Cognitive Resource Management for QoS Support in Mobile Opportunistic Communications

Geneviève MANGE[1], Christophe ROSIK[2], Stéphanie LEVEIL[3],
Ulrico CELENTANO[4], Olasunkanmi DUROWOJU[5], Kamran ARSHAD[5]

[1]*Alcatel-Lucent Bell Laboratories, Lorenzstrasse 10, Stuttgart, 70435, Germany*
Tel: +49711821-41407, Fax: -32185, Email: genevieve.mange@alcatel-lucent.com

[2]*NEC Technologies (UK) Ltd, 10, rue Godefroy, Puteaux, 92821, France*
Tel: +33155688200, Fax: +33155688210, Email: christophe.rosik@nectech.fr

[3]*Thales Communications, 160, boulevard de Valmy, Colombes, 92704, France*
Tel: +33146132371, Fax: +3314613255, Email: stephanie.leveil@fr.thalesgroup.com

[4]*CWC University of Oulu, 4STOCWCTS, P.O. Box 4500, Oulu, 90014, Finland*
Tel: +35885532865, Fax: +35885532845, Email: ulrico.celentano@ee.oulu.fi

[5]*CCSR University of Surrey, Stag Hill Campus, Guildford, GU2 7XH, United Kingdom*
Tel: +3588553286, Fax: +35885532845, Email: {o.durowoju, k.arshad}@surrey.ac.uk

Abstract:

Optimizing the Quality of Service (QoS) support, providing seamless mobility and ensuring the protection of incumbent users are some of the challenges that arise when the radio spectrum is accessed in an opportunistic way. The functional concept of Cognitive Resource Manager (CRM) is presented providing cognition of the environment to optimize the allocation and exploitation of radio resources, to improve the access to these resources and to ensure mobility control in the opportunistic system. Requirements for the functional architecture of the CRM are identified and addressed by defining building blocks to manage cognitive access and mobility control as well as resource allocation and usage. These functional entities are described together with their interfaces inside the CRM and with other opportunistic system entities like the Spectrum Manager. Particular decision-making cases for resource control and usage are presented by means of message sequence flows taking the overall cognitive and opportunistic context into account. Finally selected algorithms for distributed power control that implement parts of the functionalities of the CRM while considering specific QoS constraints and protection of incumbent users are discussed. Results of simulations conducted for these algorithms in a dedicated scenario illustrate the performance achieved by this concept.

Keywords: Cognitive Resource Manager, decision-making, distributed algorithms, functional requirements, functional architecture, mobility, opportunistic environment, quality of service.

1. Introduction

The overall objectives of the work presented in this paper are to develop specific cognitive mechanisms [1] at the radio access level to improve the opportunistic use of under-utilised radio spectrum while ensuring the support of managed Quality of Service (QoS) and seamless mobility. Corresponding challenges are identified with regard to potential service degradation for the incumbent users as well as optimal service provision to the opportunistic users. To meet the challenges at the radio access level the concept of Cognitive Resource Manager (CRM) is proposed together with a set of requirements identified to model its detailed functional architecture. The internal entities are described with their interfaces within and outside the CRM while indicating where the requirements are addressed in the architecture. Resource control and usage for the cellular network scenario is illustrated, detailing the operations executed for this purpose by the CRM in the opportunistic system environment. Finally algorithms that implement specific functionalities of the CRM including transmit power control are discussed for a dedicated ad-hoc scenario and evaluated by means of simulation results.

2. Challenges in CRM design

The opportunistic use of shared spectrum poses challenges on the QoS support for the users to be served. Incumbent users should not be faced with service degradation due to interference caused by the presence of opportunistic users, and this puts limitations on the provision of opportunistic services. Available whitespaces may not necessarily offer the bandwidth needed to provide a given service for the opportunistic user and the protection of incumbent users from interferences restricts the service level offered so that the required QoS has to be optimized [2]. These aspects will be addressed in detail in the next sections 5 and 6.

The whitespaces used for opportunistic communications may be pre-empted upon appearance of incumbent users. Then the opportunistic user must vacate the resources and the service needs to be promptly handed over to another available spectrum portion; this is referred to as *spectrum mobility*. This may occur in addition to possible mobility management procedures dealing with the *physical mobility* of the served user.

Furthermore the actual context based upon spectrum availability, its usage, the interference situation and the user location, varies with time. This means that the optimisation of the actual QoS level experienced by the served users needs up-to-date access to context information which increases the system complexity.

To cope with the challenges described above a Cognitive Resource Manager is proposed besides the Spectrum Manager function. The main duty of the CRM is the provision of data service to the upper application layers in accordance with the service requirements, using the available spectrum opportunities and obeying existing rules. The context information gathered in the spectrum portfolio in a cognitive manner is provided to the CRM by the Spectrum Manager which also condenses constraints from regulations and policies. While these CRM functionalities mainly concern the resource control operations, during resource usage the CRM has also the important function of incumbent protection. The requirements to be fulfilled by the CRM will be described in more details in the next section.

3. Functional requirements

The challenges that have been discussed in the previous section imply to guarantee the level of QoS that is required by the user services and to manage the impact of spectrum or physical mobility. This translates into a set of functional requirements for QoS support and for mobility management that are presented in Table 1 and in Table 2 respectively. These requirements shall be addressed by the CRM introduced in the previous section together with the system entities the CRM is in relation with; this will be shown in the next sections.

Table 1 Requirements for QoS support

R01	The required QoS level for a given communication should be maintained in presence of variations in the available spectrum resources.

R02	The quality level of radio environment awareness shall depend on the QoS requirements.
R03	The determination of the appropriate number of reserve channels shall be based on the QoS needs.
R04	Opportunistic systems shall have the capability of scheduling quiet periods for spectrum sensing purpose – if required - without degrading the QoS of the opportunistic users below a given bound specified for the different deployment scenarios.
R05	Opportunistic systems shall have the capability to vacate their operating channel upon appearance of an incumbent user, and to switch to a free channel unless a proper level of transmit power allowing simultaneous operations can be applied.
R06	The transmission of information related to the presence of an incumbent (like e.g. sensing results) shall have priority over data transmission.
R07	The admission control shall depend on the QoS requirements and on the channel capacity provided by the available resources.
R08	Opportunistic systems shall have the capability to evict users upon resource shortage, for example due to incumbent user apparition.
R09	Efficient allocation of opportunistic resources shall fulfil the QoS needs inside given bounds specified for the different deployment scenarios.
R10	Opportunistic systems shall define a limitation on their transmit power in order to avoid interfering with simultaneous incumbent transmissions when these operations are authorised by regulations and policies .
R11	Opportunistic systems shall be able to gather or to exploit information (e.g. by means of cooperative sensing) on the environment in order to react to any change in it.

Table 2 Requirements for management of spectrum and physical mobility

R12	In corresponding scenarios like e.g. cellular based, opportunistic systems shall support handover to ensure seamless connectivity when the mobile terminal is moving across the system coverage areas (physical mobility).
R13	In corresponding scenarios like e.g. cellular based, opportunistic systems shall have after incumbent detection the capability to force handover (spectrum mobility).
R14	Opportunistic systems shall provide or exploit timely context information to ensure a quick vacation of a mobile terminal from a channel which starts to be used by incumbent users.
R15	Upon detection of incumbent users, an opportunistic terminal shall suspend its periodic idle-mode reporting to the network.

In the following section, a detailed functional architecture is proposed for the CRM in order to fulfil QoS and mobility requirements.

4. CRM architecture

In order to define the decision-making processes needed to manage the QoS and to support the mobility in the cognitive radio networks, logical functionalities have been derived from the previous requirements, thus defining the functional entities of the CRM architecture.

Figure 1 presents these different building blocks and depicts how they address the requirements and the challenges previously explained.

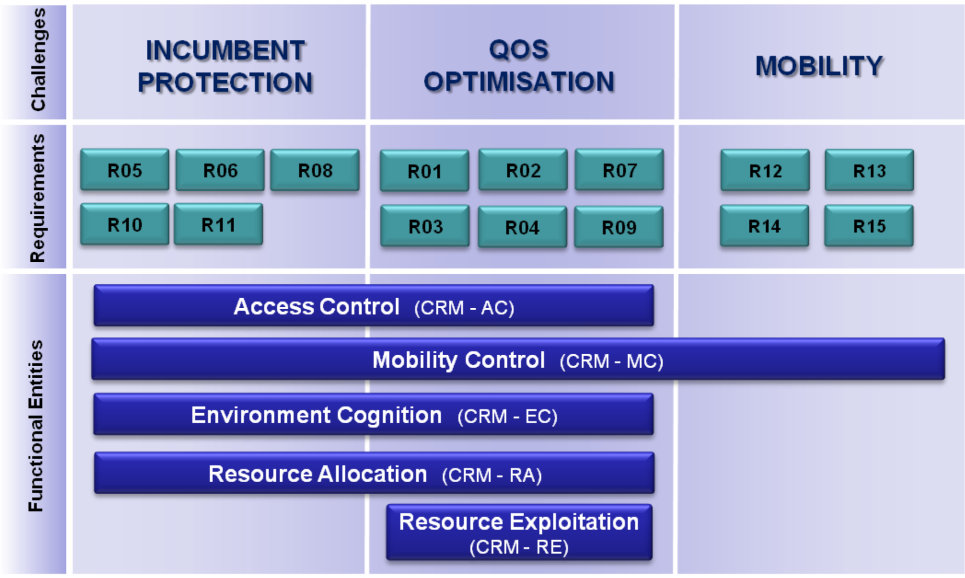


Figure 1 Challenges, requirements and functional entities, encountered in the CRM

The Environment Cognition entity (CRM EC) gathers cognitive information to quickly react to any changes in the system environment. It configures the spectrum sensing measurements if required, and prompts any new event, like the appearance of an incumbent user.

The Resource Allocation entity (CRM RA) assigns resources to users based on QoS constraints and spectrum portfolio information. It schedules when necessary the spectrum sensing measurements and provides reports on spectrum portfolio usage and performance. Upon appearance of an incumbent user, it may reallocate the resources assigned to the opportunistic user in a spectrum resource that has not been pre-empted.

The Resource Exploitation entity (CRM RE) provides service to application layers by exploiting the allocated radio resources for data transmission. It is then charged to optimize the radio link by configuring the protocols layers (MAC and PHY) depending on the signal quality and other cross-layer QoS parameters.

The Access Control entity (CRM AC) maintains the QoS of already served users by accepting or rejecting new users' connections depending on the network capacity and the requested QoS level. It also overcomes disruption periods of the opportunistic system (apparition of incumbent users, interferences with other opportunistic networks, reduction of radio resources, etc) by deciding to trigger other entities for minimizing QoS disruptive measures (drop selected users, move users in other spectrum bands, in other radio technologies …).

Finally, the Mobility Control entity (CRM MC) configures the physical measurements for supporting users' mobility and executes this mobility management depending on the measurements results or the occurrence of cognitive events (e.g. incumbents' appearance). This entity ensures the control of both user physical and spectrum mobility.

In order to address different kinds of scenarios for opportunistic systems where the CRM architecture is involved in these functional entities are organised in two groups: the ones dedicated to the Resource Control (RC) and those reflecting the Resource Usage (RU) by the opportunistic users. It should be noted that some CRM entities may be parts of these two groups as involved in both use and control of resources. The internal and external interfaces to the CRM are described in a more detailed way in Figure 2. How the functional entities of the CRM can be mapped to network elements will be shown for a specific scenario in section 5.

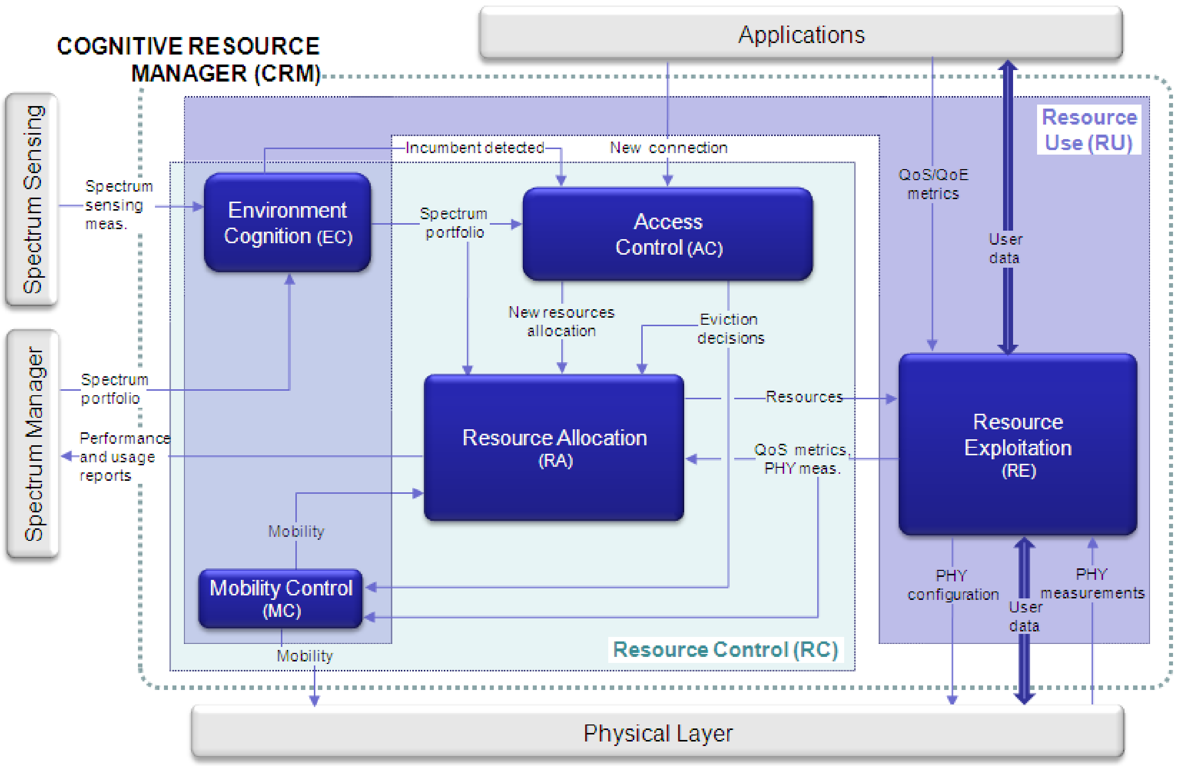


Figure 2 Detailed functional architecture of the CRM

An application example of this architecture will be shown in section 6 where in a specific scenario Distributed Power Control algorithms implemented mostly in the CM-RU entities provide extra resources for opportunistic users whilst constraining the interference to nearby incumbent users at unperturbed levels.

5. Resource control and usage

As outlined before, the CRM functional entities need to fulfil both service requirements of the opportunistic user and the constraints coming from regulations to ensure protection of the incumbent at the same time. For the cellular network scenario considered in this section, the CRM functional entities are mapped as follows to the network elements: CRM-RC and CRM-RU to the Base Station (BS) and CRM-RU to the Mobile Terminal (MT). Figure 3 illustrates the execution of operations and the exchange of messages performed performed by these entities. In this example, local spectrum sensing (SS) is assumed for simplicity; this means that spectrum sensing measurement from a single node is used to generate a decision about the presence of incumbent. Detailed requirements as defined in section 3 are also pointed out in the following when they are addressed.

First of all, in order to access whitespaces, the CRM needs the corresponding context information, which is gathered with the help of the Cognitive Spectrum Manager (CSM) entity at BS side into the spectrum portfolio, which consists of regulatory policies, constraints set by the incumbent system, etc. The context needs to be maintained in order to always contain valid information (R11, R14). As a service request initiated by the application (APPL) reaches the CRM-RC in the BS, through the CRM-RU at MT side, its admission is evaluated. If this phase is passed, the spectrum portfolio is searched to find a suitable resource for the service (R07, R09). If such a resource is found, it is allocated and the portfolio information is updated. Upon allocation of the resource and before its actual exploitation for data transmission, the CRM-RU configures the MT transceiver. These operations include the definition of a transmit power level (R10). Example methods of Distributed Power Control are proposed for a dedicated scenario in the next section.

During the exploitation of the whitespace, the absence in it of the incumbent must be ensured. To this end, spectrum sensing is performed periodically (R02, R04, R11). In case the resource is pre-empted, this is signalled to the CRM-RC (R06, R13) also to request another resource to be possibly allocated (R01, R08), or the service is dropped (R05). The CRM-RC may alternatively assign a resource outside the whitespaces (e.g., a licensed resource).

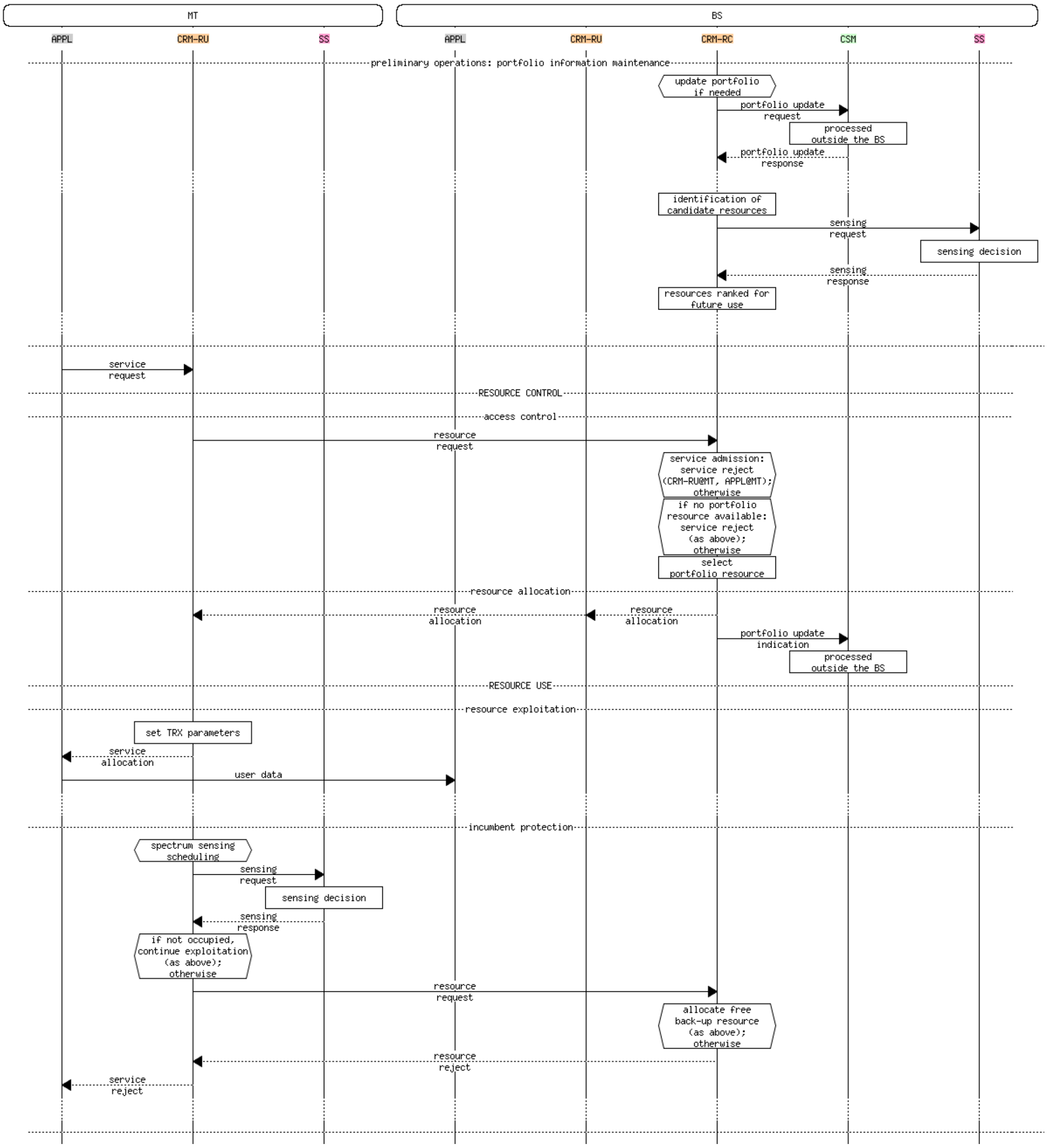


Figure 3 Resource allocation and incumbent protection

6. Distributed Power Control Algorithms for opportunistic users

As mentioned in the previous sections one of the most important functions of the CRM is the protection of incumbent users during opportunistic spectrum access. In this section this is addressed from the perspective of transmit power control for the opportunistic users. We consider the scenario of an ad-hoc Cognitive Radio Network (CRN) sharing opportunistically whitespaces with incumbent TV receivers (TVR) as shown in **Error! Reference source not found.**-a therefore focusing on the distributed operation mode of the CRM-RU functionalities. For the implementation Distributed Power Control algorithms with Incumbent Protection via Spectrum Sensing (DPC-IPSS) [5] are proposed that have the ability to satisfy tight QoS constraints for the opportunistic access.

Two general cases are envisaged: First a worse case (WC) in which the DPC-IPSS algorithms provide protection of the TVR at the edge of coverage area; see Figure 4-a. Then a non-worse case (NWC) in which the TVR location is unknown and for which a stochastic DPC-IPSS algorithm is proposed which allows the CRN to access the available capacity when the TVRs are not in total outage whilst maintaining the interference levels of nearby users still unperturbed.

The following Quality of Service (QoS) constraints are implemented:

1. Interference Event (I_E) probalistic measure of Interference Threshold Level (ITL) ξ_{th} at the worst case incumbent TV receiver during primary operation (see **Error! Reference source not found.**-a).
2. Signal to Interference plus Noise Ratio (SINR) for the CR user: QoS within the CRN can be maintained if SINR ($\gamma_{cr,i}$) for the i^{th} CR user is greater than a predefined SINR threshold (γ_{cr}^{th}).

I_E can then be expressed as a function of joint probabilities:

$$I_E = P(P_r \geq P_{nl}) \cap P(I_{cr} \leq \xi_{th}) \qquad (1)$$

where P_r is the power received at TVR derived from the TV transmit power P_{tv} as $P_r=P_{tv}\, g(r_{nl})\, X_p$ and P_{nl} is the threshold power at the coverage edge beyond which TV signal becomes un-decodable (≈-72dBm). I_{cr} is the aggregate interference contribution at the TVRs due to the CRs and is modelled as $I_{cr}=\Sigma p_i\, g(d_i)\, X_c$. $g(x) = x^{-\alpha}$ is a generalised channel gain for distance "x" where α is the propagation exponent subscripted as α_p for the primary TV network and $\alpha_{,c}$ for the CRN; X_p and X_c represent the shadow fading parameters.

In order to ensure the afore mentioned QoS requirements (R02, R04, R07 and R09) the CRM-RU distributed over the CRs gathers spectrum sensing information and estimates probability of detection (P_d) from a given probability of false alarm [3].

For the worse case an iterative algorithm [4] estimates the distance from individual CRs to the TVR (**Error! Reference source not found.**-a), for details please refer to [5]. In a first approach the sensing algorithm was formulated for a Rayleigh fading channel to provide tight bounds in the sensing measurements; co-operation between the nodes in the CRN could increase the integrity of sensing results in order to avoid the hidden node problem. Once the distance to the TVR is estimated according to [3] and the numbers of CRs (N) are known, the DPC algorithms can be modified by formulating a new bound $p_{i,wc}$ on the transmit power which takes incumbent protection into account as:

$$p_{i,wc} = \frac{\xi_{th}\; g^{-1}(f^{-1}(P_{d,i}) - r_{nl})}{N} \quad i \in \{1, 2, ...N\} \qquad (2)$$

For the non-worse case, the first term of equation **Error! Reference source not found.**) which defines the TVR outage probability information I_{out} can be expressed as in **Error! Reference source not found.**), where the Q function is the right tail probability of a standard Gaussian random variable:

$$I_{out} = 1 - P(P_r \geq P_{nl}) = 1 - Q\left(\frac{P_{nl} - P_{tv} + 10\log\left(f^{-1}\left(1 - P_{m,i}\right)\right)^{\alpha_p}}{\sigma_p}\right) \qquad (3)$$

where $P_{m,i}$ is the probability of missed detection estimated by i^{th} CR and σ_p the variance of shadowing for the TV signal. Accordingly, the second term of **Error! Reference source not found.**) can be expressed as:

$$P(I_{cr} \leq \xi_{th}) = 1 - Q\left(\frac{\xi_{th} - N - p_{i,nwc} - 10\log g\left(f^{-1}(1 - P_{m,i}) - r_{nl}\right)}{\sigma_c}\right) \qquad (4)$$

where $p_{i,nwc}$ represents the new power constraint in the non-worse case and σ_c is the variance of shadowing for the CR. Since the two probabilities of equation (1) occur independently of each other, the problem can be solved in a joint probability sense. Based on equations **Error! Reference source not found.**) and **Error! Reference source not found.**) and the TVR outage information I_{out} , $p_{i,nwc}$ can be established as:

$$p_{i,nwc} = \sigma_c Q^{-1}\left(1 - \frac{I_E}{1 - I_{out}}\right) + \xi_{th} - N - 10\log g\left(f^{-1}(1 - P_{m,i}) - r_{nl}\right) \qquad (5)$$

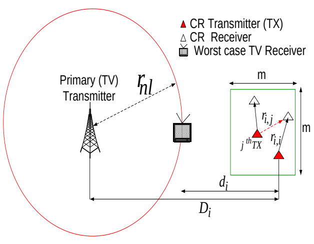
It can be easily seen that when $I_{out} \geq 0.9$, $p_{i,nwc}$ **Error! Reference source not found.**) reduces to $p_{i,wc}$ **Error! Reference source not found.**). This new power control strategy allows the CRN to access some extra capacity even in situations where the TVRs are not in total outage.

The proposed DPC-IPSS algorithms can be then derived as follows:

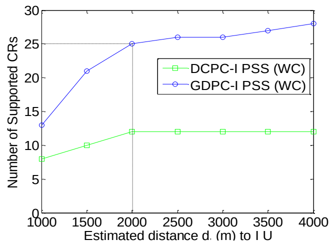
1. Distributed Constraint Power Control with IPSS (DCPC-IPSS): this algorithm implements spectrum sensing to estimate CR distance to the incumbent receiver.
   The iterative power process is written as:
   $$p_i(k+1) = \min\left\{\frac{\gamma_{cr}^{th}}{\gamma_{cr,i}^{k}} p_i, p_{i,wc}, p_{i,nwc}, P_{\max}\right\}, \ i \in \{1, 2, ..., N\}, k = 1, 2, ... \qquad (6)$$
   where k denotes the number of power control iterations before reaching a steady state. When the CRs are sufficiently far from the incumbent TV system, equation **Error! Reference source not found.**) tend to increase making {pi,wc, pi,nwc}≥Pmax hence **Error! Reference source not found.**) ensures that the CR never exceeds its maximum available terminal power.
2. Generalized DPC with IPSS (GDPC-IPSS): this algorithm has the ability to support an increased number of CRs compared to the previous one (see **Error! Reference source not found.**-b and -d) with far reduced interference environment since the CRs which do not meet the SINR threshold in every iteration are notched out, thereby increasing the transmission opportunities for other CRs to fulfil the QoS objective.
   The power updating rule in this case is:
   $$p_i(k+1) = \begin{cases} \frac{\gamma_{cr}^{th}}{\gamma_{cr,i}^{k}} p_i(t), & if \ \frac{\gamma_{cr}^{th}}{\gamma_{cr,i}^{k}} p_i(t) \leq \min\left\{p_{i,wc}, p_{i,nwc}, P_{\max}\right\} \\ \hat{P}_i \quad , & if \ \frac{\gamma_{cr}^{th}}{\gamma_{cr,i}^{k}} p_i(t) > \min\left\{p_{i,wc}, p_{i,nwc}, P_{\max}\right\} \end{cases} \quad i \in \{1, 2, ..., N\}, k = 1, 2, ... \qquad (7)$$
   where $\hat{P}_i$ is an arbitrary low power value.

Error! Reference source not found.-c shows that with the proposed method, the interference environment of the worst case TVR remains unperturbed at all times, while QoS is also fulfilled within the CRN as illustrated in **Error! Reference source not found.**-b. The result here is not optimal in terms of the achievable capacity of the CRN; as seen when the stochastic power algorithm comes into picture, it can be seen from **Error!**

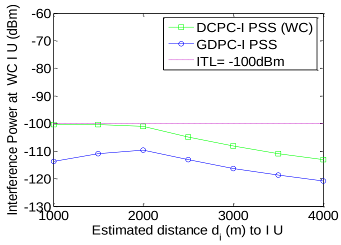
Reference source not found.-d that some amount of CRs can still be supported depending on the incumbent outage probability without degrading the interference limit at nearby TVRs as shown in **Error! Reference source not found.**-e. Therefore the incumbent TV spectrum could be re-used owing to spatial opportunity.



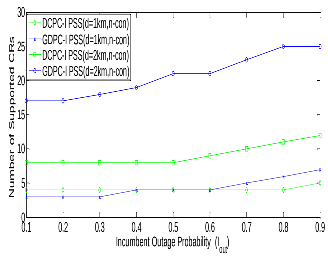
4-a: System Model



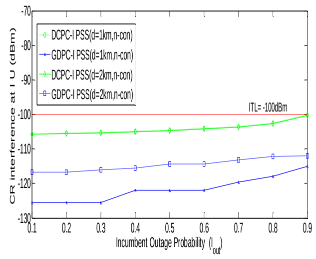
4-b: SINR QoS fulfilled (WC)



4-c: ITL fulfilled(WC)



4-d: SINR QoS fulfilled (NWC)



4-e: ITL fulfilled (NWC)

Figure 4 Simulation results for Distributed Power Control algorithms

7. Conclusions

The focus of this paper is on the opportunistic use of shared spectrum by mobile users. In order to address the challenges that are posed in this context at the radio access level, we present the concept of Cognitive Radio Manager (CRM). The specification of this CRM is driven by specific challenges related to the support of QoS and mobility. The related requirements that are identified for that purpose are addressed by the definition of specific functional building blocks of the CRM that contribute to the elaboration of its architecture. The mechanisms that are established to manage these requirements and the algorithms implementing some of them show the pertinence of the architectural choices that have been made. First simulations results are presented to assess the performance of these algorithms. Subsequent research work on the CRM will include further studies on specific functionalities and operations in different network topologies as well as their evaluation by means of simulations.

Acknowledgments

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