models, and satellite systems has been made at the initial step of the project. The development of scenarios and use cases for application of CR to satellite systems is also taken into account. The technical work carried out regarding the selected scenarios includes the use of ready-made simulation models if they are needed and applicable. Otherwise, link budget calculations and analytical methods are considered.

B.2.1.3 Challenges

The main challenges of the project were toward the search of pertinent solutions for application of CR to satellite communication, analysis of the scenarios in detail, coming up with a technology roadmap for the future, as well as selecting the applications to be further studied.

B.2.1.4 Benefits

The benefits can be mostly identified in a knowledge gain on cognitive radio techniques and their applicability in satellite systems. This project will help in finding good solutions for the efficient use of available resources both in broadcasting and two-way satellite communications.

B.2.1.5 Status and Conclusions

The ACROSS activity was completed in July 2012. It studied the applicability of cognitive radio techniques for satellite communications and defined several application scenarios that were validated in the project. A technology roadmap for the application of cognitive radio technologies in satellite communications is presented. In addition to technical aspects, the roadmap draws attention to business area both in terrestrial and satellite domain.

Based on the work carried out in the ACROSS project, the most relevant system study cases for further detailed analysis were proposed. Both technical and business viability of the proposed dynamic spectrum sharing case were explained.

As a main conclusion, ACROSS determined that significant amount of research work is required to address the many technical challenges of cognitive radio systems before the techniques can be applied in real-world telecommunication systems. For example, spectrum awareness methods, protocol design, adaptive antennas, and dynamic spectrum allocation methods will all play an important role when the CR techniques are applied for satellite systems or satellite frequencies. In addition to technical work, improvements are needed in the non-technical areas:

- New policies and regulations are needed to improve the efficiency of spectrum use to fulfil growing future requirements. For example, the Ka-band seems to have lots of potential for spectrum sharing.
- Cross-talk between different domains is required to have clear understanding on the business potential of these techniques. Market research in the area of satellite communications with the major players in the industry might open up the business potential and advance the inclusion of CR techniques for satellite communication.

Both the technical results as well as the proposed roadmap serve as a fruitful source for the research and development work in the area of application of cognitive radio techniques to satellite communications.

B.2.2 "ESA _1-5800": The Changing Regulatory and Evolutionary Environment and its impact on the Satellite Communication Business

Consortium: EADS Astrium GmbH, EADS Astrium SAS, Inmarsat Navigation Ventures Ltd, SES and Fraunhofer IIS

This section provides information on the project "The Changing Regulatory and Evolutionary Environment and its impact on the Satellite Communication Business", funded by ESA under the ARTES 1 Programme.

B.2.2.1 Objectives

The fast growing demand on frequency spectrum for the provision of broadband mobile radio services increases the competition for the allocation and potential sharing of frequency spectrum allocated to the Mobile-, Fixed-, and Broadcasting Satellite Services (MSS/FSS/BSS).

The objective of this project was to support ESA in light of a changing regulatory and technically evolutionary environment in defending the needs of the satellite communication community to maintain future availability and growth potential of frequency spectrum needed for the provision of satellite communication and broadcasting services. The project supported the studies in the regulatory domain at national, regional (CEPT), and international (ITU-R) level to find and promote additional allocations for the MSS and BSS domain under Agenda Items for the World Radiocommunication Conference 2012 (WRC-12).

Other major objectives were to investigate the potential impact of software defined radios and cognitive radio systems on future radio regulations, and to examine the impact of CGC in the 1.5-1.6 GHz MSS bands.

B.2.2.2 Features

The main features of this study resulted in the clarification and promotion of eight key SatCom items in the regulatory domain, of which three dealt with applicable regulation in the EU and the CEPT while the other covered issues in preparation of Agenda Items dealt with at the WRC-12.

The study, in support of the WRC-12 Agenda Items (A.I.):

- investigated the impact of service convergence in line with Resolution 951 (WRC-07) and the impact on SatCom frequencies (A.I. 1.2);
- followed the technical and regulatory studies on the harmonisation of spectrum usage in the band 21.4-22 GHz taking new developments in the 3D/HDTV-technology into account (A.I. 1.13);
- investigated the impact of software defined radio (SDR) and cognitive radio system (CRS) on future radio regulations taking options for flexible spectrum management (FSM) into account (A.I. 1.19);
- investigated options for additional spectrum allocations to the MSS with a particular focus in the frequency range 4-16 GHz (A.I. 1.25).

The study also analysed the consequences of the use of Broadband Wireless Access (BWA) systems authorised by EC decision 411/2008/EC for FSS operations in the C-band 3.4-3.8 GHz. The study also looked at ECC Report 100 on compatibility studies in the band 3.4-3.8 GHz between BWA systems and other services. It also investigated the impact of Complementary Ground Components (CGC) considered by some MSS systems to extend their service availability into areas of critical RF propagation (urban canyons, in-door, tunnel, etc.). This investigation put emphasis on the options for using CGCs in MSS L-band (1.6/1.5 GHz) in Europe while carefully watching the developments in the US.

D.2.2.3 Project Plan

Since the study followed closely the on-going study process in preparation of the WRC-12, the majority of activities were aligned with corresponding meetings of the regional preparatory and ITU-R meetings. Key elements of this study, besides providing contributions to these processes, were three Workshops that were convened to develop and coordinate positions on each issue to achieve a coherent approach among the promoting stakeholders on SatCom agenda items.

- Workshop#1 on FS/MS(BWA)/FSS regulation in the European Community at ESTEC, Noordwijk, The Netherlands (23rd February 2009).
- Workshop#2 on Software Defined and Cognitive Radio Systems and their potential impact on future Radio Regulations in support of WRC-12, Agenda Item 1.19 at Fraunhofer Institute (IIS), Erlangen, Germany (10th September 2009).
- Workshop#3 on the need for more frequency spectrum allocated to the MSS in support of WRC-12, Agenda Item 1.25 convened in Berlin, Germany before the CEPT Conference Preparatory Group (CPG) meeting (27th September 2010).

All Workshops also contributed to working meetings of ESA's Spectrum Management Advisory Group (SMAG). The interim final presentation was also combined with a SMAG meeting in Paris, France (January 25, 2011).

D.2.2.4 Challenges

Eight key issues were tackled as part of the ESA _1-5800 study:

1. fact finding of currently existing frequency spectrum resources allocated to the mobile (MSS), fixed (FSS), and broadcasting (BSS) satellite service;
2. the impact of service convergence on potential future radio regulation;
3. support on the analyses of the use of frequency spectrum in the 21GHz BSS band;

4. investigations on software defined radio (SDR) and cognitive radio systems (CRS) enabling flexible spectrum management scenarios and their potential impact on future radio regulations;
5. additional spectrum allocations for MSS;
6. analysis and consequences of the EU deliverables on making spectrum available to BWA;
7. the regulation for the use of complementary ground components in MSS L-band systems;
8. analysis on the current and potential future use of Ka-band spectrum for satellite communication in the CEPT member states.

B.2.2.5 Benefits

The main benefits comprised to protect SatCom frequency spectrum from sharing with other radio services and to envisage further allocations to ensure sufficient growth potential for new mobile and broadcasting satellite services.

B.2.2.6 Status and Conclusions

The main work was performed in 2008 – 2010. The support to all affected agenda items of WRC-12 was delivered. National and CEPT positions were formally taken by concluding the preparatory process. Particular work continued in support of Ka-band studies within CEPT. Difficult conditions for an additional allocation to the MSS in the frequency range 4-16GHz, made the research in Ka-band even more important. It was also concluded that the demand for spectrum to provide broadband MSS still needed further support by CEPT Administrations.

B.3 National Projects

B.3.1 CO2SAT

Consortium: SnT, University of Luxembourg; SES Engineering.

This subsection provides a short description on the rationale, main scenarios and current status of “CO2SAT: Cooperative and Cognitive Architectures for Satellite Networks”. This project is funded by the Luxembourgish Research Foundation (FNR) for the period 2011-2013 and the project partners are SnT, University of Luxembourg and SES.

B.3.1.1 Rationale

The demand for broadband access is ever increasing with various applications in business, education and entertainment. However, the available frequency resources are becoming scarce due to spectrum segmentation and the dedicated frequency allocation of the standardized wireless systems. In addition, the power consumed by current communications systems has become a limiting factor in the face of global warming, leading to the concept of green radio. Therefore, it becomes crucial to define and investigate new network architectures that have the ability to support higher system throughput and energy efficiency, while providing large-scale coverage.

In this direction, cooperative and cognitive satellite systems constitute innovative and promising network architectures, which can combine all of the aforementioned characteristics. Cooperative satellite networks operate by jointly processing the spatially distributed users at the ground station. In this context, multiuser encoding and decoding techniques can be utilized to maximize the spectral and energy efficiency. This is achieved by minimizing the inter-beam interference in multi-spot-beam satellite systems. The additional signal processing required for those techniques can be transferred to the ground station in order to maximize the satellite lifetime. Moreover, cognitive satellite systems are based on hybrid networks that combine a ground and a satellite component operating over the same frequency bandwidth. Based on cognitive overlay and underlay techniques, both ground and satellite components can communicate simultaneously with the users without the need of orthogonalization (Frequency Division), minimizing the need of purchasing expensive bandwidth. In addition, this concept can lead to the integration of satellite and terrestrial services in order to support ubiquitous indoors and outdoors coverage.

The objective of this project is to evaluate the performance gain of the aforementioned satellite network architectures in comparison to the traditional satellite systems. Although cooperative and cognitive techniques have been investigated in the context of terrestrial networks, the application is not straightforward to satellite systems due to their inherent characteristics: distortion from payload relay, power constraint, strong line-of-sight, high path loss, long shadowing. In this direction, the following figures of merit will be employed in order to quantify the system performance: i) bits/sec/Hz/Km^2 for the spectral efficiency; and ii) bits/sec/Hz/Joule/Km^2 for the energy efficiency. In all examined scenarios, the optimal figures of merit will be calculated using information-theoretic concepts in order to maintain a fixed framework of reference. In order to crosscheck and verify the performance results, the following methodologies will be utilized: i) mathematical analysis based on matrix theory and optimization techniques; and ii) Monte Carlo simulations over multiple channel instances. In the context of cooperative satellite networks, linear and non-linear precoding and decoding techniques will be considered for optimizing the system. Regarding the cognitive satellite networks, the concepts of interference alignment, interference temperature and cognitive beamforming will be employed.

B.3.1.2 Cognitive Hybrid Satellite Networks

Cognitive Hybrid Satellite Networks comprise of two communication links sharing the spectrum: i) satellite to satellite user terminal; and ii) terrestrial Base Station (BS) to terrestrial user terminal (Figure 66). In this context, it is assumed that the satellite link has priority over the terrestrial link. A possible scenario for this network architecture would be the exploitation of the VHF analog spectrum, which is going to be available after the switch to DVB-T. This spectrum could be shared by a satellite to vehicle service and a terrestrial mobile network. The objective would be to investigate how overlay cognitive techniques can be used in order to: i) help satellite users who are in low SNR conditions; and ii) provide some service to terrestrial users without degrading the QoS of the satellite link. Although these two tasks seem intuitively antagonistic, the BS can exploit the cognition of the satellite messages and achieve an optimal utilization of the available spectrum.

In this direction, the available underlay and overlay cognitive techniques are investigated in order to propose an efficient transmission scheme for this hybrid satellite network architecture. In the underlay domain, power allocation techniques which jointly optimize the system based on the interference constraints will be studied. In the overlay domain, the focus will be on cognitive transmission techniques, which employ the appropriate scheme (*e.g.*, rate splitting, relaying, known interference cancellation) according to the current channel state.

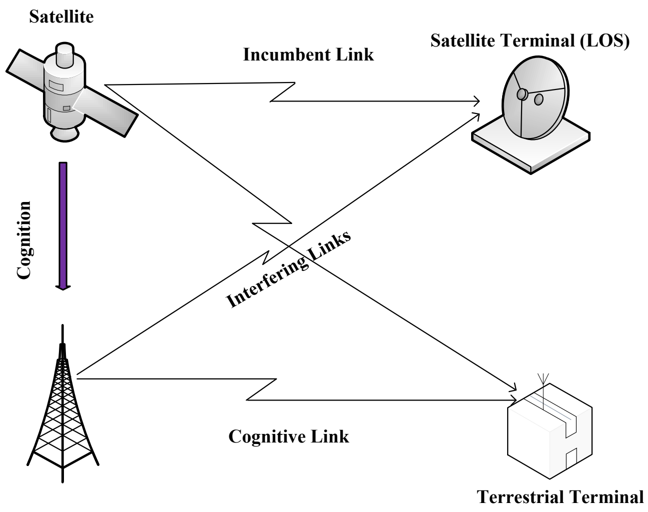

Figure 66 - Cognitive hybrid satellite network

The following table summarizes the satellite system parameters for advanced and benchmark scenarios:

Parameter	**Benchmark Scenario**	**Advanced Scenario**
User Category	Low mobility (pedestrian, nomadic) High mobility (vehicular)	
Satellite Orbit	Single GEO as a baseline, but as a second alternative three HEO to provide high elevation coverage	
Frequency Bands	Primarily S-band. Secondarily lower (L-) or higher (C-) frequency bands	
Type of Coverage	Single beam coverage	
Feeder Link BW	Feeder link could be operating at a higher band than the user link (e.g. Ku). This will determine the feeder link BW.	
User Link BW	5MHz for the incumbent service / <<5MHz for the cognitive service	
Services	Incumbent Service (e.g. broadcasting of audio/video)	Incumbent + Cognitive service (e.g. traffic or weather info)
Relevant Satellite Standard	DVB-SH or –NGH like / BGAN like	
Objective		
Benchmark vs. Advanced	Insert to the integrated/hybrid satellite communication system a cognitive service not affecting the incumbent (broadcasting) service via cognitive mechanisms.	

B.3.1.3 Cognitive Satellite Constellations

Cognitive satellite constellations (Figure 67) can be employed in order to provide overlapping satellite services over the same frequency resources and coverage area. One service is assumed to be incumbent and have priority over the share spectrum. Furthermore, it is assumed that the data streams for each service originate from different ground stations. An example of this scenario could be an operational DTH incumbent service and a cognitive vehicular multimedia service over a common set of frequencies.

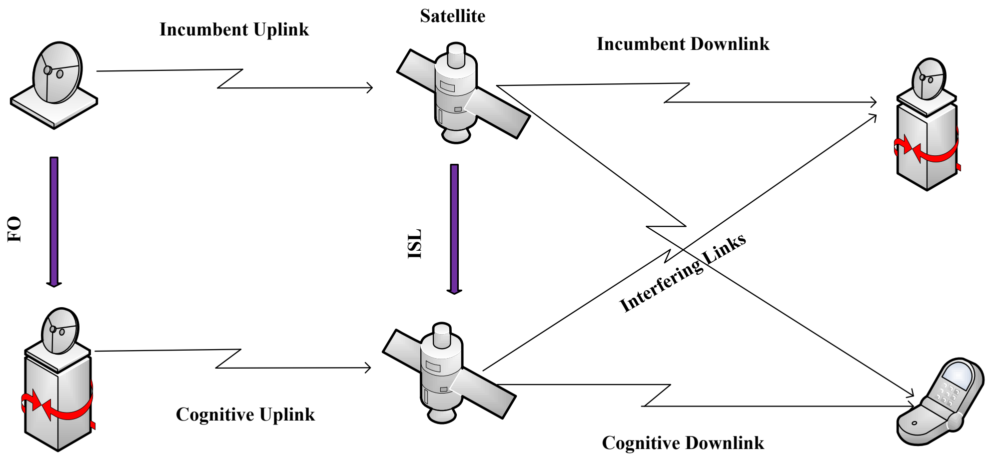

Figure 67 - Cognitive Satellite Constellations

Cognition can be enabled by considering that the incumbent system feeds the data streams and channel state information to the cognitive system. This could be possible: i) on the ground, *e.g.*, a fiber optics link feeding the cognitive information to the cognitive ground station; and b) in space, *e.g.*, an optical inter-satellite link feeding the cognitive information from incumbent to cognitive satellite. The received cognitive information can be exploited by the cognitive ground station or satellite to optimize the cognitive service performance without degrading the QoS of the incumbent service. In this direction, both overlay and underlay techniques can be exploited depending on the level of cognitive information. If only channel state information is available, cognitive power allocation techniques will be studied, while if the incumbent data stream is known, overlay cognitive techniques (as described in section 3.1) will be investigated.

The following table summarizes the satellite system parameters for advanced and benchmark scenarios:

Parameter	Benchmark Scenario	Advanced Scenario
User Category	Mobile Users – Emphasis on vehicular	
Satellite Orbit	Two independent satellite systems - one GEO and one LEO – operating orthogonal to each other	
Frequency Bands	C-, X, Ku- and Ka-bands	
Type of Coverage	Single beam coverage	
Feeder Link BW	• Feeder link could be operating at a higher band than the user link (e.g. Ku). This will determine the feeder link BW. • ISL is on higher RF or optical bands.	
User Link BW	Broadband, depending on the band	

Services	Depending on the cognitive technique
Relevant Satellite Standard	Mobile Services in high freq. bands are provided by the AmerHis satellite system. Relevant standard DVB-RCS+M
Objective	
Benchmark vs. Advanced	Investigating the cognitive synergy of introducing a cognitive LEO satellite system into an existing GEO satellite system. The general framework addresses mobile services in higher (broad) bands, which is currently also investigated by SES.

B.3.1.4 Current Status

The WP "Cognitive Hybrid Satellite Networks" started in June 2012 and will conclude by the end of 2013. Although the original scenario was focused on MSS scenarios, FSS scenarios were also considered. The following paragraph overviews the current status and contributions of the WP.

The most common cognitive techniques can be categorized into interweave or Spectrum Sensing (SS), underlay, and overlay techniques. In SS only techniques, SUs are allowed to transmit whenever incumbent users (PUs) do not use that particular band, whereas in underlay techniques, SUs are allowed to transmit as long as they meet the interference constraint of PUs. The concepts of spectrum sharing in the frequency, time and spatial domains have been considered in much literature but the polarization domain has not received much attention in SS literature. In existing literature, the polarization domain has been used for diversity and multiplexing purposes. In **[51]** the problem of enhancing Spectrum Sensing (SS) efficiency in the context of cognitive satellite communications (SatComs) has been considered and the polarization domain has been exploited as an additional degree of freedom to explore efficient SS and transmission schemes. By deploying two orthogonally polarized antennas, any type of receive or transmit polarization can be derived. Detecting the polarization state in addition to energy of a certain carrier frequency can significantly enhance the spectrum efficiency by investigating suitable cognitive techniques in the polarization domain. In this direction, the analysis of different combining techniques has been carried out for SS using a dual polarized antenna. Furthermore, polarization states of the received signals have been exploited and based on obtained polarization states, Optimum Polarization Based Combining (OPBC) technique has been used for carrying out SS in the satellite terminal equipped with a dual polarized antenna. The sensing performance of the proposed OPBC technique has been compared to Selection Combining (SC), Equal Gain Combining (EGC) and Maximum Ratio Combining (MRC) techniques. With the help of simulation results, it has been shown that the OPBC technique achieves a significant improvement in sensing performance over other considered techniques at the expense of complexity in a dual polarized AWGN channel.

In **[4]**, the problem of exploiting SS techniques for a dual polarized fading channel has been considered. Since dual polarized channel is getting important attention in current state-of-the-art related to cognitive communication, it remains an open challenge to explore the best SS technique in this channel. In this context, performance analysis of an ED based SS technique in a dual polarized fading channel using different combining techniques such as SC and EGC has been considered. Starting with single antenna case, analytical expressions for probability of detection (Pd) and probability of a false alarm (Pf) have been presented for these techniques in AWGN, SIMO and MIMO Rayleigh fading channels. Then the sensing performance of these techniques has been studied through analytical and simulation results in a dual polarized fading channel. The simulations as well as theoretical results show that the performance of ED technique in a MIMO fading channel is much better than in SIMO and SISO fading channels. Furthermore, the effect of cross polar discrimination (XPD) on SS efficiency has been analyzed and it has been concluded that the detection performance in a dual polarized fading channel increases with the value of cross polar ratio (XPR) and its lower and upper bounds occur for a SIMO fading channel and an ideal MIMO fading channel respectively.

In **[5]** different cognitive techniques such as underlay, overlay, interweave and database related techniques have been discussed with their salient features by reviewing the current state-of-the-art. Different transmission modes for hybrid satellite/terrestrial cognitive scenario have been presented. Exact beam patterns of a multi-beam satellite have been plotted over the Europe map and interference modelling between terrestrial Base Station (BS) and satellite (SAT) terminal has been carried out on the basis of interference power level. Based on results obtained from the interference modelling between terrestrial BS and SAT terminal, it has been observed that satellite terminals near polar region get more interference from a terrestrial BS than the SAT terminals located near the equator due to variation in elevation angle. Furthermore, it has been noted that interference on SAT terminal from terrestrial BS becomes worse if we move from 52^o to the North and it has been concluded that different cognitive techniques can be considered based on interference power level. SS and DB techniques seem to provide best performance in high interference region and in low or medium interference region, interference from cognitive system to incumbent system can be suppressed by using some form of underlay technique. Although overlay technique can be used in both high interference and low interference scenario by using advanced coding and suitable modulation, it appears to be suitable only for integrated systems with very high level of interaction.

In **[57]** starting with the rationale of cognitive communication, two different coexistence scenarios have been presented in the context of satellite cognitive communication. The coexistence scenarios mentioned in this paper are hybrid satellite/terrestrial scenario and dual satellite scenario. Furthermore, the benefits and challenges of cognitive SatComs have been provided and possible frequency bands for cognitive coexistence of hybrid and dual satellite networks have been listed. Then stating the importance of spectrum regulation in the context of cognitive SatComs, the current status of spectrum regulation has been presented and the relevant decisions of World Radio Conference 2012 (WRC-12) have been included. Finally, the technical aspects and regulatory challenges of this technology have been presented and future roadmap from research, industrial and regulatory perspectives has been presented. It has been concluded that if technology, market and policy are adapted to the requirements of this technology properly, the spectrum scarcity problem can be solved by deploying satellite cognitive radio systems in the near future.

B.3.2 CORE+

Consortium: EB; EXFO Nethawk; NSN; Pehutek; PPO; Renesas; Rugged Tooling; Finnish Defence Forces; VTT; CWC; Centria.

The CORE+ project aims at improving the resource usage of future mobile communication systems by introducing CRS technology to facilitate spectrum sharing and gain access to new spectrum bands.

The project will exploit the trial environments developed in the Cognitive Radio Trial Environment (CORE) project and enhance them further to trial new CRS related cellular network management concepts including:

- Authorised Shared Access (ASA) for LTE;
- Active Antenna System (AAS);
- Full Duplex Radio (FDR) and CRS;

- Device to Device (D2D) extension for FDD LTE.

The project aims to:

- enhance CORE cognitive solutions and demonstrate them using the real-life trial environments;
- perform interface and performance measurements on selected use cases;
- contribute on CRS related regulation.

The cognitive cycle shows basic operations of cognitive radio systems.

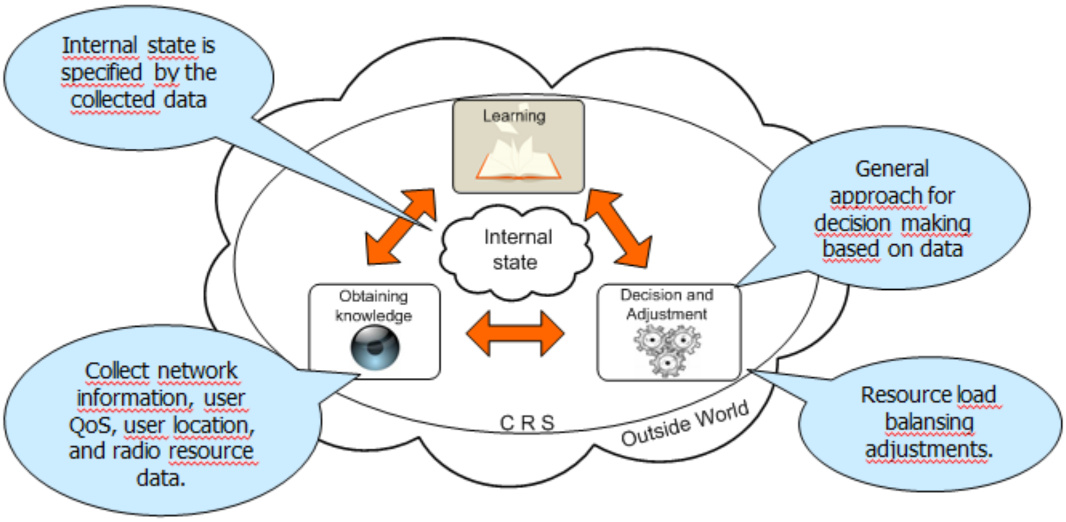

Figure 68 - CORE Cognitive Cycle

The CORE cognitive trial environment implements functions such as obtaining knowledge, making decisions and reconfiguration adjustments on the system under cognitive control. The learning function is supported by allowing the end user to modify the decision making and monitor the CORE cognitive trial environment.

The CORE cognitive trial environment provides the following tools:

<u>For obtaining knowledge from external system</u>

- CORE Client tools concept
- CORE Cognitive API

<u>For decision making</u>

- CORE Cognitive Engine
- Rule-based decision algorithm
- CORE Trial Environment User Interface
- CORE Cognitive Manager

<u>For making adjustments to external system</u>

- CORE Client tools

B.3.3 SALICE

Consortium: University of Florence; University of Rome Tor Vergata; Polytechnic of Turin; University of Reggio Calabria; University of Trento.

The project Satellite-Assisted Localization and Communication systems for Emergency services (SALICE) was an Italian project, funded by Italian Ministry of Research which started in Oct 2008 and finished in Oct 2010. Partners of the project are: University of Florence, Polytechnic of Turin, University of Rome Tor Vergata, University of Reggio Calabria and University of Trento.

The SALICE project aimed at identifying the solutions which can be adopted in an integrated reconfigurable NAV/COM device and studying its feasibility in realistic scenarios. The SALICE project aimed at providing the definition of the baseline scenarios and of the system architecture which will allow the design of new and effective solutions for what concerns integrated communications and localization techniques, Software Defined Radio (SDR) and Cognitive Radio (CR) NAV/COM devices, satellite and HAPS integration in the rescue services, heterogeneous solutions in the area of intervention (IAN, Incident Area Network). The major focus was the optimization of the resource management strategies and to the cognitive approaches [3].

In this context a specific important topic is the "Cooperative Localization" of rescue entities (persons and means) that intervene in emergency situations, where timely and precise localization of the rescuers is essential for the coordination and planning of search, rescue and disaster relief operations, in terms of efficacy and safety for both rescuers and injured people. This focus is motivated by the consideration that the indoor/outdoor location and tracking capability, integrated with the required communication infrastructure, has been recognized to be the single most important technological development enhancing emergency response operations.

B.3.4 SPECTRA

Consortium: Thales Communications; EureCom; Institut Mines Telecom; TeamCast Technology SAS; CNRS-LEAT; Monaco telecom; INDRA sistemas (SA).

During 2010 and 2011 (1/09/2010 – 31/12/2011) the project SPECTRA (Spectrum and Energy Efficiency Through Multiband Cognitive Radio) was funded by "AVANZA2" framework of Industry, Tourism and Commerce Ministry (Ministerio de Industria, Turismo y Comercio). After that period, it was funded by the participation of 2 additional Spanish partners: Wellness Telecom e Inabensa. During the time period (2012-2014) this project is funded by the R&D Subprogram of AVANZA 2 (id: TSI-020401-2012-7) launched by the Industry, Energy and Tourism Ministry (Ministerio de Industria, Energía y Turismo).

Energy efficiency and flexibility in the use of spectrum resources are two major research challenges for the development of future wireless communications technologies. To address these challenges, SPECTRA project develops a multi-band cognitive radio technology. New techniques for the global efficiency of wireless systems will be developed.

The innovation and impact brought by SPECTRA project are in the combination of innovative approaches on Radio Frequency (RF) front-end and base band components design with new cognitive radio algorithms integrated into a demonstrator platform. Thanks to the developed platform, medium term (2013-2020) application scenarios will be validated. The major outcome of SPECTRA project is a proof-of-concept able to communicate cognitively in real time, which corresponds to concrete needs today in Europe. SPECTRA project will address the minimization of the ICT environmental impact in general since it addresses the minimization of the number of electronic components and the energy optimization in wireless communication terminals. In order to minimize the electronic components, SPECTRA will use a Software Designed Radio (SDR) approach to design a flexible and agile architecture for the RF including antennas, the Analogue to Digital conversion and the digital base band processing. SPECTRA also propose Baseband/RF co-design techniques for the energy minimization in wireless communication terminals. Considering the current ICT challenges, SPECTRA project, by designing and validating new techniques for spectrum and energy efficiency in wireless communications is expected to have a significant impact on future wireless mobile systems.

B.3.5 LICoRNe

Consortium: Eurecom; Nomotech sa; Thales Communications s.a.; LaBRI Universite bordeaux i; UPMC Universite paris VI.

Efficient spectrum management and optimization are becoming the cornerstones for the deployment of our future mobile communications systems and, in this way, severely impact the incredible deployment of various mobile wireless technologies that would enable the instantiation of the 4G vision. As a direct result, cognitive radio networks are emerging as the new wireless standards that shall replace the traditional single frequency homogeneous environments. The concept of cognitive radios is based on using dynamically any available spectrum band for their communications. The LICoRNe (Leveraging Insurance for services providers cohabitation over Cognitive Radio Networks) project proposes to go beyond this emerging concept by investigating media transmission, services engineering, and management techniques over advanced cognitive radios. More specifically, the project aims to study what services can be offered to end users over a multi-hop cognitive radio network and how a dynamic and opportunistic optimization of cognitive radios shall be undergone to provide these services.

Practically, one key challenge for the cognitive radio networking to overcome resides in ensuring the cohabitation over a dynamic environment of several types of networks having each different constraints to satisfy. LICoRNe aims to study the interaction between incumbent and cognitive networks from both a user and an operator point of view. Specifically, the objectives are in one hand to develop adequate techniques to protect incumbent users' activity, and on the other hand to cohabit efficiently several cognitive networks with different requirements over the residual spectrum. This cohabitation is considered to be successful only if concrete services can be enabled. In order to achieve the specified objectives, the LICoRNe project has to overcome the following scientific and technical challenges:

- develop and study realistic business models that allow cohabitation of networks and services over the same spectrum band dynamically;
- undergo PHY design through adapted distributed coordination schemes in an unstable and opportunistic multi-channel wireless network in order to maximize the physical capacity of the wireless network;
- exploit interference holes left over the spectrum opportunistically while mapping them to different service requirements for end users;
- develop and implement multi-criteria routing techniques to take into account instability, availability, learning capacities, and diversity of cognitive radio environment;
- adapt and ensure adequate transport level for the different services to offer;
- build a feasible and dynamic management infrastructure;
- validate service cohabitation with representative scenarios over a test platform and a real-life implementation hosted at a network operator.

B.4 Other Projects

Some projects related to coexistence of heterogeneous cognitive radio networks have been completed in University of York (UK). For example, "Coexistence of Heterogeneous Cognitive Radio Systems" deals with establishing how broadband terrestrial and High Altitude Platform systems should use the same spectral allocation in order to maximize system capacity and quality of service. Similar project "Cognitive Networking for Heterogeneous Wireless Systems" has been completed at the same department as well.

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