Resource Management for QoS support in Cognitive Radio Networks

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Abstract - Cognitive radio technology is a key enabler to reuse a finite, scarce and expensive resource: the radio spectrum. Guaranteeing required levels of Quality of Service (QoS) to cognitive users and ensuring necessary protection to incumbent users are the two main challenges in opportunistic spectrum access. This article identifies the main requirements and challenges for QoS support in cognitive radio networks. A framework for a two-fold cognitive manager is presented; one part managing spectrum availability on longer timescales and the other handling resource management on shorter timescales. This article gives particular focus to the functionalities of the latter cognitive manager related with resource management. Finally, we present a few key scenarios and describe how QoS can be managed with the proposed approach without disturbing the communications of incumbent users.

Introduction

Recently, there is a tremendous growth in the number of mobile broadband subscribers; posing opportunities as well as challenges to the cellular operators all over the world [1]. Further, data usage per mobile subscriber is expected to increase significantly in the coming years; this is mainly due to the attractive incentives from the service providers e.g. flat-rate tariffs in conjunction with the proliferation of large screen smart devices and video/bulky traffic. Radio spectrum is used in all wireless communications. The inefficient use of this finite resource necessitates the development of opportunistic spectrum access mechanisms in which cognitive radios can access licensed spectrum without harming the operation of the incumbent users (incumbent users may also be referred to as primary users or licensed users). These spectrum access opportunities are commonly referred to as "whitespaces" (WS).

The TV band is a prime example of a spectrum band that is currently being considered to allow for cognitive radios to access licensed spectrum. The digital switch over of TV broadcasting services is already finished in major parts of European countries and is planned to be finalized in 2012 almost all over Europe (including UK)[1]. In the case of TV whitespaces (TVWS), the incumbent users are the TV broadcasters and, in some countries, other devices such as wireless microphones (Programme Making and Special Events – PMSE – equipment is an example of these

other devices). In the USA, the FCC has already published rules to allow for the use of TVWS [2]. It is expected that other regulators, particularly in Europe like, e.g., Ofcom started in UK [3], will soon publish their own set of rules for their own regions. The TV band exists in the UHF spectrum band which, due to its low frequency, has very good propagation characteristics. This makes TV whitespaces particularly well suited to certain scenarios such as cognitive ad-hoc networks, coverage extension in cellular bands etc. Several standards are already defined for the use of TV whitespaces such as IEEE 802.22 [4] and ECMA-392 [5], while others are due to be completed soon like IEEE 802.11af [6] and the ETSI RRS technical report [7].

Among other challenges [1], it is important to ensure that opportunistic use of spectrum by cognitive radios does not contribute towards the potential service degradation of the incumbent users (e.g., TV broadcasting services). At the same time, it is a natural requirement for any network and service provider to provide end-to-end QoS to its own users and this should be true with cognitive radio networks. This is a challenging task as, in this case, the radio resources are shared and can be sporadic in nature.

Providing good QoS and user experience at the right price is a key to the commercial success of cognitive radio networks. For instance, investigations conducted for collaborative cognitive radio resource management algorithms in [8] were based on QoS metrics together with network statistics in order to show the benefits expected for the overall system performance.

To cope with the peculiar challenges described in the following section (Figure 1), the parts of the proposed two-fold cognitive manager described later in this article (Figure 3) address the relative duties. In this article, we describe how a cognitive radio network may be controlled by the cognitive manager (CM) for spectrum management (CM-SM) and resource management (CM-RM) with a particular focus on the cognitive resource management part (Figure 4) which handles all the operations related to resource control and usage. The CM-RM also plays an important role in incumbent protection which will be described in detail.

The rest of this article is organized as follows. we first discuss the QoS requirements and major challenges in cognitive radio networks. Then, we describe our proposed approach to tackle challenges identified in the previous section. Finally, we detail the applications of our solution approach in a few selected scenarios and then conclude the article.

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[1] The switch over is completed in Austria, Belgium, Czech Republic, Croatia, Denmark, Estonia, Finland, France, Germany,. Latvia, Netherlands, Norway, Slovenia, Spain, Sweden and Switzerland. It is planned to be completed during 2012 in Hungary, Ireland, Italy, Lithuania, Portugal, Slovakia and UK. Poland, Ukraine and Russia will catch up by 2013, 2014 and 2015, respectively. (Source: www.digitag.org.)
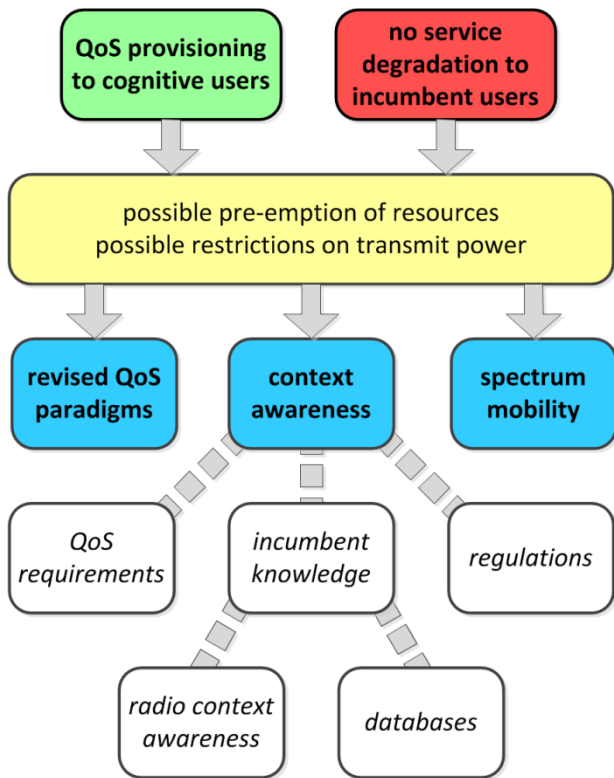
Figure 1 *Constraints about QoS provision and incumbent protection, and high-level requirements for cognitive radio networks*

QoS Challenges and Requirements in Cognitive Radio Networks

The deployment of cognitive radio technology raises new challenges to manage the radio resources while the protection of the incumbents must be addressed as a matter of priority. Incumbent users should not be faced with service degradation due to interference caused by the presence of cognitive radios, and this puts limitations on the provision of cognitive services. Available whitespaces may not necessarily offer the bandwidth needed to provide a given service for the cognitive users and the protection of incumbent users from interference restricts the service level offered so that the required QoS has to be optimized.

Figure 1 summarizes the derivation from the constraints of challenges and high-level requirements as far as QoS is concerned. A cognitive radio network which makes use of whitespaces faces the extra challenge that its users are opportunistic users, and there are incumbent applications which are non-cognitive and may unexpectedly take control of spectral resources. When an incumbent starts using (or it is close to do so) any particular channels the use of these channels by cognitive radios will be terminated abruptly, imposing a very serious challenge for providing QoS guarantees: the cognitive user must vacate the resource and the service needs to be promptly handed over to another available spectrum portion (spectrum mobility).

Some key requirements from [9] accounting for both the QoS and resource management for cognitive radios and the protection of incumbents are presented in Table 1. These requirements imply the need to develop advanced cognitive mechanisms using knowledge of the relevant regulatory constraints, of the available resources and of the QoS needs of the cognitive radios. In particular, this includes the knowledge about the appearance of an incumbent user which can be *a priori* or *a posteriori* [10], i.e.,

achieved by using geo-location/geographical databases or spectrum sensing, respectively. These two methods of information gathering (spectrum environment awareness) can be used in an integrated way, to exploit the benefit of each (as discussed in the 10th meeting of the CEPT SE43 working group in July 2011 [11]), or alternatively, depending on the regulatory rules.

QoS for cognitive users	The required level of QoS should be maintained in presence of variations in the available spectrum resources.
	The quality level of radio environment awareness shall depend on the QoS requirements.
	The reserve channels for use when an incumbent is detected shall be identified according to QoS needs.
	The admission control shall depend on the QoS requirements and on the channel capacity of the available resources.
	Efficient allocation of the opportunistic resources shall fulfill the QoS needs inside given bounds specific to the scenario.
Incumbent protection	Cognitive networks shall have the capability to evict users upon resource shortage, for example due to incumbent user apparition.
	Cognitive networks shall schedule quiet periods for spectrum sensing purpose, when required, without degrading the QoS of the cognitive users.
	Cognitive networks shall vacate their operating channel upon appearance of an incumbent user, or use a transmit power allowing simultaneous operations.
	The transmission of information related to the presence of an incumbent shall have priority over data transmission.

Table 1 *Key requirements for QoS and resource management, and for incumbent protection in cognitive radio networks*

How Can QoS Be Controlled?

To fully appreciate the challenge of providing end-to-end QoS in a cognitive radio network, it is important to be aware of the wide range of actors involved. End users, not worried about how services are provided, request an acceptable QoS level. Content providers offer applications with different delivery requirements through service providers, who acquire connectivity and capacity from network operators. A spectrum database owner provides extra spectrum environment awareness information to cognitive radios. The amount of available resources has a huge impact on the levels of QoS that can be provided. Service Level Agreements (SLA) set the service levels that will be supplied and fix the penalties when the parameters agreed are not fulfilled. Figure 2 depicts the relationship among the actors and their agreements in the end-to-end QoS chain.
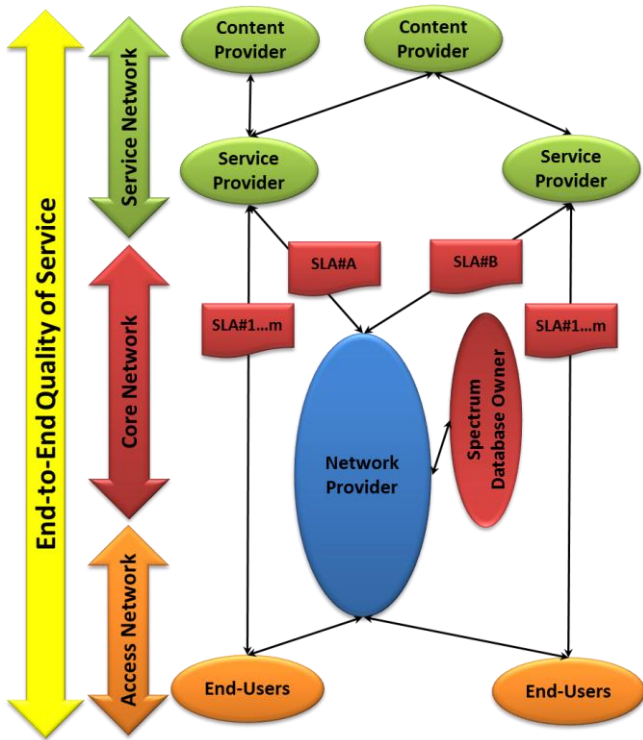
Figure 2 Configuration including multiple service providers

The key novelty introduced in this architecture, designed for optimizing QoS management mechanisms in cognitive radio systems, is the presence of a two-fold cognitive manager. This QoS management proposal acts at various levels; on the one hand, the CM-SM identifies the available spectrum and builds a spectrum portfolio that operates on a larger time scale. On the other hand, the CM-RM makes maximum use of the existing resources and divides them efficiently among users, operating on a shorter time scale. Use of the spectrum will become more efficient if local decisions focus on what spectrum to occupy for a particular service at a particular time. If a mix of distributed triggers (e.g. from the user terminals) and centralised ones (e.g. from the network) can be used in a cognitive decision making process, cost savings will be achieved through massive reuse of spectrum resources.
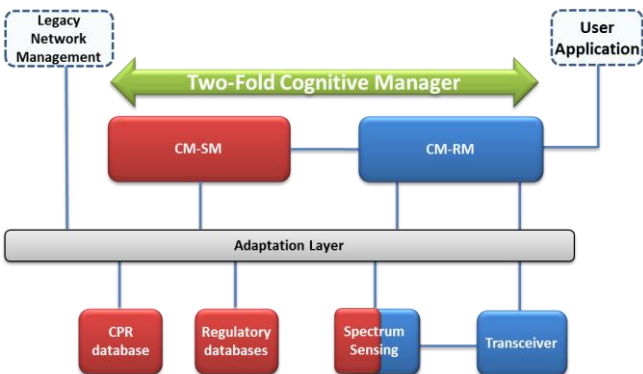

Figure 3 Overall System Architecture

Figure 3 depicts the proposed architecture. It contains, besides the CM-RM and CM-SM, two main databases storing information about spectrum usage and regulatory constraints, a block for spectrum sensing, a transceiver focused on physical layer interactions and an adaptation layer in charge of facilitating information exchange among the different blocks.

In order to provide reliable links, the CM-SM attempts to keep as much usable spectrum identified as possible. The CM-RM will then distribute this broad range of resources among cognitive radios, and maintain open channels on as many frequencies as possible, some only as backup. The CM-RM keeps a list of operating channels and backup channels allowing users to carry on with their transmissions without a temporary halt, in the case that some channels become unavailable. However, the CM-RM has to cope with any decreases in available bandwidth. Due to this, conventional radio networks handovers may decrease QoS; however, our proposal performs a completely seamless handover mechanism exploiting diverse resources in the most efficient manner.

There are many options, based on the chosen network topology, for how the functional entities of this proposed architecture can be mapped to system elements [12] [13]. For centralised topologies, the CM-SM functionality will be placed in access points/base stations and also, if present in the topology, partly in the core network. In distributed topologies, the CM-SM also has to be present in user equipment so that each CM-RM can receive necessary portfolio information. As described in the following, in all kinds of topologies the CM-RM will be present in controllers (e.g. access points/base stations) and user equipment so that resources can be exploited in both the downlink and uplink.

To achieve its goals, the CM-RM is organized into two functional groups in charge of the respective duties at the terminating and networking domains [12] and correspondingly involved in resource usage (RU) and resource control (RC) (see Figure 4).
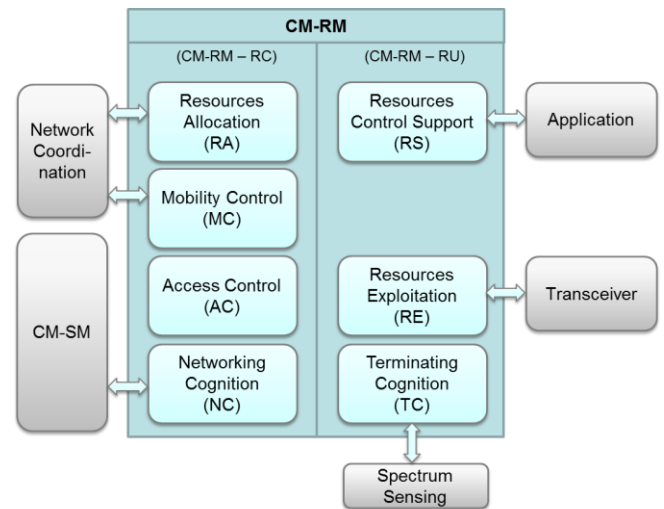

Figure 4 CM-RM overview

There are three functional entities within RU; the first of these is the terminating domain cognition (TC). This controls the gathering of information on the environment in the terminating domain. This information can aid in mobility support and also for the configuration and collecting of sensing measurements. The second entity within RU is resource exploitation (RE). This provides the data service to upper layers and optimizes the use of lower layers. The lower layer optimizations include mapping logical channels to physical channels and configuring the transceiver. The final entity in RU is resource control support (RS), which is in charge of supporting at terminating domain the resource management done at the networking domain. This

includes such things as the configuration of the transceiver through the RE and executing decisions made by the TC.

The first of the four functional entities within the RC is resource allocation (RA) which assigns resources based on current QoS constraints and information from the CM-SM. This also includes the reallocation of resources when an incumbent appears. The access control (AC) entity will gather context information to make admission decisions for service requests. This will also be involved in handover decisions. The networking domain cognition (NC) entity gathers environmental information relevant to the networking domain. This includes spectrum portfolios from the CM-SM and collecting measurement of performance and sensing from active and backup channels (sensing only in backup channels). Finally, the mobility control (MC) entity provides mobility support and execution of mobility management. This is for both spectrum mobility and physical mobility.

The mapping of RU and RC entity groups to network devices in done accordingly to the presence of centralised or distributed resource control [12]. With centralised resource control, as in an ad hoc network with star topology or a cellular access network, the RC is located at the gateway device or the base station, respectively. With distributed resource control, the RC is present in any peer device. The RU is needed in any device having a radio interface and is therefore present in user equipments, base station and peer devices in the above examples. Those examples are further illustrated and discussed in the following section.

QoS Management in Selected Scenarios

An important functionality of the CM-RM is to make sure that incumbents and cognitive radios QoS are satisfied simultaneously during the opportunistic spectrum access. In order to demonstrate the applicability of mechanisms discussed in this article, in this section we discuss a few applications of cognitive networks and illustrate how QoS is maintained in these scenarios.

Cognitive Ad-hoc Scenario

In this scenario, cognitive radios at a particular location (e.g. home, office, shopping centre etc.) setup an ad-hoc network to efficiently communicate with each other. Such an ad-hoc network may be created to fulfil simple tasks like file sharing to more complex tasks like providing access to Internet (e.g. relaying other terminals in the ad-hoc network). Cognitive ad-hoc networks are typically limited in space and time and opportunistically access whitespaces for communications.

Depending on the scenario and application, a cognitive ad-hoc network can be created for example with a star or mesh topology. In star topology, there is a master node that is responsible for all resource management related functions. In this case, the CM-SM block within the master node establishes a connection to the spectrum databases in order to get environment awareness as well as comply with regulatory needs. In cases when the regulatory regime does not require the use of a database, the incumbent protection constraints translate into stricter requirements on spectrum sensing (for environment cognition). The CM-RM of the master node manages resources within the cognitive ad-hoc network locally.
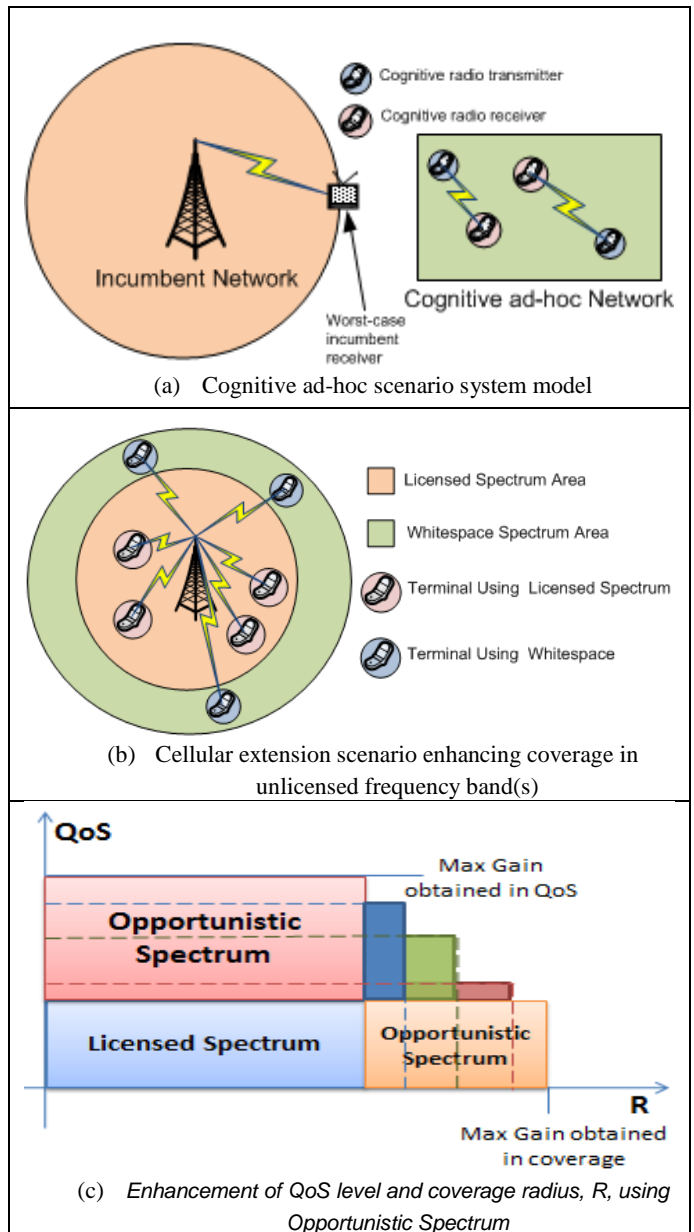

(a)   Cognitive ad-hoc scenario system model

(b)   Cellular extension scenario enhancing coverage in unlicensed frequency band(s)

(c)   *Enhancement of QoS level and coverage radius, R, using Opportunistic Spectrum*

Figure 5 *Examples of QoS Management for Cognitive Radio Systems*

In a cognitive ad-hoc network with a mesh topology, there is no master node and hence distributed operation of cognitive radios is required. In this case, cognitive radios are autonomous[2] and to fulfil tight QoS constraints for cognitive radios as well as incumbent protection is a challenging task. As an example, a system model for sharing TV whitespaces by a cognitive ad-hoc network is shown in Figure 5a.

To demonstrate the efficacy of the concepts presented in this article, we assume the worst-case location of a TV receiver (incumbent) by arguing that if the worst-case user is protected then all the incumbent receivers within the coverage area of the incumbent transmitter are also protected. In this setting, the CM-RM of each cognitive radio fetches portfolio information from the CM-SM and initiates a sensing phase. All cognitive users perform

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[2] The ad hoc network considered here is autonomous in that it does not rely on external entities for its control. However, in compliance with regulations, it may need to exchange information with external entities through a CM-SM, even if this connection is not continuously needed.

spectrum sensing to estimate their distance from the worst case incumbent receiver. Based on the estimated distance from the incumbent receiver (for details refer to [14]), cognitive users initiate Distributed Power Control (DPC) algorithms to simultaneously guarantee QoS requirements for their respective receivers, but also to avoid harmful interference to the incumbent. QoS requirements for incumbents and cognitive radios can be stated in terms of tolerable interference at incumbents and signal to noise-plus-interference thresholds at cognitive radios [14]. Simulation results and details of distributed algorithms are detailed in [14] demonstrating that the QoS of incumbent users is always protected.

Cellular Extension in Whitespace

This scenario aims at cellular networks utilizing whitespace spectrum in addition to their own licensed spectrum, thus gaining additional bandwidths to benefit the user. This is shown in Figure 5b.

The use of the WS spectrum must be shared among the different mobile operators. The information provided by the CM-SM will be exploited in the most effective way by the CM-RM. The main advantages derived from the use of the whitespaces lie on two main aspects (Figure 5c):

- Enhanced coverage area. Addressing long range requirements by using low frequency whitespaces such as TV whitespaces.
- Enhanced capacity. Fulfilling short range requirements.

Depending on the QoS required by the different services offered to the users, the configuration of each connection will be modified according to the needs and availability. This process carried out by both cognitive managers takes into consideration not only the availability of spectrum but also the services contracted by the different users.

Thus, the CM-RM may take the advantages of both licensed and unlicensed spectrum characteristics to optimize the utilization of available radio resources. As it is not possible to entirely guarantee the QoS by an exclusive access to the whitespace spectrum, the CM-RM may, for example, assign these opportunistic resources to low priority services while reserving the licenced band to high priority services, such as, emergency communications. Another example is where cognitive managers, deployed in networks supporting spectrum aggregation, may use the available radio resources in a more flexible way, mapping signalling logical channels onto the licensed band (in order to guarantee user connection, even upon incumbent apparition) and mapping user data logical channels onto the whitespace band. In this context, CM-RM implements key enabling decision-making mechanisms for supporting user QoS while protecting incumbent operations.

One illustration of these protection measures is the spectrum mobility which consists in forcing a cognitive user to handoff from its initial cell to a neighbour or co-located cell operating in a channel other than the one pre-empted by the incumbent. This contributes to release the relevant radio resources in the impacted cell and to limit the QoS degradation of the served connections. In parallel, the cognitive manager adapts its admission control decisions for supporting this unexpected increase of handover demands, in order to prevent degrading the dropping probability in the neighbour cells as well as the blocking probability in the impacted cell.

The features of this scenario are beneficial for the operators, obtaining extra operational bandwidth resulting from load balancing, improving link quality, and offering more flexible services, thus enhancing user experience.

Conclusions

Cognitive radio networks, accessing licensed spectrum on an opportunistic basis, can vastly improve the efficient use of the radio spectrum. This benefit can help to support the rapidly growing demand for high-rate and multimedia-rich traffic in wireless networks. This paper explains that for this benefit to be realised, a cognitive radio network must employ advanced QoS mechanisms for its opportunistic users whilst ensuring, at all times, that incumbent users of spectrum are protected.

This paper highlights some of the main challenges facing cognitive radio networks and describes a two-fold cognitive manager that can allow for these challenges to be resolved, ensuring QoS and incumbent protection at the same time. Particular attention is paid to the resource management aspects of the cognitive manager which provides resources to opportunistic users over short time scales. Selected scenarios have been described to demonstrate how this cognitive manager can provide various QoS mechanisms. These scenarios, cognitive ad-hoc networks and cellular extension in whitespaces, act as just a small flavour of the vast range of potential scenarios for cognitive radios that could thrive in the future.

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Acknowledgements

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