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Cognitive Architecture and System Solutions to Offload LTE Networks in TVWS

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Abstract: This paper presents an application of cognitive radio system concepts for the off-loading operation of LTE networks by the opportunistic use of TV whitespace (TVWS). A flexible functional architecture based on two cognitive managers for spectrum management and resource management respectively, and developed for various mobile scenarios, is mapped to the LTE network architecture. Corresponding system solutions for incumbent protection and quality of service management (including spectrum sensing, interference monitoring and flexible transceiver techniques) are introduced and described in more details for that scenario. Finally, a possible system realisation is shown with enhancements to evolved node B's and User Equipments accessing the TVWS in an opportunistic way. A timeline for rolling out this realisation taking standardisation plans and regulatory constraints into account is also given.

Keywords: cognitive system architecture, system solutions, spectrum and resource management, LTE, TV whitespace

1. Introduction

Cellular telecommunication systems for mobile services have usually been developed with exclusive long-term spectrum licences for the operators. However, the expected heavy growth of mobile data traffic is very unlikely to be covered by the licensed spectrum available for mobile services. The idea of primary (incumbent) and secondary (opportunistic) spectrum use is well established, but dynamic access on the spot when and where it is needed, is new. Cognitive Radio (CR) systems have been developed to take advantage of dynamic spectrum made available locally in flexible amounts and time slots to solve the conflicts between spectrum demand growth and spectrum under-utilisation. Opportunistic users access in a non-interfering manner some licensed spectrum bands as long as this does not result in harmful interference to the legitimate incumbent users of that licensed spectrum, for which a sufficient level of protection and Quality of Service (QoS) need to be guaranteed.

The operation of CR networks demands flexibility in the design of the system architecture for its application to the various scenarios envisaged. The challenges related to the opportunistic use of resources impose the most important requirements on incumbent protection and QoS management. The cognitive system concept developed in [1, D2.2] is studied in detail to show how it can be applied specifically to the scenario of offloading the LTE network operation by User Equipments (UEs) accessing TV whitespace (TVWS) in an

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opportunistic way. For this, a brief recall of the flexible cognitive functional architecture and the scenarios envisaged is done. Then the detailed mapping of the proposed architecture to the LTE functional network elements is illustrated. Furthermore, system solutions for incumbent protection and QoS management in the LTE offloading scenario are addressed for their execution by the functional entities. A last step is to show a possible system realisation based on this cognitive functional architecture and enhanced LTE network elements taking regulatory constraints into account.

2. Cognitive functional architecture and its mapping onto LTE

2.1 Introduction

The flexible use of TVWS shared spectrum poses additional requirements on the design of future generation mobile communication systems, in order to provide the users with the desired QoS [1, D1.4][2]. Correspondingly, the top level requirements include reliable protection of incumbent users and effective resource management for opportunistic users to meet the required QoS levels. Moreover, developed technologies should be applicable to a range of scenarios, such as those identified in [3]. To cope with the above goals, a system concept has been developed based on a cognitive functional architecture [1, D2.3] capable of responding to the requirements and flexible enough to be mapped to the scenarios considered [4]: cognitive ad hoc network, cognitive femtocell, and cellular extension in the TVWS.

2.2 Overview of the cognitive functional architecture

Concerning incumbent protection, accessing regulatory information through specific use of databases is deemed in most circumstances as a necessity while spectrum sensing may show its usefulness in some cases [5]. The proposed functional architecture addresses both methods and includes therefore besides the regulatory databases (REG) a dedicated Spectrum Sensing (SS) block. Two Cognitive Managers (CM) are in charge of the corresponding duties of Spectrum Management (CM-SM) and Resource Management (CM-RM). They are based on decision-making mechanisms and characterised by longer and shorter time-scales, respectively. The CM-SM controls co-existing players by managing and optimising spectrum PortFolios (PF), whereas the CM-RM achieves effective handling of time-varying spectrum resources, including reserve channels [5]. An Adaptation Layer (AL) serves as the means for cognitive communication and signalling dispatcher between all system entities. These functional blocks are specified to allow a flexible mapping of the architecture across the scenarios [6]; the case of an LTE topology is illustrated in the following section.

2.3 Mapping onto the LTE example scenario

The scenario selected for cellular extension in the TVWS includes rural broadband and LTE network offloading [7]. The mapping of the functional architecture to the latter case, where LTE UEs are using TVWS opportunistically and whose deployment is discussed in chapter 4, is illustrated in Figure 1.

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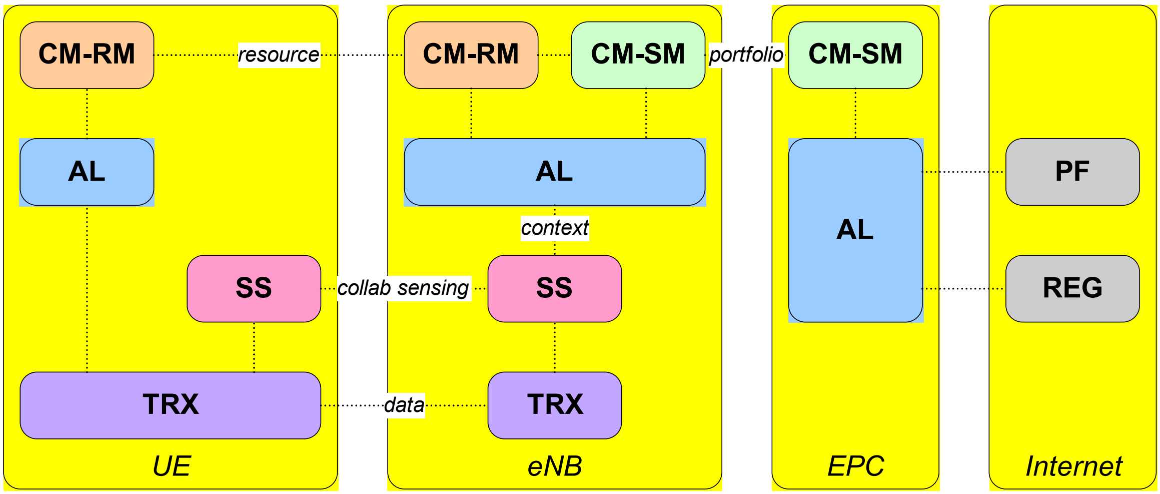

Figure 1: Cognitive functional architecture mapped to the LTE offloading scenario.

A spectrum PortFolio (PF) is built by the CM-SM at the Evolved Packet Core (EPC), accessing all the repositories spectrum and geo-location databases (REG), as required by applicable regulations. A need for a PF may be triggered by the CM-RM at the eNB, which is tracking the network load and the corresponding resource requests from UEs and allocating the resources as usual. PFs are therefore pulled from the CM-RM for deployment to the evolved node B's (eNB), and pulled from the EPC for revocation as needed, e.g. due to changed needs at the CM-RM, at the incumbent side, or due to negotiations. In this way, the TVWS can be accessed by UEs for their data exchange by using their flexible transceivers (TRX). In order to support radio context acquisition, the SS at eNB exploits the SS units at the UEs to realise collaborative sensing, thus exploiting the UEs acting as scattered sensors. In addition for incumbent protection whenever applicable (the SS feature is made available for possible future enhancements, in accordance for example with regulation recommendations), the SS service is used by the CM-SM for PF repository maintenance, thus augmenting the geo-location data for improved calculations. This repository merges all the relevant regulatory constraints with the augmented information, such as the radio context from the SS and the network load and usage reports provided by the CM-RMs within the scope of that PF.

3. System solutions

3.1 Introduction

As introduced above, CR system concepts must meet the two main requirements of incumbent protection and QoS management for the opportunistic use of incumbent spectrum. This section provides an overview of system solutions addressing such requirements in a scenario of LTE cellular extension in TVWS for network offloading. A comprehensive selection of developed solutions can be found in [1, D2.4].

3.2 Solutions for LTE network offloading

Several categories of solutions can help in guaranteeing the protection of incumbent users and their required QoS levels in a TV-LTE coexistence scenario, which include:

- *Spectrum sensing techniques*. SS techniques acquire relevant information on the presence and activity of the incumbent system, based on local and/or collaborative approaches. Various solutions can be used to improve the performance of SS [1, D3.5]. For example, the use of background processes for noise estimation can virtually lead to an ideal noise-free detection performance. The use of advanced methods for devices

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present in TVWS, such as Programme Making and Special Events (PMSE) devices, can lead to an improved detection performance, as well as hybrid detection methods combining the benefits of energy and cyclo-stationary detection for OFDM and PMSE signals. Smart antenna processing techniques can be exploited in cyclo-stationary feature detection on OFDM TV waveforms. Multiple measurements performed by a sensing UE can be exploited by mobility-tolerant methods to provide detection performance gains. Collaborative SS can provide further improvements by selectively deciding which sensing nodes send their sensing reports to the fusion centre (reducing overhead and energy consumption), or discarding reports from malfunctioning or misbehaving UEs based on the credibility score assigned by a reputation system.

- *Interference monitoring*. Interference monitoring is an advanced framework for incumbent protection, which combines SS and geo-location database approaches. Interference monitoring consists of performing measurements at monitoring UEs near an incumbent TV receiver to be protected in order to estimate the Carrier-to-Interference Ratio (CIR) of the incumbent receiver and then compensate for the inaccuracy of the path loss prediction. This enables an optimum transmission power for the opportunistic LTE system and increases the number of TVWS opportunities, [1, D3.5].

- *Transceiver techniques*. Transceiver techniques are designed to minimise the amount of out-of-band radiation of opportunistic signals, thus leading to extremely low Adjacent Channel Leakage Ratio (ACLR) and enabling opportunistic users to exploit TVWS opportunities without causing harmful interference to the incumbent users in adjacent TV channels [1, D4.3]. Out-of-band radiations can be reduced by filtering opportunistic OFDM signals with a smooth windowing scheme (instead of using the conventional rectangular filter, which has a poor ACLR performance). Out-of-band radiations can also be reduced with non-contiguous OFDM transmissions capable of producing deep notches at the channel(s) where an incumbent system is in operation; for instance, Interference Avoidance Transmission by Partitioned Frequency- and Time-Domain Processing (IA-PFT) can achieve a high suppression effect for the entire band of the notch by using a proper combination of time-windowing and cancellation carriers. Another option to improve the ACLR performance is to use modulation techniques with a low out-of-band radiation such as Generalised Frequency Division Multiplexing (GFDM) and Filter Bank Multi Carrier (FBMC).

3.3 Selection of channel, bandwidth and load

When building up a PF for opportunistic operation, the CM-SM needs to account for the consequences on the incumbent system in terms of the resulting interference levels. This requires a careful selection not only of the TV channel(s) (i.e., TVWS) to be accessed opportunistically, but also of the amount of bandwidth reused from the TVWS itself and the amount of LTE traffic offloaded to the TV band. This concept is illustrated in Table 1, which shows the minimum protection distance that allows an opportunistic LTE UE to reuse a TVWS. As suggested by Table 1, appropriate solutions for the dynamic selection of channel, bandwidth and amount of offloaded traffic need to be put into place in order to guarantee interference-free operation while at the same time dealing with mobile UEs and varying LTE traffic loads [1, D6.6]. An optimised access control with cognitive capabilities for an LTE network opportunistically operating in TVWS has been developed to include admission control, scheduling, eviction control and bandwidth adaptation [1, D5.3].

Table 1: Required protection distances from the border of the TV coverage area. The LTE uplink component is considered with three different possible reused TVWS bandwidths (1.4, 5 and 20 MHz). The ratio of users to resource blocks is 1:5 (low load), 1:2 (medium load) and 1:1 (high load) [1, D6.6].

		System Load		
		Low	***Medium***	***High***
TVWS Bandwidth	***1.4 MHz***	10 km	15 km	20 km
	5 MHz	20 km	22 km	25 km
	20 MHz	25 km	30 km	35 km

Besides the protection of incumbent users, opportunistic systems need to provide certain QoS levels to their users. Channel, bandwidth and load selection algorithms play an important role in determining the final user QoS level as illustrated in Table 2; remark: a larger reused TVWS bandwidth for greater number of served users increases the system internal interference [1, D6.6]. Spectrum Management and Resource Management solutions need to be designed bearing in mind these aspects and how they are affected by spectrum mobility, which can force handovers from TVWS opportunities pre-empted by incumbent users. The corresponding design of a CM for the scenario of cellular extension in TVWS scenario, taking into account spectrum mobility, has been addressed in [5]. Optimised QoS provisioning for opportunistic users under spectrum mobility is realised by a decision-making framework for joint admission control, eviction control and bandwidth adaptation to support QoS in opportunistic LTE networks.

Table 2: Average user uplink throughput (same configuration as in Table 1) [1, D6.6].

		System Load		
		Low	***Medium***	***High***
TVWS Bandwidth	***1.4 MHz***	940 kbit/s	320 kbit/s	130 kbit/s
	5 MHz	780 kbit/s	310 kbit/s	120 kbit/s
	20 MHz	770 kbit/s	300 kbit/s	110 kbit/s

4. Realising and deploying system solutions to offload LTE networks

4.1 Overview and deployment assumptions

The considered system enables a cellular operator to utilise the TVWS spectrum in addition to its own licensed spectrum, with the objective to improve the capacity of its network. It is assumed that an ecosystem exists between other actors and that the general conditions for commercial operation and service delivery are present. The main assumptions following this are then:

- System solutions should normally be part of global standards, but in lack of such, available equipment can be considered.
- Regulations allowing opportunistic or shared use of frequencies on a larger scale are endorsed and effective in several markets in order to create a global momentum.
- Network equipment is available off-the-shelf or at least on vendors' roadmaps.

Devices and networks able to operate in both the licensed band and in the TVWS should improve the access to the operator's services, especially during a high-loaded period. It could boost the capacity of a user's connection in case of simultaneous data transfer on both bands. Figure 2 depicts the option of deploying multi-band licensed and TVWS enhanced eNBs for realising this scenario. Other options are co-localised eNBs each for licensed and TVWS operation as well as reconfigurable eNBs.

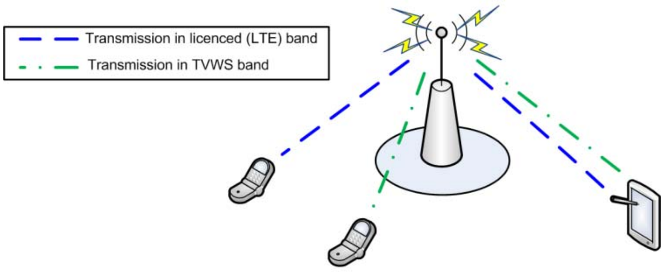

Figure 2: Deployment assumptions for offloading of LTE network.

4.2 QoSMOS system realisation

Figure 3 presents a possible realisation of the cognitive system concept presented in chapter 2 within an LTE network architecture, providing enhanced eNBs operating in both legacy (licensed) and opportunistic (TVWS) bands and serving cognitive UEs. These cognitive eNBs are connected to new network entities in addition to the legacy LTE ones. The Spectrum Manager elaborates the spectrum PF according to the information provided by the global databases (REG) located in the Internet.

Figure 3 also depicts interfaces between the system entities, which are the legacy ones as defined by 3GPP LTE [8] as well as the ones defined by the proposed cognitive system concept [1, D2.3].

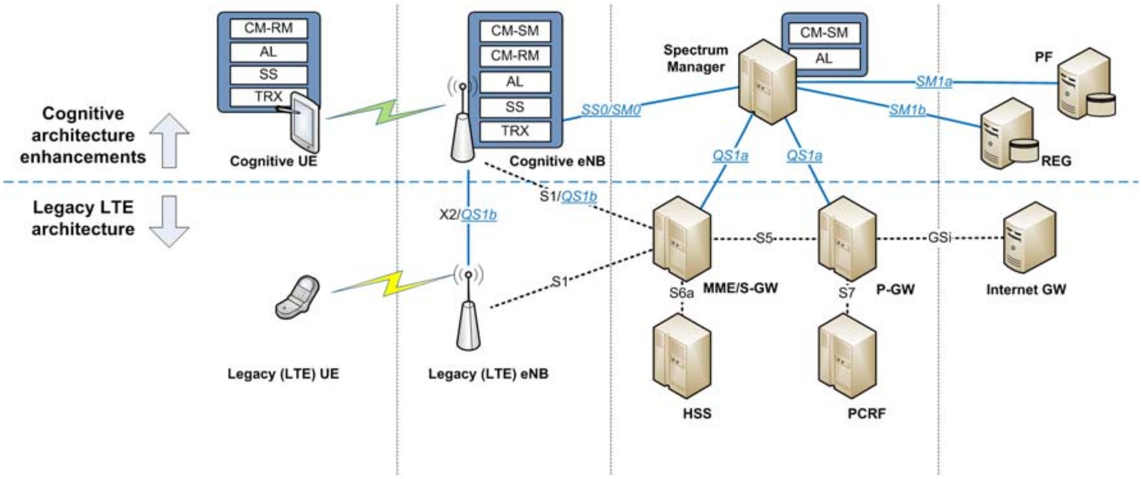

Figure 3: System overview for offloading of LTE.

4.3 Regulatory alignment and constraints

Dynamic and secondary spectrum access can be realised by cognitive radio systems as discussed above. Such a scheme requires a set of new regulatory rules that are being discussed, and some countries have taken actions and have implemented an initial solution allowing cognitive radio in the TV spectrum.

First attempts have been launched in the US with a geo-location database system showing which frequencies are not used at a given location. A mobile operator can then offload data traffic to these frequencies using a cognitive radio system.

In the UK, Ofcom has stated that licence-exempt White Space Devices (WSD) will be allowed and has issued a consultation on requirements for such WSD [9].

The European Commission (EC) has recently issued a mandate to CEN, CENELEC and ETSI to standardise “Reconfigurable Radio Systems” [10]. Their timeline indicates that standards and standardised solutions may be available in 2015.

The regulatory conditions are one of the methods to get access to the frequency through the system of geo-location databases, i.e., identify which frequencies are available via the database system, and then use devices with limitations to the maximum transmit power, location (such as height above terrain), and others. The Federal Communications Commission (FCC) is the forerunner and their requirements on maximum transmit power, Power Spectral Densities (PSD), and adjacent channel limits are summarised in Table 3 for different types of devices [11]. In addition an antenna gain of 6dBi is allowed for fixed devices.

Table 3: FCC limits on power, PSD and adjacent channel power [11].

Type of TV bands device	Power limit (6MHz) [dBm]	PSD limit (100kHz) [dBm]	Adjacent channel limit (100kHz) [dBm]
Fixed	30 (1W)	12.6	–42.8
Personal/portable (adj. channel)	16 (40mW)	–1.4	–56.8
Sensing only	17 (50mW)	–0.4	–55.8
All other personal/portable	20 (100mW)	2.6	–52.8

4.4 Suggested roll-out plan

The time line indicated by the EC in their standardisation mandate (see previous section) suggests that the LTE offloading scenario can be realised in the near future; a possible roll-out plan is proposed hereafter. In order to provide the corresponding services the following must be considered and dealt with:

- Whitespace spectrum resources availability both from regulatory point-of-view and actual amount of whitespaces.
- Geo-location database access must be established.
- Equipment must be available when the operator wishes to roll-out the service based on Whitespace spectrum for both network equipment and user terminals.
- The mobile network operator must inform and promote the new solutions and point both at the improved user experience made available through cognitive solutions and possibly establish some incentives towards the users.

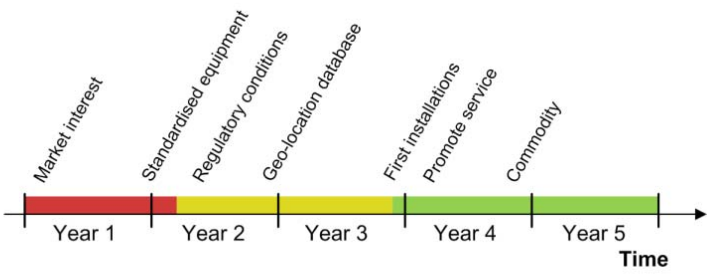

Figure 4: Offloading of LTE networks timeline

A timeline for offloading LTE networks is suggested in Figure 4 showing a four-year period from early concluded market interest in year 1 to an offered service in year 4.

5. Conclusions

In this paper the applicability of a proposed cognitive functional architecture to the LTE offloading scenario has been shown, taking advantage of its modularity for addressing the challenges posed. System solutions for incumbent protection and QoS management, including spectrum sensing, interference monitoring and flexible transceiver operation, have been proposed for this scenario. More specifically, the operating points in terms of protection distance from the TV coverage area have been quantified for different re-used TVWS bandwidths and system loads together with corresponding average user QoS levels. The enhancements needed in LTE network elements like UEs and eNBs have been illustrated by the new cognitive functionalities and interfaces needed as well as the location in the network of repository databases for the spectrum portfolio. From an operator point of view, an example of system realisation for the LTE offloading scenario was given together with an indication for phased rollout according to standardisation plans and regulatory constraints. Future studies should address in more detail other scenarios, (e.g., cellular extension for rural broadband, but also the cognitive ad hoc scenario) in order to illustrate further system realisations of the cognitive architecture presented.

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