Resource Management of Centrally Controlled Cognitive Radio Networks

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Abstract: The realizationof cognitive radio networks is a key solution to meet the raising expectations for high data rates and quality of service in mobile communications. This implies the design of a two-fold cognitive manager for resource management (CM-RM), to manage an opportunistic use of the whitespaces as introduced in this paper, and for Spectrum Management (CM-SM). The proposed CM-RM has been designed to be applicable to all kinds of control topologies (centralised/distributed). This paper presents the study of CM-RM functionalities for several scenarios based on a centralized management of the resources. The scenarios that have been selected are: cognitive ad hoc networks, cognitive femtocells, and cellular extension in TV white spaces. Each of them is introduced, specific mechanisms implemented in the CM-RM are proposed, and performance results are presented for validation purpose.

Keywords: Cognitive radio, resource management, QoS, mobility, ad hoc network, femtocell, cellular extension.

1. Introduction

The raising expectations for high data rates and quality of service (QoS) in the field of mobile communications, due to the increase of the number of subscribers and to the emergence of new usages, motivates the development of new approaches for a more efficient use of the limited radio resources. Among those approaches, there is the identification of spectrum opportunities, or whitespaces, in which cognitive radio networks can be deployed without interfering with the incumbent users.

The main objective of this paper is to present new mechanisms to allow cognitive operations in the whitespaces. Such mechanisms include the protection of the incumbent users, but also the management of the QoS and mobility. These mechanisms are controlled by the cognitive manager for resource management (CM-RM), which is introduced in section 2, using a spectrum portfolio and the related polices that are provided by the cognitive manager for spectrum management (CM-SM), also outlined in section 2, with an access to regulatory information through specific databases. The context information provided by the CM-SM is combined by the CM-RM to the sensing measurements reported by the sensing nodes in the network.

Three selected deployment scenarios, cognitive ad hoc networks, cognitive femtocells, and cellular extension in TV whitespaces, are considered in the sections 3 to 5. In each case, an overview of the scenario is presented, specific resource management mechanisms are detailed, and the study is completed by performance results in sections 3 and 4.

2. Resource management in a cognitive network

A multi-faceted problem such as the control and management of a cognitive network can be approached with a two-fold cognitive manager for spectrum management (CM-SM) and for resource management (CM-RM) [1]. In such a view, the CM-SM is in charge of providing the available spectrum opportunities to the CM-RM which in turn is responsible for their actual allocation and usage. The opportunistic resource management is more involved than the one needed for operation in licensed spectrum or even ISM bands. Resource management in cognitive wireless communication networks demands specific functionalities, such those described in [2].

The CM-SM manages the context information related to the spectrum candidate for opportunistic use, for both protection of incumbent users (sometimes referred to as primary users) and QoS support for opportunistic users (also known as secondary users). To this end, the CM-SM accesses repositories such as regulatory and geolocation databases. Building on that, the CM-SM provides the spectrum portfolio with the spectrum opportunities [1]. The spectrum portfolio is then fetched by the CM-RM. Among the available spectrum opportunities, the so-called active channels, the operating channels used for communication and the reserve channels used for back-up when any operating channel would need to be vacated on appearance of an incumbent, are categorised according to some specific rule (see for example section 3). Supporting the functionalities of CM-SM and CM-RM, a spectrum sensing (SS) entity provides them with radio context information An adaptation layer (AL) provides a means for cognitive information delivery [1] between the system entities. Figure 1a illustrates the main functions of the CM-RM, further described below, in relationship with its surrounding entities, without the overall role of the AL for sake of simplicity.

The required functionalities of such a CM-RM are split [2] according to the topological domains [1] into a resource control (RC) group and a resource usage (RU) group, assigned to the topological networking and terminating domains, respectively. In centrally controlled networks, like those studied in this paper, the RC group of the CM-RM resides at the base station (BS) or access point (AP) or cluster-head/gateway (GW), whereas the RU group of the CM-RM is located at the user equipment (UE). The UE covers the terminating domain as shown in Figure 1b whereas the BS/AP/GW spans over both the networking and the terminating domains.

The RC group includes functions for admission control (AC) and mobility control (MC), with the duties of QoS maintenance and mobility management, where needed. The resource allocation (RA) block at RC is aided by the resource control support (RS) block at RU. Acquisition and processing of cognitive information is also split according to the topological domains into networking domain cognition (NC) and terminating domain cognition (TC). Finally, a resource exploitation (RE) block in the RU establishes a link between the transceiver (TRX) and the upper layers (ULYR).

The cognitive resource management in the three selected centrally controlled scenarios [3, 4] is described in the following sections.

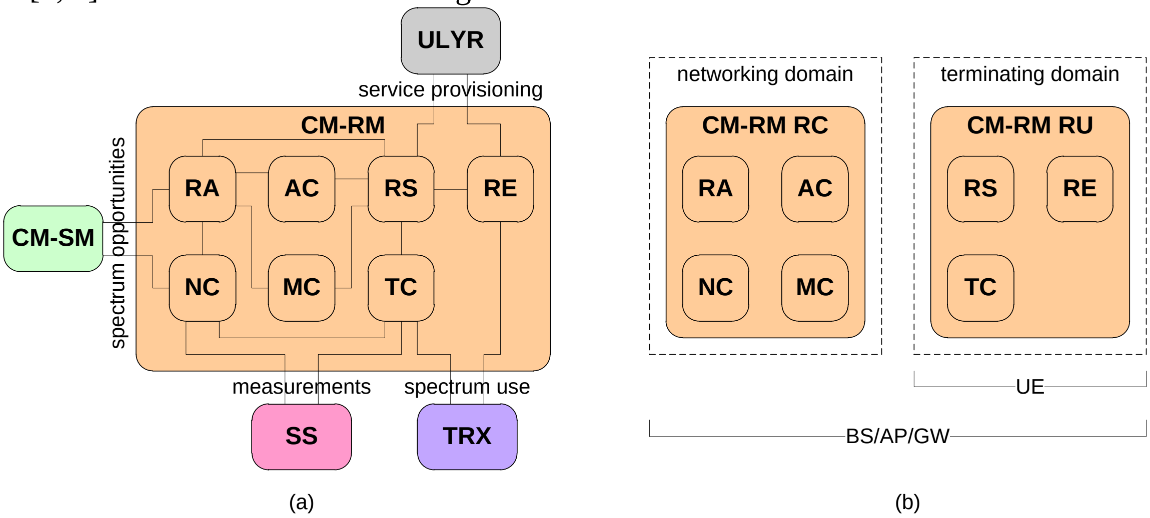

Figure 1: Cognitive manager for resource management (a) and topology mapping (b).

3. Resource management in cognitive ad hoc networks

Cognitive ad hoc networks can be set up by different types of nodes which may be static, nomadic or mobile UEs depending on the use cases envisaged. Their existence is limited in time (like for emergency or big event) and they allow the operating frequency band to be adapted to the specific needs in bandwidth, range and QoS. The scenario considered in this section is based on a star network topology as depicted in Figure 2. In this cluster-based ad hoc network the nodes/UEs are grouped into one cluster with one node/UE having the additional functionality of cluster head. We assume that the management of the resources is centralized and implemented in the cluster head providing routing, resource allocation and power control functionalities whereby communication flows are exchanged directly between the nodes.

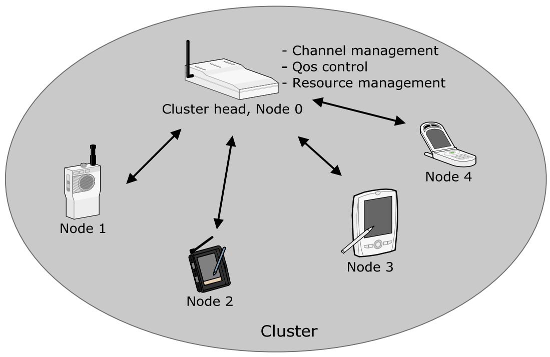

Figure 2: *Cluster based ad hoc network with star topology.*

3.1 – Channel selection algorithm

The role of the proposed channel selection algorithm (CSA) is to provide a list of active channels (see section 2) sorted out from the best (ranked #1) to the worst, the best being taken as the operating channel. The remaining channels are kept to serve as reserve channels in case the operating channel needs to be freed, and are selected in the decreasing quality order. The CSA process is performed at the NC block of the CM-RM using the sensing measurements results that have been configured and transmitted by the TC block (see Figure 3). The detail of the sensing operations, taking place at the corresponding SS entity, is not shown on this figure for sake of simplicity.

A metric that reflects the channel quality needs then to be chosen in order to sort out the active channels. We assume that at a given time in the ad hoc network we have identified all the links that need to be served (called "links in operation" in the sequel) and for each of them the corresponding doublet (data rate demand, priority). The metric we consider here is then the maximum data rate that the cluster can achieve for the set of links in operation, and for the highest priority. This metric allows fulfilling the QoS since the highest priority will be served first and the maximum data rate ensures that the maximum of links in operation will be served.

The first approach to compute the metric is to run the corresponding resource allocation algorithm (RAA) for all the channels. This will guarantee that the order of the channels will be in accordance with the RAA capabilities. The possible issue with this approach is the computation complexity since the RAA is rather demanding, and this method would need to run the RAA as many times as the number of candidate channels.

To overcome the issue of the first approach, we propose to use a more simplistic metric computation that is defined as the weighted sum of the link capacity (over the set of operating links) computed using the Shannon capacity as a function of the Signal-to-Interference-plus-Noise-Ratio (SINR) and is referred to as SLA (Sum Link Approach). The weight applied to each link in the metrics computation is the data rate demand normalized by the total data rate demand. This metric requires little computation effort to the expense of a more simplified modelling that could lead to performance degradation. We present hereafter computational results to evaluate the performance of the SLA compared to the RAA.

3.2 – Performance results

For this paper we have compared both approaches through simulations. The simulation settings are: $N = 10, 20, 30$ nodes in the cluster, Rayleigh fading, a fixed transmit power and a set of seven modulation and coding schemes: BPSK 1/2, BPSK 2/3, QPSK 1/2, QPSK 3/4, QPSK 8/9, QAM-16 3/4 and QAM-16 8/9. The multiple access scheme is OFDMA, where the smallest number of subcarriers that can be allocated per user is equal to 16 among a total of 512. The number of the candidate channels in the spectrum portfolio provided by the CM-SM is 15.

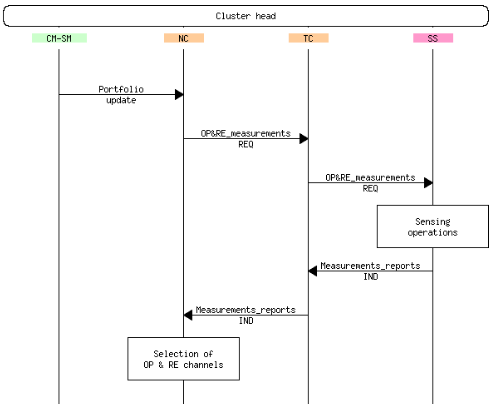

Figure 3: Centralized selection of operating and reserve channels.

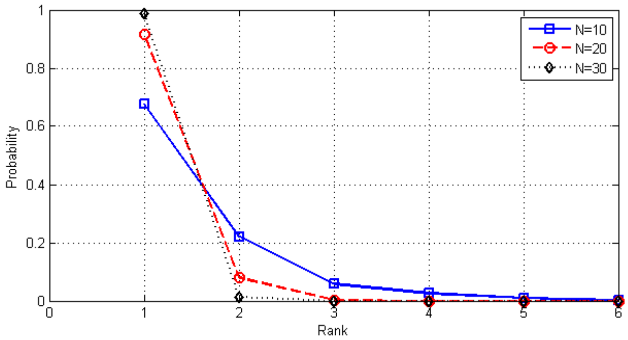

Figure 4: Probability that the k^{th} channel identified by SLA is equal to the operating channel (#1) chosen by the RAA.

Results are reported in Figure *4* which presents the probability that the k^{th} channel identified by the SLA is equal to the operating channel (#1) chosen by the RAA for $N = 10, 20, 30$. We can see that the SLA performs well and that the performance is improved when the number N of nodes increases. The probabilities that the two methods choose the same operating channel are equal to 0.68, 0.92, 0.99 for $N = 10, 20, 30$ respectively. This can be explained by the average effect since the number of operating links increases with the number of nodes. Thus from the simulations we can conclude that, when the number of nodes is large enough (e.g. $N \geq 20$), the SLA can be a good alternative to the RAA by achieving comparable performance at a lower computational cost.

4. Resource management in cognitive femtocells

A cognitive femtocell network comprises two main types of network elements: the base stations or access points (the "femtocells") with gateway and access control functionalities and the mobile UEs. The femtocells are LTE or Wi-Fi based and connected to a core network via a fixed infrastructure. They build "hot spots" where user mobility is in principle rather low but demands on QoS and throughput are high. Providing QoS to the mobile users in a cognitive femtocell is challenged by the random deployment and the dynamic topology of the femtocells, since interference protection has to be ensured for the macrocell incumbent users and a cognitive femtocell must vacate a spectrum portion when needed by incumbent users. The scenario, depicted in Figure 5, is realized by a centralised topology for resource allocation allowing adaptive interference control and coverage.

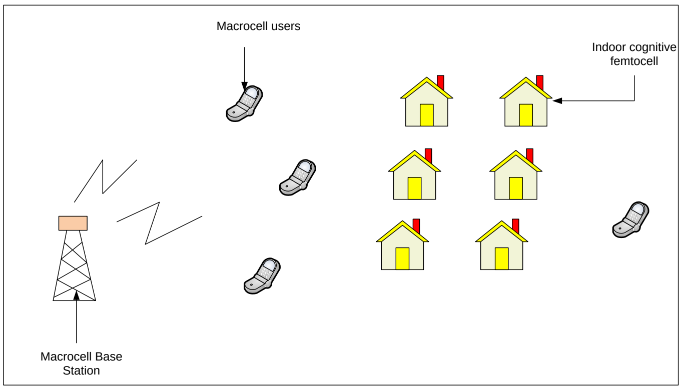

Figure 5: Cognitive femtocells within a macrocell.

4.1 – Algorithm description

In such a scenario as described above, with large number of femtocells, it is very difficult to guarantee a level of QoS for the cognitive femtocell user terminals (FUTs). This implies the need to develop advanced cognitive femtocell resource allocation schemes (implemented in the CM-RM) under QoS needs of the cognitive FUTs, available resources and regulatory constraints (fetched from the CM-SM). The aim of the CM-RM is to allocate resources efficiently to the cognitive FUTs and avoid any harmful interference to nearby incumbent macrocell users as well as in neighbouring femtocells. This task is performed by first analysing the available resources (based on the information received from the CM-SM) and then sorting them into two categories. As shown in Figure 6, initially each femtocell access point (FAP) allocates resources to its users randomly and after a certain period, the FUTs report back any interference faced and the path loss in the downlink. Once the FAP receives this feedback from its users, it updates the CM-SM about the resources they are using. In addition, it will also request any information about its neighbouring femtocells over the infrastructure about the spectrum resources used by the neighbours as well as the interference measurements of those resources. The FAPs can partially cooperate with their neighbours through an X2 interface as documented in 3GPP [5].

After getting knowledge about their surrounding environment including sensing measurements, the FAPs populate two tables A and B. Table A lists the resources that are considered as interference free w.r.t. to specific rules and thus can be used at maximum power, while the table B contains the shared/restricted resources used with lower power according to a dedicated power control algorithm. The purpose of categorising the resources is to ease the allocation process for the CM-RM if interference free resources are available. Further, in case table A contains no entry the CM-RM allocates resources from table B. This means, the resources should be used in such a way that no interference is caused to the macrocell user or neighbouring FUTs, whoever is using the same resource at that moment.

4.2 – Simulation results

For the scenario selected as shown in Figure 5, it is assumed that the FUT requires at least one channel to satisfy its QoS needs. The incumbent macrocell system is supposed to have 5 MHz of total bandwidth, which is divided into 25 chunks, equal for simplicity. At any given instant of time, 20 incumbent users are active in the macrocell area and occupying 20 resource blocks or channels. At the same time, 10 femtocells each having one FUT are also active. The indoor femtocells in this scenario are femtocells within each residence of a colony. The simulations are carried out with the femtocells having a transmit power of 20 dBm, while the macro base station having a transmit power of 50 dBm.

If the resources are randomly allocated to the FUTs, they might face interference from the incumbent macrocell system as well as neighbouring femtocells, resulting in poor SINR values at the FUTs. Two path loss models are used in this case, where (1) is the indoor path loss model recommended by 3GPP [6] and (2) is a simplistic outdoor to indoor path loss model [7]:

$$PL_{in} = 16.9\log_{10}(d) + 32.8 + 20\log_{10}(f_c) \quad (1)$$

$$PL_{inout} = 15.3 + 37.6\log_{10}(d) + n\Phi \quad (2)$$

where d is the distance (in meters) between the transmitter and receiver, n is the number of walls, Φ is the wall penetration loss and f_c the frequency band (in GHZ).

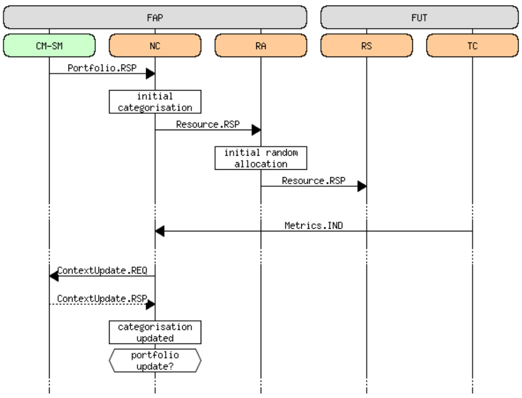

Figure 6: Resource allocation in cognitive femtocell.

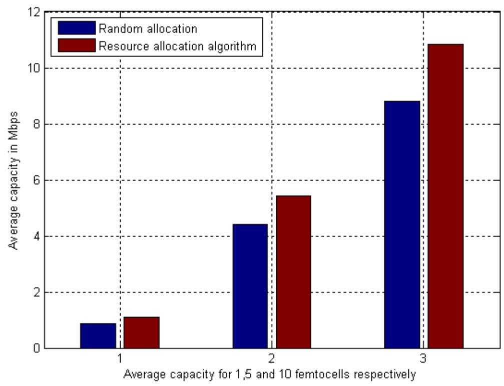

Figure 7: Comparison of resource allocation algorithms.

The simulation results (Figure 7) show that the proposed algorithm for resource allocation can provide higher capacity compared to a random resource allocation scheme. It should be noted that the improvement is even seen in the case of smaller number of femtocells, each containing one user and occupying only one channel. The overall average capacity is increased even if femtocells would not always get table A resources. This is due to the selection of best quality resources available so that the cognitive femtocell can transmit with higher power and achieve higher SINR and capacity.

5. Resource management for cellular extension in whitespaces

Cellular-based mobile networks may use free portions of radio spectrum (whitespaces) in addition to their own licensed spectrum in order to increase their operational bandwidth. An example of such a scenario is given by the LTE cellular extension in the TV whitespace (TVWS) spectrum band. One mobile network operates in its own licensed bands and, whenever available for opportunistic access, in the TVWS spectrum additionally as depicted in Figure 8. Another mobile network may also access the TVWS spectrum in opportunistic way so that in some areas both mobile networks are sharing the TVWS spectrum.

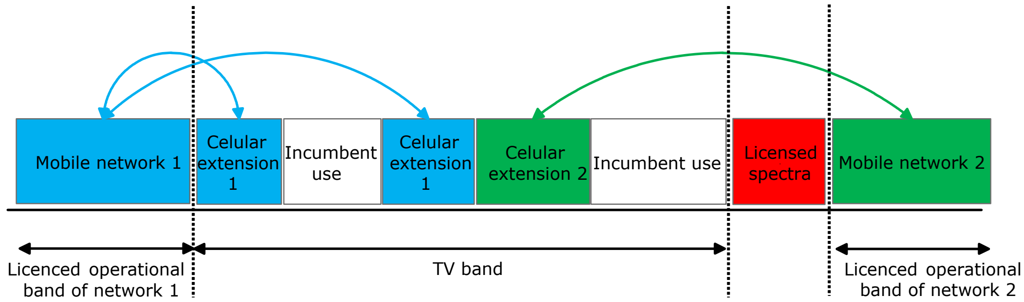

Figure 8: Cellular extension in TVWS.

5.1 – QoS and mobility functional designs

In the scenario described above there are certain QoS and mobility functions to comply with by the CM-RM, beginning with the sensing measurements scheduling, used to identify the possible gaps occurred during transmission, where the sensing measurements can be done efficiently. This measure is needed as long as the identification of channels is mandatory for adapting UE slots to the most effective band. In addition, the channels within the portfolio provided by CM-SM must be prioritized, as seen also in the scenario described in section 3.1. These priorities can be refined through the use of local policies and information based on sensing measurements results. This way, QoS slots are identified in order to be assigned to different users.

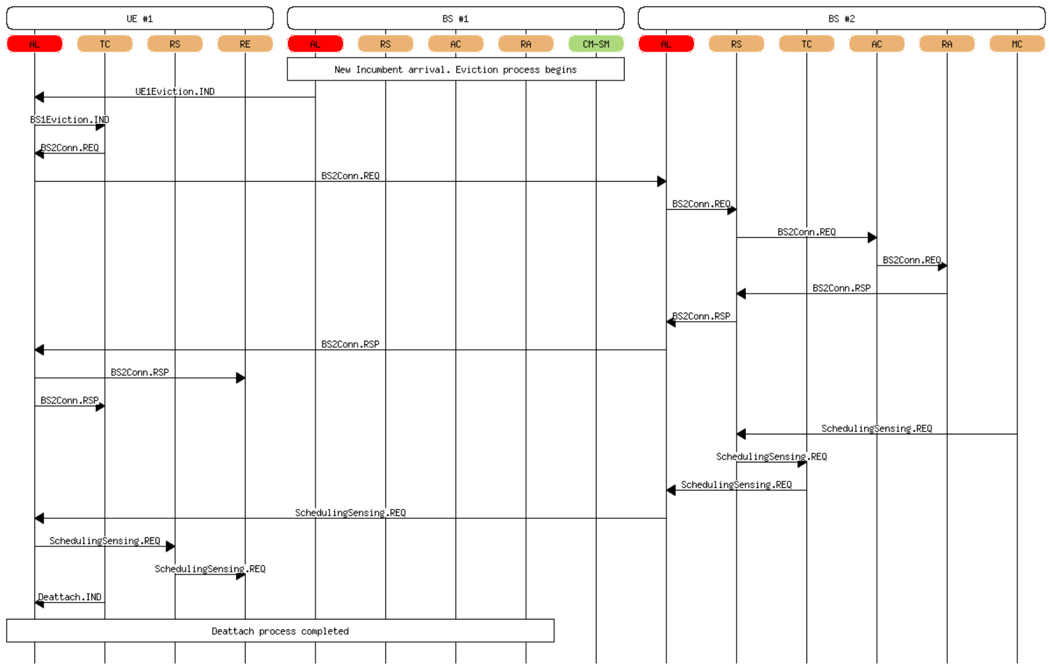

Figure 9: Handover scenario scheduling sensing measurements.

As for the selection of channels, a decision-making mechanism needs to be present in the CM-RM, permitting to choose the operating channels from the set of active ones, leaving the rest of them as reserve ones. Finally, a gathering of context information is made, which provides the means for reacting to changes in the environment.

Regarding the main activities that can be carried out by the CM-RM, one of the most outstanding ones refers to the spectrum mobility, which offers the capability to force the handover of static or mobile users to another access point that operates in a different channel than the one pre-empted by the incumbent user. This could be a neighbour cell operating in a reserve channel or another radio access technology present in the user vicinity.

In addition, through some other functions in the CM-RM, it is possible to evaluate performance-related metrics for all active channels, providing information to the CM-SM about them as needed by the portfolio. Finally, through the handover parameter optimization procedure, the best values for the different parameters that enable the proper management of the QoS level provided to the UEs are selected.

This last functionality is best presented in the message sequence chart (Figure 9), where the UE #1 makes a handover between BS#1 and BS#2 and this new access point is required to schedule some sensing measurements, trying to provide the user all the resources it could need to carry on the activities it is interested in.

6. Conclusions

The focus of this paper is on the design of new mechanisms to manage efficiently the use of the resources in the context of an opportunistic access to whitespaces. To perform these cognitive operations, the concept of a two-fold cognitive manager for resource management and spectrum management is introduced, with specifically the two objectives of incumbent protection and QoS and mobility support for the resource manager.

A study of resource management mechanisms is then conducted for three scenarios of centrally controlled cognitive radio networks. A particular emphasis is made on the classification of the active channels in the case of cognitive ad hoc networks in order to determine the operating channel. Performance results show the good performance of the proposed algorithm compared to the resource allocator of reference. The management of the available resources by cognitive femtocells is also investigated, based on a classification of the channels which are either shared or used with restrictions in terms of power, or interference free. The algorithm proposed in this context shows that it achieves higher capacity than a random resource allocation scheme. In the third scenario of cellular extension in TV whitespaces, QoS and mobility functionalities are presented. In particular they include the scheduling of sensing measurements to optimize the handover process.

Acknowledgments

The research leading to these results was derived from the European Community’s Seventh Framework Programme (FP7) under Grant Agreement number 248454 (QoSMOS).

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