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DR9.1
Identification of relevant scenarios, use cases and initial studies on JRRM and ASM strategies

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Abstract:

This deliverable (DR.9.1) identifies relevant scenarios and use cases, enabling initial and further studies related with the following research fields: radio resource management, joint radio resource management and advanced spectrum management techniques and strategies. These studies are under the heterogeneous networks framework. A state of the art for each main research field, initial studies, and in some cases, preliminary results, are presented in this deliverable. A special attention to OFDMA spectrum measurement and management, game theory and cognitive networks is given.

Keyword list: RRM, JRRM, ASM, Game Theory, OFDMA Spectrum Management and Cognitive Networks.

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1 INTRODUCTION

1.1 Objectives

WP R.9 addresses the development and evaluation of advanced Radio Resource Management (RRM) and spectrum management techniques for wireless communications systems in heterogeneous scenarios, where different access technologies co-exist, so that by means of a joint use of the pool of resources significant capacity gains and a more efficient use of the spectrum can be achieved. The introduction of cognitive network functionalities in the developed strategies is explored in order to provide the different systems with the ability to adapt to changing conditions.

The WP is structured into three tasks:

- Task TR9.1: Joint Radio Resource Management (JRRM) strategies in heterogeneous networks.
- Task TR9.2: Advanced Spectrum Management (ASM) strategies.
- Task TR9.3: Cognitive functionalities in the JRRM-ASM strategies.

Nevertheless, this report, entitled “Identification of relevant scenarios, use cases and initial studies on JRRM and ASM strategies” is not structured according to the tasks, in order to better reflect its goals. The main idea was to address the specific matters of the report, namely the aspects of scenarios and use cases, as well as initial studies and algorithms on the main areas of the WP.

Although research can be performed without considering applications and end use situations (this is certainly the case for basic research), when addressing RRM and ASM in heterogeneous networks, there is an added value in considering specific systems, or technologies, since the algorithms and strategies, and their performance in particular, end up depending on particular systems. This deliverable, offers this perspective, by presenting various models and algorithms, followed by the description of several use cases.

1.2 Document Organisation

The work methodology taken for this deliverable was as follows: WPR9 partners were organised in Working Groups (WGs), and for each WG (at least two partners involved per WG, Table 1), a specific research topic was identified. However, the organisation of this deliverable follows a coherent and global view of the different research fields, thus, at chapter level, some WGs worked together in order to propose a common and integrated result, where experience and data exchange among partners took place.

Table 1 – WPR9 Working Groups organisation.

WGs	WG Name	Involved Partners
WG1	JRRM in heterogeneous networks	IST-TUL, CNIT-Bologna
WG2	Spectrum allocation for OFDMA networks	CNIT-Pisa, PUT, UPC
WG3	Game Theory for optimisation of RRM, distributed algorithms for CR	PUT CNRS-Supelec, CNRS-Eurecom, CNIT-Pisa
WG4	Measurements to detect spectrum availability. Partners:	UPC, CNRS-Supelec
WG5	Cognitive Radio Network based on Sensorial radio bubble	CNRS-Supelec, UPC, CNIT Bologna, CNRS-Eurecom.

The organisation of this document is as follows: besides this first and short introductory chapter, Chapter 2 deals with Radio Resource Management, and mainly JRRM, algorithms at different levels, a state of the art being presented, as well as initial studies. Some optimisation schemes for RRM (spectrum allocation strategies) and JRRM (fuzzy logic control optimisation) are also addressed. A Game Theory state of the art and a framework for RRM is also described. Additionally, a particular attention for recent Orthogonal Frequency Division Multiple Access (OFDMA) spectrum allocation based networks is also presented, where single- and multi-cells studies are described. Chapter 3 is devoted to ASM strategies. In this chapter, different techniques are described, as well a framework for

ASM development based on the Cognitive Network concept. The possibility to create Cognitive Networks based on the Sensorial Radio Bubble concept is also addressed. Additionally, initial spectrum measurements results to detect spectrum occupancy in different bands are also presented. In Chapter 4, some relevant scenarios and respective use cases, useful to study previous strategies and algorithms, are described in detail. Finally in Chapter 5, major conclusions are highlighted.

2 RRM AND JRRM ALGORITHMS

2.1 Introduction

In this chapter RRM and JRRM strategies and algorithms are addressed. The RRM and JRRM algorithms sections were addressed by WG1. Other RRM particular areas were also addressed, like the Game Theory, handled by WG3. WG2 contributions are focused in OFDM spectrum allocation techniques, presenting single and multi-cells studies.

2.2 RRM and JRRM State of The Art

2.2.1 JRRM

All technologies that integrate wireless and heterogeneous systems have in common the function of RRM that controls the used capacity of the radio interface and maintains operations stable, by handling functions such as admission control, power control, and handover control. The dynamic behaviour of RRM is only indirectly controlled by network management Operation and Maintenance (OAM) functions in an operator network. RRM algorithms work on much faster timescales than network management functions, so they must optimise the real-time operation and behaviour of the network. In addition, RRM algorithms operate on a more localised view of the network performance (the network element or sub-network level) than network management functions, which consider entire networks and inter-networks. RRM and Network Management interact in providing performance measurements and fault information (performance and fault management) by RRM, and in the long-term modification and adaptation of RRM algorithm parameters by Network Management functions (network planning/optimisation and configuration management). Efficient and flexible RRM is an essential requirement to optimise the usage of the scarce spectrum resources, and to offer the best end-to-end QoS to users.

In a heterogeneous environment, RRM functions are even more important, as the adopted policies and strategies will produce additional information being generated, as a result of the existence of more users and types of users in different radio environments in the network, and more frequent enhancements of the RRM algorithms. The overall evolution of the relationship between RRM and Network Management can be viewed in a cooperative perspective, leading to a new entity, the JRRM, which executes high level decisions and implements management policies, and can support advanced auto-tuning solutions. Thus, the objective of this section is to provide a state of the art concerning RRM and JRRM, providing some initial studies, and proposing some models that can handle the previous concepts. Moreover, advanced artificial intelligence techniques to support monitoring and self-managing on heterogeneous infrastructures, based on advanced RRM and JRRM rules and QoS, are also addressed. Based on this, the infrastructure will monitor network performance continuously from the available data sources, evaluate service quality, and calculate RRM parameter settings better suited to a certain situation and adapted to changing traffic conditions.

While scanning the literature concerning JRRM strategies, Cost Function (CF) based algorithms applied to cellular networks are frequent. These are usually provided by a simple CF, which is computed based on the given network Key Performance Indicators (KPIs) set. In this context, CFs are typically used to solve network optimisation problems, like the cases presented in [1] where Base Station's (BS) cost and KPIs are mapped onto colours (KPIs and RGB association), providing a human perception of the network conditions. In [2], the soft handover in UMTS is optimised based on a normalised CF that uses weighted KPIs to classify the UMTS BSs conditions.

In some cases, the CF is used to perform JRRM decisions (e.g., vertical handover decisions), like the cases proposed in [3], [4], [5], and [6], where, based on a CF result, the best network interface and the best moment to perform handover is presented. Based on these, one may conclude that the CF is also a good way to build a common and comparable parameter to all Radio Access Network (RANs) in a heterogeneous cellular network environment.

The RRM and JRRM entities, and corresponding functionalities and algorithms, must perform important decisions based on a huge amount of spatiotemporal data. These data consist of counters and performance indicators generated mainly by BSs. Since the number of these parameters is increasing, and JRRM requires a high level view of the network performance, a common and integrated parameter that can evaluate radio resources availability or network conditions, is required. In order to implement this important task, a CF model must be defined.

As already mentioned, an important mechanism in JRRM is the handover; in a heterogeneous networks environment, the handover process can be done in two different ways: Horizontal Handover (HHO) and Vertical Handover (VHO). The HHO case is the "classical" handover that happens inside a given cellular system at RRM level; in this case the handover can be triggered by the Mobile Terminal (MT) movement (signal strength level), traffic reasons (e.g., BS load balancing) or even in some cases by other particular operator policies. In the VHO process, decisions can be very interesting, since this type of handover can be triggered based on a wide set of parameters, and/or operator policies/strategies.

Many of them have the signal level and the service financial cost in common, as VHO triggering parameters. But looking at the most recent publications the trend is to include others, like operator's policies and network conditions. Therefore, in the future, it is expected to have a more complex process, not only caused by the increasing number of parameters considered in the decision method, but also by the increasing number of wireless systems available to a multi-system MT.

In the IST-AROMA project, [6], a so-called Fittingness Factor (FF), defines a generic model that tries to capture all the effects influencing the RAN selection decisions. Specifically, in order to cope with the multi-dimensional heterogeneity, two main levels are identified in the RANs selection problem:

1. Capabilities: a user-to-RAN association may not be possible due to limitations by the user terminal capabilities (e.g., single-mode MTs only able to be connected to a single RAN) or the type of services supported by the RAN (e.g., videophone is not supported in 2G networks).
2. Suitability: a user-to-RAN association may be suitable, depending on the matching between the user requirements in terms of QoS and the capabilities offered by a given RAN (e.g., a business user may require bit rate capabilities feasible on Medium Bit rate Networks (MBNs) and not on Low Bit rate Networks (LBNs), or these capabilities can be obtained in one technology or another depending on the RAN occupancy, etc.).

In the literature, different authors address this issue, using different parameters to trigger VHO: in [7], the service type, network conditions, operator policies, user preferences, and signal level are taken into account for a VHO decision; authors in [8] use the service financial cost, signal level, QoS, user velocity, and link capacity; similar, in [9], the service financial cost, signal level, and throughput are taken into account. The fuzzy control approach is also considered in [10], which is based on signal level, service financial cost, and bandwidth. In [11] and [12], the signal level, signal to interference ratio, and Bit Error Ratio (BER) are used, therefore, being much focused on signal quality, neglecting other network conditions. In [13], a combination of signal level, service delay sensitivity, service financial cost, and mobile conditions is used. A novel and interesting approach is taken in [5], where signal level, QoS, user's and operator's preferences, and load balancing are used. Finally, a set of references propose VHOs triggers using less parameters: authors in [14] take only user velocity, only signal level and distance are considered in [12], and in [15] HO uses only delay and users velocity.

In [16], a Joint Call Admission Control (JCAC) algorithm for heterogeneous networks is presented, which considers the user's preference in making admission decision. A specific case where the user prefers to be served by the RAN that has the least service cost is modelled and evaluated using Markov Decision Processes; the results shows that overall service cost in a heterogeneous network can be significantly reduced by using the proposed JCAC algorithm. In [17], JRRM strategies that achieve lowest blocking rates are presented, numerical results comparing the different JRRM strategies and point out the advantages and drawbacks for each of them; the best performance is obtained when

VHOs are performed. In [18], an admission control strategy for JRRM is presented, highlighting the advantages of statistics based methods over counter-based ones.

2.2.2 RRM Optimisation and Monitoring

Recent trends in joint radio access network optimisation research include the concept of autonomous or self-managing systems and the application of artificial intelligence techniques to support self-management tasks, such as optimisation, monitoring and fault diagnosis.

In a heterogeneous environment, RRM functions are even more important, as the policies and strategies adopted will result in additional information being generated as a result of more users and types of users in different radio environments in the network, and more frequent enhancements of the RRM algorithms. The overall evolution of the relationship between RRM and Network Management can be considered as a part of the auto-tuning solution.

There is a set of parameters controlling the RRM function, and these parameters are normally set when planning a mobile network. The parameters can vary among different BSs, and the operator can adjust the parameters to obtain a desired performance. The objective of the mobile RAN optimisation process is to optimise RRM parameters in order to improve network capacity, maintain or improve the QoS level desired by the operator, or perform quality vs. capacity trade-off.

The authors in [19] present GSM automated radio access optimisation methods and examples on promising results achieved using those. The methods they presented include mobile measurement based frequency planning, measurement based adjacency planning, and handover parameter optimisation. The work in [20] is focused on UMTS network planning and optimisation; there have been fewer studies on automated radio access parameter optimisation for UMTS than for the GSM. Finally, in [21], the authors present the challenges and goals of the automated optimisation using cutting-edge cost function and optimisation algorithms.

One of the prior projects that addressed JRRM strategies is IST-AROMA [22], whose objective was to devise and assess a set of specific resource management strategies and algorithms for both the access and core network parts that guarantee end-to-end QoS in the context of an all-IP heterogeneous network. IST-AROMA aimed at providing tangible contributions, in terms of resource management, which take into account GSM EDGE RAN (GERAN), UTRAN, High-Speed Downlink Packet Access (HSDPA), and including the newly emerging RAN technologies (e.g., WLAN, WIMAX) and services, for the 2010-2015 time frame.

There is a relation between RRM and Network Management, and more specifically with policy based management. One of the advantages of policy based management is the flexibility of the management system, since it can adapt to changing network/service requirements over a period of time. The IST-EVEREST project [23] examined the role of Policy Management in the provision of RRM and selection of access technologies in a heterogeneous radio environment to provide end-to-end QoS. This project built on the Policy Management and QoS architecture outlined in Release 5 and 6 of UMTS.

Regarding automated optimisation, [24] presents a more extensive literature survey in the area of automated RRM parameter optimisation, and, in particular, presents admission control related theory and references. This reference gives an extensive summary on the measurements and on the single and multi-parameter optimisation methods, and introduces good results obtained in rule-based HO parameter optimisation. A general statement of this work is that the focus of the paper is set on comparing rule-based optimisation methods to fixed parameter settings, therefore, the range of optimisation methods compared was not large. Similar results can likely be obtained with other optimisation methods, but the rule-based optimisation has the advantage of being fairly transparent to the operator. In one particular case, a rule-based method was compared to the gradient descent cost function optimisation method, and in this case the rule-based method was slightly better. However, the main conclusion was that the significant increase in capacity obtained when using the automated optimisation methods warrants their consideration as features for the network managements system.

Fuzzy Logic Controllers (FLCs) are especially suitable for the management of complex systems that cannot be easily characterised by analytical expressions, but are feasible to be controlled based on experience using conditional "if-then" policies. Mobile networks are such systems, as it is very difficult to find a formula relating network parameter values with KPIs. Based on system knowledge and experience, network operators are currently able to adjust network parameters in such a way that the system behaviour is stable, even though the performance may not be at its optimum level, or potential changes in the network may yield to challenging conditions to operators. Within this framework, FLC can play the role of the human operator. Once the conditional rules are set based on experience, the system is automatically controlled.

Fuzzy logic techniques are being progressively introduced and applied as a real alternative to more traditional methods in most areas related to RRM, especially in present and future heterogeneous inter-system scenarios. Therefore, a lot of references addressing the issue of RRM and JRRM using either fuzzy or neuro-fuzzy controllers can be found in the related literature. More specifically, [25] shows how a multi-radio network (GSM, UMTS and WLAN) can be managed by using a neuro-fuzzy technique. The controller, based on each network load, received power and MT speed, selects the most appropriate Radio Access Technology (RAT).

In [26], the authors introduce fuzzy inference systems applied to the issue of soft handover in Code Division Multiple Access (CDMA) mobile communication networks, presenting new algorithms for threshold adjustment aimed at reducing call blocking probability and controlling QoS. Likewise, [27] presents intersystem HO control procedures based on fuzzy techniques in heterogeneous wireless networks, showing the potential of fuzzy reasoning in contributing to provide seamless VHO. The work in [28] shows the capabilities of fuzzy reasoning when defining load balancing and call admission control strategies for exploiting the advantages of heterogeneous systems when trying to maximise system capacity while preserving the desired QoS.

In the monitoring domain there are many methods for analysis of data and an overview can be found in [29]. The widely used neural network and unsupervised learning method called the Self-Organising Map (SOM) is very useful for multivariate data clustering and visualisation. SOM was selected to be a key component in this work due, to its popularity in multivariate data analysis, its excellent unsupervised learning capabilities, its ability to map a high-dimensional data space into a low-dimensional data space and its clustering capabilities. SOM has been applied for mobile network data analysis in [30], for radio network planning and in particular for finding optimal theoretical locations of BS sites in [31].

In [1], the authors suggest that a performance profile of a mobile network or network cells can be built using the SOM and performance indicator data collected from the network. The performance profile is called performance spectrum and can be used for cell clustering and cell behaviour trend analysis. The clustering results can be used to apply the same network parameters on cells in same cell clusters, which mean that network parameters optimisation can be done at the cell cluster level.

2.3 JRRM Strategies

2.3.1 Architecture

In a heterogeneous infrastructure, multiple cells from different radio technologies will be overlapped in the same area and multiple layers will co-exist. In this complex environment, multi-mode MTs can be connected to different cells, and, unless there is knowledge about each cell, it would be very difficult to optimise network performance and to manage resources efficiently. In addition, it would be reasonable to direct different services with different QoS classes to the most suitable radio access.

The whole set of radio resources for an operator is considered to be partitioned into "radio resource pools". These radio resource pools are controlled by two different types of functional entities [32]:

- RRM entity: functional entity responsible for resource management of *one* radio resource pool, i.e., this characterises the radio resource pool;
- JRRM (or CRRM) entity[1]: functional entity responsible for a global resources management, i.e., coordination of overlapping/neighbour radio resource pools controlled by different RRM entities.

The JRRM entities in the multi-system mobile networks are responsible for the coordination among different RRM entities of different RANs. It has information on the state of the radio resources in each RAN to make RRM decisions that improve QoS, performance, and provide efficient usage of resources. The RRM entity is defined in each RAN of a heterogeneous infrastructure in an independent way, regardless its physical location. RRM functions are implemented in the form of specific algorithms, such as call admission control, power control, handover, among others. RRM algorithms are not subject of standardisation, so they can be implemented in different ways among manufacturers and operators.

One can consider the JRRM entity to be the logical entity aiming to support intelligent interworking among RRMs of different subsystems. The role of JRRM can also be to know the status of all cells in the networks and advise local RRMs in order to adjust the cell parameters for optimal performance. This function is called auto-tuning of multi-systems RRM parameters. RAB auto-tuning improves the overall network performance by adjusting certain radio RRM parameters to adapt the network to the traffic variations. JRRM and RRMs entities are required to provide input information and to take into account the new configuration settings. Consequently, the network elements already related to the JRRM may be affected by the auto-tuning process.

Using the same principle of 3rd Generation Partnership Project (3GPP), the architecture of JRRM entities is either centralised in only one node or decentralised and implemented in each RAN. On the centralised approach, the JRRM server according to the 3GPP definition, [33], Figure 1, RRM and JRRM entities are implemented on separate nodes, and JRRM is a stand-alone server. The JRRM server controls local RRM entities implemented in each RAN. Consequently, each RRM entity in the functional model may be requested by its responsible JRRM entity to report certain information with respect to its radio resources. Then, the JRRM server gathers measurements from cells under its control. For each specific operation (HO, cell change order, etc.), the RRM sends to the JRRM server the list of candidate cells, including the MT measurements for these cells and information about the QoS required by the MT. This function allows for requesting immediate replies to a measurement request as well as event- or timer-triggered measurement reporting. The JRRM server, after applying some algorithms, returns the prioritised list of candidate cells.

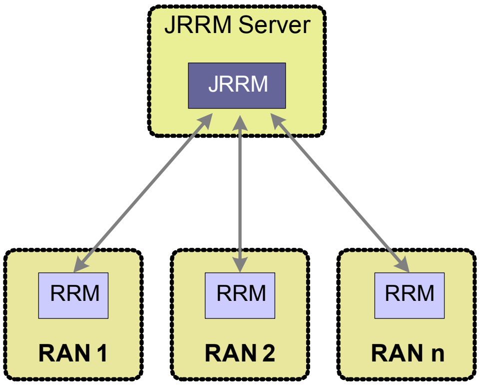


Figure 1 - JRRM Server approach, proposed by the 3GPP.

[1] One should note that the terms CRRM (Common Radio Resource Management), JRRM (Joint Radio Resource Management) and MRRM (Multi Radio Resource Management) can be found in the literature with the same meaning.

The second solution consists of a decentralised approach, the Integrated JRRM by 3GPP. This approach integrates the JRRM functionality into the existing RAN controller nodes, which are equipped with a JRRM and local RRM entities, Figure 2. The main benefit of this Integrated JRRM solution is that, with limited changes and already existing functionalities, it is possible to achieve optimal system performance. The co-location of JRRM and RRM in only one node does not influence the decisions of the local RRM. JRRM is not supposed to be consulted for basic RRM decisions, since the RRM entity handles these kinds of cases. JRRM is used only for inter-system selection and reselection. Here, both JRRM strategies and architecture are analysed and evaluated, in order to adopt a suitable architecture on automated optimisation process.

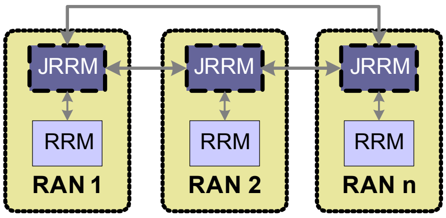


Figure 2 - Integrated JRRM approach.

Different wireless systems have different ways of managing their radio resources, this diversity being closely related to the implemented radio interface technology. Thus, RRM must comply with the system's characteristics and natural needs, enabling the most suitable radio resource allocation to MTs. Considering the restrictions imposed by the radio interface, RRM algorithms and functions are responsible for decisions that have quite an impact on radio interface behaviour, QoS, and performance. When wireless networks are close to the maximum capacity, RRM takes an important role on the overall QoS. Currently, mobile industry, standardisation bodies, and research groups are developing new cellular architectures related to heterogeneous wireless cellular environments. These efforts lead and confine the definition of JRRM strategies that are sustained in a heterogeneous architecture platform, which is basically the integration and joint management of different types of systems. In the present case, examples of RANs consider cellular and WLANs: UMTS Release 99 (R99), UMTS Release 5 (R5), and the IEEE 802.11 (WiFi) family.

JRRM functions are intended to achieve an efficient use of the radio resources in heterogeneous scenarios, by means of a coordination of the available resources in the existing RANs. Therefore, JRRM is a general concept, applicable to any combination of RANs, although the specific implementation and the degree of coordination depend highly on the degree of coupling that exists among the specific RANs.

The RRM unit carries out the management of the radio resources in a pool of a given RAN. This functional unit aggregates different physical entities in the BSs and radio controller subsystems, being assumed to be resident on the radio controller part. The JRRM unit executes the coordination management of the resource pools controlled by different RRM units, ensuring that the decisions of these RRM entities also take radio resources availability of other RRM units into account. Each JRRM unit controls several RRM ones, and may communicate with other JRRM units as well, thus, collecting information about other RRM entities that are not under its direct control.

Information exchanged between JRRM and RRM units is mainly of two types:

- Measurement information, which allows the RRM unit to inform the controlling JRRM one of the current status of their controlled cells, like load, capacity, and available resources, among others measurements (QoS related). Besides RRM to JRRM reports, it is also possible to exchange information among JRRM units, enabling access to measurements reported by RRM units controlled by other JRRM one.
- RRM decisions, which depend on how the JRRM unit is implemented, e.g., a JRRM unit can be the master, or not, of a given decision (e.g., the RRM unit binds the JRRM decision, or only advises it).

2.3.2 Cost Function Model

As previously mentioned, heterogeneous cellular networks may be defined by several parameters, KPIs, which determine their performance. In order to guarantee a desired QoS, a proper balance of these KPIs is required. An approach to integrate a set of KPIs into a single one by using a CF that takes these KPIs into account, providing as output their corresponding cost, which in reality reflects both network conditions and each of the individually players in the network, BSs and MTs, is needed. Since JRRM deals with multiple RANs, which have intrinsically some differences on QoS indicators, it is required to identify a particular CF definition for each RAN, by using slightly different KPIs. Thus, each BS-RAN type has its own CF, supported on different and appropriate KPIs.

A CF model should include not only the KPIs of a given RAN, but also a set of RANs types (e.g., UMTS R99, UMTS R5 and WLAN), this being aligned with the scenarios section. Furthermore, this CF model includes different perspectives from two important players in the network, operators and users. Thus, the total cost of the set of RANs may be computed with high information level, coming from the network player's sensitivities and perspectives.

One important objective/role of this model is the offered capability to RRM and JRRM entities to perform decisions (e.g., select a given BS, based on their cost and QoS criteria). In the proposed model, HHO and VHO processes can be handled at the same level. This means that the triggering method is common to both HO processes. The reference scenario is based on a hotspot area, where UMTS R99, UMTS R5 BSs and 802.11'x' APs coexist, having different coverage areas, due to different factors, like BS antennas height and pilot power settings. Therefore, coverage presents some cellular hierarchy, which of course has influence on the signal coverage, and naturally in the HO regions. Additionally, mobility profiles will impose some impact on RRM and JRRM performance, since the number of changes in the air interface will be more or less dynamic. From the viewpoint of the proposed CF model, the hierarchical structure is transparent: since VHO is based on the CF criterion, if one desires to include this in the VHO decision, then, a new KPI should be added to the model, in order to consider this issue in the HO process or other.

The proposed model enables the addition of many KPIs, which means that it is not a closed model. The idea is to provide a CF model capable of including new requirements from existing and future networks. Therefore, by using this framework a heterogeneous network operator can add new features or constraints to the model. Nevertheless, in this work, it is assumed that general RRM follows a JRRM centric approach, which means that some RRM functions are executed by the JRRM entity. However, fast procedures, like power control, are executed at the RRM level. The BS re-selection procedure is based on a BS candidate list, this list being sorted according to the CF results (stored and frequently updated in each BS). This means that JRRM entity algorithms are able to process HHOs and VHOs. The MT/user cost is based on previous events experience by a given individual MT (e.g., service session average delay); however, BSs cost is based on their long memory counter (e.g., packet delay). Therefore, the sorted list created by the JRRM is based on the combination of the BSs cost added with the active MTs cost attached to each BS.

Another important issue related to the computation of the CF model is the different perspectives that different network players have over the network, which in this model are operators and users. When each of these groups "looks" at the cellular network, they are sensitive to different parameters: for a user, the operator/network is seen as a service provider/infrastructure, hence, e.g., service cost (being lower) and quality (being higher) are important; however, for an operator, the same parameter can have opposite perspectives, e.g., service cost should provide good revenue and simultaneously be competitive with other operators. Therefore, in order to provide a more realistic balance in the overall network solution, the overall CF should be able to combine both operator's and user's perspectives. Table 2, presents a list of KPIs identified for both perspectives [34]. This table was defined by considering the following question: "What are the most important parameters that really matter from both users' and operators' viewpoints?". One should note that not all KPIs have a correspondence to both perspectives, e.g., Interference is clearly a very important parameter for an operator, but it does not carry any meaning for a typical user.

Table 2 - User and Operator CF Parameters.

Parameters/KPIs	Perspective	
	User	**Operator**
Delay	Service	BS Average
Blocking	Service	BS Average
Cost	Service (Free, Flat, Volume or Time dependent)	BS
Throughput	Service	BS Average
Service Availability	Number of RANs available	-
Drop Rate	Service	VHO and HHO
User type	-	Mass Market, Premium
Interference	-	BS Level
Load	-	BS
Channels	-	BS Occupied resources

Based on the previous concepts, the network total CF is divided into two sub-CFs, one being related to the operator and the other to users. Furthermore, the operator CF is also sub-divided, since different CFs are computed for each different RAN type. Each one of these sub-CFs is weighted with different values, enabling the implementation and evaluation of different policies on the JRRM and RRM algorithms over each type of RAN.

The network total cost, C_{NT}, is defined by:

$$C_{NT} = \frac{1}{W_o + W_u}\left(W_o \cdot \frac{1}{\sum_{r=1}^{N_{RAN}} Wo_r} \sum_{r=1}^{N_{RAN}} Wo_r \cdot Co_r + W_u \cdot \frac{1}{N_U} \sum_{n=1}^{N_U} Cu_n \right) \tag{1}$$

where,

- W_o and W_u are the operator's and user's weights;
- N_{RAN} and N_U are the number of RANs and users;
- Wo_r is the operator's weight for each RAN r;
- Co_r is the operator's total cost for RAN r;
- Cu_n is the n^{th} user cost.

The value of Co_r for a given RAN r (e.g., $r \in$ {UMTS R99, UMTS R5, 802.11'x'}) is calculated as follows:

$$Co_r = \frac{1}{N_{BS_r}} \sum_{b=1}^{N_{BS_r}} Co_{r,b} \tag{2}$$

where,

- N_{BSr} is the total number of BSs for a given RAN r,
- $Co_{r,b}$ is the operator's cost for each BS b, in RAN r.

$Co_{r,b}$ is computed by:

$$Co_{r,b} = \frac{1}{\sum_{i=1}^{N_{KPIr}} w_{r,i}} \sum_{i=1}^{N_{KPIr}} w_{r,i} \cdot k_{b,i} \tag{3}$$

where,

- N_{KPIr} is the total number of KPIs of a given RAN r;
- $w_{r,i}$ is the weight of each KPI i;
- $k_{b,i}$ represents the normalised value of each KPI ($0 \le k_{b,i} \le 1$).

The minimum value for k_b, i, is 0, which means that this KPI has the optimum value, and the maximum one, 1, means the saturation of that KPI, or that it has reached the worst value possible. In some particular cases, it can be above 1, which means that the current KPI is above the recommended maximum value. In this work, high values (when above the maximum) trigger alarms that should be handled by the JRRM separately.

The cost for each user n, Cu_n, is given by:

$$Cu_n = \frac{1}{\sum_{i=1}^{N_{KPIu}} w_i} \sum_{i=1}^{N_{KPIu}} w_i \cdot ku_i \qquad (4)$$

where,

- N_{KPIu} is the total of KPIs;
- ku_i corresponds to each user i KPI;
- w_i is the weigh of the KPI.

All cost parameters are normalised, thus, they should be between 0 and 1. One should note that some ku_i must be conveniently adapted, in order to have the same meaning of other KPIs, e.g., the throughput must be normalised to its maximum value.

In [1], [2], the authors typically use two or three main network KPIs to compute the CF, like blocking, load or link capacity, because these KPIs, in some cases, are sufficient to represent the overall network QoS, proposals being used to optimise these few parameters. However, in this work, this is not the case, since JRRM decisions may depend on many other KPIs, but also on different RANs, these being presented in Table 3. Furthermore, in order to evaluate JRRM behaviour/sensitivity to KPIs, other KPIs are included into the CF computation. Most KPIs calculation or measurement processes have a straightforward method, since they can be compute directly by counters (e.g., blocking or delay). However, some of them may present ambiguities (e.g., load or interference). BSs load, in downlink (DL), is computed by the ratio between all BS active connections, including pilot channels, and the maximum available power. Since only DL is considered in this work, BS interference is defined according to the interference that all MTs, attached to a given BS, are experiencing in DL, i.e., both from inter- and intra-interferences.

Table 3 - CF parameters adopted for each RAN type.

Network Type (RAN)	Blocking	Delay	Load (Power)	Throughput	Occupied Channels	Interference	BS Cost	User Type	HO Drop Rate
UMTS R99	√	√	√	√	√	√	√	√	√
UMTS R5	"√"	√	√	√	√	√	√	√	√
802.11'x'	"√"	√	NA	√	NA	√	√	√	√

Parameters like Delay, Throughput, Interference, BS Cost, HO Drop Rate (VHO and HHO) and User Type are used by the CF in all RAN types. Since these parameters reflect BS/APs HO capabilities and RAN status, e.g., allow the avoidance of high risk HOs areas/BSs, they will influence RRM and JRRM decisions. Thus, they are included in the CF of each network element. Load and Occupied Channels KPIs are excluded in WLANs, since it is assumed that communications between MTs and BSs in WLANs are performed one at a time. Note that the blocking concept characteristic of Circuit Switch (CS) services, is applied to UMTS R5 and 802.11'x' (the "√" notation), because it is assumed that there are applications over Packet Switch (PS) networks that are almost Real Time (RT) ones, introducing the blocking concept in PS based networks (e.g., VoIP). The Not Applicable (NA) case corresponds to the CF parameter and related RAN not having a clear relation or meaning.

The CF result applied to all BSs in a heterogeneous cellular network offers to RRM and JRRM entities a good way to evaluate and implement the Always Best Connected (ABC) concept [34], since each BS has a number associated to it, the cost value. Based on these values, the JRRM entity can sort a list of BSs reported/visible by each MT via the RRM. On the top of this list, it is expected to have the best BS (the lowest cost one) that potentially offers the best connection to a given MT.

Similar to BSs, each MT has a cost value attached to it. This information is vital to take users' interests into account in the overall network management, which is ensured by JRRM algorithms and strategies. The CF model was implemented and tested by using the JRRM Simulator developed by the IST-AROMA project, presented in [35], where the HHO and VHO processes are managed by the same algorithm, Figure 3, since they are based on the cost computed for each BS, produced by the JRRM/CF policy. Signal outage is a key element to trigger JRRM algorithms, meaning that outage events will require a RRM/JRRM decision, being a HHO or VHO one. The main goal is to simplify the JRRM algorithms criteria, using the most active and relevant air interface parameters, which are combined into a single one. Additionally, this combination can be policy oriented. In this case, VHO is based on the CF approach that is capable to integrate several radio parameters.

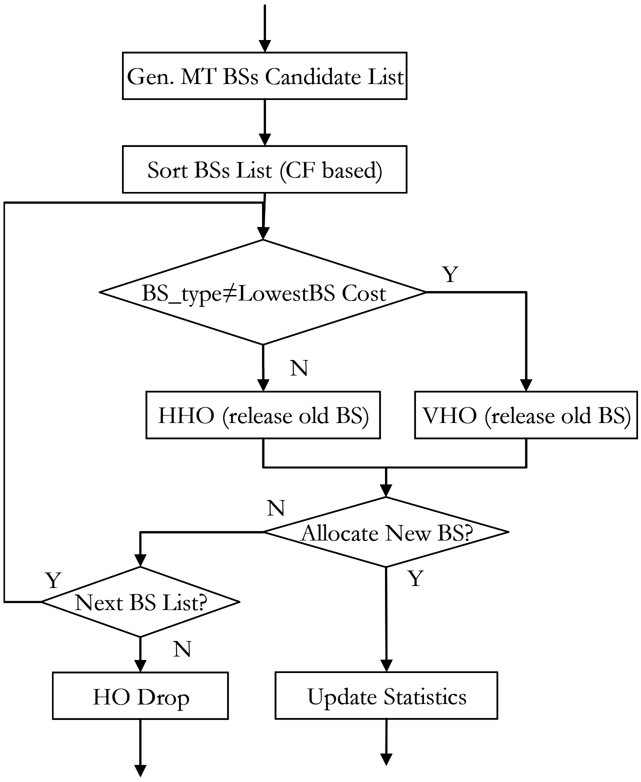


Figure 3 - HHO and VHO processes.

This algorithm is as follows: first, a candidate list is generated, based on the MT/service and on the communication capabilities between BSs and the current MT; after this, the list of BSs is sorted based on cost; if the lowest BS cost in the list is from other RAN type, then, a VHO is performed, but if the RAN type is the same, then, a HHO is triggered. After this decision, the old BS releases the radio resources regarding the MT/service, and the selected/new BS is requested; if in this process the BS (for any reason) rejects the request, then, the next BS from the sorted list is selected, the allocation process being repeated, until the list is empty or after a successful HO is achieved; otherwise, the algorithm returns a drop indication, and the MT/service drops the current service.

2.3.3 Automated Model

The automated optimisation and monitoring process is organised on a three level functional architecture, Figure 4. The heterogeneous network is a multi-technology infrastructure including several RANs and supporting multi-system usage. At this local level, RRM entity functions manage the local radio resources and gather statistics and indicators on resource usage and user behaviour. These elements collect measurements concerning the performance of each RAN, and information on the capability of the equipments.

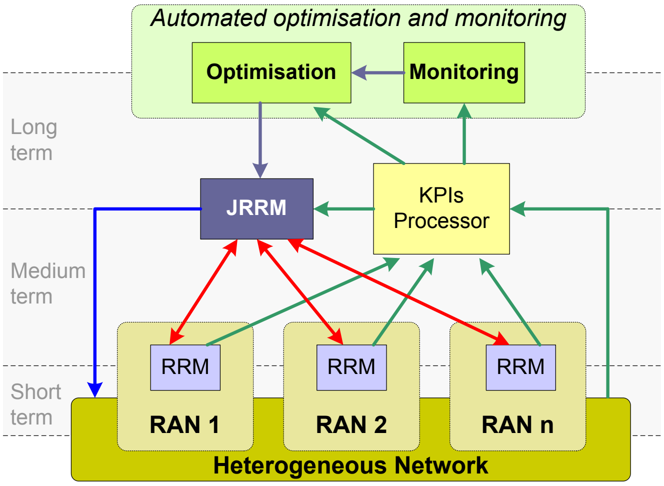


Figure 4 - Automated optimisation process architecture.

All collected information is further transferred to the KPIs Processor to be refined and processed, defining the related KPIs. The role of the KPIs Processor is to make the correspondence between the different KPI defined in each RAN, since each RAN can produce different types of KPIs. So the role of this part is to render transparency indicators from different RANs for the JRRM. The statistics are, in general, based on the measurement collected on the KPI Processor and counters defined by each RAN. These statistics are not always sufficient from the heterogeneous infrastructure point of view. So, to collect more data and to create more KPIs, the heterogeneous network reports directly some statistics to the KPI Processor, which later provides an extra measurement, and supplementary network indicators, giving a more accurate vision on the network performance.

As mentioned before, the JRRM entity is responsible for the global, multi-RAN RRM, and aims at improving QoS in the global network. JRRM differs from the RRM, since it exploits the total available heterogeneous infrastructure to provide efficient RRM. Whenever the RRM entity is unable to reconfigure the system in such a way to solve a problem, the information can be directed to a higher level, and the problem may be treated and solved at the JRRM level. This involves VHO, selection and reselection, as well as roaming of users from one service provider to another. JRRM can reconfigure RRM parameters that will suit better network needs, or take a decision such as RAN selection for a new application.

The Monitoring module has the role to respond to any anomaly and to any traffic overload situation. For that purpose, one needs to define a large number of KPIs that characterise the stable (or not) network behaviour. Whenever one of these KPIs reaches a predefined threshold, the monitoring system should generate an alarm, in order for the congestion problem to be faced. In general, the monitoring element collects the measurement from all the system entities, and based on this information, it proposes a hardware modification to respond to network anomaly. Another important issue of monitoring is the multivariate data clustering and visualisation clustering that can be used by optimisation.

The Optimisation module consists of two phases: monitoring the performance of the key parameters, and assessment of the performance of these parameters with respect to capacity and coverage. Based on reported KPIs, the optimisation generates sets of revised JRRM and RRM parameters relevant to each RAN. The optimisation requests and receives KPIs directly from the KPI Processor module. These indicators, together with indicators from the Monitoring module, construct a cost function that guides the auto-tuning optimisation process. The module also requests and receives intersystem service target indicators from the monitoring module, such as blocking and dropping rates in each system. These indicators, together with those from the KPI Processor, are used to guide the optimisation process. The optimiser checks the current parameter settings of the JRRM to guarantee coherence of the proposed modifications. The CF is computed using all KPIs and service target values, and a modification order of JRRM parameter settings is finally transmitted to the JRRM module.

In the proposed architecture, the overall resources optimisation occurs at three levels and timescales. In the short term, immediate timescale local radio resources must be managed to satisfy incoming service requests and to balance available resources amongst the active users; this is accomplished by normal RRM procedures in each RAN. In the medium timescale, users move in the system and potentially between RAN; JRRM has a role in providing a level of load balancing among RAN and pushing user sessions and requests around in order to best use available resources, which in turn frees up resources in the RAN to be managed by local RRM entities. Finally, in a long term timescale, the overall performance and optimisation of networks is essential for the long term health of the network.

2.4 Spectrum Allocation for OFDMA Networks

2.4.1 Introduction and Objectives

The main challenge for future wireless communication systems will be to provide wideband wireless access to a large number of subscribers, fulfilling at the same time strong requirements in terms of QoS. Most of the candidate technologies of future generation broadband wireless networks employ a multiple access scheme based on the Orthogonal Frequency Division (OFDM) modulation [36], [37]. Provided that the system parameters are accurately dimensioned, OFDM transmissions are not affected by Inter-Symbol Interference (ISI) even in highly frequency-selective channels [38]. Moreover, OFDM can effectively exploit the channel frequency diversity by dynamically adapting power and modulation format on all subcarriers, [39], [40]. In an OFDM based multiple access (OFDMA) system, a different subset of orthogonal subcarriers is allocated to each user. If the transmitter possesses full knowledge of the Channel State Information (CSI) of each user, the overall spectral efficiency can be increased by allocating the subcarriers according to certain optimality criteria, thus exploiting the so-called *multi-user diversity*. In recent years resource allocation has been envisaged as one of the most efficient techniques to increase the performance of multicarrier systems.

One of the objectives of this WP is to study and define algorithms for allocating power and subcarriers for OFDMA systems. The analysis will encompass both the single and multi-cell scenarios aiming at finding efficient solutions with a low-complexity implementation. As it emerges from the analysis of the state of the art, the single-cell scenario has already been thoroughly investigated, and thus the main results of this study are used as a starting point for the more complex and challenging multi-cell scenario. Under the hypothesis of a distributed system where no coordinated information is exchanged between cells, one aims at implementing a network with (quasi) full reuse of the available spectral resources.

2.4.2 State of the Art Analysis

Following the path opened by the seminal article by Wong et al. [41], many resource allocation algorithms have been proposed to take advantage of both the frequency selective nature of the channel and the multi-user diversity. Most of the works in literature follow either the *margin adaptive* approach, formulating dynamic resource allocation with the goal of minimising the transmitted power with a rate constraint for each user [42]-[44], or the *rate adaptive* approach aiming at maximising the overall rate with a power constraint [45], [46]. In this latter case, the optimal solution for resource allocation in DL is often found as an application of the well-known water-filling algorithm [47]. In particular, in [46] and [48], it is shown that OFDMA is the optimal multiple access scheme in a multi-user multicarrier DL system. Furthermore, capacity is maximised by assigning each subcarrier to the user with the maximum channel gain on it, and distributing the power over subcarriers using the water-filling solution with respect to the allocated channel gains. In [49], an iterative water-filling solution is proposed for a multiple-access channel in a single-cell scenario where multiple uncoordinated transmitters send independent information to a common receiver. However, all these works only consider allocation in a single cell. Because of its complexity, resource allocation in multi-cellular systems has not been fully studied yet, and only few works tackle the problem [50]-[54].

Thus, the state of the art of RRM for spectrum allocation on OFDMA-based cellular networks is focused on both single- and multi-cells scenarios. In each of these cases, several RRM optimisation problems arise depending on different factors, such as optimisation criteria, optimisation constraints and available resources.

2.4.3 RRM for spectrum allocation in OFDMA-based cellular networks

Due to the spectrum scarceness and the limited availability of power for mobile radio terminals, efficient RRM is probably one of the most important issues in multi-carrier networks. While, in most cases, it is possible to formulate the RRM as a cross-layer problem [55], practical RRM solutions tend to be implemented in a layered architecture to reduce the overall complexity. Thus, channel allocation, bit and power loading are performed at the physical layer and resource provisioning, packet scheduling and load control are performed at the MAC/Network layer.

RRM techniques at the physical layer intend to exploit the several sources of diversity present in the wireless cellular systems in order to allocate the available radio resources in the best possible way so that the system capacity and coverage are maximised and the QoS requirements of the users are guaranteed. In the following, one lists the most important RRM techniques related with spectrum allocation for OFDMA-based cellular systems:

- Dynamic Channel Assignment (DCA): The propagation channels are independent for each user, and thus subcarriers that are in a deep fade for one user may be in a good state for another (multi-user diversity). Therefore, there is a great potential gain that can be exploited by assigning different sub-carriers to different users on the base of the knowledge of their channel gains. Moreover, different sets of sub-carriers may be allocated dynamically to different BSs in order to avoid or coordinate inter-cell interference among neighbour cells (multi-cell diversity).
- Bit Loading: This technique is also known as Adaptive Modulation and Coding (AMC). It exploits time and frequency diversities in order to allocate the most suitable modulation and coding format to each subcarrier (frequency diversity) according to its Signal-to-Interference plus Noise Ratio (SINR).
- Power Loading: Since each sub-carrier experiences a different channel gain (frequency diversity), it may be advantageous to dynamically adapt the power of each sub-carrier to channel conditions.

The DCA technique can be executed on both short- and long-terms, depending on where it is performed. If spectrum allocation is performed on BSs, it is regarded as short-term, while if it is executed on a centralised controller or RRM server, it is regarded as long-term. The other techniques listed above are regarded as short-term, since they are usually performed to adapt to fast channel variations.

RRM strategies performed at higher layers are out of the scope of this document and their outcome can be regarded as a potential input for the optimisation process at the physical layer. For example, load control algorithms decide what users are granted access to radio channels, or packet scheduling determines the amount of resources that can be allocated to each user, or the parameter that are assigned to each user when a weighted sum rate is calculated.

The difference between the different layers is sometimes thin, and the literature [55] presents several scheduling algorithms that operate across the layers that optimise the QoS, allocating resources on the base of inputs from the physical, link and network layers.

2.4.4 Single-cell studies

This case is characterised by the presence of a BS or an AP, and K multiple MTs. The overall bandwidth is divided in N orthogonal subcarriers. Since the subcarriers are orthogonally partitioned among users and there is only one cell, there is no Multiple Access Interference (MAI) and the measure of the quality of the channels is the Signal-to-Noise Ratio (SNR).

$$SNR_{k,n} = \frac{p_{k,n} G_{k,n}}{B N_0} \tag{5}$$

where $p_{k,n}$ is the power that user k transmits on channel n, $G_{k,n}$ is the squared module of the channel response and B is the bandwidth of a subcarrier.

The multi-user diversity is exploited by assigning different sub-carriers to different MTs at any given TTI. To formulate the DCA problem, one introduces the binary allocation variable $x_{k,n}(t)$, which is defined by

$$x_{k,n}(t) = \begin{cases} 1 & \text{if subcarrier } n \text{ is assigned to UE } k \text{ at time } t \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

In the following, unless differently stated, one focuses on a given time and, to simplify notation, the time indication in the allocation variable is omitted, i.e., $x_{k,n}$ is used instead of $x_{k,n}(t)$.

There is one constraint that is common to most optimisation problems: within the cell a given sub-carrier can be allocated to only one user. This solution is optimal only under mild conditions [46], [54], but it greatly simplifies the allocation problem. This can be mathematically expressed by the following constraint:

$$\sum_k x_{k,n} \le 1, \quad \forall\, n, \quad x_{k,n} \in \{0,1\} \tag{7}$$

Exclusive assignment implies that DCA is a problem defined on integer variables (integer linear programming, ILP). The fact that the variables are integer makes the overall DCA not convex, and thus many algorithms relax the condition in (7) as

$$\sum_k x_{k,n} \le 1, \quad \forall\, n, \quad x_{k,n} \in [0,1] \tag{8}$$

and let $x_{k,n}$ vary continuously between 0 and 1. This is sometimes called convex relaxation of the constraint, and it leads to an interpretation of the assignment problem as a FDMA-TDMA optimisation problem [56].

In the literature, there are many DCA algorithms. Most of them, anyway, fall in one of the two following classes:

- Rate Adaptive (RA): The objective is to maximise the overall bit rate of the cell at each TTI, subject to constraints on the maximum transmit power of the BS [57], [58]. This optimisation criterion presents a problem related to fairness among the users, because MTs experiencing bad channel conditions can be starved without access to the channel. Thus, to cope with the fairness problem, some authors, reformulate the RA problem aiming at the maximisation of the minimum throughput [45], [57], [58].
- Margin Adaptive (MA): A dual way to formulate the DCA is to minimise the overall transmit power with a constraint on the rate of each terminal. The main difference with previous problem is that, while in the RA formulation there is only one global constraint (the overall transmit power), in the MA formulation there are as many constraints as the number of users.

Both optimisation problems cited above are integer programming problems. As such, depending on their formulation, they might belong to the group of NP-complete combinatorial optimisation problems [57], and thus be of prohibitively large complexity. Hence, the majority of the proposals focus on sub-optimum heuristic solutions that can be summarised as follows:

- Convex relaxation: The idea is to relax the integer constraint on the sub-carrier or bit assignments, so that each sub-carrier can be assigned to multiple different MTs and can carry a non-integer amount of bits during one TTI. By doing this, both RA and MA problems become convex problems, which can be solved efficiently with standard tools. However, one must have in mind that after solving the relaxed problem, the relaxed solution has to be re-evaluated because only integer solutions are feasible from the network's point of view.
- Problem splitting: This approach uses the concept "divide to conquer", i.e., split the complex problem into two or more simple ones so that a sub-optimum solution close enough to the optimum one can be found.

Two are the most common approaches followed to compute the throughput offered by a certain connection: either to use Shannon channel capacity or to rely explicitly on the spectral efficiency of modulation formats and error correction codes. In this second case, it is necessary to specify a target value for the error probability. Both choices have advantages and disadvantages. Shannon capacity is the maximum rate that can be transmitted on a given channel with null error probability. It is a theoretical limit that can be attained only with infinitely long codes but it is easy to calculate and, in present day communication systems, it is possible to achieve performance quite close to the Shannon bound. Using explicitly the features of the signal modulation and of the error protection codes has the advantage of modelling a more realistic setting and of getting closer to practical implementation. On the other hand, the results obtained following this approach are less general and in any case they do not incorporate all the physical layer details of a practical implementation. Thus, in most cases, the choice of one or the other depends on the particular application for which it has been studied. For example, when studying bit loading algorithms, it is quite common [59], [60] to resort to explicit modulation formats rather than using the abstract Shannon capacity.

The most common mathematical formulation of the RA problem is

$$\begin{aligned}
&\max_{\mathbf{p},\mathbf{x}} \sum_k \sum_n F\left(\frac{p_{k,n}\cdot G_{k,n}}{\sigma^2}, P_e\right)\cdot x_{k,n} \\
&\qquad s.t. \\
&\quad \sum_k x_{k,n}(t) \le 1, \quad \forall n \\
&\qquad \sum_n p_{k,n} \le P_{\max}
\end{aligned} \tag{9}$$

where $F(\cdot)$ is a piece-wise constant convex function that delivers the rates of the available modulation and coding formats with respect to the SNR and a predetermined target error probability P_e, $p_{k,n}$ is the power of the k-th user on the n-th sub-carrier, $G_{k,n}$ is the squared module of the channel gain of the n-th sub-carrier with respect to the k-th MT, $\sigma^2=BN_0$ is the noise power, and $P_{\max}$ is the maximum allowed transmit power of the BS. The optimisation variables are $\mathbf{x}$, the vector of the allocations, and $\mathbf{p}$, the vector containing the power levels of all sub-carriers.

The resulting integer programming problem can be solved easily and with computational efficiency by a greedy algorithm as described in [46]. The algorithm assigns each sub-carrier to the terminal with the highest channel gain. Then, a loading algorithm is applied in order to distribute the transmit power with respect to the objective function.

The same problem can be formulated using Shannon capacity, and in this case the function $F(\cdot)$ is computed for P_e=0, i.e., $F\left(\frac{p_{k,n}\cdot G_{k,n}}{\sigma^2}, P_e=0\right)=\log_2\left(1+\frac{p_{k,n}\cdot G_{k,n}}{\sigma^2}\right)$. As in the previous case, each sub-carrier is assigned to the terminal with the highest channel gain, and then the power distribution across subcarriers is found with a water-filling algorithm.

The RA allocation (9) tends to starve the users with the worse channel gains, i.e., the users that are more distant from the BS. Thus, in [44] and [45], the RA problem has been formulated with the goal of maximising the minimum capacity offered to each user, thus introducing fairness among the users. In general, fairness among MTs comes at the cost of a decreased overall throughput of the cell.

$$\begin{aligned} & \max_{\mathbf{p},\mathbf{x}} \varepsilon \\ & s.t. \\ & \sum_n F\left(\frac{p_{k,n} \cdot G_{k,n}}{\sigma^2}, P_e\right) x_{k,n} \geq \varepsilon, \quad \forall k \\ & \sum_k x_{k,n} \leq 1, \quad \forall n \\ & \sum_k \sum_n p_{k,n} \leq P_{\max} \end{aligned} \tag{10}$$

where ε is a lower bound of all terminals' throughput.

Another approach that tends to maximise the cell throughput complying with fairness considerations is the weighted sum rate maximisation (WSRmax) problem. In this case, the packet scheduler determines for each user k a weight λ_k, opportunely chosen to enforce fairness in the radio utilisation. The WSRmax problem is

$$\begin{aligned} & \max_{\mathbf{p},\mathbf{x}} \sum_k \lambda_k \sum_n F\left(\frac{p_{k,n} \cdot G_{k,n}}{\sigma^2}, P_e\right) x_{k,n} \\ & s.t. \\ & \sum_k x_{k,n} \leq 1, \quad \forall n \\ & \sum_k \sum_n p_{k,n} \leq P_{\max} \end{aligned} \tag{11}$$

The solution of (11) is found as the so-called *multi-level water-filling*, which is NP-complete. In [56] and [62], the authors propose a low-complexity iterative solution of (11) in the dual domain.

One of the first efficient algorithms that solved the RA problem was proposed by [61]. The authors used the problem splitting approach in order to solve it. The first step consisted of combined power and sub-carrier allocation based on the average channel gain calculated over all sub-carriers for each user. The second step was to solve the so-called assignment problem, which decides on the best sub-carrier/terminal pair, and has as the graph-theoretic counterpart the bipartite weighted matching problem [57]. The authors in [61] suggested using the Hungarian algorithm [63] to solve the assignment problem. The last step was to apply adaptive power loading to each terminal in order to distribute his allocated power among the sub-carriers assigned to him. Another work that uses the problem splitting method is [64]. In this paper, a proportional rate adaptive resource allocation method for multi-user OFDM is proposed, where sub-carrier and power allocation are carried out sequentially to reduce the complexity, and an optimal power allocation procedure is derived.

Some proposals to solve the RA problem were based only on heuristics [45], [65]. Apart from proposing integer relaxation or problem splitting, the authors in [45] base their heuristic algorithm on a constant power assignment for all sub-carriers. They claim that since most sub-carriers assigned to the users will be in quite a good state, the constant power distribution does not reduce the system performance too much. It was shown in [57] that, at least for wireless point-to-point connections, constant power distribution achieves almost the same performance as power loading. On the other hand, the authors in [65] propose a heuristic algorithm that performs joint sub-carrier and power allocation while taking into account the frequency selective nature of users' channels.

Some works have used more than one optimisation approach to cope with the RA problem. For example, a solution combining integer relaxation and problem splitting was proposed in [44]. The optimal sub-carrier and bit allocation problems, that have been formulated in [45] as nonlinear optimisations, were converted into linear ones and solved by integer programming. Based on this, a suboptimal approach that separately performs sub-carrier allocation and bit loading was proposed.

The objective of the MA optimisation problem is to minimise the overall transmit power (the sum over the individual power shares per sub-carrier), while guaranteeing the individual data requirements of the users, r_k. Its mathematical formulation is

$$\begin{aligned} &\min_{\mathbf{p},\mathbf{x}} \sum_k \sum_n p_{k,n} x_{k,n} \\ &\quad s.t. \\ &\sum_k x_{k,n} \le 1, \quad \forall n \\ &\sum_n F\left(\frac{p_{k,n} G_{k,n}}{\sigma^2}, P_e\right) x_{k,n} \ge r_k, \quad \forall k \end{aligned} \tag{12}$$

The main difference between the RA and MA approaches is that the former has only one global constraint (the overall transmitted power), and thus is particularly suited for DL applications where the BS is allocated a certain amount of power, while the latter has as many constraints as the users, and thus it is more suitable for uplink (UL). In [44], it is shown that the problem (10) and the problem (11) lead to exactly the same solution in case one has $e=r_k$ for each user k.

When DCA is implemented with a dedicated scheduler, the problem (12) can be reformulated taking into account different scheduler weights μ_k for each user k. In this case the weighted sum power minimisation (WSPmin) problem is

$$\begin{aligned} &\min_{\mathbf{p},\mathbf{x}} \sum_k \mu_k \sum_n p_{k,n} x_{k,n} \\ &\quad s.t. \\ &\sum_k x_{k,n} \le 1, \quad \forall n \\ &\sum_n F\left(\frac{p_{k,n} \cdot G_{k,n}}{\sigma^2}, P_e\right) \le r_k \quad \forall k \end{aligned} \tag{13}$$

The problem (12) is NP-complete and is studied in [62], where the author proposes a low-complexity solution based on the method of the sub-gradient in the dual domain.

Application of convex relaxation to solve the MA problem was first presented in [41]. The authors relaxed the integer constraint of the sub-carrier assignment and assumed that the function $F(\cdot)$ was continuous. A suboptimal solution to this problem was proposed, in which the sub-carrier is assigned to the user that has the greatest share of that sub-carrier. Then, a power loading algorithm is utilised to perform the power distribution among sub-carriers in order to fulfil the MT rate requirements with minimum power. Due to the assumed simplifications, the obtained solution gives a lower bound estimation of this minimum required transmit power. However, it is shown in [41] that this sub-optimal solution is very close to the optimal one. This initial work described in [41] serves as comparison basis for multiple later studies on the MA problem.

Some works were based only on heuristics [67], [68]. In [67] the authors propose a heuristic real-time algorithm that consists of two phases: first, an initial sub-carrier allocation is obtained via a constructive algorithm, which is based on ordered lists of sub-carriers; and then iterative swapping of the sub-carrier between users is done on the initial allocation in order to minimise the objective function. Experimental results showed that the performance of this real-time algorithm was close to that of the optimal allocation. The work described in [68] proposed a cross-layer adaptive resource allocation algorithm for packet-switched OFDM systems composed of two parts: virtual clock scheduling, which provides guaranteed performance and fairness from the data link layer's perspective; and adaptive sub-carrier and power allocation, which exploits the system diversities and provides guaranteed transmission efficiency and proportional fairness in the physical layer. Regarding the sub-carrier and power allocation algorithm, the authors proposed to apply the allocation algorithm presented in [67] and to use linear integer programming to solve the sub-carrier assignment problem.

The problem splitting and heuristic approaches were used in conjunction in [42]. The two steps were the resource allocation and sub-carrier assignment. The first step was responsible for determining the number of sub-carriers each terminal should receive and was done using a greedy algorithm called BABS (Bandwidth Assignment Based on SNR). Once the resource allocation is determined for each terminal, the specific assignment of the sub-carriers is done in the second step by the ACG (Amplitude Craving Greedy) algorithm. Simulations results show that the power requirements of the combination BABS/ACG are only slightly higher than those of [41], while CPU run times are smaller by a factor of 100. Other works that employ the combination of the problem splitting and heuristics optimisation approaches are [69] and [70].

An effective trade-off among bit-rate maximisation, fairness, and QoS is desired in wireless resource allocation process. The issues of efficient and fair resource allocation have been well studied in economics, where utility functions are used to indicate the benefit of usage of certain resources. In communication networks the utility theory can be used to evaluate the level of service requirements satisfaction of users' applications. The basic idea of utility functions is to map the resource use (bandwidth, power, etc.) or performance criteria (data rate, delay, etc.) into the corresponding values and optimise the established pricing system.

Utility functions, representing the level of user satisfaction received for the system, play a key role in resource management and QoS differentiation. Different applications can use different utility functions and different parameters, e.g., the utility functions of best effort applications are with respect to throughput, whereas those of real-time applications are usually with respect to delay [71]. Thus the utility functions may be used to represent the different optimisation criteria for the resource allocation optimisation process.

The optimisation problem may be formulated as one that maximizes the aggregate utility in the system subject to the capacity limit determined by the physical layer techniques. The utility optimisation problem cannot be directly solved, since most optimisation objectives are in terms of long-term performance criteria. However, DCA and Bit and Power Loading can be performed at each time slot. Thus, the optimisation objective has to be an instantaneous optimisation objective, which can be regarded as a summation of utility functions with respect to instantaneous data rates, which is defined as [71], [72]:

$$\sum_i U_i\left(r_i[n]\right), \tag{14}$$

where $r_i[n]$ is the instantaneous data rate for user i at time n, and $U_i(r_i[n])$ is the corresponding utility function. The development of algorithms that maximise the sum of utility functions is very challenging, since utility functions are usually nonlinear. For the utility functions that are convex there exist efficient theories and algorithms such as the methods previously proposed. However, some research shows that the convex utility functions are appropriate only to model elastic services and do not capture the properties of services with strict QoS demands. And the nonconvex utility maximisation problem is significantly hard to be analysed and solved, even by centralised computational methods.

It has been proven in [72] that the problem specified in (14) is a convex optimisation problem when the objective function in (14) is either a non-decreasing convex function or a non-increasing concave function. Thus the employed utility functions have to satisfy the following condition [72]:

$$U_i''(r_i[n]) \leq U_i'(r_i[n]), \tag{15}$$

For the case of non-decreasing convex function or a non-increasing concave utility functions, which are applicable to most applications, the methods previously described may be used to solve the optimisation problem shown in (15).

The use of utility functions for specifying the optimisation criteria provides great flexibility to the resource allocation process. Depending on the used functions, one could achieve, e.g., rate-adaptive optimisation or delay-based optimisation. Most network applications can be classified into two types: best effort (non-real-time) and delay-sensitive (real-time) traffic.

Rate-adaptive optimisation is mostly applicable when the best effort traffic is dominant. Best effort applications have no specific QoS requirements. The throughput of a best effort connection is controlled by its transport layer according to the level of network congestion. Hence, a commonly accepted utility function for best effort traffic is the logarithmic function $\ln(\bar{r}_i[n])$, where $\bar{r}_i[n]$ is the long-term average throughput for user *i* [71]. It is shown in [73] that the optimisation of (15) can be performed by maximising the formula:

$$\sum_i U_i'(\bar{r}_i[n]) r_i[n] \quad (16)$$

Thus, the optimisation depends on the first derivative of utility function $U_i(\bar{r}_i[n])$ and the long-term average throughput for user *i* [71].

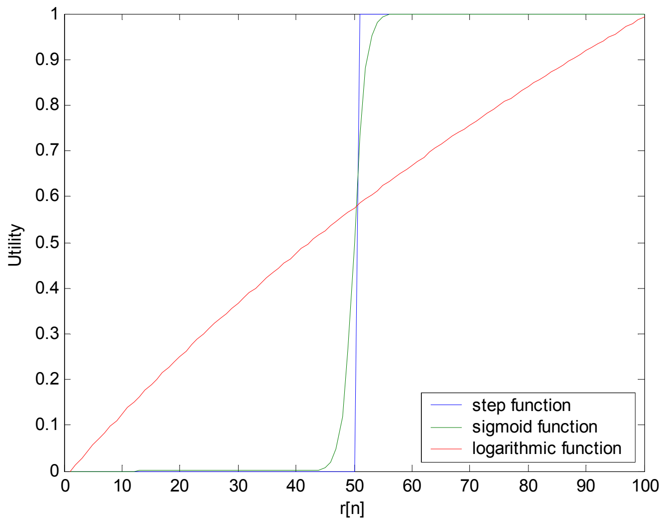


Figure 5 - Examples of utility functions.

In case of rate-adaptive optimisation the adequate utility function depending on the throughput for the delay-sensitive services that require approximately constant data rate could be the step function defined as [74]:

$$U_i = \begin{cases} 1, \text{if } \bar{r}_i[n] \geq r_{\min} \\ 0, \text{if } \bar{r}_i[n] < r_{\min} \end{cases} \quad (17)$$

However, the when using the step function it is difficult to solve the optimisation criterion specified in (15), thus for the delay-sensitive services sigmoid (non-decreasing) utility functions are used. The sigmoid function may be defined as follows [72]:

$$U_i = \frac{1}{1 + e^{-\bar{r}_i[n] + r_{\min}}} \quad (18)$$

One of the most important criteria when considering the rate-adaptive optimisation is fairness between the users, which is the most important factor when considering the best effort services. Proportional fairness provides each connection a priority inversely proportional to its long-term average throughput, and lets each connection have an equal access chance. It has been shown in [75] that the logarithmic utility function is associated with the proportional fairness in case of utility-based optimisation.

When considering the delay-based optimisation, the optimisation problem is usually associated with the average waiting time $W_i[n]$ of user i, so the utility can be specified as $U_i(W_i[n])$. Thus, the longer the delay of each user, the lower its satisfaction (utility), and it is reasonable to assume that the employed utility function is decreasing. Hence, the optimisation criterion can be specified as [76]:

$$\max \sum_{i \in M} \frac{\left| U_i'(W_i[n]) \right|}{\bar{r}_i[n]} \min\left(r_i[n], \frac{Q_i[n]}{T_s} \right), \tag{19}$$

where M is the number of users, T_s is the duration of time slot and $Q_i[n]$ is the queue length of user i. The min(x,y) function is to make sure that the service bits of each user are less than or equal to the accumulated bits in its queue to avoid bandwidth wastage [71]. Because the utility functions used in delay-based optimisation are mostly monotonically decreasing, the z-shaped function is commonly used for delay-sensitive services.

The key issue when considering the delay-based optimisation is the stability of the system, i.e., the service rate must be larger than the incoming rate of the data stream. Generally, channel-aware-only scheduling schemes cannot reach stability since they are unable to sense the queuing information, which reflects the status of networks. The described method of delay-based optimisation can provide the stability when the polynomial delay-based utility functions are used [71].

Many algorithms employing the concept of utility functions have been proposed for wireless OFDMA systems. Interesting examples of rate-adaptive optimisation can be found in [79] and [74] and the delay-based algorithms are proposed in [71] and [77].

2.4.5 Multi-cell studies

Recently, the problem of dynamic resource allocation has been studied also in multi-cell scenarios. The reason thereof is quite straightforward: an efficient channel allocation may reduce interference among neighbouring cells and thus allow a closer reuse distance of radio frequencies leading to a better spectral efficiency. Because of the spectrum scarcity, spectral efficiency is probably the single most important parameter to optimise in next generation radio networks. Nonetheless, the problem is complex and so far little literature is available on the topic [50]-[54]. The multi-cell scenario is characterised by several neighbouring cells that transmit over the same bandwidth, divided in N orthogonal subcarriers. Within each cell there is a BS and K multiple MTs. Because of the presence of inter-cell MAI, interference needs to be taken into account and the measure of the channel quality is the SINR. The SINR for user k situated in cell j, calculated on subcarrier n is

$$SINR_{k,n} = \frac{p_{k,n} G_{k,n}^{(j)}}{\sum_{\ell \neq j} p_n^{(\ell)} G_{k,n}^{(\ell)} + BN_0} \tag{20}$$

where $G_{k,n}^{(j)}$ is the squared value of the channel gain between the BS in cell j and the user k calculated on subcarrier n, $p_n^{(\ell)} = \sum_k p_{k,n}^{(\ell)} x_{k,n}^{(\ell)}$ is the power transmitted in cell ℓ on subcarrier n and $x_{k,n}^{(j)}$ is the allocation variable, which is set to one if subcarrier n the is assigned in cell j to user k and zero otherwise. The optimisation problems presented in the single-cell case can be generalised to the multi-cell case, the price to pay for taking into account the MAI in the optimisation process is a large increment of the algorithms' complexity.

In a multi-cell case different sub-carriers can be allocated to different BSs taking advantage of the so-called *multi-cell diversity*. Furthermore, the Admission Control (AC), which assigns users cells, can be jointly optimised with resource allocation.

Centralised RRM schemes are characterised by the presence of a central entity, for example an RRM server, which is connected to all BSs and has full knowledge of the CSI for all users in all sub-carriers in all cells. This central controller is responsible for the allocation of all system resources, such as groups of sub-carriers, transmission power and modulation formats. The main limit of centralised schemes is their complexity and overhead: in most networks the amount of resources needed to feedback the CSI of all MTs, the computational effort necessary to generate the resource allocation and the signalling overhead to send the assignment information to the users make the centralised approach unfeasible. Nevertheless, centralised schemes are expected to provide the optimal allocation solution and thus represent an ideal benchmark for comparison with more realistic distributed schemes.

Several centralised algorithms use the concept of *reuse partitioning*, whose main objective is to reduce the impact of co-channel interference for users next to cell borders by increasing the Frequency Reuse Factor (FRF) for the sub-carriers assigned to them. The whole set of sub-carriers is partitioned into two or more subsets, where each one uses a different FRF.

In particular, looking at the centralised approached available in the open literature, the main purpose of the algorithm proposed in [80] is to minimise the transmit power while maintaining the rate requirement of each UE, which is aligned with the Multi-cell Margin Maximisation problem. In order to provide the required Bit Error Ration (BER), the SINR of a sub-carrier allocated to an MT should not drop below a certain threshold. The power allocation tries to maintain all SINRs above this threshold. In order to find the optimal sub-carrier allocation, a cost matrix must be created. Each entry of this matrix is achieved by solving the power allocation problem for every possible allocation of sub-carrier n to MT j in the active cell. If, for some combinations of j and n, no feasible solution exists then these combinations are indicated as banned in the active cell and are not used in the process of sub-carrier allocation. This protects the links in the other cells from quality degradation. After that, it is only needed to choose the column with the minimum total power.

Alternatively, a two-step-based algorithm was proposed in [81] whose objective was to maximise the total system data rate, which is very aligned with the Multi-cell Multi-user Bit Rate Maximisation problem. The paper uses the concept of a Rate Requirement Violation ratio (RRV), which calculates the ratio of users in the system that did not achieve their rate requirements (unsatisfied). The first step of the algorithm is called Opportunistic Sub-carrier Allocation and intends to fulfil the rate requirements with FRF_1 for all sub-carriers. For all cells, the algorithm chooses the unsatisfied MT with the best SINR on a given sub-carrier and allocates it to the MT. After each sub-carrier is allocated to one MT, the rates are updated. Then, the RRV is calculated, and if it is lower than a certain threshold, the allocation process is finished. Otherwise, the results from the first phase are ignored and an interference limitation phase is launched to reduce the number of unsatisfied MTs. The idea behind this second step is to dynamically adapt the FRF in order to reduce the RRV. This step begins by allocating sub-carriers with FRF_1 following the same criteria as before: MTs with better channel conditions have priority in receiving sub-carriers. Whatever is the sub-carrier, the average SINR of co-channel MTs should be above a given threshold to guarantee an acceptable level of interference on that sub-carrier. When the number of sub-carriers whose average SINR is below this threshold reaches a defined limit, the FRF is changed to FRF_2. After all MTs are satisfied, FRF_1 is set for all remaining unallocated sub-carriers.

Next, the FRF concept and the problem splitting strategy were used in [82] to propose a centralised algorithm. It is composed of two steps: the Bandwidth Allocation and Sub-carrier Assignment. Based on the number of near and far users, the first step determines the number of sub-carriers belonging to each FRF. In the second step, sub-carriers are assigned to MTs according to the significance of the SINR estimated over them. The objective of the algorithm is to guarantee that a maximum number of MTs can achieve their data rate requirements.

The authors in [83] propose a flexible FRF design mechanism that provides an intermediate value between 1 and 3. Conventional schemes are dedicated to use some integer numbers such as 3, 4, or 7. With such a scheme, they show that a FRF of 7/4 achieves better throughput than FRF 3 and overcomes the inter-cell interference problem of FRF 1, which would be the best choice in terms of cell throughput if not plagued by MAI.

The power division reuse partitioning scheme presented in [84] further improves the performance of systems based on FRF, since it manages to achieve full reuse of the available frequencies. The authors divide the cells in three concentric regions: outer, middle and inner areas. Different sub-bands are allocated for MTs in the outer region of each cell. The remaining sub-bands are allocated to user in the middle region. The users inside the inner area transmit over the whole bandwidth. By such a scheme the actual FRF is smaller than one! Inner users employ a cancellation receiver that removes the stronger signal relative to users in the middle or outer regions and the users in the middle and outer regions regard the signal of users in the inner region as noise.

RRM algorithms for OFDMA-based systems are strongly related to the available architecture and signalling structure. Centralised RRM produces near-optimum channel allocation at the expense of high signalling overhead, so distributed schemes appeared as an alternative to the centralised ones. In distributed RRM algorithms, there is no central entity responsible for receiving measurement reports or distributing resources to MTs or BSs. In addition, it is assumed that the BSs cannot communicate among them.

In [85], the authors assumed a multi-cell system where the cells are tri-sectorised and virtual cells are composed by three adjacent sectors from different BSs. Within a given virtual cell, the total bandwidth is adaptively assigned among the active MTs and the total bandwidth can be reused in adjacent virtual cells. The resource assignment problem in each virtual cell is solved in three steps: decision of the number of sub-carriers for each user, sub-carrier assignment to the users, and finally a bit and power loading algorithm is applied. The first and second steps are based on BABS and ACG algorithms proposed in [42] and described previously. The results show that the system performance is improved compared to traditional systems with fixed channel allocation.

Distributed RRM algorithms for multiple services in a multi-cell OFDMA system were presented in [86]. Two optimisation criteria were discussed in the paper. The former aims to minimise the transmission power based on the rate requirements so that the interference power to other cells will also be minimal, which is similar to the Multi-cell Margin Adaptive optimisation problem. The latter tries to minimise the number of used sub-carriers subject to MT rate requirements, and then allocate suitable transmit power among sub-carriers. The authors claim that the former is worse because it might use a large number of sub-carriers, increasing the generation of interference. Four resource allocation techniques are proposed: Random Sub-carrier Allocation (RSA), Best Sub-carrier Allocation (BSA), n-Best Sub-carrier Allocation (n-BSA) and BSA with interference learning. The RSA algorithm does not use channel information and has three steps. The first step defines the minimum number of sub-carriers for each user based on MT rate requirements and maximum rate delivered by link adaptation, in a similar way as the BABS algorithm proposed in [42]. The second step of the RSA assigns the number of sub-carriers defined in the first step at random for each MT, and finally in the last step, an equal bit loading algorithm is performed among the sub-carriers. The BSA algorithm has also three steps, but on the other hand it does have knowledge of CSI. The first step is exactly the same as the RSA algorithm. In the second step the users are ordered according to their average channel gains. The ones with lower average channel gain have priority when choosing their strongest sub-carriers. Finally, the adaptive loading algorithm proposed by [87] is performed in order to distribute power among sub-carriers. In the n-BSA algorithm, the second step of BSA is modified in order to avoid persistent interference. Users choose at random their sub-carriers in the set of their n best sub-carriers. In case the number of sub-carriers defined in the first step is greater than *n*, the user continues choosing among the remaining sub-carriers. Finally, in BSA with interference learning, the sub-carriers are classified in two groups, good and bad sub-carriers, according to some quality metric like SINR or Frame Erasure Rate (FER). This classification must be performed frequently according to the channel coherence time. When a given sub-carrier does not meet an acceptable quality, it is moved to the bad sub-carrier set. The BSA with interference learning algorithm is performed only in the good sub-carriers set, except when this set is not large enough. In this case some sub-carriers from the other set can be used. The results presented in the paper show that the variants of the BSA algorithm outperforms the standard one and also the RSA algorithm.

In [54], the authors focus on DL of a multi-cellular system with universal frequency reuse. Allocation is performed in a distributed way, without resorting to a centralised allocator. Each cell follows a greedy approach and allocates iteratively its resources aiming at maximising its own objective function. The proposed algorithm is iterative since the allocation in a particular cell interferes with the allocation in all other cells. Because of the uncoordinated multi-access interference, the main problem of distributed resource allocation is the convergence of the proposed scheme. Inter-cell interference is managed by progressively reducing the cell load until a stable traffic configuration is found.

There is another class of RRM algorithms in which the allocation procedure is sub-divided in tasks that are performed by different network nodes that are in different hierarchy levels in the system, for example an RRM server and the BSs. Due to this characteristic, this class of RRM algorithms tends to be a good trade-off between the centralised and distributed ones.

The scenario assumed in [88] consists of an RRM server that communicates with a group of BSs, where each of them knows the MT traffic status (arrival rates, buffer occupancies, CSI, etc.). The RRM server determines the specific set of sub-carriers assigned to each BS for a given super-frame and the recommended MTs for each sub-carrier. Locally, the BSs make the pairing between the sub-carriers and MTs based on MT channel fading and traffic conditions.

In [89], the authors firstly formulated an MA-like problem in a multi-cell OFDMA system in order to assign sub-carriers and allocate bits and power to MTs. However, the formulated problem was a three dimensional, non-linear and combinatorial one. Due to this complexity, the authors proposed a three step heuristic algorithm to solve the problem in a suboptimum way. The algorithm is triggered by the arrival of a new user and it is structured in three steps. In the first step, the serving cell for a new user is determined based on the greatest average channel quality among all sub-carriers. This channel quality is assumed as the channel Gain-to-Interference plus Noise Ratio (GINR). This new user is blocked if the estimated minimum number of sub-carriers to be used by him plus the sub-carrier already assigned in the serving cell is greater than the total number of sub-carriers. In the second step, a modified version of BABS and ACG algorithms proposed in [42] is utilised to allocate and assign sub-carriers to the new user and the ones already present in the system. Finally, in the last step a simple adaptive loading algorithm to allocate bit and power to the sub-carriers is used. If the allocation of power and bit necessary to satisfy the requirements of the new user affects the QoS of ongoing connections in the system, this user is blocked. Simulation results show a superior performance of the proposed method when compared to classical RRM techniques.

2.5 Game Theoretic Framework for RRM

2.5.1 Scope and Objectives

The main purpose for using the game theory [90], [91] in flexible radio spectrum access and RRM is to model some strategic interactions among agents (the players) with a need and a potential to access the limited spectrum resources and to make the best use of these resources. It derives well-defined equilibrium criteria to study the optimality of game outcomes for various game scenarios (static or dynamic, complete or incomplete information, non-cooperative or cooperative). The application of the economic concepts, such as competition, cooperation or the mixture thereof, allows one to analyse the problem of flexible usage of limited radio resources in a competitive environment. Game theory can be a powerful tool for finding its solution in overlapping, QoS supporting, standardised or proprietary wireless networks.

In order to provide efficient and flexible radio spectrum usage and RRM, several problems need to be handled: the unreliable nature of wireless channels, user mobility, dynamic network topology, its various infrastructures, and unpredicted network-users' behaviours, which can be cooperative, selfish, and even malicious [92]. Traditional RRM methods assume cooperative, static, and centralised network settings and require a large amount of signalling overhead, in order to acquire information on the multiple channels quality and distribute the information on the spectrum assignment. The centralised, inflexible and arbitrary decisions are taken based on some fairness-based or efficiency-based criteria, which from a single-user standpoint may be missed. Thus, it seems necessary to widely analyse the network users' intelligent behaviours and interactions at first. Moreover, the Cognitive Radio (CR) concept assumes that a radio node is an intelligent entity, which senses the environment, takes rational decisions and learns from its past experiences. One should stress here that "rational" decisions do not really mean "optimised" nor "selfish". The CR-node learning involves updating of its knowledge base, or of its algorithms, and impacts the decision making in the future, just like in the case of an intelligent player's behaviour in a repeated game. It seems that game theory is a perfect tool to study conflict and cooperation actions among intelligent rational decision makers, which match flexible RRM problems in changing radio environment.

The general objective in WG3 is to consolidate partners' research *in the direction of modelling the conflicting and competitive behaviour of the cognitive network users and nodes as a dynamic and flexible resource-sharing game, as well as of algorithms development for the desired demeanour towards efficient radio-resource usage*. To this end, one should first be able to consider some possible scenarios and relevant wireless networks. For each considered network, its infrastructure, topology, wireless access and its spectrum resources, one should define game models. In general, a strategic form of each game consists of three basic elements:

- the set of players,
- the strategies for each player,
- the utility function, which measures the outcome (the payoff) of each player or a group of players.

Depending on the scope in our game for resources, the set of players may include a number of users of equal rights, or the primary and secondary users of the wireless network, or BSs. The strategies of each player include various actions related to the operation of spectrum sharing and RRM, which are available for the certain player to be processed. For example, for OFDMA network users of equal rights, their strategies could be the specific subcarriers they want to use as well as the transmission parameters (adaptive modulation and coding scheme and the power levels) they would adopt at these subcarriers to receive their data with a certain quality. As another example, one may consider the strategy space for primary users, which could include numbers of unused channels that they could lease to secondary users and how much they will charge secondary users for using their spectrum resources. Secondary users may define their strategies as the licensed channels they would use together with the maximum price they agree to pay for leasing these channels. The payoffs in the game usually are determined by the applied utility function, whose arguments depend on the adopted strategies. Moreover, the payoffs depend of the cooperativeness of players. For a group of cooperative users the utility function represents their common communication goal, and the payoffs in the coalition depends on how much a player contributes to this common goal in the coalition. For selfish users the utility function and resulting payoffs describe their independent interests. The payoff for malicious users illustrates their possible damage to the efficiency of spectrum usage [92].

Furthermore, one should consider non-cooperative games for resources without centralised management when it is not possible for the users to cooperate. This way, more efficiency in spectrum sharing and utilisation can be obtained. In cooperative games, the players should be able to share the resources, by forming coalitions, either by using centralised control or by exchanging some necessary information between them. Traffic requirements of the applications determine whether a strategy should pursue cooperative behaviours to increase payoffs or non-cooperative ones [93].

After defining game models for the chosen scenarios, the next goal should be to apply appropriate mechanisms to obtain desired outcome. This brings the problem how to define this desired outcome of a game, i.e., the optimality criteria.

To summarise, the main objective defined at the beginning of this subsection should be achieved in the pace of meeting the following sub-goals:

- to consider and pick one or two wireless network scenarios reflecting up-to-date and future demands of users;
- to define relevant game models;
- to develop appropriate algorithms converging to the desired game solution (meeting optimality goals);
- to verify proposed models and algorithms via computer simulations.

We anticipate that the joint research will naturally result in joint papers, patents and future projects.

2.5.2 State of the Art Analysis

As mentioned above, game theory has recently been considered as a tool to model a decisive behaviour of a node in a wireless network competitive environment. Depending on the environmental awareness, radio nodes can play cooperative or non-cooperative games against each other. Such games when appropriately defined have fair and efficient (in various terms) solutions. In telecommunications, game theory has been first applied for solving power control problems [94], [95] such as the UL power control in CDMA systems [96], [97] or power control in multi-cell Orthogonal Frequency Division Multiplexing (OFDM) systems [98]. In those applications, power control problems were modelled as non-cooperative games and their distributed solutions were sought for. Examples of games dealing with network service pricing, QoS handling, routing, slotted-Aloha medium access control, interference avoidance, power control and trust management in cooperative radio networks are shortly discussed in [99]. There, an interested reader can also find a bibliography of the vast field of game theory applications in wireless networks. Applications of game theory to wireless ad-hoc networks have been surveyed in [100].

The major interest is in game models and equilibrium (or optimality) criteria dealing with radio resource management and common spectrum utilisation to achieve desired solutions for various network architectures, spectrum allocation schemes and radio access techniques. Below, one presents the state-of-the-art of such game theory applications for flexible spectrum usage in radio communication networks. We focus on the following types of games, which have been considered in the literature, so far: non-cooperative games having Nash equilibriums as solutions, cooperative games, with the Nash Bargaining Solution (NBS) and cooperative games based on auctions. Moreover, in Section 2.5.3, one presents the application of game theory in the Dynamic Subcarrier Allocation (DSA) and RRM in OFDMA networks where the users' strategies are multi-dimensional, because they concern subsets of subcarriers.

In [101], game theory is applied to model the DCA problem for the Broadband Fixed Wireless Access based on Packet Reservation Multiple Access. There, the players are APs, which share the spectrum available at a certain area, in which the frequency reuse principle is applied. The distributed APs system is considered, which means that an AP can make decisions concerning channel allocation on its own. The payoff is defined as the number of packets that are interference-free per time-unit. The APs involved in a game do not cooperate, but use mixed strategies reflecting the time spent to scan the available channels and the time spent on actual channel exploitation. The proposed game-theoretic method for the DCA shows better performance (in terms of the received-SNR cumulative distribution function) when compared with other methods based on random channel allocation and the so-called *least interfered* method.

Another approach, presented in [102], is focused on investigating self-enforcing spectrum sharing non-cooperative game played among secondary users in the Dynamic Spectrum Access Networks (DySANs – which will be shortly discussed in what follows). Game rules and the corresponding game outcome (efficiency) measured in total throughput obtained from available spectrum resources are defined. To analyse the spectrum sharing interactions among users in a long-run scenario a repeated game model is proposed. The payoff in the considered game reflects a normalised discounted summation of the payoffs acquired at the end of each one stage game. Because the users in a repeated game are able to make decisions conditioned on their past moves, thus allowing for “good” reputation effect and retribution, the considered game converges to efficient self-enforcing spectrum sharing.

In [103], the price of anarchy is studied for non-cooperative spectrum sharing games. This price of anarchy is the ratio between the worst possible Nash equilibrium and a social optimum that can be achieved when a central management is available. For example, the price of anarchy in the scenario of a WiFi network represents the ratio between the number of APs assigned to the spectrum channels in the worst Nash equilibrium and the optimal number of covered APs if a central authority assigns the channels. It is shown, that the price of anarchy is unbounded unless some certain constraints are applied, e.g., a certain distribution of users.

In [93], the problem of resource sharing among WLANs coexisting and operating in unlicensed frequency bands is discussed. There, the cooperative game is discussed, where the players are WLANs, which interact with each other, however this interaction refers only to selecting strategies, and estimating the opponent’s strategies. The opponent player’s behaviours are classified to judge her intentions. The paper focuses on repeated single-stage games that form a multi-stage game. The authors of [93] discuss different dynamic strategies, and compare their achievements with respect to their capabilities for the QoS support. It is also shown that a player can adapt to its environment (co-existing WLANs) by deriving information about what action the opponent takes, without knowing the exact QoS requirement of the opponent.

In [104], a game theoretic approach to radio resource allocation for the DL multi-hop link capacity is presented. The fair resource sharing among mobile nodes of a single multi-hop link is based on a cooperative game using the NBS. It is shown, that sharing of the DL capacity between multiple nodes using a non-cooperative approach is inefficient because it penalises the downstream nodes. The authors discuss a cooperative agreement, in which all nodes share the radio resources equally, and downstream nodes are allowed to pay compensation to prevent upstream nodes from exploiting the DL capacity and encourage them to cooperate.

A local bargaining approach is being proposed in [105] for achieving distributed spectrum assignment adapted to network topology changes. This approach consists of two strategies:

- one-to-one bargaining is proposed to efficiently exchange channels between two neighbour users,
- one-buyer-multiple-seller bargaining is proposed for a buyer to purchase spectrum channels from several neighbours based on Feed Poverty [105] fairness strategies.

It is necessary to note that using this bargaining method, the optimal resource assignment does not need to be recomputed after each change of the network topology. This makes this approach interesting from the complexity point of view.

As it will be further detailed in chapter 3, dynamic spectrum access allows unlicensed wireless users (secondary users) to dynamically access the licensed bands from legacy spectrum holders (primary users) on a negotiated or an opportunistic basis. As shown in [92], the dynamic spectrum access is provided by the dynamic spectrum sharing process, which results in the efficient and fair spectrum allocation or scheduling solutions among primary and secondary users. This process usually neglects management of other resources, such as power, and thus, can be considered as the spectrum-resource management with on-off power management.

Wireless networks constructed with the usage of the auction-based game theory usually belong to the category of DySANs, which are supposed to provide efficient spectrum usage by dynamic spectrum access techniques in heterogeneous network architectures. It means that the secondary users are given the ability to access spectrum resources from primary users through opportunistic or negotiation-based methods while not causing harmful interference or channel collision. As shown in [106], the well developed auction theory, one of the most important applications of game theory, can be applied to build and analyse interactions among users in such scenarios.

In auction games, described in [106] in detail, the principles (auctioneers) determine resource allocation and prices on the basis of bids from the agents (bidders). In the considered game, the primary users are the principles, who try to sell unused channels to the secondary users. The secondary users are the competing bidders who want to buy the permission of using primary users' channels. Furthermore, multiple sellers and buyers may coexist, which indicates the scenario proper for the double auction game model, in which not only the secondary users but also the primary users need to compete with each other to make beneficial transactions. In the double auction scenarios of the SSG, the supply function can be defined as the relationship between the acquisition costs of primary users and the number of channels [106]. The demand function in this case can be defined as the relationship between the reward payoffs of the secondary users and the number of channels.

In [107], two auction mechanisms are proposed, which account for the payment metrics specific for the spectrum buying-selling auctions:

- the first one is to charge secondary users according to their received signal-to-interference-plus-noise ratio,
- the second one is to charge secondary users according to their received power.

Furthermore, an iterative and distributed bid updating algorithm has been derived to have auction-based spectrum sharing converge to the social optimal equilibrium by Vickrey-Clarke-Groves mechanisms.

As shown in [108], the complex scenarios of DySANs with multiple primary and secondary users can be handled using the belief-assisted pricing. There, the belief metrics are proposed to predict other users' future strategies based on the game history. It is also proposed to define one belief function for each user based on the observable bid/ask prices. The primary/secondary users' beliefs are defined as the ratio of their bid/ask being accepted at different price levels. By using the proposed belief functions, each user is able to make the optimal decision for the next bid/ask with only local information, leading to the distributed algorithm which converges to the optimal equilibrium, and decreases the overhead of bid/ask information.

A market-based approach can be also applied to the system of BSs, which act as independent sellers (for those having excess capacity to offer) or buyers (for those requiring additional capacity). Such an approach has been shortly described in [109], where the possibility for the BSs is discussed to express value using some sort of a "currency" that can be traded for resources. This value depends on the willingness of the contending BSs to pay.

2.5.3 Game Theory in OFDMA Studies

OFDMA is considered as one of the most promising multiple access techniques for future high data rate wireless systems. One considers this technology as one of the basics scenarios for the research on game-theory application to flexible spectrum usage and RRM. Allocation of resources in OFDMA in both single- and multi-cells environments should aim at the most efficient (and possibly fair among the users) spectrum utilisation. Additionally in multi-cell scenarios, minimisation of the co-channel interference between neighbouring cells has to be handled. Most of the algorithms for flexible resource allocation in OFDMA, which have been presented in the literature, are centralised ones (which naturally imply the signalling overhead) or assume some limited cooperation between the cells, and very few of them employ the game theory.

Similarly, as in the case of more general spectrum allocation and RRM, game-theoretic scheduling for OFDM has been also considered in the literature in two major directions. The first one is centralised subcarrier allocation, which allows for more efficient and fair spectrum utilisation and applies cooperative game theory, Nash-bargaining and arbitrary Pareto-optimal solutions. The second one is distributed decision making, which on the contrary, deploys non-cooperative games and results in Nash equilibrium as a game solution.

In [50], distributed resource allocation algorithm is presented for multi-cell OFDMA systems, which adopts a game theoretic approach. The problem of the resource allocation is modelled as a noncooperative game among the cells, i.e., among BSs, which act as players. The proposed strategies incorporate both the transmit power levels and the sub-channel allocation, and thus, are multi-dimensional because of multiple sub-channels. The utility function suggested by the authors reflects the system performance in the presence of co-channel interference. Based on the defined game elements, an iterative algorithm for Distributed Resource Allocation (DRA) is proposed, which does not require cooperation (coordination) among BSs. This proposed DRA algorithm converges to the existing unique Nash-equilibrium within a relatively small number of iterations, as shown in the paper.

In [110], a centralised and fair scheme of the OFDMA subcarrier allocation, rate, and power is proposed. Fairness here is not considered as equity, but as proportional fairness based on NBS within the coalitions of two users. The goal of the players in the cooperative game, modelling the OFDMA subcarrier allocation, is to maximise the overall system rate, under each user's maximal power and minimal rate constraints. The first approach considered in the paper is an algorithm for bargaining subcarrier usage between just two users. Then, a multiuser bargaining algorithm is developed. It is based on grouping pairs of users into coalitions either by a random choice or by using the Hungarian method [111]. The NBS is applied to each coalition, and the process is repeated. By iterative process of coalitions formation the subcarrier allocation is optimised until no improvement can be obtained.

In [112], an extension of the above work is presented, in which an OFDMA DL resource allocation is tackled. Again, the resource allocation problem is modelled as a cooperative (proportional-fairness-based) game. Apart from the minimum rate requirement, the authors introduce also the users' maximum rate requirement, and apply the Raiffa-Kalai-Smorodinsky bargaining model, which regulates the bargaining outcome (Raiffa-Kalai-Smorodinsky Bargaining Solution - RBS) of a game. In the abovementioned paper, a reduced complexity algorithm is proposed to achieve transmission rates as close as possible to the Pareto optimal rates. The authors use a generalised proportionally-fair scheme based on optimal coalitions and NBS presented in [110], but they use also RBS as an alternative bargaining solution within a coalition. Moreover, they propose a reduced complexity algorithm (as compared with the one presented in [110]) to allocate sub-carriers, rate and power for multiple users in an OFDMA system.

The OFDMA technology can be considered as one of our basis scenarios. OFDMA-based cognitive radio networks seem to have a great potential to support future mobile multimedia traffic in a flexible manner. Such networks can operate in an opportunistic manner, filling in the spectrum "holes" in the WiMAX, WiFi or Long Term Evolution (LTE) networks, as well as in an ad-hoc manner. So, OFDMA is suggested as a working scenario for game-theoretical RRM studies within WPR.9. In the first phase of our studies, the mobile single-cell multi-user OFDMA scenario defined in Section 4.3 is considered. In this first phase, one assumes that users are able to detect available spectrum resources, and to adopt a subset of accessible subcarriers, as well as the transmission rate and power associated with these subcarriers. One focuses on the distributed allocation of subcarriers for multiple CR nodes within a cell in an OFDMA-based network, what aims at rational and efficient spectrum utilisation. Rationality in our case means that apart from maximising the spectral efficiency (the number of bits per second per Hertz) the network and each individual CR-node aim at lowering the cost of this efficiency (in terms of the power consumption and the total transmitted power) and increasing the Quality of Experience (resulting from the number of served users). This can be done based on non-cooperative game model, which includes the concept of pricing (or coercive taxation). After the acquisition of radio resources (OFDM subcarriers), a CR node should be able to maximise its throughput by adopting the rate and power on distinct subcarriers, taking the fact into account that the CSI is not perfect (e.g., due to the estimation and prediction error, feedback delay, etc.). This could be the outcome of another game, which the CR nodes play independently against their radio environment. This approach of first playing the game against the other network users (or nodes) and then, against the channel can be viewed as the *top-down approach* to maximise the spectral efficiency, network capacity while economising the power of the CR nodes.

In the next phase of our research, one concentrates on multi-cell OFDMA scenarios, in which interference management through interference-limiting power allocation games are considered. Both cooperative and non-cooperative solutions are sought for. Again, imperfect CSI will be assumed, as well as energy and spectral limitations.

3 ASM STRATEGIES

3.1 Introduction

3.1.1 Flexible Spectrum Management

Together with the evolution of wireless technologies to allow delivering more advanced multimedia services, the regulatory perspective on how the spectrum should be allocated and utilised in a complex and composite technology scenario is evolving as well. The evolution is towards a cautious introduction of more flexibility in spectrum management together with economic considerations on spectrum trading. This new spectrum management paradigm is driven by the growing competition for spectrum and the requirement that the spectrum is used more efficiently [113]. Then, instead of the classical fixed spectrum allocation to licensed systems and services, which may become too rigid and inefficient, the possibility to use Flexible Spectrum Management (FSM) strategies that dynamically assign spectrum bands in accordance with the specific traffic needs in each area is being recently considered [114]. There are different FSM scenarios presenting different characteristics in terms of technical, regulatory and business feasibility. While a fully enabled FSM scenario can be envisaged at a rather long-term perspective, there are already some basic FSM scenarios that are becoming a reality. Spectrum refarming, providing the possibility to set-up communication on a specific RAT in different frequency bands (e.g., refarming of GSM spectrum for UMTS/HSPA communications), is a first example. Another case for FSM arises from the so-called digital dividend, which corresponds to the frequencies in the UHF band that will be cleared by the transition of analogue to digital television. The cleared spectrum could be used by mobile TV or cellular technologies, like UMTS, LTE, WiMAX, etc., and also for flexibly sharing spectrum among smart radio technologies. The exploitation of the so-called TV White Space, which refers to portions of spectrum that are unused, because either there is currently no license holder for them, or they are deliberately left unused as guard bands between the different TV channels, is another opportunity for FSM mechanisms.

As a result of the above trend, future wireless terminals will have to be reconfigurable in nature and will have to face the challenge of having to identify which is the spectrum band that can be used for each specific service. In turn, networks will have to adapt themselves to the varying conditions by being able to change the spectrum bands that they are operating with. Consequently, future wireless systems will have to be designed under the principles of cognition, re-configurability and adaptability. Several works in the literature have recently dealt with FSM strategies. In [115], the DIMSUMNet architecture is presented for coordinated, real-time dynamic spectrum access based on a centralised entity called Spectrum Broker as opposite to other opportunistic, uncoordinated methods. In particular, this architecture introduces the concepts of coordinated access band and statistically multiplexed access to spectrum. Further work on this topic has considered different formulations for solving the spectrum allocation problem based on linear programming techniques.

One of the open points to enable the efficient operation of MTs in FSM scenarios is to devise mechanisms to assist them with the procedure of discovering which are the available access technologies and the frequencies in which they are operating. In that sense, different proposals exist such as the Common Spectrum Coordination Channel (CSCC) in [116] or the Cognitive Pilot Channel (CPC) in [117], [118], [119]. It consists of a channel that carries the information corresponding to the operators, RATs and frequencies available in a given area, so that cognitive terminals do not require scanning the entire spectrum in order to find out which these available systems are and which frequencies are they using.

3.1.2 Secondary Spectrum Usage

The traditional approach in spectrum management has been the definition of a licensed user granted with exclusive exploitation rights for a specific frequency. While it is relatively easy in this case to ensure that excessive interference does not occur, this approach is unlikely to achieve the objective to maximise the value of spectrum, and in fact recent spectrum measurements have revealed a significant spectrum underutilisation, in spite of the fact that spectrum scarcity is claimed when trying to find bands for new systems. From an economical point of view, economists have long argued that market mechanisms should be applied to radio spectrum. From the technology point of view, advances in recent years such as ultra-wideband (UWB) and cognitive radios enable other forms of spectrum access. Cognitive radios, as devices with the capabilities to be aware of actual transmissions across a wide bandwidth and to adapt their own transmissions to the characteristics of the spectrum, offer great potential of developing more advanced spectrum management approaches.

As a result of the above, one of the current trends in the spectrum management are the so-called Dynamic Spectrum Access Networks (DSANs), in which unlicensed radios, denoted in this context as Secondary Users (SUs) are allowed to operate in licensed bands provided that no harmful interference is caused to the licensees, denoted in this context as Primary Users (PU). The proposition of the TV band Notice of Proposed Rule Making (NPRM) [120], allowing this secondary operation in the TV broadcast bands if no interference is caused to TV receivers, was a first milestone in this direction. In this approach, SUs will have to sense the spectrum to detect PU or SU transmissions and should be able to adapt to the varying spectrum conditions, ensuring that the primary rights are preserved. These events culminated in the creation of the IEEE 802.22, developing a cognitive radio-based physical and medium access control layer for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV broadcast service.

The primary-secondary (P-S) spectrum sharing can take the form of cooperation or coexistence. Cooperation means there is explicit communication and coordination between primary and secondary systems, and coexistence means there is none. When sharing is based on coexistence, secondary devices are essentially invisible to the primary. Thus, all of the complexity of sharing is borne by the secondary and no changes to the primary system are needed. There can be different forms of coexistence, such as spectrum underlay (e.g., UWB) or spectrum overlay (e.g., opportunistic exploitation of white spaces in spatial-temporal domain sustained on spectrum sensing, coordination with peers, and fast spectrum handover). As for cooperation, again different forms of P-S interactions are possible. For example, spatial-temporal white spaces that can be exploited by SUs can be signalled through appropriate channels. In addition, the interaction between PUs and SUs provides an opportunity for the license-holder to demand payment according to the different QoS grades offered to SUs.

One of the key enabling technologies for DSAN development is the cognitive radio, which allows the terminals determining which portions of the spectrum are available, selecting the most appropriate channel for transmission, and vacating the channel whenever a licensed user is detected. In this respect, there are a number of techniques to be developed for an efficient secondary spectrum usage and can be categorised as [121]:

- spectrum sensing techniques: they are devoted to detect unused spectrum and sharing it without harmful interference with other users;
- spectrum management techniques: they intend to selecting the best available spectrum to meet secondary user communication requirements;
- spectrum mobility techniques: they try to maintain seamless secondary communication requirements during the transition to a better spectrum portion due to, e.g., the appearance of a primary transmission in a channel occupied by a secondary user that, as a result will have to vacate this channel;
- spectrum sharing techniques: these techniques intend to provide fair spectrum scheduling methods among coexisting secondary users.

3.1.3 Framework for Developing ASM Strategies Based on Cognitive Network Concepts

Considering a flexible spectrum management framework, these types of strategies are devoted to decide the suitable spectrum assignment to cells and RATs within a given operator domain, in accordance with the current traffic demands in a certain area. Intra-operator ASM re-arranges the spectrum bands allocated to that particular operator, enabling the dynamic management of spectrum blocks within a single or between different RATs. Consequently, it determines the capacity for each different RATs of the operator.

ASM methodologies concern traffic changes from medium to long time scales (e.g. minutes, hours or days) that affect a specific area of the network. For a given system, they aim at ameliorating spectrum efficiency by finding the best frequency allocation to cells. Moreover, they should be able to detect the limits of the network to support existing traffic with its allocated carriers. ASM methodologies should be able to ask for more carriers if the required number of carriers is higher than the actual number of carriers associated to the system.

The last few years have witnessed a fast pace in the development of ASM methodologies exploiting the new degrees of flexibility introduced by the emerging vision of regulatory bodies about spectrum pooling and sharing in composite networks where different RATs and different operators coexist [122]-[130]. These methodologies use some metrics that reflect system performance at cell level as inputs for optimisation algorithms, such as local search or genetic algorithms, in order to find a spectrum allocation as close as possible to the optimum allocation.

In order to cope with the inherent dynamism in mobile communication networks due to different aspects propagation conditions, traffic generation processes, interference conditions, mobility of radio transceivers, etc., modern networks must provide mechanisms to adapt to changes by introducing cognitive network features [131], [132], which can be applied in a natural way to the development of ASM strategies. The central mechanism of a cognitive network is the cognitive process, which can perceive current network conditions, and then plan, decide and act on those conditions. Then, this is the process that does the learning and decides on the appropriate response to observed network behaviour. The cognitive process acts following a feedback loop in which past interactions with the environment guide current and future interactions. This is commonly called the Observe, Orient, Decide and Act (OODA) loop, which has been used in very different applications ranging from business management to artificial intelligence, and which is analogous to the cognition cycle described by Mitola [133] in the context of cognitive radios.

Figure 6 reflects how the cognitive cycle can be exploited in the development of ASM strategies, involving the following steps:

- *Observe*: The observation of the network status involves a large number of measurements and metrics. Measurements and metrics can be obtained at different network elements (e.g., MTs and BSs). Measurements relevant for a particular function of the cognitive cycle need to reach the network element(s) where the corresponding function is implemented. Measurements and metrics of interest may be at connection level (e.g., path loss from terminal to cell site, average bit rate achieved over a certain period of time, etc.) or at system level (e.g., cell load, average cell throughput achieved over a certain period of time, etc.).
- *Analyse*: This stage considers relevant inputs obtained from the observation phase and its objective is the identification of relevant changes in the network status affecting the provisioned QoS levels. Furthermore, the analysis may consider the dynamics on inter-cell interactions (i.e., mutual interference from any pair of cells) as a key indicator reflecting the radio interface conditions and its evolution due to changes in requested services, spatial distribution of users, etc.. For example, inter-cell interactions can be represented in smart forms, such as the so-called coupling matrix [134] in the context of WCDMA systems. The coupling matrix has interesting mathematical properties that can be used as performance indicators, such as the high correlation existing between its spectral radius (i.e., the eigenvalue with the highest modulus) of the coupling matrix and the outage probability (i.e., the probability that a given user is not reaching the target QoS).
- *Learn*: In this phase the network bases on accumulated previous experience in order to identify patterns of behaviour that can help in reaching the desired solutions. Many strategies can be envisaged as learning procedures with the ultimate goal of acquiring knowledge. In the context of cognitive networks, machine learning has been widely considered as a particularly suited framework, with multiple possible approaches. The choice of the proper machine learning algorithm depends on the desired network goals. In any case, one of the main challenges here is that the process needs to be able to learn or converge to a solution faster than the network status changes, and then re-learn and re-converge to new solutions when the status changes again, so that convergence issues are of particular importance. Machine learning algorithms can also be

organised in different categories (supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning being the most common ones) depending on how their desired outcome is obtained. Some of the identified machine learning strategies studied in the literature are neural networks, genetic algorithms, expert systems, case-based reasoning, Bayesian statistics, Q-learning, etc.

- *Decide* and *act*: This stage would correspond to the dynamic spectrum management algorithm itself that, based on the outcomes of the observe, analyse and learn stages, would determine the adequate spectrum to be assigned to each of the cells in the scenario.

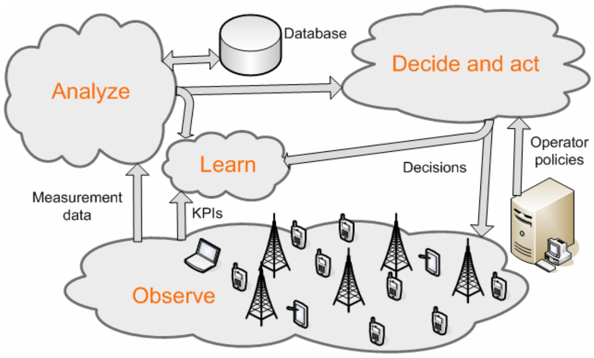


Figure 6 - Integration of spectrum management strategies in the cognitive cycle.

The result of the execution of the ASM algorithm can lead (1) to re-arrange the frequency assignment plan (i.e., dynamic network planning) while keeping the same total available amount of spectrum, (2) to release, globally or locally, some spectrum blocks, which could be used by other RATs or placed in market for inter-operator ASM purposes, (3) to request additional spectrum to inter-operator ASM mechanisms.

ASM should cope with (1) cell load variations, which may be associated with an increase/decrease in the number of users or in the requested service characteristics (e.g., increase/decrease of the required bit rates) and/or (2) inter-cell interference conditions variations, which may be associated with changes in spatial user distribution. An illustrative ASM algorithm is shown in Figure 7 in the form of a flow diagram. The algorithm is developed in order to come up with a suitable spectrum assignment in the scenario (i.e., mapping of carriers to cells). When relevant variations in the traffic distribution occur, this means that some of the cells that share the affected carriers are experiencing high interactions and should no longer use the same carrier. Thus, the detection of this event is a very important issue in the overall ASM methodology to guarantee the required QoS levels. Based on this methodology, in [135] the authors propose an ASM algorithm for WCDMA networks. A similar approach for an OFDMA network can be found in [136].

3.1.4 ASM Related Activities in NEWCOM++ WPR9

Based on the above framework, the rest of the chapter presents the activities that are currently being carried out in NEWCOM++ WPR9 related with spectrum management mechanisms. Specifically, in Section 3.2, a first activity in order to identify spectrum availability for secondary spectrum use is carried out based on a measurement campaign. The purpose here is to detect how primary users are using the different frequency bands in different regions in order to analyse and extract patterns of behaviour that can be useful in a further development of spectrum management techniques for improving the efficiency in spectrum utilisation through enabling a secondary spectrum usage.

In Section 3.3, another activity is presented in which cognitive networks based on the "sensorial radio bubble" concept are developed. With this methodology, cognitive radios are able to identify how the spectrum is being used in its environment and to take the appropriate decisions.

Finally, Section 3.4 presents a methodology for spectrum sharing between primary and secondary users based on distributed power allocation.

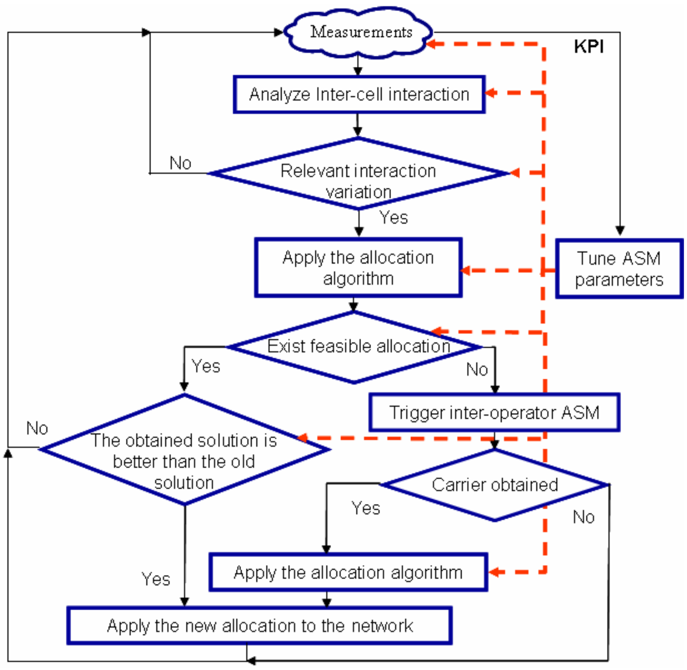


Figure 7 - High level vision of an ASM algorithm.

3.2 Measurements for the Identification of Spectrum Availability

3.2.1 Introduction and Objectives

Cognitive Radio Networks (CRNs), also referred to as DSANs, have been paid much attention in both academic and industrial spheres during the last years for their capability to solve the conflicts between spectrum demand growth and spectrum underutilisation. The basic principle on which this paradigm relies is to allow certain unlicensed users to access some licensed radiofrequency bands when they are not being used by any licensed users. Hence, unlicensed opportunistic access to spectrum is allowed provided that no harmful interference is caused to legitimate users. This will result in increased spectrum usage efficiency. Nevertheless, before investigating the technical issues of this type of communication systems, it turns out to be necessary to have a clear picture of how different frequency bands are being used in specific environments. An appropriate analysis and characterisation of the current spectrum occupancy will allow us to study and analyse the availability of temporarily unoccupied spectral resources in terms of frequency, time, and space, and to identify the most suitable and interesting bands for the deployment of future CRNs/DSANs. The measurement of real network activities provides an important step towards a realistic understanding of dynamic spectrum utilisation. In this context, the aim of the activities to be carried out in Working Group 4 (WG4) of WPR9 as a part of task TR9.2 "Advanced Spectrum Management (ASM) strategies" is to perform an extensive spectrum measurement campaign in order to characterise current spectrum usage and identify frequency bands suitable for CRN applications.

The objectives to be fulfilled in the framework of this activity can be summarised as follows:

- To perform a broadband spectrum measurement campaign in different specific scenarios embracing spectral bands of interest up to 7 GHz.
- To analyse and characterise spectral occupancy in order to enable a better understanding of how wireless communication systems use the allocated spectrum.
- To study the spatial dimension: spectrum occupancy at different geographical locations (urban, sub-urban, rural), correlation between spectrum utilisation in different areas (e.g., how big are the areas where certain frequency bands are not being used, etc.)
- To study the temporal dimension: temporal patterns of spectral utilisation (e.g., spectrum utilisation during day/night), etc.

3.2.2 State-of-the-Art Analysis: Previous Measurement Campaigns

Several researchers have performed similar measurement campaigns as the one it is being planned here to determine the degree to which allocated spectrum bands are occupied. These measurement campaigns were performed in different places all around the world. However, most of them were done in the USA, and therefore evaluated the American spectrum regulations and usage. Few studies have been carried out in Europe. The spectral occupancy in European countries and the evaluation of European spectrum regulations are therefore rather unexplored issues.

Table 4 summarises the main similar spectrum measurement campaigns of interest to this activity. The first larger spectrum occupancy measurement campaign was performed between 1995 and 1998 by the National Telecommunications and Information Administration (NTIA) [137], responsible for managing the Federal Government's use of the radio spectrum in the USA. The study measured the spectrum usage in several metropolitan areas in the USA across the frequency range 108 MHz to 19.7 GHz. The main conclusion of the study was that the spectrum occupancy was found to be higher in coastal cities because of the presence of naval radars. However, measurements did not provide the needed temporal spectrum use information required to obtain free spectrum estimates.

Table 4 - Summary of the main spectrum measurement campaigns of interest (RBW = Resolution bandwidth).

Ref	Year	Place	Environment	Location of equipment	Meas. period	Antennas	Freq. Range [GHz]	Detector	RBW [kHz]	Pre Amp.
[137]	1995 – 1998	Denver, San Diego, Los Angeles (USA)	Sub-urban	Hilltop	2 weeks	–	[0.108, 19.7]	–	–	Yes
[138]	2004	Virginia (USA)	Rural	Ground	≈1 hour	Below 1 GHz: Horizontal log periodic Create Model CLP-5130-2N (105 MHz – 1.3 GHz) Discone (30 – 1000 MHz) Between 1 and 3 GHz: Horizontal log periodic (unspecified)	[0.03, 3]	–	10	Yes
[139]			Urban	Ground						
[140]			Urban (noise and interference)	Roof of building						
[141]		New York (USA)	Urban (period of unusually high spectral usage)	Roof of building	48 hours	Below 1 GHz: Discone (unspecified) Between 1 and 3 GHz: Log periodic (unspecified)				
[142]		Virginia (USA)	Rural (very low spectral occupancy)	Ground	9 hours					
[143]			Urban	Roof of building	15 min to 2 weeks					
[144] [145]	2005	Chicago (USA)	Urban (presumed high level of wireless activity)	Roof of building	48 hours					
[146]	2007	Dublin (Ireland)	Dense urban	Roof of building	48 hours	Below 1 GHz: Discone Diamond D-130J (25 – 1300 MHz) Between 1 and 3 GHz: Discone AOR DA5000 (700 – 3000 MHz)				
[147]	2007	Maine (USA)	Rural (testing of aeronautical systems)	Top of control tower	48 hours				30	
[148][149]	2005	Atlanta & North Carolina (USA)	Urban, sub-urban, and rural	Building roof (urban & sub-urban), top of a tower (rural)	–	Vertical and horizontal log periodic Create CLP-5130-2 (400 MHz – 1.2 GHz) Vertical and horizontal pyramidal log periodic Electro-Metrics EM-6970 (1.2 GHz – 7.2 GHz)	[0.4, 7.2]	Positive peak	10	Yes
[150]	2007	Auckland (New Zealand)	Urban	Balcony (outdoor) Floor (indoor)	20–30 min	Dipole (806 – 1000 MHz) Discone (1000 – 2750 MHz) Unspecified models	[0.806, 2.75]	Positive peak	15 120 250	No
[151]	2007	Aachen (Germany)	Urban	Roof of building (outdoor) Floor (indoor)	7 days	Discone AOR DA-5000 (20 – 1520 MHz) Discone AOR DA5000JA (1.5 – 3 GHz) Radom Antennentechnik Bad Blankenburg AG KS 1-10 (3 – 6 GHz)	[0.02, 6]	Average	200	<3 GHz

In turn, the measurement campaign from the National Science Foundation (NSF) [138]–[147] can be considered as a rigorous and methodical spectrum study, covering a wide range of locations and environments, but it only covered the frequency range up to 3 GHz. Additional spectral bands above

3 GHz may exhibit interesting opportunities for dynamic spectrum access and should thereby be measured and analysed. The work reported in [148] and [149] covered the frequency range up to 7 GHz; unfortunately, an unusual decision method was considered, which lead to particular occupancy statistics that cannot be compared with the results from other measurement campaigns. Outside the USA, [150] evaluated the spectral occupancy in New Zealand, but only up to 2.75 GHz. In Europe, [151] measured the spectral occupancy in Aachen, Germany, between 20 MHz and 6 GHz. However, the study concluded an unexpected occupancy of 100% below 3 GHz in outdoor environments that need to be compared to the results of other European measurement campaigns as the one planned in WG4. Moreover, the spectrum measurements reported in [151] were performed with a resolution of 200 kHz, which can arguably be considered as inappropriate for some licensed bands. Other studies reported in the literature exclusively focused on particular frequency bands [152]–[158].

In this context, the aim of the activities to be carried out in WG4 is to perform an extensive, comprehensive, and rigorous broadband spectrum measurement campaign in a European city taking advantage of the lessons learned from previous measurement campaigns reported in the literature. The empirical data collected in WG4 will enable appropriate analysis and characterisation of the current spectrum occupancy, and therefore a realistic understanding of dynamic spectrum utilisation.

3.2.3 Spectrum Measurement Setup

This section describes the general measurement equipment employed in studies reported in the literature and usual measurement setup. They will serve as the basis for the development of the measurements to be carried out in the activity considered here. Depending on the purposes of the study and on the resource availability different configurations have been used ranging from a single antenna directly connected to a spectrum analyser and controlled by a laptop [155] to highly sophisticated designs including specific-purpose components [137], [149]. As a general example, Figure 8 shows the measurement equipment and setup employed in the measurement campaign ordered by the NSF [138]–[147] (other measurement equipments and setups follow the same structure). The equipment consisted of an antenna system, antenna rotator, filters, pre-amplifiers, shielded enclosure, and a spectrum analyser controlled by a laptop.

The antenna system is usually composed of two or more antennas. When covering small frequency ranges or specific licensed bands, a single antenna may suffice. However, in broadband spectrum measurements two or more broadband antennas are required in order to cover the whole frequency range from a few MHz up to several GHz. Most of spectrum measurement campaigns are based on omni-directional measurements. To this end, omni-directional vertically polarised antennas are the most common choice (usually discones and sometimes monopoles). Alternatively, directive linearly polarised antennas (usually log periodic antennas) mounted on an antenna rotor with vertical polarisation are also used. Horizontally polarised antennas are rarely employed, since the majority of RF transmitters are vertically polarised. Even though some transmitters are horizontally polarised (e.g., TV and FM broadcast), they are usually high-power stations that can still be detected with vertically polarised antennas [149]. In some cases, directive and polarisation-dependent measurements are also of interest [149], thus requiring directive linearly polarised antennas (log periodic antennas).

The antenna system is usually followed by a low-noise pre-amplifier that is used to increase the signal-to-noise ratio, thus improving the detection of licensed signals. Some spectrum analysers include a built-in low-noise pre-amplifier that can be activated in order to improve the measurements. In other cases, external pre-amplifiers are connected between the antenna system and the spectrum analyser.

When measuring frequency bands with very different signal levels, a large dynamic range is required in order to correctly detect the presence of low power signals in the presence of strong signals. In this case, a good option is to use a bank of filters between the antenna system and the pre-amplifier in order to remove high power signals and thereby improve the detection of weak signals. Stopband filters for FM and TV frequency bands are usually required in the VHF/UHF range. In other cases a bank of filters and selectors is employed in order to obtain more accurate measurements. Figure 1 shows the setup employed in [138]–[147].

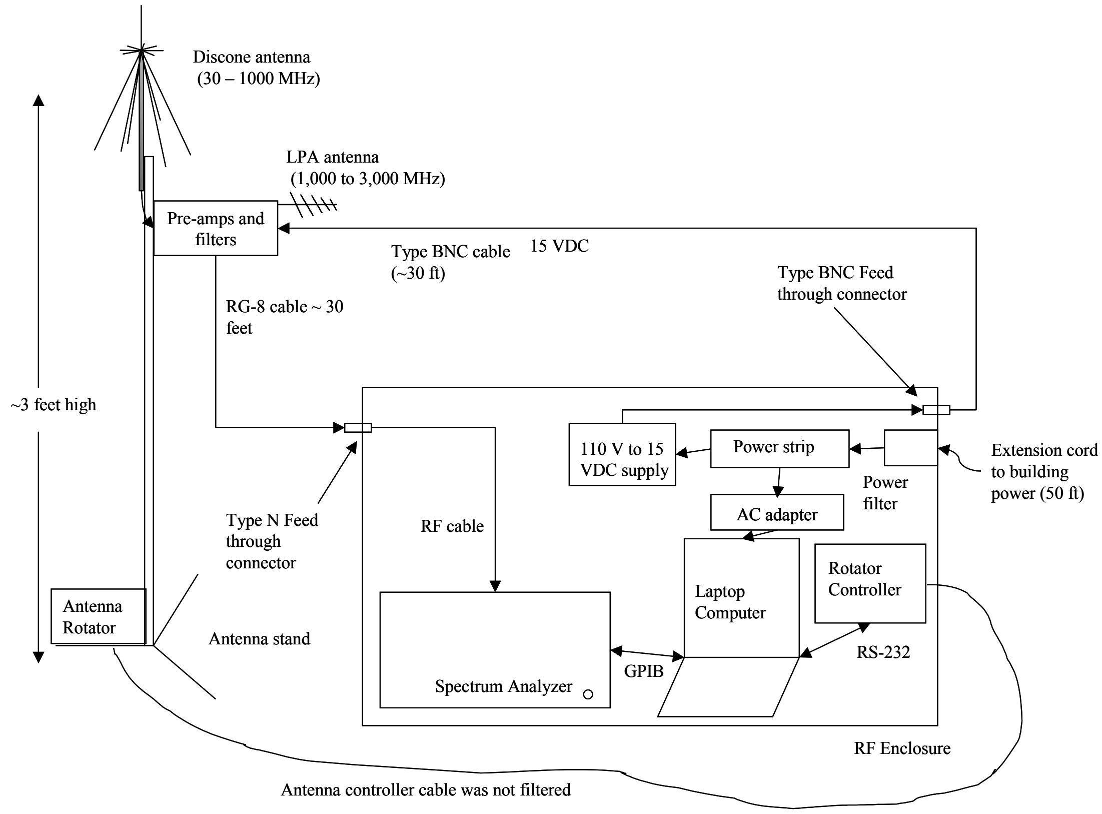


Figure 8 - Example of measurement equipment and setup employed for spectral measurements [138]–[147].

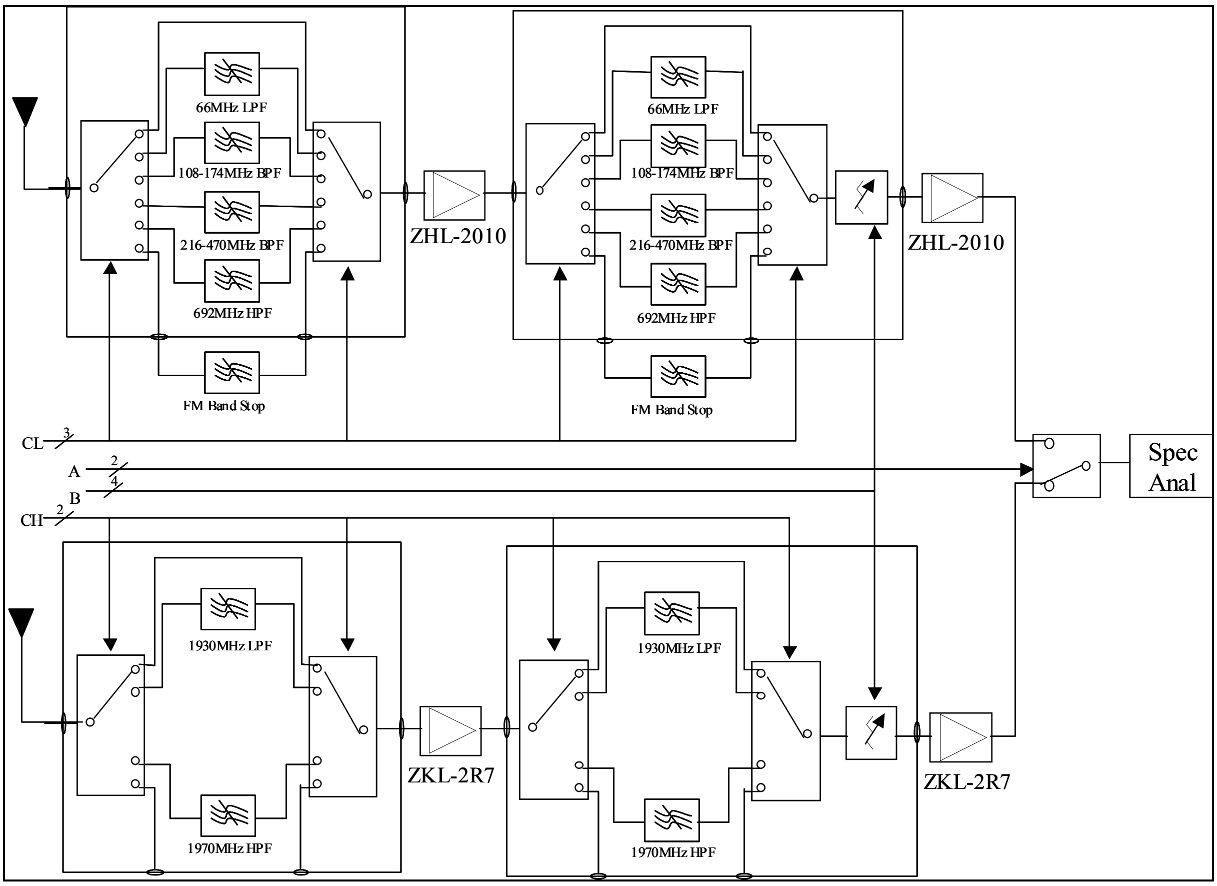


Figure 9 - Bank of filters, selectors and pre-amplifiers used in [138]–[147].

The spectrum analyser and the controlling laptop are usually enclosed in a shielded box in order to avoid unwanted emissions that might be captured by the antenna system when both components are reasonably near to each other.

Finally, other accessories such as cables, connectors and/or adapters need to be used in order to connect all the components. Before performing any measurements, all the equipment between the antenna output port and the spectrum analyser input port need to be calibrated using a network analyser such that the power loss/gain introduced by them is know over the whole frequency range. These values are stored in look-up tables and are used during the post-processing phase to provide amplitude corrections for the measured data.

3.2.4 Spectral Parameters of Interest

This section provides a description of the main parameters that are typically considered relevant when measuring, evaluating and quantifying the level of spectral occupancy. Some of them are directly provided by the measurement equipment and some others are obtained by post-processing the measured data. All them provide however different information about several interesting aspects of spectral occupancy. The spectral parameters considered in this section are *power spectral density*, *spectral occupancy percentage or duty cycle*, and *amplitude probability distribution.*

a) Power spectral Density

It is well known from Fourier theory that any time-domain electrical phenomenon can be expressed as the sum of one or more sine waves of appropriate frequency, amplitude, and phase. The Power Spectral Density (PSD) of a signal is the graphical representation of its frequency content, with the abscissa being the frequency and the ordinate being the amplitude (the phase information is not captured by a spectrum analyser). PSD can be measured in different ways in order to obtain different PSD graphs, mainly the average PSD, maximum PSD and minimum PSD. The average PSD is obtained by averaging all the traces captured by the spectrum analyser. Each frequency point of the average PSD is computed as the arithmetic mean of all the values sampled by the spectrum analyser at such frequency. Similarly, maximum and minimum PSD can be obtained by retaining the maximum and minimum values recorded by the spectrum analyser at each frequency point, respectively. Therefore, the maximum/minimum PSD represent the maximum/minimum power level ever observed at each frequency point. Figure 10 shows an example extracted from [151].

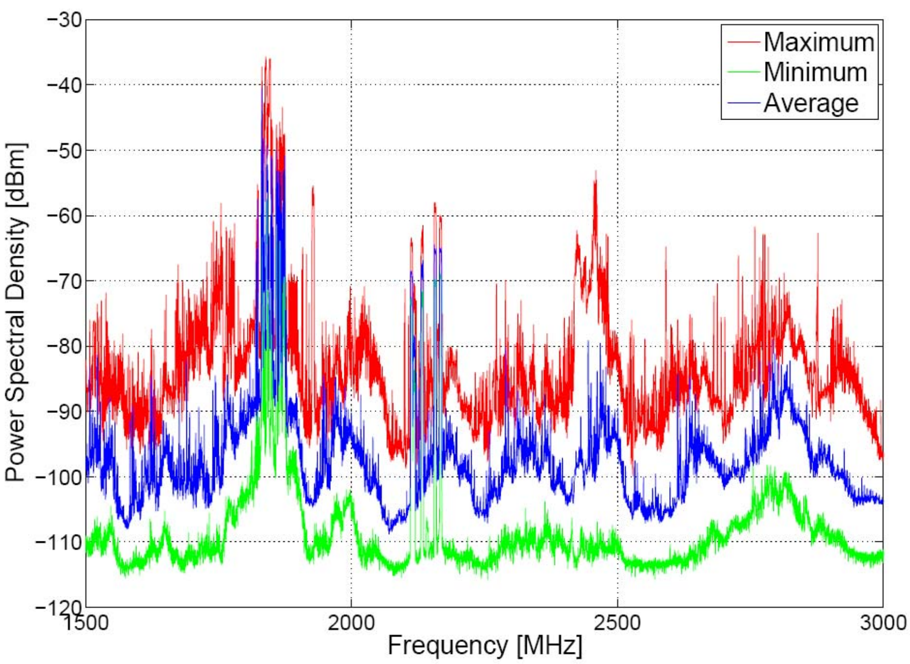


Figure 10 - Example of average, maximum and minimum Power Spectral Density (PSD) [151].

When considered together, average, maximum and minimum PSD provide a simple characterisation of the temporal behaviour of a channel. For example, if the results are quite similar, it suggests a single transmitter that is always on, experiences a low level of fading and so is probably not moving either. At the other extreme, a large difference among average, maximum and minimum PSD suggests more intermittent use of the spectrum and therefore indicates a potential opportunity for CRNs.

b) Spectral occupancy percentage or duty cycle

The relevant metric to determine the degree to which spectrum is used in the temporal dimension is the spectral occupancy percentage, or simply the spectral occupancy, also referred to as duty cycle. It is defined as the fraction of time that a given channel or frequency band is determined to be occupied by a licensed signal. CRNs may take advantage of idle time periods to opportunistically access the available spectrum. Therefore, frequency bands with low duty cycles offer an interesting opportunity for the deployment of CRNs.

To detect whether a frequency band is being used by a licensed user, different sensing methods have been proposed in the literature [159]. They provide different trade-off between required sensing time, complexity and detection capabilities. Depending on how much information is available about the signal used by the licensed network different performance can be reached. However, in the most generic case no prior information is available so that the energy detection method is the only possibility left. Energy detection compares the received signal energy in a certain frequency band to a usually predefined threshold. If the signal is above the threshold, the band is determined to be occupied by the licensed network. Otherwise the band is supposed to be idle and could be used by a CRN. When evaluating the spectral occupancy with a spectrum analyser, energy detection is assumed. Thus, the measured PSD is compared to a threshold in order to determine whether a band is occupied or not. Based on this principle, the spectral occupancy or duty cycle is computed as the fraction of measured samples with a signal level greater than the predefined threshold.

When computing the spectral occupancy or duty cycle, an overall value for a given frequency band can be determined in order to numerically quantify the degree to which spectrum is used by a certain licensed system and hence identify the most interesting bands for the deployment of CRNs. Nevertheless, the temporal evolution of this metric (e.g., averaged of 1-hour periods or days) can also provide interesting information about the temporal utilisation of the spectrum.

c) Amplitude probability distribution

Key characteristics of the licensed system such as signal bandwidth, transmitter mobility and number of transmitters can be very well estimated by evaluating the histogram of the received amplitude samples. This method is known as the Amplitude Probability Distribution (APD) analysis method [151]. As shown in Figure 11, the APD is a three-dimensional histogram with one axis being amplitude, one being frequency span, and another being the probability of each amplitude value throughout the whole measurement period. The underlying principle of APD analysis is that different equipments and devices show distinct behaviour in terms of PSD and signal characteristics. Such transmitter characteristics can be inferred from the statistical distribution of the amplitude probability.

A single peak with narrow and sharp shape and large amplitude is associated to a fixed transmitter with rather constant power. The height and the width of the peak jointly describe the stability of the transmission power. The higher and the narrower the peak the more constant the transmission power is. A single wide peak with large amplitude represents a transmitter applying Amplitude Modulation (AM) or a transmitter with mobility. If multiple transmitters are received with similar distribution of received power values a single peak could also represent a group of stations though. Whether the widening of the peak is due to AM or mobility can usually be differentiated by referring to frequency regulations. If it is an MT transmitter, the mobility is determined by the width of the peak; the wider the peak the higher the mobility of the transmitter is. A wider distribution with many peaks but small maximum amplitudes is associated to many devices received from different distances, or congregation of various services with distinct power regulations. Again, these cases can be distinguished using frequency regulation information. Finally, the received power allows in some cases to infer the rough operating power of the transmitter directly from the APD histogram. All this information can and should be used to improve the search for idle spectrum bands available for opportunistic usage.

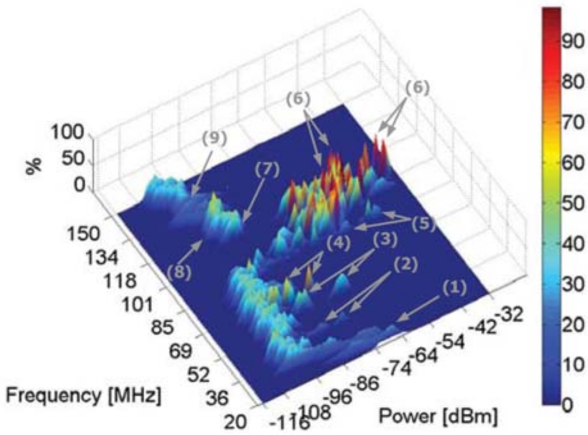


Figure 11 - Example of APD as defined in [151].

3.2.5 Activity Development

The stages to be completed in order to guarantee the success of the measurement campaign are listed below:

1. Identification of measurement and transport equipments: Up to date, the following measurement equipments have been identified:
   a. Spectrum analyser: Anritsu Spectrum Master MS2721B High Performance Handheld Spectrum Analyser (9 kHz – 7.1 GHz).
   b. Antennas: AOR DN753 (European reference) / DS3000 (American reference) / DA753G (Japanese reference) wideband discone antenna from 75 MHz to 3 GHz, and JXTXPZ-100800/P wideband discone antenna from 1 GHz to 8 GHz.
   c. For later phases: think in possible transport solutions like a car or a van.
2. First assessment of spectrum use and identification of some initial target frequency bands.
3. Definition of the measurement methodology for each location: Campus Nord at UPC, Barcelona outskirts, etc..
4. Identification of human resources.
   a. Two persons for fieldwork.
   b. An additional researcher for data post-processing and analysis.
5. Realisation of measurements.
6. Post-processing and analysis of data. This stage includes the comparison of measurements obtained from different scenarios and the analysis of the grade of correlation, in order to extract possible spectrum usage models.
7. Exploitation of results.

From an integration point of view, the obtained measurements can be made available to other institutions inside NEWCOM++ working in similar aspects. In addition, results can be used as inputs for the development of new spectrum management algorithms. It is also expected that other partners can provide inputs to the measurement campaign by specifying potential aspects of interest to be measured or analysed that may be useful to other activities.

3.2.6 Scenarios and Use Cases for the Activities on Spectrum Measurements Campaign

The measurement campaign activity will consider a set of predefined potential scenarios where the measurement and analysis of the spectrum usage can potentially be considered of interest. The scenarios of interest for this measurement campaign include those that have already been considered in previous spectrum measurement campaigns reported in the literature, namely urban, sub-urban and rural. Within each scenario, different measurement conditions can be identified that will presumably provide a better understanding of spectrum occupancy under different circumstances.

At an initial phase, the measurement campaign will start in an urban environment in Barcelona, Spain, a densely populated city. This phase of the measurement campaign will consider both outdoor and indoor environments. For outdoor measurements, three different scenarios will be considered: high points, open areas and narrow streets.

- *High points*: in this scenario the equipment will be placed on the roof of the Department's building in Campus Nord. This is a strategic location with direct line-of-sight to several transmitting stations located a few tens/hundreds of metres away from the measuring station. This strategic location will enable us to accurately measure the spectral activity of, among others, a TV repeater, FM broadcast station, a nearby BS for cellular mobile communications, several microwave radio links, and a military headquarter as well as maritime transmitters due to the relative proximity to the Barcelona's seaport.
- *Open areas*: in this scenario the equipment will be hold by a researcher who can move by foot along the city. In particular this scenario includes: big squares and avenues or boulevards. These environments will be evaluated during an ordinary day and during events of unusually high spectrum use, such as football matches or the GSMA Mobile World Congress.
- *Narrow streets*: in this scenario the equipment will also be hold by a researcher who can move by foot along the city. In particular this scenario includes narrow streets where buildings can block the radio-electric signal impeding to detect signals that can be measured on the roof.

For indoor measurements, the equipment will be moved inside the building.

3.2.7 Initial Results

In the following the first measurement results that have been obtained in a fixed position in the range 75 MHz – 3 GHz are presented. The equipment consisted of a broadband discone antenna AOR DN753 (vertically polarised with omni-directional receiving pattern in the horizontal plane) specified for this frequency range, which was connected with a 10 m low loss coaxial cable RG-58A/U to a high performance handheld spectrum analyser Anritsu Spectrum Master MS2721B. The spectrum analyser was controlled by a laptop connected via a cross-over Ethernet cable.

During the measurements the antenna was placed on the roof of a UPC building in Barcelona (latitude: 41º 23' 20" north; longitude: 2º 6' 43" east; altitude: 175 m). This is a strategic location with direct line-of-sight to several transmitting stations located a few tens or hundreds of metres away from the antenna and without buildings blocking the radio propagation. This strategic location enabled us to accurately measure the spectral activity of, among others, a TV repeater, a FM broadcast station, several nearby BSs for cellular mobile communications and a military headquarter as well as some potential maritime transmitters due to the relative proximity to the Barcelona's harbour.

The main configuration parameters used for the spectrum analyser are shown in Table 5. The measured frequency range was divided into six consecutive 500 MHz blocks, each being measured during a continuous period of 48 hours (more than 10 000 traces for each block). The traces were saved in an external storage device and post-processed off-line using MATLAB in a powerful PC.

Table 5 - Spectrum analysed configuration.

Parameter	Value
Centre frequency [MHz]	Block 1: 250; Block 2: 750; Block 3: 1250; Block 4: 1750; Block 5: 2250; Block 6: 2750
Frequency span [MHz]	500 MHz
Resolution/video bandwidth (RBW/VBW) [kHz]	10 kHz / 10 kHz
Sweep time	Automatically selected
Reference level [dBm]	– 20 dBm
Scale	10 dB/div
Detection type	RMS detector
Measurement period	48 hours (continuous) each 500 MHz block

The obtained measurement results are shown in Figure 12 and Figure 13. Each figure is composed of three graphs, each one corresponding to a specific occupancy metric. The upper graph shows the minimum, maximum and average Power Spectral Density (PSD) measured for each 500 MHz spectrum block. The middle graph shows the temporal evolution of the spectrum occupancy during the whole 48 hour measurement period. A black dot indicates that the corresponding frequency point was measured as occupied at that time instant, while the white colour means that the frequency point was measured as idle. To determine whether a given frequency is occupied or not, energy detection is assumed. Following this principle, the measured PSD is compared to a given threshold. Measured samples above the threshold are assumed to be occupied; the rest of frequencies are assumed to be idle. To compute the decision threshold, the antenna was replaced by a matched load of 50 Ω in order to measure the system's noise. At each frequency point the decision threshold was fixed such that only 1% of the measured noise samples lied above the threshold, which implies a false alarm probability of about 1%. It is worth noting that the decision threshold obtained with this method is not constant since the system noise floor slightly increases with the frequency. Finally, the lower graph in each figure shows the duty cycle or percentage of time that each frequency point is measured as occupied by a licensed signal. The average duty cycle over the whole 500 MHz block is also shown.

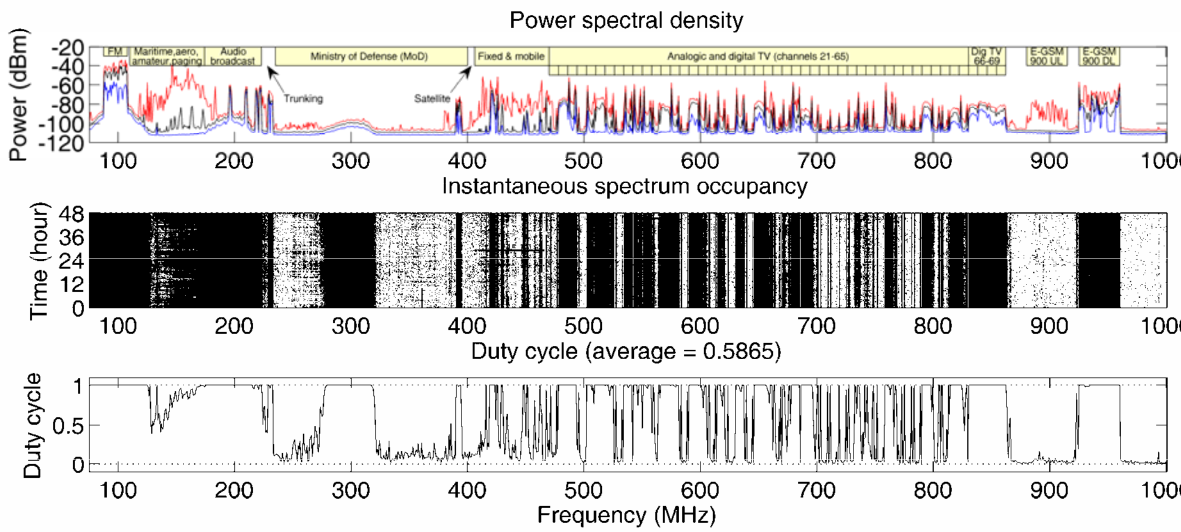


Figure 12 - Occupancy results between 75 and 1000 MHz.

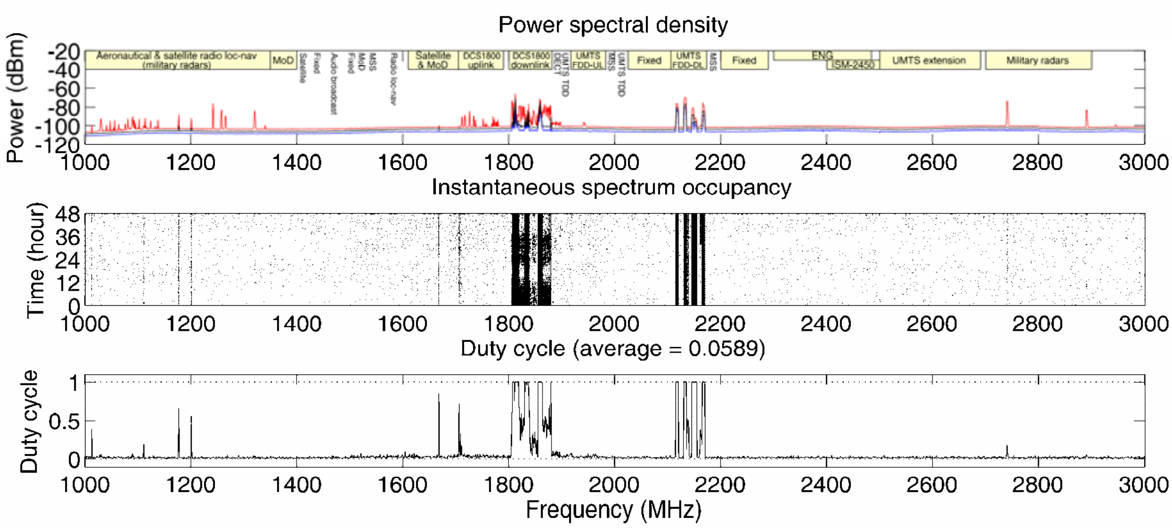


Figure 13 - Occupancy results between 1000 and 3000 MHz.

The occupancy results shown in Figure 12 and Figure 13 indicate that spectrum experiences a relatively high use below 1 GHz while remains mostly underused in [1, 3] GHz, with some exceptions such as GSM1800 ([1710, 1785] MHz and [1805, 1880] MHz) and UMTS ([1920, 1980] MHz and

[2110, 2170] MHz). In fact, while the average duty cycle between 75 and 1000 MHz is 58.65%, the value for this parameter between 1000 and 3000 MHz is only 5.89%, as shown in Table 6. The overall average duty cycle over the whole frequency range considered in this study is 22.57%, which indicates the existence of a significant amount of unused spectrum that could potentially be exploited by future CRNs. Although these results indicate low spectrum utilisation, they do not provide a detailed description of how spectrum is used in different bands allocated to different specific services. Therefore, in the following one discusses in detail the spectrum usage in some allocated bands of interest.

Table 6 - Average duty cycle statistics.

<table>
<tr><th>Block</th><th>Frequency Range [MHz]</th><th colspan="3">Average duty cycle [%]</th></tr>
<tr><td>1</td><td>75-500</td><td>60.98</td><td rowspan="2">58.65</td><td rowspan="6">22.57</td></tr>
<tr><td>2</td><td>500-1000</td><td>56.67</td></tr>
<tr><td>3</td><td>1000-1500</td><td>2.07</td><td rowspan="4">5.89</td></tr>
<tr><td>4</td><td>1500-2000</td><td>12.08</td></tr>
<tr><td>5</td><td>2000-2500</td><td>7.57</td></tr>
<tr><td>6</td><td>2500-3000</td><td>1.85</td></tr>
</table>

Although spectrum occupancy below 1 GHz is relatively high, some opportunities for CRNs can be found. One example is the frequency band [470, 862] MHz, which is allocated to analogue and digital terrestrial TV. The frequency range [830, 862] MHz assigned to digital TV exhibits an intensive usage that precludes CRN applications in this band. Moreover, several channels in the band [470, 830] MHz are also occupied. Note that occupied TV channels show a duty cycle about 100%, i.e., continuous broadcasting, which impedes temporary opportunistic usage of those channels. However, the band [470, 830] MHz shows several TV channels that are received with very weak signal levels. The average duty cycle in this band is 66.58%, which indicates that one third of the band (approximately 130 MHz) is unoccupied due to the weak reception of the signals broadcasted from those TV stations. Therefore, although this band is considerably populated, it provides some interesting opportunities for secondary usage.

The E-GSM 900 band for UL [880, 915] MHz appears as another potential candidate for CRN applications with an average duty cycle equal to 4.03%. However, in this case it is important to highlight that the low activity recorded in this band does not necessarily imply that it could be used by CRNs. The considerably higher activity observed in the E-GSM 900 DL [925, 960] MHz and the fact that GSM is based on FDD suggest that the actual usage of the E-GSM 900 UL band might be higher than the activity level recorded by the spectrum analyser.

The frequency bands [235, 273] MHz and [322, 390] MHz show some potential opportunities for secondary access with average duty cycles equal to 18.14% and 12.89% respectively. However, the whole band [235, 400] MHz is exclusively reserved for security services and systems of the Spanish Ministry of Defence, which in principle precludes the use of such spectrum bands by CRNs. Other bands below 1 GHz with low or moderate levels of activity but narrower available free bandwidths are those assigned to wireless microphones and RFID [862, 870] MHz, CT1 cordless phones [870, 871] MHz and [915, 916] MHz, cellular access rural telephony [874, 876] MHz and [919, 921] MHz, R-GSM 900 [876, 880] MHz and [921, 925] MHz, trunking systems [223, 235] MHz and several fixed and mobile services [400, 470] MHz. The lower spectrum bands, assigned to FM broadcasting [87.5, 108] MHz, maritime and aeronautical radionavigation [108, 174] MHz and audio broadcasting [174, 223] MHz show intensive usage with average duty cycles between 90% and 100%.

Above 1 GHz, the highest spectrum usage is observed for the bands allocated to mobile cellular communication systems GSM1800 [1710, 1785] MHz and [1805, 1880] MHz and UMTS [1920, 1980] MHz and [2110, 2170] MHz. Note that the differences between UL and DL usage patterns that were appreciated for E-GSM 900 are also observed for GSM1800 and UMTS. In the case of GSM1800, the differences are more accentuated due to the fact that MTs in GSM1800 have a lower transmission power than in GSM900, which results in a reduced duty cycle in UL (3.52%). In the case of UMTS, the difference is higher due to the spread spectrum nature of the WCDMA radio technology employed by UMTS. WCDMA signals are modulated over larger bandwidths, which results in very low transmission powers. Such signals might not be detectable by a spectrum analyser. As a result, very low activity was recorded in the UMTS UL (2.86%). Although in DL GSM1800 and UMTS show a higher level of activity (59.75% and 48.38% respectively), these bands also provide some opportunities for secondary access. In the case of GSM1800, some portions of the DL band show a well defined periodic usage pattern (higher occupancy between 0-12 and 24-36 hours) that could be exploited by secondary CRNs. In the case of UMTS, several 5 MHz channels appear to be unoccupied. Moreover, the bands reserved for UMTS TDD [1900, 1920] MHz and [2010, 2025] MHz and the extension of UMTS [2500, 2690] MHz are not used. The ISM-2450 band [2400, 2500] MHz also appears to be unused in the measurement location, which could be explained by the fact that this frequency band is usually occupied in indoor environments and signals at such frequencies are severely attenuated by walls. The rest of spectrum in [1, 3] GHz remains mostly unused, with the exception of some signals with very low duty cycle in bands allocated to aeronautical and satellite radiolocation and radionavigation, [960, 1350] MHz and [1610, 1710] MHz, DECT cordless phones [1880, 1900] MHz and military radars [2700, 2900] MHz.

3.3 Cognitive Networks Based on Sensorial Radio Bubbles

3.3.1 The "Sensorial Radio Bubble" for Cognitive Radio Equipment

In a cognitive behaviour, the perception of the stimulus is the means to react to the environment and to learn the rules that permit to adapt to this environment. In the context of reconfigurable CR equipments, the environment is mostly the radio electromagnetic field. A CR system aims at using the radio resources with a good efficiency at the system level, and not only at a point-to-point optimisation as usually done. This contributes to a global capacity increase and a better use of spectrum resources within all the standards in the area. One major impact expected with CR is to improve drastically frequency occupation in space and time (at the system level) while providing the appropriate QoS (not too low, but also not too high) for a given service transmission (at the level of one equipment). One proposes to define a volume around the equipment, called the "sensorial radio bubble" or (SRB), the diameter of which is at the scale of the sensing possibility of the equipment. It will be the responsibility of a CR equipment to be aware and interact with all the pertinent information available in the area that can help the equipment to match its functionality to the global state of its environment. A CR system as presented for the first time in [160], implies that an equipment is able to adapt its behaviour to its environment through capabilities of analysing its situation, smartness to take adequate decisions and capabilities of self-reconfiguration, as presented in [163], to adapt its functionality. The work presented here is a generalised approach of the work of [164], in which an equipment can recognise a set of standards and adapts its operation accordingly. CR often focuses on spectrum issues and how to efficiently use the frequency resource [160], [161], [162]. But the concept of CR may be extended at a larger scale as in Figure 14, where a communication system is modelled in main layers.

Sensors	Layer	Literature concepts
User profile (price, personal choices) Localization, sound, video, position, speed, security.	Application	Context Aware
Intra-network, and inter-network vertical handover , standards, load	Transport Network	Interoperability Ambiant networks
Access mode, power modulation, coding, Frequency, handover. Channel Estimation	Data link Physical	Link adaptation
"Middleware" and abstraction Layer		
True Wide Band Software Radio		

Figure 14 - Model in 3 layers of Cognitive Radio versus OSI layers.

The 3 main layers are:

- upper layer corresponding to the classical application layer of the OSI model and the human interface,
- intermediate layer in which one considers the classical transport and network layers,
- lower layer for the physical and link layers.

Any means that permits to analyse the environment, and that may be helpful for the adaptation of the communication system to the constraints imposed by the environment, is worth being taken into account. At each level, examples of sensors which are able to give information related to this layer (left side of Figure 14), are associated. In addition, at the right side, one identifies areas of current research which are more or less connected to CR. As one would like to optimise the overall system, obviously there is also a connection to the cross layer adaptation and optimisation topics.

A CR is a radio whose behaviour respects the cognitive cycle of Figure 15. The first step consists of sensing or observing the environment. Parameters measured from the environment of the equipment could be for instance: spectrum use, presence of other equipments in the area, multipath propagation conditions, standards available, etc.. But the notion of environment of equipment can be generalised. From a CR view point, the speed of the equipment or its position is also addressed. Moreover, internal conditions are also considered, such as battery level, hardware and software resources occupation for. In a second step, an analysis of the acquired parameters can be used to synthesise high level information. This high level information gives a global vision of the equipment context. In the next step, decision step, the system selects the solution which optimises the parameters of the radio equipment. In the last step, the equipment activates actions to adapt to its environment in order to reach its objective. The cognitive cycle operates in a continuous way so that the CR equipment dynamically adapts to the evolution of the parameters of its environment. The SRB uses all the 3 layers already defined (from PHY to application layer) to explore the environment of the equipment. Considering the cognitive circle, SRB is situated in the sensing function as illustrated in Figure 15. The SRB is a virtual sphere of several metres to several dozens of metres of diameter around the equipment. The diameter depends on the visibility of each sensing means. One can talk about a multi-dimensions space, with one dimension for each sensing capability. The spatial dimension is one of them, and is given through the information provided by the channel sounding sensor for its size and the positioning sensor for its centre. The spectrum dimension is another dimension, and is given through, for example, carrier frequency sensor, bandwidth channel sensor, standards recognition sensor, etc..

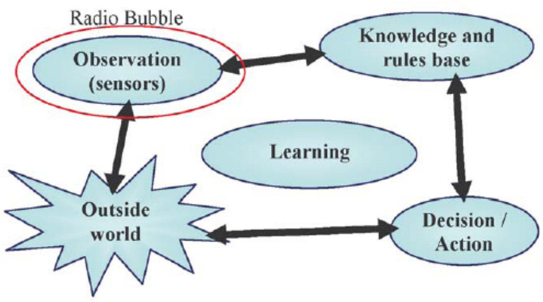


Figure 15 - Illustration of the cognitive circle with SRB.

This work addresses the context of a double mobility:

- a classical mobility associated with the horizontal handover, in space;
- a spectrum mobility associated with the vertical handover, in frequency.

One suggests hereafter to map these two types of mobility onto two different maps, in order to illustrate and validate our concept of the SRB:

- a classical spatial map, which already exists, and in which the equipment is moving;
- a new spectrum map, containing all the environment information given by the corresponding sensors of the SRB; the way to build this map is described in [165].

In order to simply expose our concept, one uses two analogies: the first and most important one is the well known psychological and physiological human bubble; the second analogy addresses the human bubble within a car. A spectrum map is defined as a road map, therefore one can translate rules from the latter to the spectrum approach with the objective to secure transmissions the same way as motorists on the road. One already proposed in [165] a traffic code analogy; a close analogy was proposed also in [167]. One focuses here on the two maps representation of our concept and highlights the need of information exchange between several SRB in order to assure a secure transmission (good QoS). It has to be stressed that this new spectrum map evolves as soon as the equipment is moving in the spatial map. So as to better explain this approach, one proposes in the following to describe two analogies at the origin of the SRB concept.

The well-known physiological and psychological "human bubble" is a virtual space, whose dimensions are given thanks to the human senses. A person knows all information inside his bubble and consequently has a feeling of safety and comfort. It is partly given by the five human senses. SRB on its side, collects information through sensors which analyse the received electromagnetic waves. For example one sensor detects spectrum holes, another one, the best (in respect to some criteria) standard for the communication. In addition, as the health condition of a human being may influence his behaviour and mood, the internal state of an equipment should de considered (battery level, processor load, etc.). The radio bubble communicates this information to the higher layers of the CR equipment, which then may reconfigure itself to improve its global functionality [168]. To make maximum benefit, this behaviour implies that the equipment is a fully Software Radio (SWR) one.

The second analogy we took into account is the "vehicle bubble" analogy. This is clearly an extension to the car situation in the traffic of the "human bubble". Now the virtual sphere is around the car and moves with the car. The car driver should know everything within its bubble, and understand all the information inside the bubble. This bubble information is given thanks to the human driver senses with the help of:

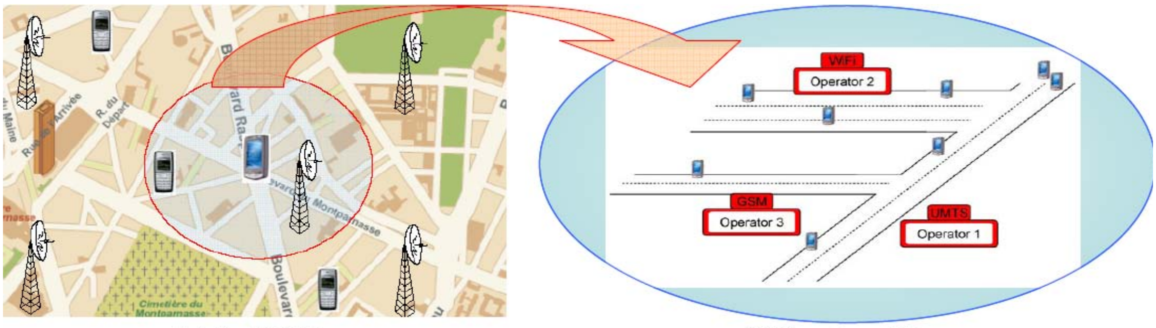
- signs of other cars and road infrastructure,
- rules known and respected by everybody,
- anticipation, prediction, thanks to previous experiences.

One can continue the analogy with the following example:

- the aim of a car driver is to go from one point to a destination without accident with respect to some constraints (time, number of kilometres, price, etc.), given its "bubble" all along the trip;
- the aim of a CR equipment is to send its information to the right recipient without accident (good QoS) with respect to some constraints (time, throughput, price, etc.), given its "bubble" as well.

Two maps were defined and completely described in [165]. The first one (classical map) describes the spatial environment. The second one describes the spectrum environment. The objective is to build a spectrum map in which the equipment could move. The spatial map presents a set of pertinent information that is reported in a geographical map. These parameters can be, for example, the position of hotspots or access points, the position of others equipments, etc.. To build the spectrum map, a different set of sensors contributes to analyse the spectrum using signal processing techniques. This map identifies and represents different spectrum parameters existing in the radio bubble that vary with the movement of the bubble, e.g., the carrier frequency, the free channels and the telecommunication systems inside the bubble. In the spectrum map, this information can be represented as roads.

In Figure 16 one presents the projection of the bubbles in respect to a specific dimension (a sensor) on the different maps: Figure 16 (a) presents the projection of the Direction of Arrival sensor, whereas Figure 16 (b) presents the projection of the Standard Recognition Sensor.



(a) Spatial Map (b) Spectrum Map

Figure 16 - Projection of the "Bubble" respect to a specific sensor on the corresponding map.

3.3.2 The Sensors of the "Radio Bubble"

The word sensor is used in its broad sense. It represents all means that can give information of the environment. It could be either a classical sensor (microphone, …) or it could be a smart sensor based on advanced signal processing. One classifies sensors in three ways. The first way is related to the layer model one gave in Figure 14.

From the model, one concludes that it is mandatory to adapt the equipment to the user's needs, user's behaviours. In this context, one has to detect its presence, to identify him it to analyse its behaviour and finally to interact with him. The less invasive sensor for that type of purposes is the video sensor. It is now possible to detect, in real time, faces in video sequences. All the applications which will use this detection as, for example, face recognition need that all the face characteristics points (nose, eyes, mouse…) are well identified and well aligned. This is still today a very big technical challenge. One possible answer for that challenge could be the used of Appearance Active Model (AAM). These models are very promising but not yet sufficiently robust against luminosity variations. One proposes below a solution to tackle this difficulty.

From the previous model, one identifies several sensors as load on a link, horizontal handover. One considers that one of the most important is the standard recognition and it is exactly what is described below through three different possibilities to carry out it. This Standard Recognition Sensor uses several sensors from the lower layer (physical layer) as Bandwidth, access type, modulation type sensors.

The CPC (Cognitive Pilot Channel) is a recent concept issued from the CR domain. It is mainly studied within the framework of the IST European project E²R. It has been published in [117], [118], [119]. The concept is a particular radio channel in which the CR equipment can find information such as frequency band allocation, RATs and operators. This way finding the RAT given the CPC offers several advantages:

- the connection time to a network could be very short;
- reduces the computation time;
- consequently reduces the consumption;
- it should facilitate spectrum management like DSA/FSM.

The main drawbacks are:

- Find a common frequency (or frequency band) for all countries and all regions in the ITU sense.
- Operators should accept to share information, which could be today hidden for business reasons.

This very simple solution has been published several years ago (using GPS for localisation purpose) [172] and is patented [173]. The assumption is "At each location and at each time there is a predefined set of known standards". Therefore knowing this information and knowing the location one knows the standards available in the vicinity of the CR equipment.

One defines 4 types of coverage in order to fill the table, Figure 16. Each standard of the previous assumption has a particular type of coverage. This information could efficiently be used for starting again the process.

Figure 17 - Coverage examples.

The system is briefly described in Figure 16, in a very simple overall scheme.

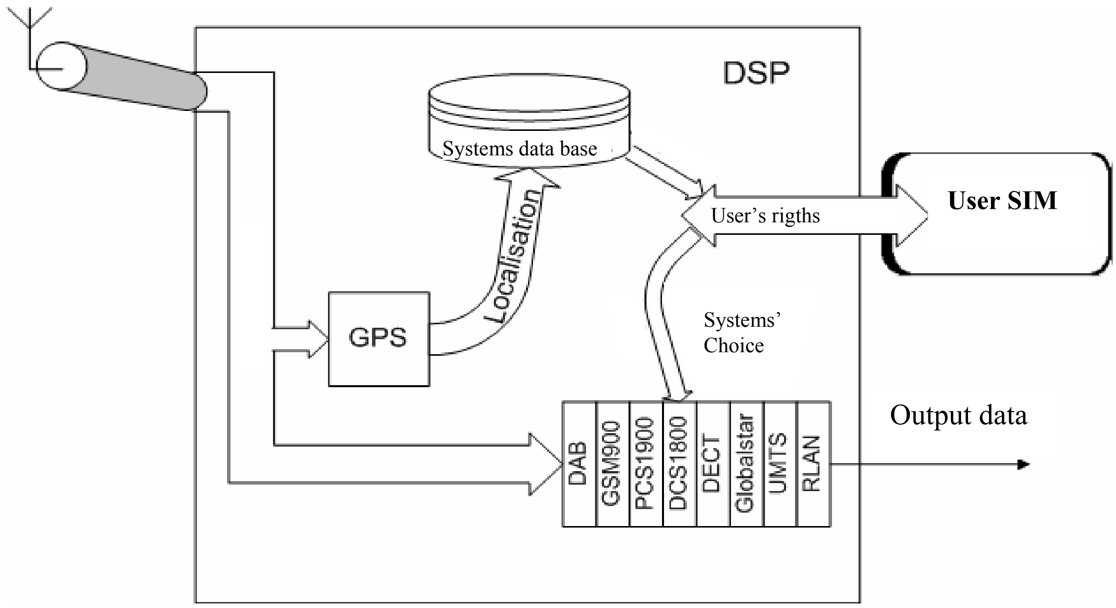


Figure 18 - Processor Architecture.

There are 4 possibilities for updating the data base:

- Over The Air Reconfiguration.
- A downloading using the (SIM[2]) module.
- Downloading trough classical network (Internet) before travelling.
- Manual reconfiguration in case unidentified.

This is clearly the most difficult point of this system. The question is: "How big should be the data base?" The answer depends on coverage, on the frequency it is updated, etc..

As it is described in Figure 19, this sensor analyses the received signal in three steps. The first step is an iterative process that decreases the signal bandwidth to be analysed further, so that the band of

[2] SIM : Subscriber Identification Module

analysis is reduced only to the non zero regions. During the second step an analysis is performed thanks to several sensors. Then during the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present. During the second step, different sensors analyse the bands selected in step one. Many sub-sensors could be used for the recognition of the standard in use as: positioning of the equipment, presence of the telecom signal, detection of the Carrier frequency, recognition of the bandwidth of telecom signal, recognition of the FH/DS signal, recognition of Single/Multi carrier. In the results (see below) only three sub-sensors are used for the recognition of the standards in Table 7.

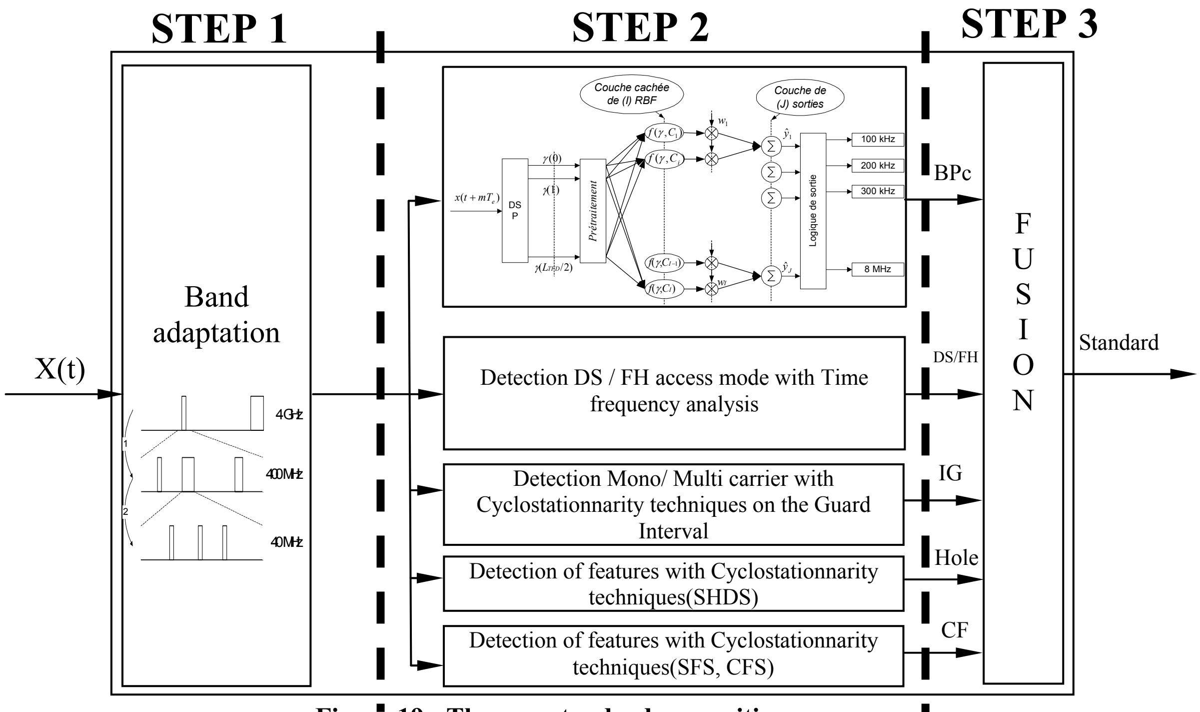


Figure 19 - The new standard recognition sensor.

A detailed analysis of the three steps follows.

1) Step 1: Bandwidth adaptation
The difficulty here relies in the fact that the ratio between the global bandwidth to be analysed and the smallest bandwidth parameter to be recognised may be very high. Therefore an iterative adaptation of the bandwidth to be analysed is performed to solve it. At each iteration, the process analyses energy in the band with a conventional periodogram, then filters and decimates the samples around the detected peak of energy.

2) Step 2: Analysis with sensors
We chose three sub-sensors to analyse and identify the received signal according with a list of predetermined standards: The bandwidth recognition, Single/Multicarrier detection and FH/DS signal detection. Other sensors could be used to identify other parameters.

2.1. The bandwidth recognition
In [164], it is claimed that, in the frequency domain, the channel bandwidth (BWc) was a fully discriminate parameter. To find the bandwidth shape on the received signal a choice has been made to perform a power spectrum density (PSD) on this signal in order to obtain its BWc shape. This shape is compared with reference spectrum shapes given by:

$$\hat{\gamma}_{ref}(k)=\left|Fem_s\left(\frac{f_p}{f_e}-k\right)\right|^2 \gamma_{mods}\left(\frac{f_p}{f_e}-k\right) \quad (21)$$

Fem being the shape transmitter filter and γ_{mod} the PSD of the modulation.

This comparison is performed by Radial Basis Functional Neural Networks (RBF NN). Using the RBF NN, this PSD is compared with the reference signals PSD, then a neuron will be active. To each neuron *i* corresponds the bandwidth of the standard *i*. This is illustrated in Figure 20.

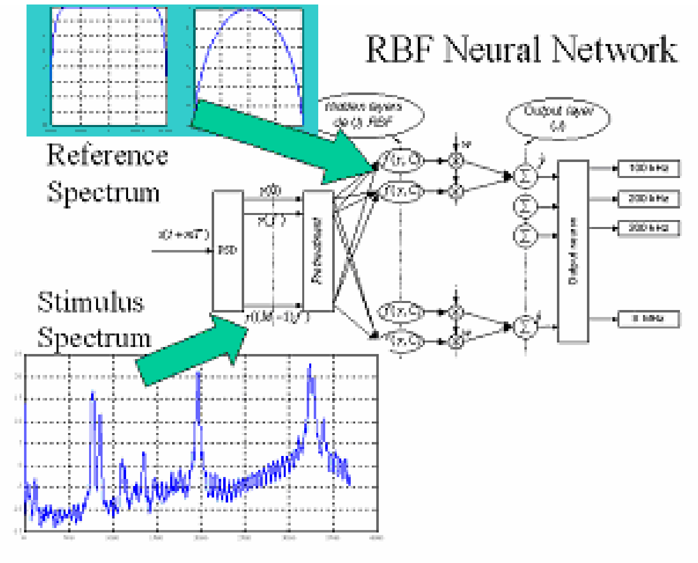


Figure 20 - The RBF neural network.

2.2. Single/Multi carrier detection

The overall results presented in [164] show that the recognition rate between DVB-T and LMDS on the one hand, DAB and DECT on the other hand, was not good enough. Therefore, one proposes to improve this recognition adding a new sensor that discriminates between single and multi-carriers systems based on Guard Interval (GI) detection. It is well known that a GI is inserted in multi-carriers systems in order to avoid inter-symbol interference (ISI). There are several possibilities for creating this GI, the simplest and the most usual way being to copy the end of the symbol in the GI. After the computation of the autocorrelation function, the cyclic frequency corresponding to the GI is derived; an example is presented in Figure 21.

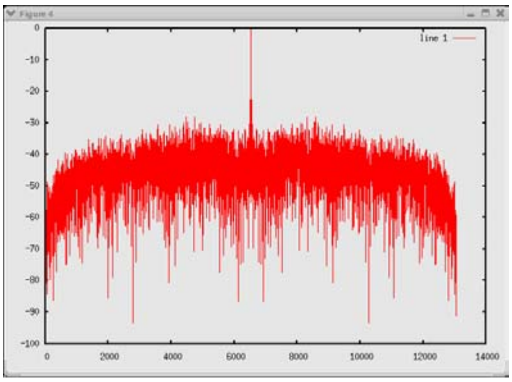


Figure 21 - Detection of GI in OFDM signal (*Symbol OFDM 2K, GI/Tu=1/6*).

2.3. FH/DS signal detection

The results previously presented with the fusion of the two previous sensors are not sufficient yet. It fails in the discrimination of Bluetooth and IEEE 802.11b at 2.4 GHz in Frequency-hopping Spread Spectrum (FHSS) mode. In this situation, the two standards coexist at the same time in the same frequency band, so the resulting spectrum is the product of the original spectrums and consequently the previous sensor does not run correctly, therefore, one needs to find another parameter. The detection between FH and DS modes should solve this difficulty. Recently, [171] addresses this particular problem and proposes to use Wigner-Ville Transform in order to discriminate between Bluetooth and IEEE802.11b, i.e., discriminate between Frequency Hopping FH and Direct Sequence DS signal. The results are adapted to the current needs.

3) Step 3: Fusion
   Then during the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present. At the end of the analysis step, three indicators are obtained. The simplest way to make the fusion is to apply some logical rules on these indicators. This method could be improved by the use of a neural network (like a Multilayer Perceptron). Moreover as these indicators give information which could be weighted by a reliability factor, a future work will further explore solutions based on Bayesian network.

Table 7 summarises the qualitative comparison between the described sensors at the intermediate layer. It is clear that the standard recognition sensor, except for the computational aspect, fills all the other requirements.

Table 7 - Comparison between the existing sensors at the intermediate layer.

Methods	Need of an External service Provider	Content level [3]	Coverage dependant[4]	Computational complexity	Standardisation process	Spectrum consuming	Operator dependent	Need of an additional link
CPC	Yes	High	Yes	Low	Required	Yes	Yes	Yes (CPC itself)
LBI	Yes	Medium	No	Medium	No	Yes	Yes	Yes (GPS)
BSRS	No	Low	No	Very high	No	No	No	No

From the starting point of CR these are the most important sensors to use free bands. The "Free bands detector" sensor is a physical layer sensor as shown in Figure 22.

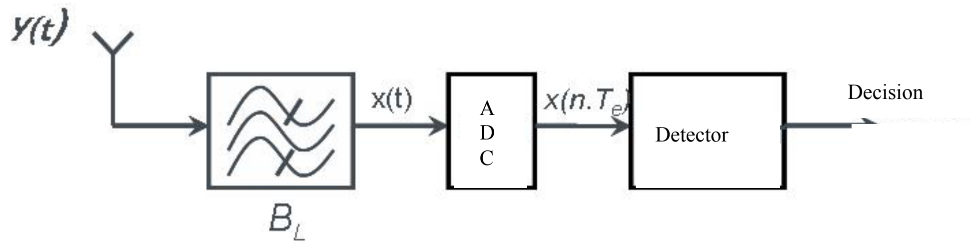


Figure 22- Free Band detector architecture.

Radio signal $y(t)$ received at the antenna is first filtered on a bandwidth B_L before, then digitised and sent to the detector block that states on the band between: free or occupied.

Depending on the reuse type, several definitions exist for a free band. In this document, one considers that a band B_L is free if the signal received in this band B_L is only made of noise (thermal, atmospheric, etc.). On the opposite, e.g., if noise and telecommunication signals are detected, the band is declared occupied. This is a detection issue of signals in noise, which can be stated as the following hypothesis:

$$
\begin{aligned}
H_0 &: x(t) = b(t) \\
H_1 &: x(t) = \sum_i s_i(t) + b(t),
\end{aligned}
\qquad (22)
$$

where H_0 is the free band B_L and H_1 corresponds to occupied B_L. The function $b(t)$ is noise and $s_i(t)$ is a telecommunication signal.

Depending on the knowledge level of the CR equipment on the telecommunication signals transmitted on B_L, many detection techniques may be considered. Among them, one describes below the 3 most known and proposed in the literature: matched filter, energy or power detection, cyclostationarity properties detection.

[3] This metric means that the information given by the method is higher with CPC than with BSRS. In fact CPC will give in addition information about the standard, the operators, the services,…, whereas BSRS will only give an information of existence of Standards (to reach more information imply to demodulate the standard).

[4] This metric means that the information given by the method is dependant of the coverage. In fact it is difficult to imagine that CPC gives precise information on Wifi standards in a small specific area whereas BSRS could detect these standards as well as LB under the assumption the data base is correctly filled.

Matched Filter is the optimal solution for signal detection in presence of noise [174] as it maximises the received SNR. It is a coherent detection method, and needs the demodulation of the signal, which means that cognitive radio equipment has the knowledge a priori on the received signal(s), e.g., order and modulation type, pulse shaping filter, data packet format, etc.. Most often, telecommunication signals have well-defined characteristics, e.g., presence of a pilot, preamble, and synchronisation words, which allow the use of these detection techniques. Based on a coherent approach, matched filter has the advantage to require only a reduced set of samples, being a function of *O(1/SNR)*, in order to reach a convenient detection probability [175]. In the CR context, the main disadvantage for free bands detection is that the equipment should have as many detection chains as the number of potential signals to detect.

Energy Detection or radiometer method lies on a stationary and deterministic model of the signal mixed with a stationary white Gaussian noise with a known single-side power spectrum density σ_0. A simplified diagram of a radio meter is shown on Figure 23.

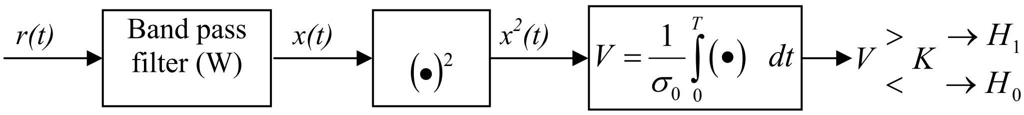


Figure 23 - Radio-meter block diagram.

It can be shown [176] that the statistic test V follows a Chi-Two law, χ^2, at $2TW$ degrees of freedom. Under H_0 hypothesis this law is centred, whereas under H_1 it is not centred, with a non centralisation parameter λ equal to E_s/σ_0, E_s being the energy of signal $s(t)$. For a TW increase, V tends to be a Gaussian variable. Figure 24 and Figure 25 show for different values of P_{fa} the minimum SNR E_s/σ_0 required for the detection as a function of TW.

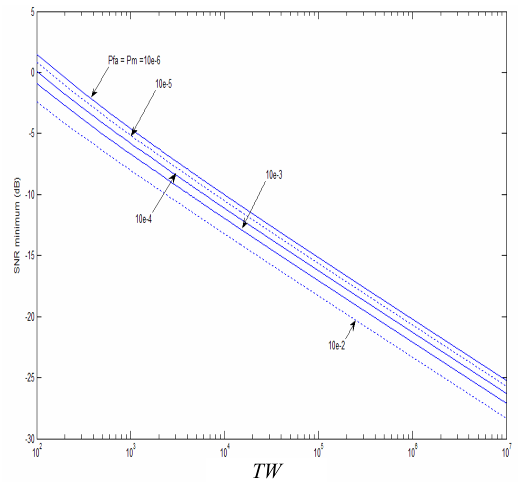


Figure 24 - Minimum required SNR: known noise.

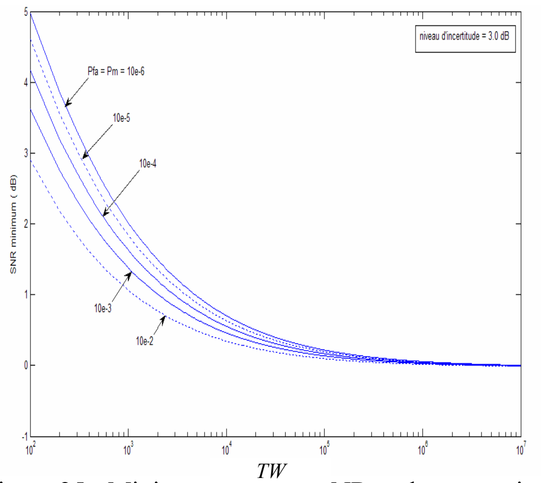


Figure 25 - Minimum required SNR: unknown noise; U=3 dB.

This theoretical result shows that the radiometer can detect a weak signal within noise. Nevertheless, it supposes a precise knowledge of the noise level σ_0. On the contrary, if for instance $(1-\varepsilon_1)\sigma_0 \le \hat{\sigma}_0 \le (1+\varepsilon_2)\sigma_0$, radiometer performances decrease [177] even if TW is infinitely increased, as it is shown on the theoretical curve of Figure 25. Parameter U is defined by:

$$U = 10\log_{10}\left[\frac{1+\varepsilon_2}{1-\varepsilon_1}\right] \quad (23)$$

References [178] and [179] give examples of statistical distribution of V when the searched signal is an amplitude modulated one, or has been submitted to a Rayleigh, Rice or multi-path channels.

In current telecommunication systems, channel estimators allow to evaluate the channel properties and noise level thanks to the knowledge of a sub-part of the transmitted frame. But these estimators require the knowledge of the signal itself which is, obviously, impossible in CR systems context. Therefore, we need testing techniques independent of the noise level knowledge.

As the searched signal is a telecommunication signal, an interesting alternative consists in choosing a cyclostationary [180] model instead of a stationary model of the signal. This model is all the more so interesting that noise is stationary-like. Detection problem (22) becomes a test on the presence of the cyclostationary characteristic of the tested signal.

If $x(t)$ is a random process of null mean, it is cyclostationary at order n_0 if and only if its statistic properties at order n_0 are a periodic function of time. In particular, for n_0=2, the process is cyclostationary in the large sense and respects:

$$c_{xx}(t,\tau) = E\left(x(t)x(t+\tau)\right) = c_{xx}(t+T,\tau) \tag{24}$$

where T represents a cyclic period.

If process $x(t)$ is stationary, then its statistic proprieties are independent of time. In the context of a cyclostationary modelling, covariance function $c_{xx}(t,\tau)$ can be developed in Fourier series in terms of t:

$$c_{xx}(t,\tau) = c_{xx}(\tau) + \sum_{\alpha\in\psi} C_{xx}(\alpha,\tau)e^{i2\pi\alpha t} \tag{25}$$

with

$$C_{xx}(\alpha,\tau) = \lim_{Z\to\infty}\frac{1}{Z}\int_{-Z/2}^{Z/2} c_{xx}(t,\tau)e^{-i2\pi\alpha t}dt \tag{26}$$

Sum (25) is made of harmonics of the fundamental frequencies, determined by the periods of $c_{xx}(t,\tau)$. These fundamental frequencies represent either carrier frequencies or data rate frequencies, or guard intervals of the signal, etc.. Parameter α is called cyclic frequency, ψ is the set of cyclic frequencies and $C_{xx}(\alpha,\tau)$ is called the covariance cyclic function. In the context of a stationary process, ψ is restricted to null set.

The choice of a cyclostationary model for the signal leads to consider a free frequency band as a hypothesis test on the radio signal $x(t)$:

- if H_0, then $x(t)$ is stationary and the considered band is free,
- if H_1, then $x(t)$ is cyclostationary and the considered band is occupied.

This leads to a cyclostationarity test instead of noisy signal detection, and the solution independent of noise. Several articles [181], [182], [183], and especially [184], propose different tests on a cyclic given frequency. In [185], a test is proposed and permits to test a set of cyclic frequencies enabling to improve detection performance. A blind test of cyclostationarities presence is proposed in [186].

A new method for blind detection of vacant sub-bands over the spectrum band is also proposed. The idea of the proposed technique is based on scanning the frequency band to locate white spaces (spectrum holes) in the spectrum [187]. The vacant sub-bands can then be used of cognitive radio communication without affecting primary system QoS. This method exploits model selection tools like Akaike information criterion (AIC) and Akaike weights to sense holes in the spectrum band. Specifically, it is assumed that the noise of the radio spectrum band can still be adequately modelled using Gaussian distribution. Then one computes and analyses Akaike weights in order to decide if the distribution of the received signal fits the noise distribution or not. Theoretical results are validated using experimental measurements captured by Eurecom RF Agile Platform. Simulations show promising performance results of the proposed technique in terms of sensing vacant sub-bands in the spectrum.

At a first stage, one focuses on GSM signals at 953 MHz. Figure 26 depicts the Akaike weights obtained from the baseband GSM signal. It is clearly shown from Figure 26 that the vacant sub-band detection turns out to do a simple peak detection. At a second stage, one also considers a WiFi signal at 2430 MHz. Similarly to the case of GSM sensing, one obtains interesting results in terms of primary user signal detection. Figure 27 shows also that, for Akaike weight values larger than the threshold, one can locate vacant sub-bands, and, for Akaike weights lower than the threshold, one decides the presence of data signal.

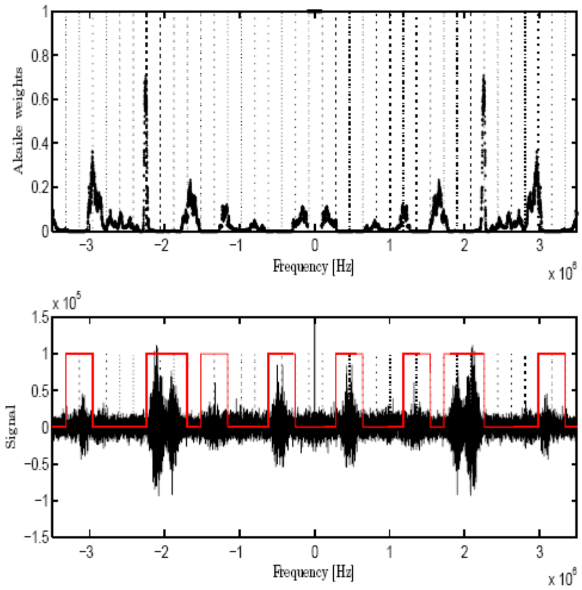


Figure 26 - Akaike weights for a baseband GSM signal at the carrier of 953 MHz.

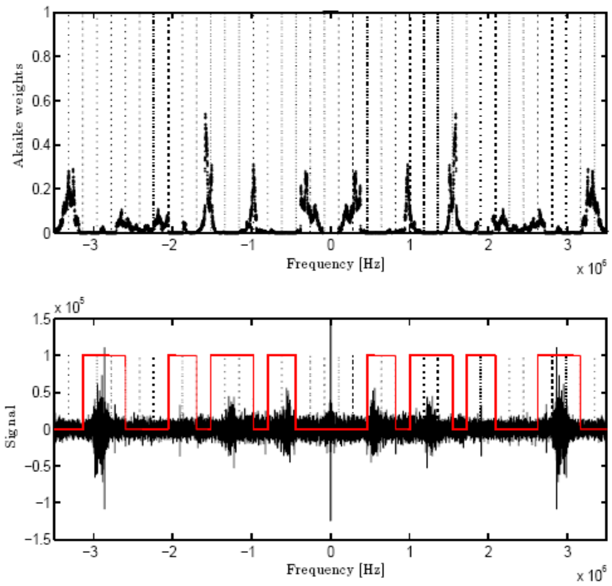


Figure 27 - Akaike weights for a baseband WiFi signal at the carrier of 2430 MHz.

The question to answer is “Which communication means should be used between sensorial bubbles?” But in the CR specific context it may also raise this new question. Should it be only dedicated to communication or could it also bring some cognitive new capability, through flexibility and intrinsic radio properties? An ideal candidate that permits to answer yes to the last question is UWB.

Moreover, as multi-standard radio capability is required for both communication (original function) and sensing purposes to retrieve information from the environment through radio means, this pleads in favour of an SDR design approach. This section explains how a SDR UWB approach for CR could then answer the issues of providing an ideal communication link between bubbles as well as new sensing features.

Even though UWB communication systems are not yet operational, it can be predicted, judging by the craze that this technology has been arousing for several years now, that they will soon become an inevitable part of our everyday life. It is difficult to give a single definition of UWB however, because it is destined to span a very wide range of applications field that extends even beyond the traditional borders of telecommunications themselves. UWB is often mentioned with accompanying terms such as radar, localisation, sounding, medical instrumentation, sensor networks, RFID, cable replacement, etc.. Yet, two main trends can be identified: Low-Data-Rates (LDR) UWB systems (hundreds of kbps) target low-cost, low-consumption applications with ranging capabilities. High-Data-Rates (HDR) and Very High Data Rates (VHDR) UWB systems (from several Mbps up to 1.6 Gbps) are meant to help throughput-intensive devices go wireless. A single UWB technology able to combine both LDR and HDR would really be beneficial for the communications between sensorial bubbles. This would permit a large scale of exchanging modes from the fastest to the slowest, enabling then huge or small amounts of data transmissions.

UWB is traditionally defined as an impulse-based transmission method. The energy of such short impulse spreads over a very wideband, so that its power spectral density is very low. Being discreet, the UWB signal can spread over frequency bands already reserved for well established communication standards without jamming them. In 2002, the FCC issued a recommendation allowing license-free UWB systems to operate in [3.1, 10.6] GHz provided that they did not exceed -41.25 dBm/MHz.

Besides, engineers who tackle UWB soon come to face some very tricky technological difficulties; VHDR solutions that target more than 1 Gbps must have the processing power to support that; LDR solutions need to track in a very precise way pulses shorter than a nanosecond in order to perform efficient localisation. In all cases, low transmitted power and possible in-band interferers (narrow-band systems) make it hard to detect and track the signal.

As can be seen from those considerations, UWB, just like Cognitive Radio, is not yet totally operational, but good hopes can be had for the future. The next two sections describe how UWB, without focusing on any particular technology, could meet many of the requirements concerning Cognitive Radio and communications between sensorial bubbles.

The exchange of information between bubbles is a way to extend the sensing range of each CR equipment outside its own horizon. Moreover, sophisticated CR systems with reconfiguration capability must maintain a constant connection to remote databases in order to download pieces of code as needed. Supposing those systems use UWB to benefit from its powerful sensing means, they could as well use its communication capabilities to download configuration data. If all CR equipments are equipped of a UWB connectivity, with a sufficiently dense population of UWB devices a CR system could obtain a ubiquitous connection to such configuration-specific links. In that sense the bubbles would create some kind of ad-hoc cellular infrastructure supporting the transit of information and data. Configuration information would then always pass through the same UWB channel between bubbles.

The throughput that can be achieved over that channel largely depends on the UWB system's characteristics. It is predictable that ubiquitous connection will be obtained through LDR devices rather than HDR most of the time. First of all because their low cost and low power consumption should favour their deployment, but also because they are supposed to cover a larger area, at the price of a lower throughput. LDR systems are expected to achieve transmission rates of about 100 kbps at 100 m, against 100 Mbps at 10 m for HDR systems. Hence, CR devices would get different reconfiguration services depending on the nature of the surrounding UWB systems. LDR would be there most of the time to provide basic ones for which downloading time is not critical, like bug fixing, code enhancement, or even downloading of a new air interface yet unknown to the CR device (it might be worth waiting a few seconds to download it if it is the only available high data-rate standard in the vicinity). Here and there, HDR UWB systems would provide local hot spots where more demanding reconfiguration scenarios would be workable, like dynamic code adaptation or handover from one communication standard to another.

These statements rely on the assumption that the CR device can accommodate to most UWB standards it might encounter, of both LDR and HDR types. In other words, it implies that the UWB system itself is flexible, either by nature (multi-purpose modulation scheme), or through reconfiguration capabilities, or both. Paper [191] describes a particular UWB air interface that could support the SDR features required to obtain such flexibility and provide an umbilical cord to the CR system.

UWB is useful to sensorial bubbles for both its highly versatile sensing means (spectrum occupancy, positioning) and its communication means (data downloading for remote reconfiguration). LDR systems will mostly provide sensing information at low speed, whereas HDR systems will be more useful when it comes to downloading configuration data at high speed. A combination of both types would bring all the CR devices the best ubiquitous connectivity to its environment.

In order to bring to the sensorial bubble a maximum of connectivity, it must be able to adapt itself to the various kinds of UWB systems it encounters. In that purpose, the CR device's UWB air interface must itself possess intrinsic flexibility properties and support SDR's basic reconfigurability principles. This can prove hard to achieve though. Indeed, SDR guidelines recommend to sample the signal as close to the antenna as possible and then let digital chips do the rest of the processing for flexibility and adaptability's sake; but digitising, and then processing, a signal that spans more than 2 GHz of band is very demanding in terms of sampling speed, computing resources and power consumption, and implementing it in a mobile handset can simply not be envisaged as of today's state-of-the-art technologies. Therefore, not all UWB solutions are good candidates for being implemented in an SDR fashion. See [191] for a candidate solution based on relaxed sampling constraints at the ADC [189].

3.4 Distributed Power Allocation Schemes for Secondary Spectrum Use

Motivated by the desire for efficient spectral utilisation, one presents a novel algorithm for power allocation for sum rate maximisation in cognitive radio context while preserving a guaranteed QoS for the primary network [190]. To this effect, one proposes a distributed cognitive radio coordination that maximises the CRN sum rate while minimising the interference to the primary users (PU). The goal is to realise spectrum sharing by optimally allocating secondary users (SU) transmit powers in order to maximise the total SU throughput under interference and noise impairments, and short term (minimum and peak) power constraints, while preserving the QoS of the primary system. In particular, it is of interest to determine, in a distributed manner, the optimal noise/interference threshold above which SUs can decide to transmit without affecting the primary users' QoS. In fact, in a realistic network, centralised system coordination is hard to implement, especially in fast fading environments and in particular if there is no fixed infrastructure for SUs, i.e., no back-haul network over which overhead can be transmitted between users. Both theoretical and simulation results under realistic wireless network settings are shown to exhibit interesting features in terms of CRN deployment while maintaining QoS for the primary system.

As intuition would expect, Figure 28 shows that the lower the transmission rate is, the higher number of active SUs one gets for a given value of outage probability. Moreover, it is clear that increasing the number of SUs yields improvements in the number of active users. Figure 29 shows however that the SUs' cognitive capacity increases as the number of SUs increases due to multi-user diversity till a certain value where interference impairment are more important. The current curve confirms that in CRN, when one attempts to maximise the number of "on" SUs, the cognitive capacity degrades asymptotically. Hence, there is a fundamental trade-off between per-user cognitive capacity maximisation and number of active SUs maximisation.

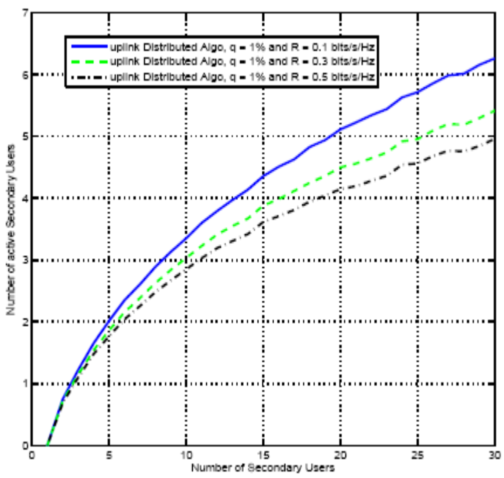


Figure 28 - Number of active secondary users vs. number of SUs for different rates and outage probability.

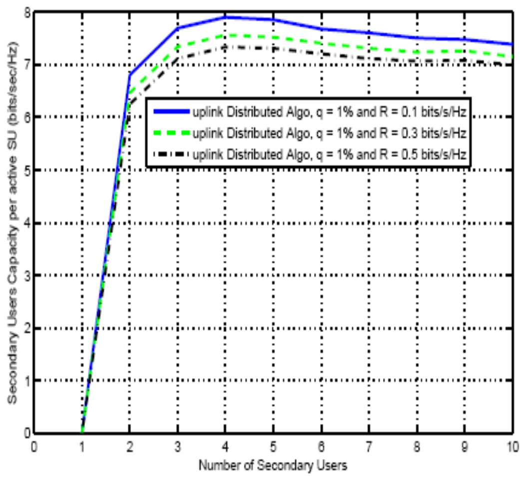


Figure 29 - Secondary user capacity per user vs. number of SUs.

One considers the DL of a cognitive radio network consisting of multiple secondary transmitter and receiver communicating simultaneously in the presence of a primary user. The key idea within this work is to combine multi-user diversity gains with spectral sharing techniques through intersystem coordination, in order to maximise the secondary user sum rate while maintaining a guaranteed QoS to a primary user [192]. One first presents a distributed power allocation algorithm that maximises the capacity of the cognitive ratio network. The algorithm is simple to implement, since a secondary user can decide to either transmit data or stay silent over the channel coherence time depending on a specified threshold without affecting the primary users QoS. Then, one analyses performance of such an algorithm in terms of number of cognitive users able to transmit while minimising interference to guarantee QoS for the primary user. Simulation results carried out based on a realistic network setting showed promising results.

Figure 30 captures the number of active SUs for DL for different rates and outage probability. As expected, it is shown that increasing the target data rate, less SUs are allowed to transmit. Although not shown here due to lack of space, one also remarks that, asymptotically, i.e., as the number of SUs goes large, the number of active SUs keeps constant due to the influence of interference impairments on the PU's QoS. Figure 31 depicts the sum secondary user capacity per user. It is clear that increasing the number of SUs yields significantly increase in capacity because the increase in degree of freedom more than compensates for the decrease in SINR due to interference. However, reaching a certain number of SUs, the sum SU capacity per user slightly decreases as the number of SUs increases.

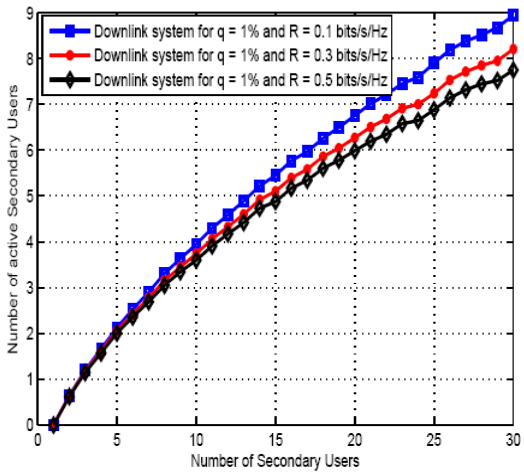


Figure 30 - Number of active secondary users vs. number of SUs for different rates and outage probability.

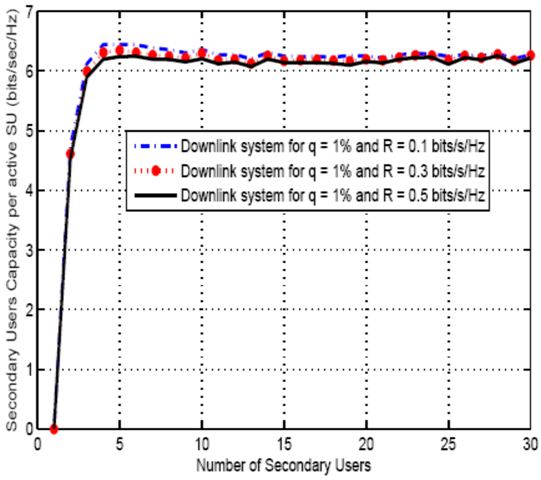


Figure 31 - Sum secondary user capacity per user vs. number of SUs for different rates and outage probability.

4 SCENARIOS AND USE CASES

4.1 Context Scenario

4.1.1 Initial Considerations

There are many ways of looking at the users and their use of technologies, in particular the wireless and mobile technologies. One can generate categories based on which people use particular devices and applications for, what particular communities of users use technologies for, particular Application Packages, the places where wireless technologies are used, etc.. Users can be individuals, but also organisations that provide individuals with wireless technology, and the suppliers of technology infrastructure. However, the role of this document is to go beyond a person-centred approach, and try and describe the context of use of telecommunications services and radio access technologies. This entails describing the locations of use, and the devices and application software use to access them. The aim of this document is to create models for JRRM testing, design and simulation. NEWCOM++ scenarios enable us to link research on people behaviour to future JRRM strategies.

Context Scenario structures and brings together material for the creation of Use Case Scenarios. Within this definition there are four perspectives: Location, User, Device and Application Package, Figure 32. For each perspective a number of characteristics are developed, relevant to the characterisation of services, i.e., in relation to geographic space, number of users, Data Applications, demand for services, expected QoS, etc.. Within each perspective a number of examples or *context scenarios* identifying relevant characteristics are described. Any Use Case Scenario will draw on the context scenarios of a particular user, in a particular place, with a particular device using a particular Application Package.

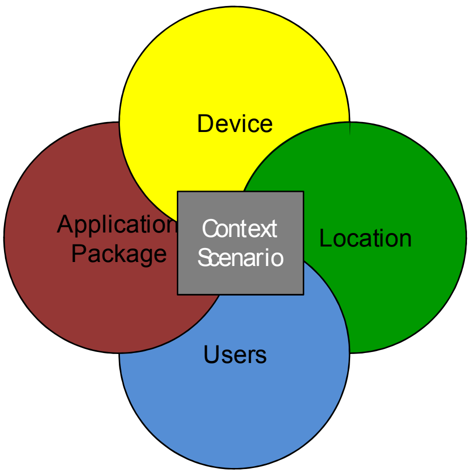


Figure 32 - Generation of context scenarios.

The following proposed Context Scenario and Use Case Scenarios are based and adapted from the IST-FLOWS project [197]. The selected Context Scenario, ***Business Traveller on the Train***, describes a business traveller on a medium distance train travelling from the city, through the suburbs and rural areas, stopping regularly at stations. In the next subsections, one defines each perspective of this Context Scenario.

4.1.2 Application Package

The Application Package relates to the particular activities that a user is engaged in, and the set of Data Applications and services that are relevant to that activity. The concept of Application Package links the activities of users to the use of the technology. Application package refers to particular activities, such as education, work, leisure and life management.

In Table 9, a mapping of services and the selected applications for the Service Scenario, by each application is presented and a summary of service characteristics is given. This is a very important input towards the performance evaluation of the JRRM performance, which is one of the main objectives of the WP.R9. The bit rates used for evaluation purposes may be higher than the typical values quoted, but still within the indicated range. The user scenarios also offer indications of whether to use higher of lower values. Further refinement may be considered. For example, the audio and video components in video telephony could be treated separately, or the full range of network services for an application might be included (e.g., e-mail or file transfer browsing and download).

The ranges and values given in Table 9 are from existing models and best practice, for present modelling. However, there is considerable uncertainty on several values, since they refer to use of applications and services in the future. For example, one cannot possibly tell what the average ‘web browsing’ session will be like on future mobile devices that do not exist yet. Another limitation is that the figures and model, for example for arrival rate and session duration, are generic.

4.1.3 Device

There are a number of possible devices that services can connect to, applications run on, and which offer different levels of portability. Of key importance are not only the stand-alone capabilities of the device, but the degree to which it can interconnect with other wireless and wired devices. Many Application Packages will run across a range of devices, and most users will have access to a range of devices simultaneously or in across different parts of the life space, e.g., the smartphone or laptop can always be updated from a computer and fixed wire link at home or work on a regular basis – ideal for many asynchronous solutions.

One selected device type is a smartphone terminal, which offers an impressive performance and functions for their size and weight, which makes a useful device for business users as well for consumers. Its portability, allows great versatility of use (voice telephony, MP3, email, share trading, video streaming), even if issues of affordability will make the heavier featured devices more accessible to corporate users. Because of its potential for a relatively good display size, it allows viewing of films and video clips whilst on the move. Further information considering the device capabilities and features are described in Table 8 and Table 10.

Table 8 - Device Smartphone.

Characteristics	Mobility	Size / Weight	Location	Application Package	Performance	Support Network	Extended features
Pocket sized Clip on keyboards, etc Fold out antenna Video/Audio (inc. camera) Screen size (100×50 mm^2)	Highly Vehicular Vehicular Pedestrian	$80\times130\times20$mm^3 200g Carried in Jacket Pocket, Handbag, in diary, mounted in car or in larger bag (generally within smaller bag)	Indoor/Outdoor Urban/Rural Public/ private transport Industrial Estate Airport City Centre Suburban Estate School Financial District Buses, Trains, cars Shopping Mall	Network Supported Work tools Personal Networker City Survival Kit Media Consumption Portal Traveller’s Aid	Considerable computing power (memory, storage) Battery up to 15h	WLAN Cellular Medium Bit Rate (CMBR) PAN Cellular High Bit Rate (CHBR)	Headset Camera Miniprinter Scanner Connection with Notebook Desktop Computer Other remote peripherals (printers)

Table 9 - Service Scenario: Network Service Characteristics based on selected Data Applications.

Data Application	Network Service	Service class	Bearer Characteristics						Traffic Characteristics					Performance Requirements		
			TB[5]/ NTB	RT[6]/ NRT	Uni/ Bid	Sym/ Asy	Mode[7]	CS/ PS	Arrival rate [per hour]	Example Session Duration [min] and Model	Traffic source Model	Bit Rate Range [kbps]	Typical Bit Rate [kbps]	Transfer Delay [s] (PS)	Blocking Probability (CS)	BER/FER
Voice Call	Speech-telephony	Conversational	TB	RT	Bid	Sym	O-O	CS/PS	0.2 (Light) – 0.5(Heavy)	Light users 2 [196] Heavy users 3 [203] Exponential	ON/OFF	4-25	12.2 [193]	<0.15 [193]	2% [196]	$<10^{-3}$ BER < 3%FER [193]
Video Call	Video-telephony	Conversational	TB	RT	Bid	Sym	O-O	CS/PS	0.3-0.4	Light users 2 [196] Heavy users 3 [203] Exponential	ON/OFF (audio) CBR (video)	32-384 [193]	Low quality: 64 [199] High Quality : 250	<0.15 [194]	2% [196]	< 1% FER 10^{-6} BER [193]
Real time games	Unrestricted Stringent Data	Conversational	NTB	RT	Bid	Sym	O-O	PS		20		< 8 [193]		<0.25 [193]	2% [196]	$<10^{-6}$ BER [193]
Video on demand	Video Streaming	Streaming	TB	RT	Uni	N.A.	O-O/ O-M	CS/PS	0.3	0.66 [200] Exponential	ON/OFF (audio) CBR (video)	32-384	medium quality: 32 [200]	<10 [193]	2% [196]	$<10^{-6}$ BER <1% FER [193]
Web Browsing	Multi-media Communications	Interactive	TB/ NTB	RT	Bid	Asy	O-O	PS	0.34	1-10 [202] Given by source model	WWW model	8 to 10Mbps	64	<4s/page [193]		$<10^{-6}$ BER [201]
E-mail/ messaging	Messaging	Back-ground	NTB	NRT	Uni	Asy	O-O	PS	Given by source model	0.05-3 [203]	Email model		50 [195]	<4 [193]		$<10^{-6}$ BER
File Transfer	Unrestricted Data Transfer	Back-ground	NTB	NRT	Bid	Asy	O-O	PS	-	0.5 [203]	64-400 [198] [195]	-	1-50 [203]	10s [193]		$<10^{-6}$ BER

5 TB and NTB stands for Time Based and Non Time Based
6 RT and NRT stands for Real Time and Non Real Time
7 Mode is related if the communication is One to One or One to Many.

The second considered device, the notebook, can offer all the features and applications of a desktop computer with the added benefit of being portable. It is used by a wide range of users, although it is seen as particularly essential to individuals who require a mobile office or full intranet connection for office type work. Notebooks allow business travellers and other mobile users to perform office tasks anytime anywhere, and business continuity is therefore seen as critical. Individuals who seek a wide range of applications combined with mobility often prefer a notebook, although cheaper and lower performance devices may be used as well. The notebook can be used also by students, and increasingly school children, and all those who have changing workspaces. The notebook is the ideal home computing device as well.

Table 10 - Laptop Computer (notebook).

Characteristics	Mobility	Size / Weight	User	Location	Application Package or Specific Data Applications	Performance	Support Network	Extended features
Potable Antenna on back of cover or retractable dielectric layer Screen size (approx. 40cm)	Fixed Vehicular Highly vehicular	260×330×50mm^3 1-4kg	Business Travellers Mobile workers Students School children	Indoor /outdoor Urban /rural Industrial Estate, Airport, Tourist City Centre, Suburban, Estate, Financial District, Shopping Mall, Public/ Private transport	Network Supported work tools Traveller's Aid Media consumption portal Personal Networker City Survival Kit	High processing power and storage space Battery up to 7h	WLAN CMBR PAN CHBR	PAN headset smartphone (synchronise/ use with) Docking station (car, office) Other peripherals (printers, etc.)

4.1.4 Location

A key dimension to the use of mobile and wireless services is the location where they are used. Mobile technology opens up many new spaces to the use of Information and Communication Technologies (ICTs), and this perspective highlights particular spaces that people move through and to in the course of activities, especially those that are by definition related to travel and temporary occupation. The selected Context Scenario location perspective is the Medium Distance Train, Table 11.

Medium distance train travels between nearby cities, or from a large city to surrounding cities, thus it travels for several hours, fast, but also makes frequent stops, unlike an Intercity. The train is a mode of transport that gives travellers freedom to use ICTs in many ways. The medium distance train serves some long distance commuters and travellers visiting more distance destinations. It is not normally so crowded as a local commuter train. It is used by many people on leisure and work activities who form a temporary community. The train will often carry 'real' communities - large groups of people travelling together. The train alternates between travelling at high speed and stopping in stations. The train operators control the space within the train, being able to limit use of mobile phone for example, but also provide or support local area network access. More modern trains can offer power points and possibly local wireless networks. Longer tunnels may be equipped with wireless infrastructure.

During its regular commute, the train can also be used to opportunistically exchange data with wireless sensor networks that are strategically located close to the tracks. These networks are not only useful to convey environmental data for any of the areas in the vicinity of the train's path, but also to support critical structural health monitoring applications used to facilitate the maintenance of the more complex civil structures along the trains tracks (e.g., bridges, tunnels, etc.).

Table 11 - Location Medium Distance Train.

Physical Characteristics	Type of users	Data Applications and Packages	Mobility	Device	Access Technology Infrastructure
Narrow metal tube with holes! Operates in open country, urban/suburban and in closed station areas.	Business travellers Commuters Tourists All ages Dense concentration on train and platforms	Office (email, files) Voice Game Product information News Bulletin Boards Travel information Films Video clips MMS Music download and share Video Clips Voice Games playing and downloading Web browsing	Within the train: still. Train moving very fast, or stopped (possibility for WLAN connection in stations for all passengers)	All devices	The train moves through areas of microcell coverage (city centre and pico-cell coverage main stations to suburban and rural macro cells. WLAN cells in stations. Power provided in some carriages

4.2 Use case scenarios

4.2.1 Scenario description

As mentioned previously, the selected scenario describes a business traveller on a medium distance train travelling from a given city, through the suburbs and rural areas, stopping regularly at stations, Figure 33. The main user is conducting business activities with a Network supported Work Tool and some personal communications. One has selected the User Scenario from a combination of *context scenarios* presented earlier in this document. Linking this user scenario to the Service and Access Technology Scenarios, four Use Cases scenarios, were identified providing a range and depth of test criteria and conditions that can be used in the NEWCOM++ Working Groups.

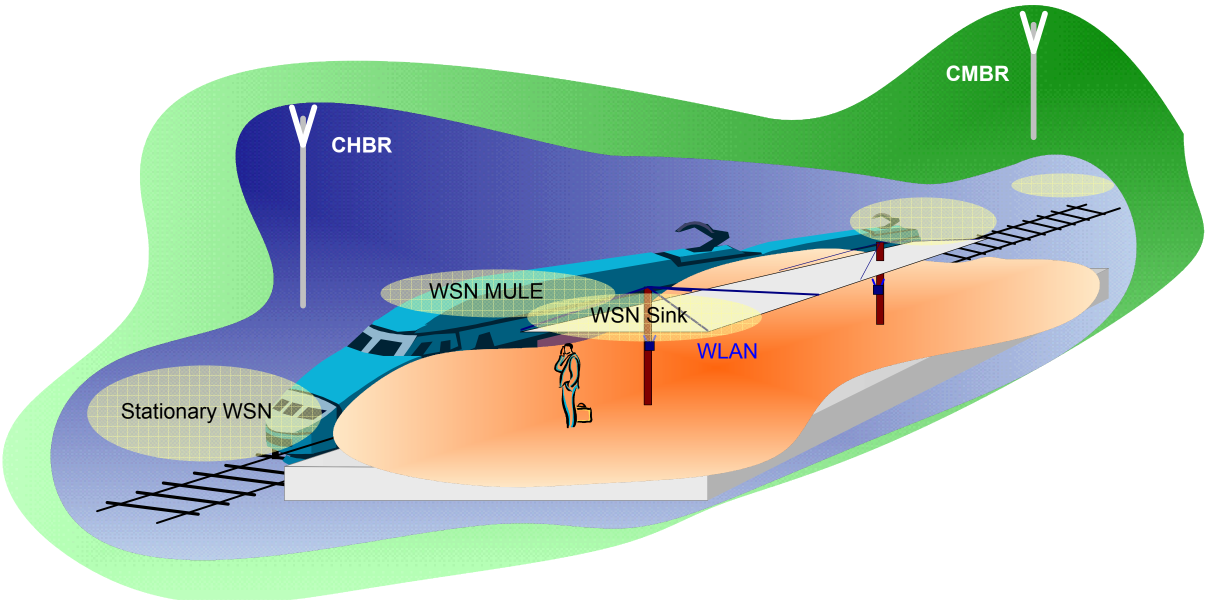


Figure 33 – Use case scenario train station example.

A detailed description follows:

- **Access Technology Scenario**: CHBR (e.g., UMTS R5), in city and urban parts of journey, WLAN (e.g., 802.11'x'), connectivity in stations, CMBR (e.g., UMTS R99), connectivity everywhere; PAN (e.g., Bluetooth), in each carriage.
- **Main User**: The user is a business executive who is travelling to a meeting. He/she needs to communicate with his office, with other colleagues in his organisation and with clients. He/she has access to on-line resources on his corporate intranet which he/she uses in his business. He/she also submits report and documents. He/she discusses documents with his colleagues on the phone

and works on them at the same time. He/she is available to his colleagues and clients/ business contacts all the time, but is able to divert calls and messages to a secretary. He/she has a great deal of resources to spend on communication and information exchange.

- **Home-work management***:* He/she has a family, but he/she travels away a great deal, and keeps in touch electronically with phone calls every day, images and video messages, and occasional video call. He/she is also able to check on his young son at the nursery via their webcam. He/she has some friends he/she shares an enthusiasm for old cars with, and other friends he/she sees on trips frequent trips to the city. He/she lives in a suburb, and uses his car, the train and aeroplanes for travel. Most regional trips are done by train due to bad congestion on the roads.
- **Location:** Medium Distance Train**.** The user is on a train that travels from the city centre across country for a trip of several hours. The train travels at speeds of 70 km/h in urban areas and 130 km/h in rural areas. It stops every 15 minutes for 3 minutes at stations. The business class coach on the train has power supply for travellers. The stations have WLAN connectivity and the train travels through areas of CHBR connectivity and continuous CMBR connection. However, it does go through tunnels that take up to 15 s to pass through. Within the train there may be 100 people doing activities similar to our user. The train also has 400 students going home for the holidays, who are making intensive use of instant messaging, voice calling, on-line gaming and web browsing.
- **The Application Packages**: Network Supported Work Tools Travellers Aid, Social Networker. He/she uses a set of applications that are provided by his/her employer to link him/her into the corporate network, and to enable communications with clients and business partner. The firm use a customised product provided by a major vendor that integrates multimedia data over a variety of networks. The package enables all the standard business documents to be worked on and shared, access to the corporate Internet and the Internet for communication, information, and making travel arrangements, placing secure orders and signing electronic contracts. The system will filter messages and webpages for unnecessary images. He/she uses an Internet travel company website on the MT to book hotels and a taxi. He/she communicates with his friends and family on a separate integrated mail/messaging account through a web interface and the telephone
- **The Devices:** He/she has two devices – a smartphone and laptop computer. All the devices are provided by his company and access services provided through a single service provider buying in connectivity from infrastructure companies. Devices cannot be used in a moving car while driving, except to take telephone calls, of listen to e-mails and documents being read. The smartphone is seen as more convenient to use than the laptop at particular times, especially on crowded trains at rush hour.
- **Specific activities:** He/she will conduct 1-2-1 and multi-way phone calls, upload and download documents up to 10 MB, and on this occasion, a 500 MB video file for a presentation. For 1 hour, he/she will discuss a multimedia document with a colleague on the phone while editing the text it in real time together. During this time he/she will check his e-mail 3 times in response to alerts, downloading 5 large files to his laptop. He/she usually checks his e-mail on the Smartphone, but can synchronise with the laptop and download larger items too. Only one of the downloads is important and must be done immediately, the rest can be done whenever the network connection is fastest and cheapest. He/she watches the business news on a subscription mobile TV on demand service. He/she looks at his children in the nursery through a low quality video link to his laptop web browser. He/she receives some small images from his children on his private messaging service, although routed through the company network. He/she books a taxi, and checks a map of the place he/she is visiting.
- **Specific Data Applications (**Table 12**):** File transfer, E-mail/ multimedia messaging, Voice phone call, Synchronous document sharing, Video on Demand, Cooperative Document editing, web-browsing including video stream.
- **WSN Functionality:** As the train moves along its course, sensor data can be opportunistically exchanged between track-side sensor nodes and mobile data MULEs on board the train. This exchange can be either from the MULE to the stationary sensor nodes, allowing the WSN administrator to retask or reconfigure the network, as well as from the sensor nodes to the MULE; in the latter case, the MULE acts as local sink transporting measured data towards the next train station. As an alternative, the MULE, based on train's schedule, might choose to forward information to destination through CHBR. Moreover, the train is also equipped with sensor nodes,

reporting the current level of occupation of coaches; this data can be taken 5 minutes before reaching the station, and might be sent through the CMBR to the next station, where a device might display it, allowing the passengers to move along the track in order to prepare for catching the less crowded coach of the arriving train.

Table 12 - Services characterisation for user activities in train traveller scenario.

User data activities	Data Applications	Network Service	Geographical topological characteristics	Network Availability	Mobility [km/h]	Device	QoS expectancy
Downloading 10MB files, 500MB file from Intranet	File transfer	Unrestricted data transfer	Urban train/ train in station	CHBR, WLAN	0-120	Laptop	Background: speed not so important
Posting 2×5 MB documents on intranet	File transfer	Unrestricted data transfer	suburban train/ train in station				Background
Browsing e-mail and 3× downloading 10 messages (length 500B-120kB each)	E-mail	Messaging	Rural train/ train in station	CHBR, CMBR, WLAN			Fast access
Receiving 5×30kB images on the PDA via messaging	MM message	Messaging	Rural train/ train in station			Smart-phone	Background activity
1 hour phone call, including multi-party parts	Voice calling	Voice telephony	Suburban and Rural	CHBR, CMBR			High Quality audio
Listen to classical music on radio when not on the phone – via phone	Radio receiver	Audio streaming/broad cast	Suburban and Rural	CHBR, CMBR, WLAN			High Audio quality
Watch business TV headlines for 10 minutes (medium quality video	Video on demand	Streaming video and audio	Suburban/Urban			Laptop	Medium/low video, high audio
Watching small video of friend's new car	File transfer	Unrestricted data transfer	Suburban			Smartphone	Background
Getting maps and booking taxi	Web browsing	Multimedia communication	Suburban				Good quality web access
Cooperative document writing	Document sharing Word-processing	Multimedia communication /Stringent Data.	Suburban/Rural	CHBR, WLAN		Laptop	'Instant' changing documents
WSN data exchange	Data transfer	Unrestricted data transfer	Rural/Suburban/urban/train in station	WSN		WSN Nodes	Background

4.2.2 Use Cases

A description of the use cases follows.

Use Case 1: A passenger travelling at 80 km/h on a train, is listening to classical music on a radio, then switches to CHBR to listen to a chosen (stored) concert. The train reduces its speed to 50 km/h and comes to a halt, and the user gets off to change trains. Standing on the platform, the traveller continues to listen to the music, but switches from CHBR to WLAN because of congestion, Table 13.

Table 13 - Use Case 1 Listening to music on train and in station.

Specific activity	Data applications	Network services	Geographical characteristics	Cell types	Network Availability	Mobility	Device	QoS expectancy
Listen to radio Downloading music	Audio broadcast Audio-on demand	Audio streaming Audio streaming	Outdoor-suburban Indoor -suburban	Macro Micro Pico	Radio Broadcast CHBR WLAN	Vehicular Pedestrian Fixed	Smartphone	Medium

Use Case 2: Whilst on a very crowded train with many MT users, the traveller accesses maps, checks the online (live) train arrivals board and books a taxi on a mobile phone via CMBR and then CHBR as the train moves between different areas of coverage, Table 14.

Table 14 - Use Case 2 Using web based travel assistance on a train.

Specific activity	Data applications	Network services	Geographical characteristics	Cell types	Network Availability	Mobility	Device	QoS expectancy
Read maps Check train arrival time Book taxi	Web browsing	Multimedia communication service	Outdoor	Pico	CHBR	Vehicular	Smartphone	High

Use Case 3: Arriving at a train station travelling at 30 km/h and then stopping completely, cooperative document writing over a CHBR and then a WLAN network for the 6 minutes when the train is stopped at the station. As the train leaves the station to travel through the city suburbs at an average speed of 100 km/h, the device switches back to CHBR (WLAN is operated by same company as CHBR), Table 15.

Table 15 - Use Case 3 File sharing on train.

Specific activity	Data applications	Network services	Geographical characteristics	Cell types	Network Availability	Mobility	Device	QoS expectancy
File sharing	Document co-authoring	File transfer	Outdoor-urban Indoor-urban Outdoor-suburban	Micro Pico Micro	CHBR WLAN CHBR	Vehicular Fixed Highly vehicular	Laptop	Very high

Use Case 4: While train is in a small town station engineers take down CHBR coverage of the area for 5 minutes, and system transfers all calls/connection to WLAN and CMBR, Table 16.

Table 16 - Use Case 4 Switching all calls in small town.

Specific activity	Data applications	Network services	Geographical characteristics	Cell types	Network Availability	Mobility	Device	QoS expectancy
250 users File sharing Phone calls Web browsing	File transfer Voice calls Web browsing	Unrestrained Data transfer Speech Interactive services	Outdoor-urban Indoor-urban Outdoor-suburban	Micro Pico Micro	CHBR WLAN CMBR	Vehicular Stationary Walking Highly vehicular	Smartphone, Laptop	Medium - High

4.3 Scenarios and Use Cases for Spectrum Allocation for OFDMA Networks

4.3.1 Scenario Definition: Single-cell and Multi-cell Scenarios

According to the studies of the existing techniques we singled out two simulation scenarios: a *single-cell* scenario, where the radio resource allocation schemes are designed to exploit channel and multi-user diversity only, and a multi-cell scenario where resource allocation has to deal with multiple access interference as well.

In this section, one presents the parameters that compose the scenarios in which will be carried out the studies about RRM for spectrum allocation on OFDMA-based cellular networks. Each parameter will be further specified according to the joint decision of other working groups.

- **Architecture**
  The system architecture is related to which network nodes will cooperate in the RRM decision and execution and how they will communicate among them. Three options will be considered: centralised, hierarchical and distributed.
- **CSI feedback**
  Efficient resource allocation algorithms in OFDMA networks need to know the channel state of the users in the system. The majority of the works found in the literature assume that the base station or the central controller has perfect knowledge of the CSI of all users in the system. However, in the present work one will take into consideration use cases where there is limited and/or imperfect CSI feedback. The amount of CSI feedback depends primarily on the parameters of the radio channel: channel coherence time and channel coherence bandwidth. The channel coherence time influences the frequency of CSI updates, the channel coherence bandwidth determines the number of subcarriers that have similar gains and therefore can be grouped together in a sub-band. In all cases, the amount of CSI feedback is obtained as a balance between the need of accurate channel information and the need of saving bandwidth for actual data transmission.

- **Signalling overhead**
  Dynamic OFDMA are subject to a certain required overhead due to signalling, since the BS must inform to the mobile terminal the full assignment set (which terminal is assigned which sub-carrier with which modulation type). As well as for the CSI feedback, the amount of signalling overhead is the result of a balance between the need of accurate addressing of all resources and the need of saving bandwidth for actual data transmission and as such depends on the same channel parameters: channel coherence time and channel coherence bandwidth. It is important to account for this signalling overhead in the system performance evaluation.
- **Radio Access Network (RAN)**
  The studies conducted in this working group will be based on a system inspired in the UTRAN LTE, which is standardised by 3GPP [204].
- **Propagation**
  As already discussed in the previous point the propagation channel plays an important role in the definition of the scenario. One will consider only the outdoor suburban/rural macro-cell and outdoor urban microcell propagation models. The simulations will use detailed models for tri-sectored antenna radiation pattern [196], path loss attenuation [196], spatial correlated shadowing [205], [206], and multipath propagation (time and frequency correlated fast fading) [207] for the macro-cell scenario. For the urban microcell scenario detailed modelling of two-sectored antennas (scenario with BSs at the crossings are not considered), path loss, shadowing and multipath propagation will be used [78]. Outdoor to indoor and vice-versa propagation will not be considered. The simulations will use channel models describing both LOS and NLOS propagation conditions. Some important parameters that need to be decided are:
  - Signal Bandwidth: 5-100 MHz
  - Number of subcarriers: 64-2048 (to group in sub-bands)
  - Channel delay spread: 0.5-5 μsec
  - Normalised coherence time: 0-10^{-2}.
- **Traffic distribution**
  Only uniform traffic distribution will be assumed in the simulations. In case of the urban micro-cell cellular grid, users will be uniformly distributed along streets. The call arrival will be modelled as a Poisson process.
- **Cellular grid**
  Three kinds of cellular grids will be considered: single-cell, multi-cell and Manhattan grid [196]. The first will be used to evaluate simpler RRM algorithms, while the latter will take into account the inter-cell interference and will allow the evaluation of more complex algorithms that can be implemented in a real cellular network with multiple BSs. In the macro-cellular multi-cell case, either a 7 or 19 hexagonal cells topology can be used. In order to avoid a difference between cells at borders and cells at the centre the architecture can be implemented in a toroidal geometry. The Manhattan grid will be used to simulate urban microcell environment, where both BS and users antenna heights are below surrounding rooftops. The Manhattan scenario includes grid of parallel and perpendicular streets. In such environment radio propagation and cell's shape are confined in area defined by surrounding buildings.
- **Mobility**
  Static or pedestrian (3 km/h) users will be assumed. For more details on the pedestrian mobility model, see [208], [209]. For the urban micro-cell environment also higher velocities (up to 50 or 70 km/h) may be considered and user mobility model will include possibility of users' direction change (into street perpendicular to the current one).
- **Services**
  Both Real Time (RT) and Non-Real Time (NRT) will be envisaged in the simulations according to the selected traffic models: Voice over IP (VoIP) [210] and World Wide Web (WWW) [196], [211], respectively. A full-buffer traffic model, which characterises any service that has always packets to transmit, will be used for simplified studies.

We will focus our studies on three different use cases one for the single-cell scenario and two for the multi-cell scenario.

4.3.2 Use cases

Use Case 1 *Single-cell Resource Allocation with Realistic Simulation Assumptions* is characterised by a single-cell grid where the short-term resource allocation decisions are taken by only one central entity (BS). The general system aspects are inspired on the UTRAN LTE system, the propagation model is macro-cell outdoor and the users will be placed uniformly over the cell. These use cases are meant to allow initial resource allocation studies on more controlled scenarios without inter-cell interference. Capitalising on previous studies on single-cell resource allocation, use case 1 is focused on the usage of realistic simulation models, such as CSI feedback with limited information (groups of sub-carriers or users), imperfect or delayed CSI feedback, impact of signalling overhead on capacity loss, pedestrian mobility model and mixed traffic scenario with VoIP and WWW traffic models.

Use Case 2 *Multi-cell Architecture with Ideal Simulation Assumptions* is defined for multi-cell scenario: inter-cell interference will be explicitly modelled, allowing the proposal and evaluation of complex resource allocation algorithms, suitable to be implemented in a cellular network. Because of the complexity of the algorithmic solutions, the simulations assumptions for this use case are idealised: instantaneous CSI feedback of all users on all sub-carriers without errors, no signalling overhead, static users and full-buffer traffic model. The main focus will be to study a distributed architecture, where the BSs cannot communicate between them so that resource allocation decisions are taken by each BS autonomously. Centralised and hybrid solutions will be also taken into account when performance benchmark are needed or in case long-term RRM algorithms need to be evaluated.

Use cases 3 *Multi-cell Architecture in Outdoor Manhattan-like Urban Environment* describes a multi-cell urban scenario modelled by Manhattan grid. Inter-cell interference, users' mobility and signalling overhead are modelled. All possible multi-cell architectures, described in the above points, will be examined (centralised, hierarchical and distributed). Both long and short term RRM algorithms will be evaluated.

Table 17 summarises the three use cases and presents the main parameters that contribute to their definition.

Table 17 - Scenario for studies about RRM for spectrum allocation in OFDMA-based cellular networks

Scenario		**Single cell**	**Multi cell**	
Use case		**1**	**2**	**3**
Architecture	Centralised	X	X	X
	Hierarchical			X
	Distributed		X	X
CSI feedback	Perfect		X	X
	Imperfect	X		
Signalling overhead	No		X	
	Yes	X		X
Mobility	Static		X	
	Pedestrian	X		X
Services	Full buffer		X	X
	WWW	X		
	VoIP	X		

5 CONCLUSIONS

This deliverable deals with RRM, JRRM and ASM Algorithms. A state of the art is presented, several JRRM techniques and strategies being described, and the most recent proposals and studies on the field being identified. Additionally, JRRM optimisation approaches, like fuzzy logic control optimisation, are also addressed. More related with RRM at the link level, a particular attention for modern OFDMA based networks is also presented, where single- and multi-cell studies are described.

This deliverable has also covered the strategies in the field of ASM, particularly focusing on the flexible spectrum management concept and the possibility to enable a secondary spectrum usage, with the application of cognitive network concepts. In that respect, one of the activities is focused on carrying out a measurement campaign to identify and characterise the utilisation of the different licensed spectrum bands in different environments, so that this can be used as an input to the development of strategies to improve the efficiency in spectrum utilisation.

As an example, a methodology for spectrum sharing between primary and secondary users based on distributed power allocation is presented. Finally, another of the activities in this field focuses on the "sensorial radio bubble" concept, and its application to the cognitive networks. With this concept, cognitive radios are able to identify how the spectrum is being used in its environment, and to take the appropriate decisions.

Finally some relevant scenarios are described, like a train and cellular based scenarios. Several useful use cases situations are also proposed, for the study of the previously described strategies and algorithms.

This deliverable has described the different activities in which researchers of NEWCOM++ WP R.9 are involved. In addition to this, and based on these activities, potential interactions with the tasks in other NEWCOM++ WPs can also be identified. In particular, regarding the activities on RRM and JRRM, interactions are identified with WP R.8 (inside the task on scheduling techniques for cognitive networks and the task on scheduling techniques for heterogeneous networks) and WP R.11 (inside the task on resource management for opportunistic networks). Similarly, for the activities on spectrum management and cognitive networks, interactions are identified with WP R.C (inside the task on multi-standard processing for cognitive radio), WP R.11 (inside the task on opportunistic spectrum access) and WP R.1 (inside the task on adaptive channel modelling for flexible radio). This work is left for further development for the remainder of the project.

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7 LIST OF ACRONYMS

3GPP	3rd Generation Partnership Project
AAM	Appearance Active Model
ABC	Always Best Connected
AIC	Akaike Information Criterion
AM	Amplitude Modulation
AP	Access Point
APD	Amplitude Probability Distribution
ASM	Advanced Spectrum Management
BER	Bit Error Rate
Bid	Bi-directional
BS	Base Station
BSRS	Blind Standard Recognition Sensor
BWc	channel BandWidth
CDMA	Code Division Multiple Access
CF	Cost Function
CHBR	Cellular High Bit Rate
CMBR	Cellular Medium Bit Rate
CPC	Cognitive Pilot Channel
CR	Cognitive Radio
CRN	Cognitive Radio Network
CS	Circuit Switched
CSCC	Common Spectrum Coordination Channel
CSI	Channel State Information
DCA	Dynamic Channel Assignment
DRA	Distributed Resource Allocation
DSAN	Dynamic Spectrum Access Network
FER	Frame Erasure Rate
FF	Fittingness Factor
FHSS	Frequency-hopping Spread Spectrum
FLC	Fuzzy Logic Controllers
FM	Frequency Modulation
FSM	Flexible Spectrum Management
GERAN	GSM EDGE Radio Access Network
GI	Guard Interval
GSM	Global System for Mobile communications
HDR	High Data Rates
HHO	Horizontal HandOver
HSDPA	High-Speed Downlink Packet Access
ICTs	Information and Communication Technologies
IP	Internet Protocol
ISI	Inter Symbol Interference
ITU-T	International Telecommunication Union – Telecommunication

JCAC	Joint Call Admission Control
JRRM	Joint Radio Resource Management
KPI	Key Performance Indicators
LAN	Local Area Network
LBI	Localisation Based Identification
LBN	Low Bit rate Networks
LDR	Low Data Rates
LTE	Long Term Evolution
MAI	Multiple Access Interference
MBN	Medium Bit Rate Networks
MT	Mobile Terminal
NBS	Nash Bargaining Solution
NPRM	Notice of Proposed Rule Making
NRT	Non-Real-Time
NSF	National Science Foundation
NTB	Non Time Based
NTIA	National Telecommunications and Information Administration
OAM	Operation and Maintenance
OFDMA	Orthogonal Frequency Division Multiple Access
OODA	Observe, Orient, Decide and Act
PAN	Personal Area Network
PS	Packet Switched
PSD	Power Spectral Density
PU	Primary User
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RBF	Radial Basis Functional
RBF NN	Radial Basis Functional Neural Networks
RBS	Raiffa-Kalai-Smorodinsky Bargaining Solution
RRM	Radio Resource Management
RT	Real-Time
SDR	Software Defined Radio
SMS	Short Messaging Service
SNR	Signal-to-Noise Ratio
SOM	Self-Organising Map
SRB	Sensorial Radio Bubble
SU	Secondary User
SWR	SoftWare Radio
TB	Time Based
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunication System
UTRAN	UMTS Terrestrial Radio Access Network
UWB	Ultra Wide Band

VHDR	Very High Data Rates
VHF	Very High Frequency
VHO	Vertical HandOver
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WG	Working Group
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless LAN