Project acronym:	**SACRA**
Project title:	Spectrum and Energy Efficiency through multi-band Cognitive Radio
Project number:	European Commission – 249060
Call identifier:	FP7-ICT-2007-1.1
Start date of project:	01/01/2010 **Duration:** 36 months

Document reference number:	**D3.4**
Document title:	Cooperative and Cognitive RRM components and architecture for the SACRA scenarios
Version:	1.0
Due date of document:	Month M32 (31/08/2012)
Actual submission date:	19/11/2012
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Project co-funded by the European Commission within the 7th Framework Programme		
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PU	Public	**X**
PCA	Public with confidential annex	
CO	Confidential, only for members of the consortium (including Commission Services)	

EXECUTIVE SUMMARY

WP3 of the FP7 EU-funded SACRA project provides the cognitive part of the SACRA system on one hand and the networking system of the cognitive radio resource management on the other. The first contribution includes the specification and implementation of rules, policies, models that the radio resource management should comply to. The latter incorporates all the sensing control and information management functionalities. These two contributions facilitate the SACRA project to implement its main objective, the provision of a real time demonstrator integrating the RF front end components, digital base band processing, embedded software and algorithms on a flexible radio platform.

This document entitled "Cooperative and Cognitive RRM components and architecture for the SACRA scenarios" intends to provide a description of the incorporation of the mechanisms developed in terms of WP3 to the SACRA scenarios (i.e., Spectrum Aggregation, Cognitive Relays, and Home Broadband Access). Furthermore, the LTE-Advanced system architecture for all the scenarios is being provided. This is enabled by the WP3 mechanisms' description and the corresponding mapping in the SACRA functional architecture, also provided in this document. The joint assessment, the provision of additional results and the enhancement of the WP3 mechanisms are also provided in this document which concludes the work performed in terms of this WP.

More specifically, D3.4 provides a short description of all mechanisms and their extensions (e.g., policies, learning capabilities etc.) in order to facilitate the mapping of each mechanism to the SACRA functional architecture; thus enabling the provision of the full WP3 functional architecture. Then, using as input the scenarios from WP1, the LTE-Advanced system architecture is provided; the actual outcome of such procedure is the provision of the location of each mechanism in the LTE-A and the identification of each functionality in the scenarios under discussion. Finally, the document provides a set of enhancements, including the joint assessment extension of the developed mechanisms. In details, the joint assessment of the Spectrum Access Control and of the Cooperative Power Control is provided – the former for the identification of the cognitive users to operate in TVWS and the latter for the identification of the optimum power levels for mitigating interference. Regarding the further advancements, the user and flow partitioning algorithm is being extended and new aspects are being identified; the mathematical formulation of the new aspects is being described in details.

This document is the final in terms of WP3 and concludes its activities by providing the consolidated version of the proposed solutions and a link between WP3 and WP1 (i.e., functional architecture and system architecture having as basis the WP1 scenarios). Thus, D3.4, using as reference the previous work (reported in D3.1, D3.2, and D3.3), suggests the document that actually reports on the addressing of the purpose of WP3 which is the development of the mechanisms and policy schemes as well as the models the radio resource management should comply with, in terms of SACRA.

CONTENTS

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

WP3 intends to design the high level cognitive part as well as the network system needed for cognitive radio resource management and coordination of the SACRA system. Thus it is divided in four sub-workpackages that provide all the required mechanisms for efficient management of resources (WP3.1), for incorporation of sensing control, rules, policies and learning mechanisms (WP3.2), identification of the required communication paths (WP3.3), and extraction of behavioural models (WP3.4). The WP3 mechanisms have been linked to SACRA scenarios (using detailed storylines) and the SACRA functional architecture [8]. Such linking has facilitated the provision of the overall WP3 functional architecture on one hand and the LTE-A system architecture on the other hand for all three scenarios considered in SACRA (i.e. Spectrum Aggregation, Cognitive Relays, Broadband Access Around Home) .

Furthermore, D3.4, given the fact that it is the final document to be delivered by WP3, using inputs by all WP3 sub-workpackages provides the final version of the WP3 mechanisms including additional results for the proposed solutions. The joint assessment of mechanisms developed in terms of WP3 is also included in this document.

The rest of D3.4 is structured as follows:

- Section 2 provides the description of RRM components and their mapping to the functional Architecture.
- Section 3 provides storylines of all three SACRA scenarios and the corresponding LTE-A system architectures.
- Section 4 contains additions in the RRM components and the joint assessment of the secondary access control and the cooperative power control algorithms.
- Section 5 concludes the document.

1.2 DOCUMENT VERSIONS SHEET

Version	Date	Description, modifications, authors
0.1	28/06/2012	Agreed ToC provided
0.2	26/07/2012	UoA provided contribution regarding Cooperative Power Control in section 2 and regarding Spectrum Aggregation scenarios in section 3.
0.3	1/9/2012	IT provided the User and Flow partitioning mechanism description.
0.4	28/9/2012	NTUK provided the description of the sensing control and configuration.
0.5	11/10/2012	UoA, IT, EURE provided additions in the description of their mechanisms and the storylines of the Home Broadband Access, and Cognitive Relays scenarios.
0.6	19/10/2012	Clean version, harmonization of the contributions, and incorporation of executive summary, introduction, and conclusion (UoA).

2 DESCRIPTION OF RRM COMPONENTS AND MAPPING TO THE FUNCTIONAL ARCHITECTURE

WP3 has developed all the mechanisms (components) related to the management of the available radio resources. More specifically, the Cooperative Power Control, the Sensing Configuration and Control, the User and Flow Partitioning and the Spectrum Access Control facilitate the RRM system to operate efficiently and manage the available resource to meet the user requirements.

In the following sections, the aforementioned mechanisms are being briefly described (the thorough description of these algorithms is being provided in [1][2][3]) and are being mapped to the SACRA functional architecture as it is defined in D1.1b [8]. Furthermore, the overall WP3 functional architecture is being provided in the concluding sub-section of Section 2. Thus, the extraction of the system architecture performed in Section 3 is plausible.

2.1 COOPERATIVE POWER CONTROL ALGORITHM

2.1.1 Cooperative Power Control algorithm description

The main scope of the Cooperative Power Control algorithm is to mitigate interference among User Equipments (UEs) acting as cognitive users in opportunistic spectrum bands [1][2][3]. For this reason, each transmitter computes its power by taking into consideration both its Signal to Interference plus Noise Ratio (SINR) and the interference it causes to the other users. This formula prevents UEs from always setting their power to the maximum valid power level so as not to cause high interference to the neighboring UEs. As also described in [1] [2], the proposed algorithm deals only with interference among opportunistic UEs after the opportunistic system has been deployed. The execution of the Access Control algorithm (described in section 2.4) before the execution of the Cooperative Power Control algorithm ensures that the UEs that have been granted access to transmit in the considered opportunistic spectrum bands will not cause interference to primary users.

Initially, a set of L pair of UEs is considered operating at the same frequency band, where K channels are available; the UEs communicate through the eNodeBs in order to exchange information regarding their transmission power [3]. Intercommunication among different operators guarantees the information fusion among UEs assigned to them. A flat faded channel without shadowing effects is considered. Since the channel is static, the only identified attenuation is the path loss h (channel attenuation or channel gain). The notion of interference price, which expresses the marginal loss of utility for receiver i if all the other users marginally increase their transmission power has been adopted from the literature [4][5] and is being computed taking into account a logarithmic utility function of Shannon capacity and a user centric parameter.

As mentioned afore, cognitive users select their transmission power value by taking into consideration their own utility and the degradation in utility of the other users. They compute the appropriate power value to transmit by maximizing the formula given below:

$$u_i(\gamma_i(p_i^k)) - \alpha \cdot p_i^k \sum_{j \neq i} \pi_j^k \cdot h_{ji}$$

Equation 1: Utility function

The first part of the equation is related to the Shannon capacity of the channel, whilst the second part expresses the utility loss to other users if user i increases its power level. It should be noted that factor α is included as a weight in order to prevent underestimation of interference that user i will cause to the others. Underestimation is caused due to uncertainties in message exchange (i.e. message loss), large delays in the message exchange between users, and users' mobility. The coefficient α is determined before the initiation of the optimization phase by executing a Fuzzy Logic reasoner. Specifically, α is defined as 1/500 of the Interference Weight derived after defuzzification [1][2][3]. The fuzzy reasoner has three inputs (number of node pairs, mobility level and update time interval for the interference prices) and one output, the Interference Weight.

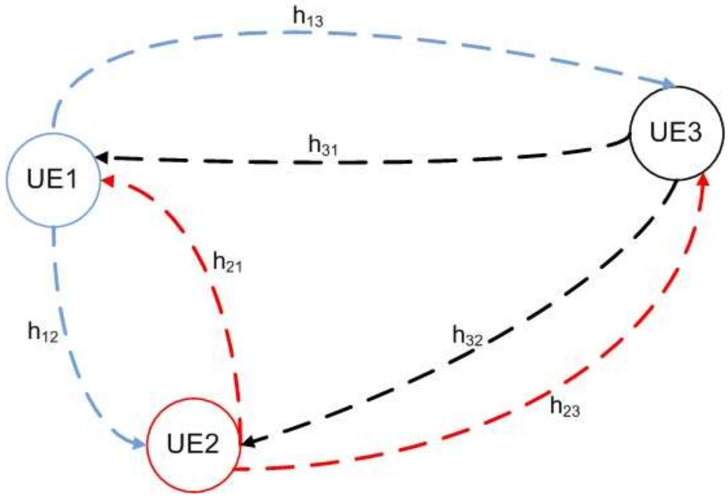

Figure 1: Representation of link gain among UE (of different operators) in the network

The proposed algorithm consists of three steps:

- The initialization, where each user sets its power value to a valid value (usually a minimum one) and calculates its interference price
- The power update, where each user computes the appropriate power value
- The interference price update, where each user computes its interference price based on the updated power value from the second step. Finally, it announces its interference price to the other users.

The second and the third step take place asynchronously for all users until a final steady state is reached. As a steady state we define a state where no further enhancement in utility of any node pair can be achieved without negatively affecting the total network utility.

2.1.2 Rules and Policies description

The aim of identified policies is to enrich the capabilities of CPC with other equivalently important aspects for the Cognitive Users, in addition to interference management [6]. More specifically, the policies considered are:

- **Fairness**: Cooperative Power Control algorithm guarantees interference mitigation and network performance optimization. This behavior might lead to undesired side effects (i.e. a portion of cognitive users will be obliged to transmit in low power values). Network operator can decide to enforce a fairness policy in order to allow the underprivileged users to transmit in higher power levels for a specific time period in order to compensate them [6]. Fairness is considered in terms of guaranteeing minimum power levels; given the fact that the prior analysis links the power levels to the transmission rate the transmission rate is guaranteed as well.

- **Convergence Time**: Rapidly reallocated spectrum resources and battery consumption of the cognitive users suggest an urgent need for algorithms that converge quickly to a steady state, thus minimizing the communication overhead on the one hand and the processing cost on the other. In the initial version of the algorithm [5] there is no conclusion about the number of steps that are required for convergence. Experimentation in terms of D3.3 [3] shows that choosing to stop the iterations of the algorithm after a few steps concludes to selecting Tx Power near to the optimum one that would be selected if the algorithm was not stopped prematurely, proving thus the claim of fast convergence for the Cooperative Power

Control algorithm. The algorithm is proved to converge in finite number of iterations [4]. In the considered policy the number of iterations is fragmented with an upper threshold of iterations [3].

- **Minimum QoS**: The SINR is a primary factor of the actual QoS the cognitive user is experiencing. Such factor expresses the influence of undesired signals at the receiver and indicates whether a transmission was successful. For this purpose this policy enables network operators to enforce a minimum allowed threshold value for SINR that the users experience.

The policy architecture proposed in [7] comprises of two main components, Policy Enforcing Point (PEP) and Policy Decision Point (PDP, also referred to as Policy Engine - PE), as depicted in Figure 2. The PEP is an entity equipped with RF transceiver and sensors; such entity is responsible for determining the state of the radio environment in which it operates and collecting information about spectrum usage, available channels and networks. The policies, according to the reference architecture, are located to the DB of the PDP, distributed by the PDP and enforced in the PEPs.

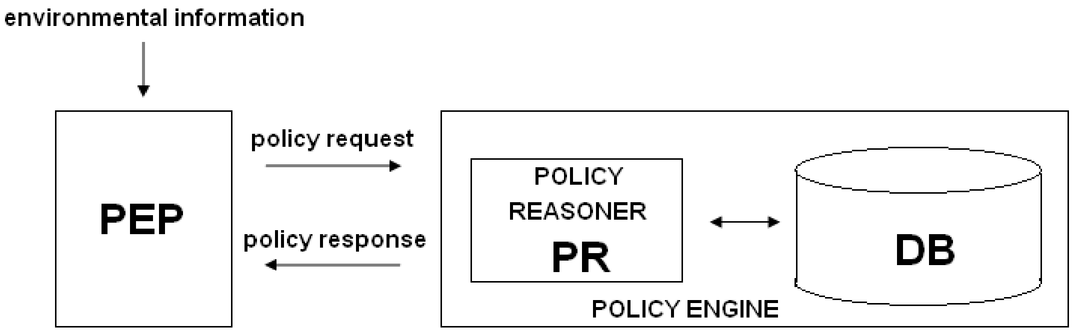

Figure 2: Policy architecture

On the other hand, the role of PDP is to perform reasoning (i.e. decision making) process. It comprises of two entities, a Policy Database (DB) and a Policy Reasoner (PR). PDP receives policy requests from several PEPs and sends policy replies (positive or negative for the enable of the corresponding policy or not). The DB contains active policies of the system, originated from operators, regulators and cognitive users. Policy Reasoner performs reasoning for each PEP request. It checks the rules forming a policy and either allows or disallows the policy request.

Consequently, when a cognitive radio wants to transmit, PEP sends policy requests to PDP. After receiving a reply from PDP, it controls the transmission of the radio according to PDP policies, contained in a positive reply. In case of a negative reply, PEP searches for a new channel and sends requests. PEP also sends requests in case channel conditions are getting worse. In addition, PEPs are present in every cognitive radio node, whereas PDP is not mandatory for each node in a cognitive radio network. In the case under discussion the network topology of Figure 3 is being followed. The PEPs are located in the user equipments whereas the PDPs are located in the eNBs. Such scheme ensures the conformance to operator's policies given the fact that the PDP are located in the network infrastructure.

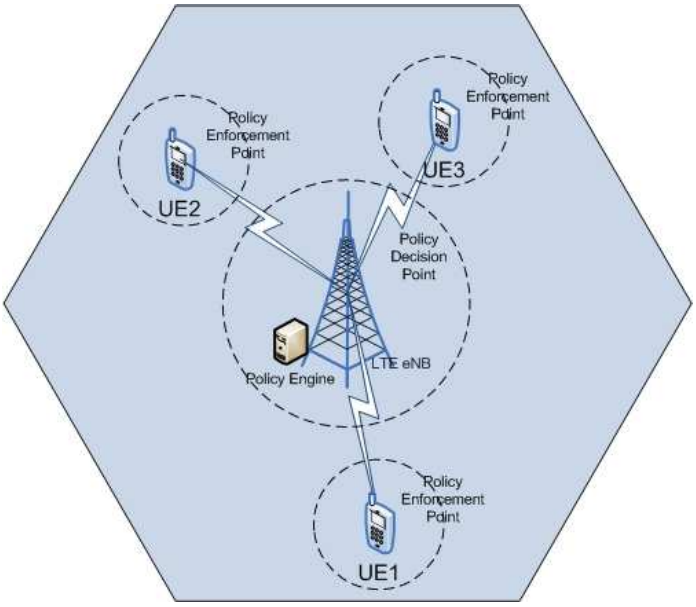

Figure 3: Representation of PDP and PEP for the energy efficient policies

2.1.3 Learning enhanced Cooperative Power Control algorithm

The learning algorithm of the CPC is placed in the outer loop and enables the User Equipments to adapt the way they perceive their environment. As mentioned afore and also described in details in [1][2][3], the objective function that the network elements use for deciding their transmission power levels is based on two parts, the former related to the Shannon capacity and the latter related to the negative effect each user has to its neighbouring ones. However, due to the nature of the communication, the negative effect might be under/over-estimated; thus the use of a fuzzy reasoned is proposed in order to ensure that the second part of the algorithm will have the appropriate weight. For the calculation of the weight the considered inputs are the mobility, the number of users and the update interval.

A fuzzy reasoned consists of three parts (as shown in Figure 4), namely the fuzzification, the inference and the de-fuzzification. In the former part the input values are being transformed to a degree of a state (e.g., low, medium, high etc). Then, using simple “IF... THEN...” rules, by the inference part, the decision maker identifies the output degree for the each rule. At the de-fuzzification all the degrees are being aggregated and mapped to the actual decision maker’s state. The brief analysis presented afore implies that if we modify the fuzzification (i.e. input membership functions) we also modify the way the decision maker interprets its environment.

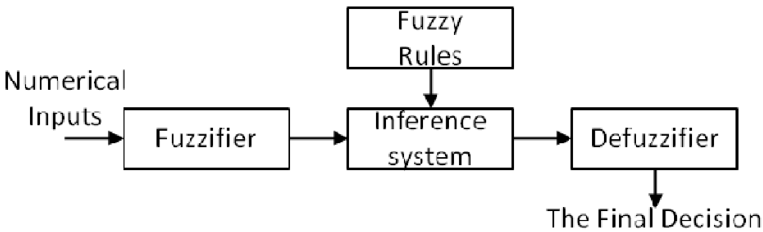

Figure 4: High level view of a fuzzy reasoner

Each terminal - part of the cooperative power control scheme – monitors its environment and evaluates the uncertainties; then it proceeds to the transmission power adjustment. Every time that the terminals collaboratively proceed in transmission power adjustment (i.e. periodically, after a complete cycle), their interference prices are being classified as low, medium and high according to the effect they have to the neighbouring terminals; the classified values are being provided to the learning points, where the data are being gathered. Once the learning points have gathered enough data they proceed in identification of the correlations of the input data by using data mining techniques. In the specific applied case k-Means is used for the extraction of the correlations. Each input is modelled by a 3 dimensional vector; these inputs are being placed in the three dimensional space and the clusters for each state (i.e. low, medium, high) are being created. The overlapping areas between the clusters suggest the areas where uncertainties exist. Then we we consider the line that connects the centres of the clusters and we identify the intersection points between the line and each sphere; thus identifying the areas where uncertainties exist, which is the overlapping areas in the input membership functions of the fuzzy reasoner (Figure 5).

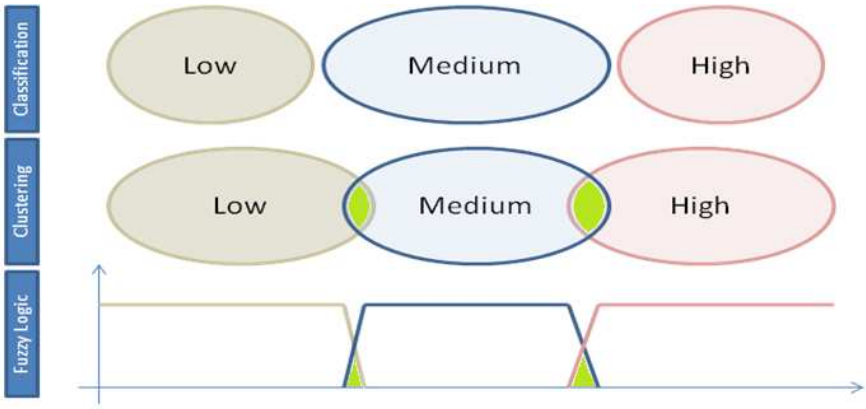

Figure 5: Clustering and bounds extraction mechanisms (areas in green indicate the uncertainty areas)

2.1.4 Mapping in SACRA Functional Architecture

In terms of WP1, SACRA D1.1b [8] describes in details the SACRA reference architecture, which is based on the description of the system requirements (functional) as captured also by WP1. The CPC focuses in the cooperative behaviour of the User Equipments for the extraction of the optimum transmission power in order to maximize the overall network's utility. Figure 6 presents where the functionalities of the Cooperative Power Control are located in relation to the SACRA reference architecture.

The CPC includes the core algorithm, which is based on the utility optimization and the cooperation among the User Equipments, regarding the information exchange, the conformance to policies (simple and more sophisticated ones) and the adaptation to the environment feedback (i.e. learning capabilities). Such functionalities are distributed among the functional blocks of the SACRA reference architecture (Figure 6).

The core CPC functionalities, which concern the Tx Power adjustment of the terminals, are located in the User Equipments' cognitive engine regarding the objective function and the interference prices calculation as well as the termination condition identification. Regarding the information fusion, among terminals from neighbouring cells the information management blocks from both the User Equipments and the RAN system are being used. The policy engine block of the Core Network is invoked by the RAN system in case policies are being incorporated. Such engine sets the rules and policies that govern the overall system's behaviour; in the case under discussion the Fast convergence, Fairness and guaranteed QoS policies are being examined. The learning functionalities are located in the terminals' cognitive engine and information management and the RAN's information management and cognitive engine. More specifically, the monitoring part of the algorithm is placed in the User Equipment's cognitive engine and the labelling part is placed in the information management block. The information management of the RAN is invoked for the information gathering from the User Equipments and for the corresponding harmonization. The cognitive engine undertakes to extract the new environment modelling (i.e. new input membership functions) which is being disseminated to the terminals.

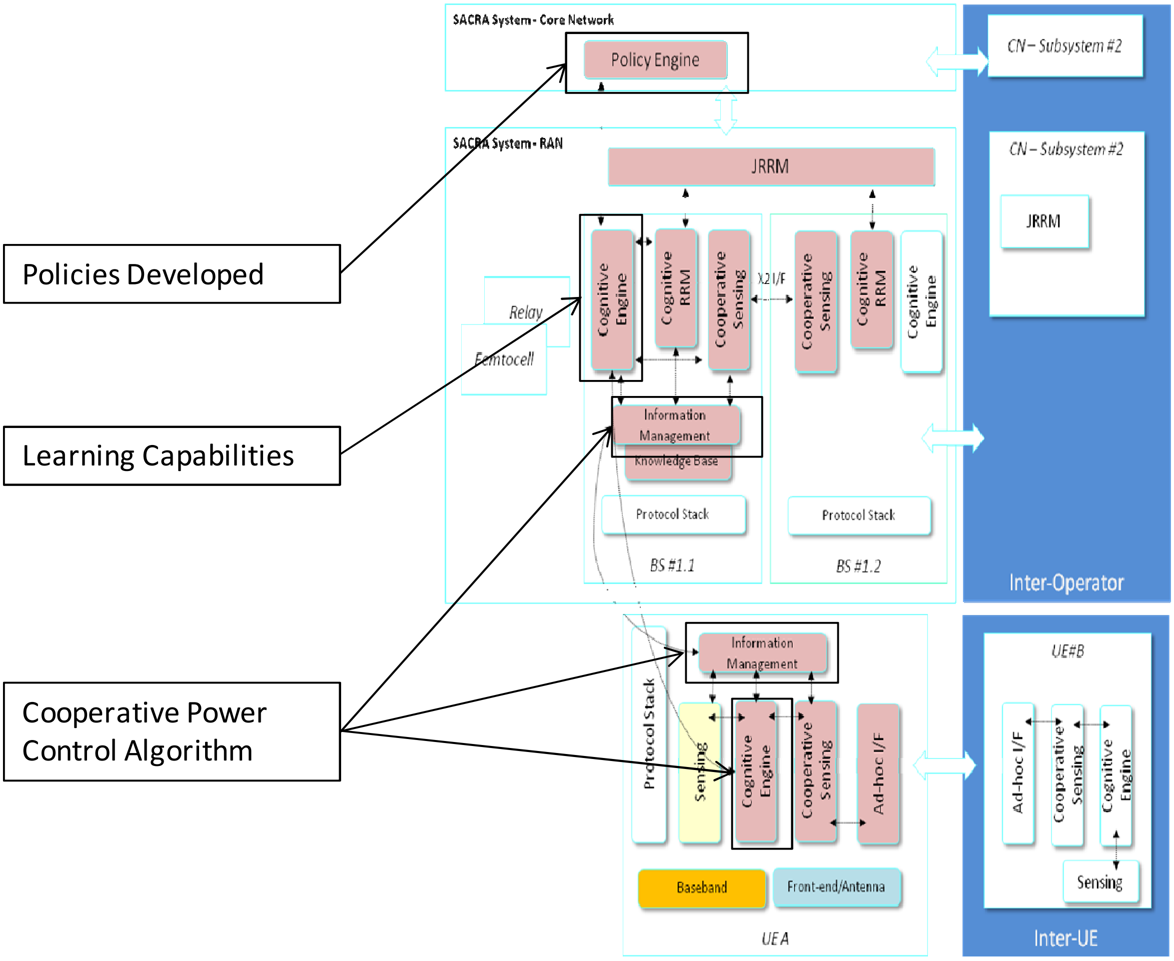

Figure 6: CPC functionalities in the SACRA reference architecture

2.1.5 Interaction with other components

The Cooperative Power Control mechanism decides the optimum transmission power of the cognitive users in order to maximize their Shannon capacity without causing interference problems to the neighboring cognitive users (refer equation 1). This implies that a first step identifying which users have been granted access to the TVWS is required. Thus, the interaction with the Spectrum Access Control is straightforward. Figure 7 captures the aforementioned interactions. A detailed description about the interoperation of the Cooperative Power Control and the Spectrum Access Control is available in D3.3 [3] and the joint assessment of the combination of the two mechanisms is provided in Section 4.

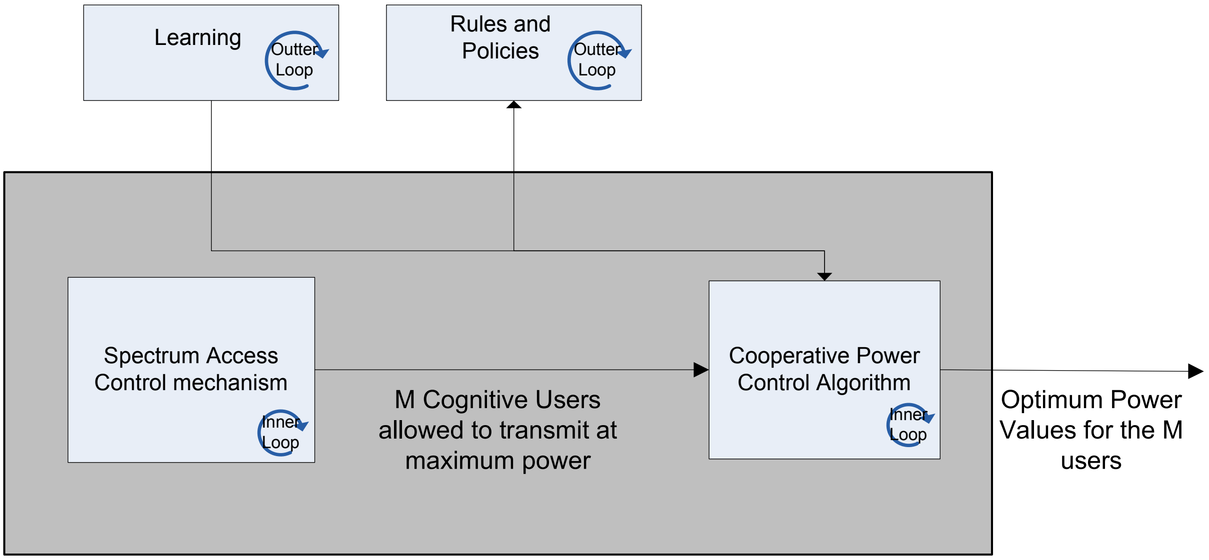

Figure 7: Interaction of the Cooperative Power Control with the other SACRA functionalities

2.2 SENSING CONFIGURATION

2.2.1 Theoretical implementation

The proposed framework for SACRA sensing configuration and control comprises the following systems as depicted in Figure 8 and well described in [3].

- A master node (which is chosen to be the SACRA base station) is in charge of selecting spectrum bands to be sensed and of scheduling the sensing task. The master node also sets the sensing configuration parameters.
- A set of selected UEs that process the sensing tasks and check the regulatory conformance related to the current sensing task. Furthermore, the UEs report the sensing decision and the primary user presence probability to the master node together with a regulatory conformance indicator.

Two sensing algorithms are implemented in SACRA UE: the energy detector and the Welch periodogram. The sensing configuration and control function allows the UE selecting dynamically the best sensing algorithm depending on the required SNR for the sensing algorithms to reach the target performance (the minimum allowed detection probability, the maximum allowed false alarm probability, a given sensing duration, and if needed a given noise estimation performance). More specifically, the selection process will select the sensing algorithm with the lowest required SNR for given configuration parameters. A knowledge base is stored in the UE which contains some off-line performance simulation results in order to aid the dynamic selection of the best sensing algorithm. Furthermore, for each sensing task, the regulatory conformance is checked and the primary user presence probability is estimated.

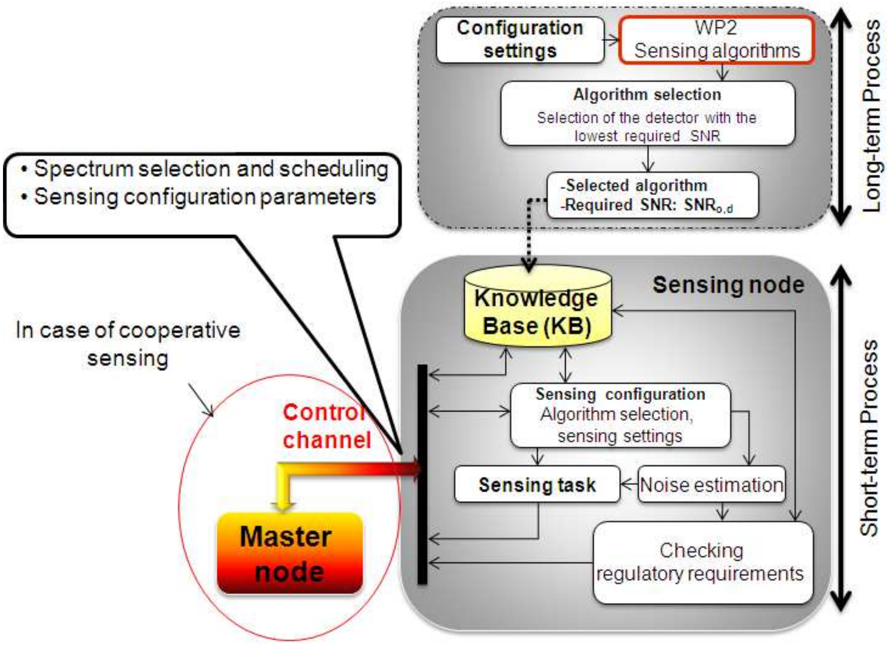

Figure 8: Architectural representation of sensing node configuration

2.2.2 Mapping in SACRA Functional Architecture

The node sensing configuration system can be mapped in SACRA functional architecture [8], as depicted in Figure 9 and Figure 10. The sensing configuration uses the following SACRA functional architecture blocks:

- SACRA “Cooperative sensing” block: the “sensing setting” function can be part of the “Cooperative sensing” block of SACRA functional architecture. The “sensing setting” function allows receiving or setting all the parameters required in configuring the cooperative sensing task.
- SACRA “Cognitive engine” block: both the “algorithm selection” and the “checking regulatory requirements” functions can be parts of the “Cognitive engine” block of SACRA functional architecture. The “algorithm selection” function allows selecting the most adequate sensing algorithm depending on the environment context, and the “checking regulatory requirements” function provides a regulatory conformance indicator showing whether the current sensing result should be assumed reliable or not.
- SACRA “Sensing” block: The “Sensing algorithms” and the “Noise estimation” functions are parts of the SACRA “Sensing” block.

The sensing configuration functionality can be implemented in the UE and/or in the base station (if the base station performs sensing task).

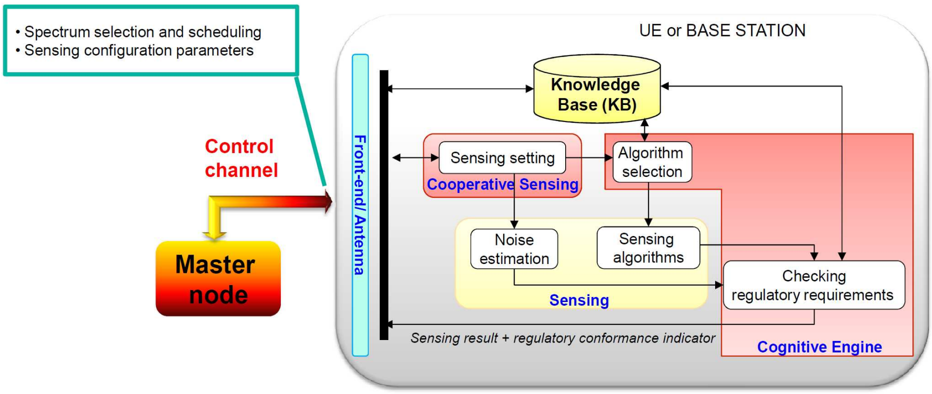

Figure 9: Sensing Configuration mechanism distribution among functional blocks

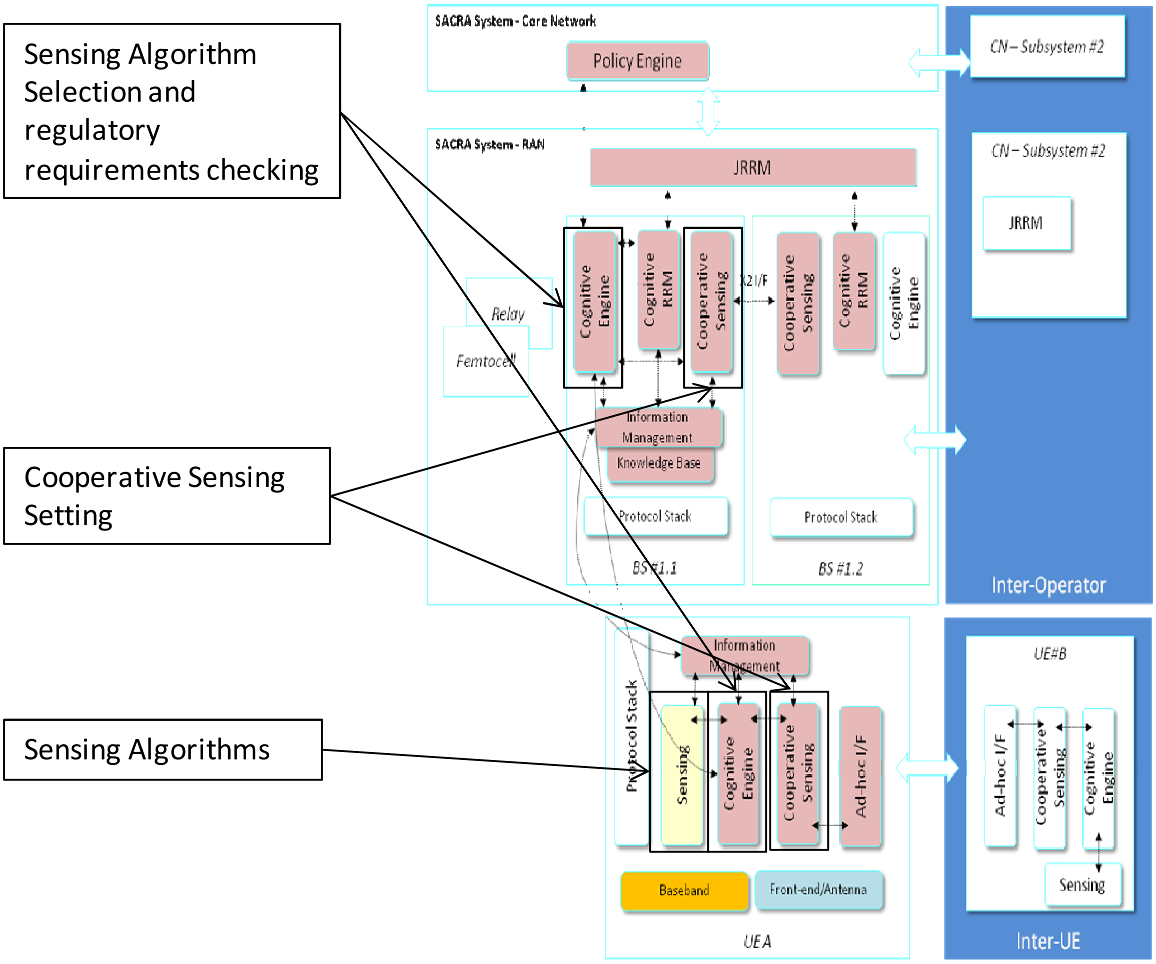

Figure 10: Sensing Configuration mapping in SACRA functional architecture

2.2.3 Interaction with other components

Whatever the scenario (spectrum aggregation, cognitive relays, broadband access around home), if sensing is required, the sensing configuration system interacts with the other SACRA components in the same manner as depicted in Figure 11. The following points define the main interaction of the sensing configuration system with the other RRM components.

- The system needs to select one sensing algorithm among the available WP2 algorithms; therefore, the system should interact with the WP2 sensing block as follows: the sensing configuration system should trigger the sensing task after selecting the most adequate algorithm among the available algorithms from WP2; the selected algorithm should return the sensing result to the sensing configuration system.
- The system could provide, to the “cooperative power control” function, the primary user presence probability, after sensing given frequency band.
- The sensing configuration system also needs the Policy Engine to know the regulatory body requirements regarding the incumbent protection, the list and features of the primary users to be protected, the sensing periodicity and the required sensing performance (maximum allowed false alarm probability, minimum allowed detection probability). In return, the sensing configuration system should request some additional sensing gaps to the Policy Engine in case a given global regulatory conformance indicator (that can be defined from the different regulatory conformance indicators returned by the single sensing nodes) is not satisfactory.

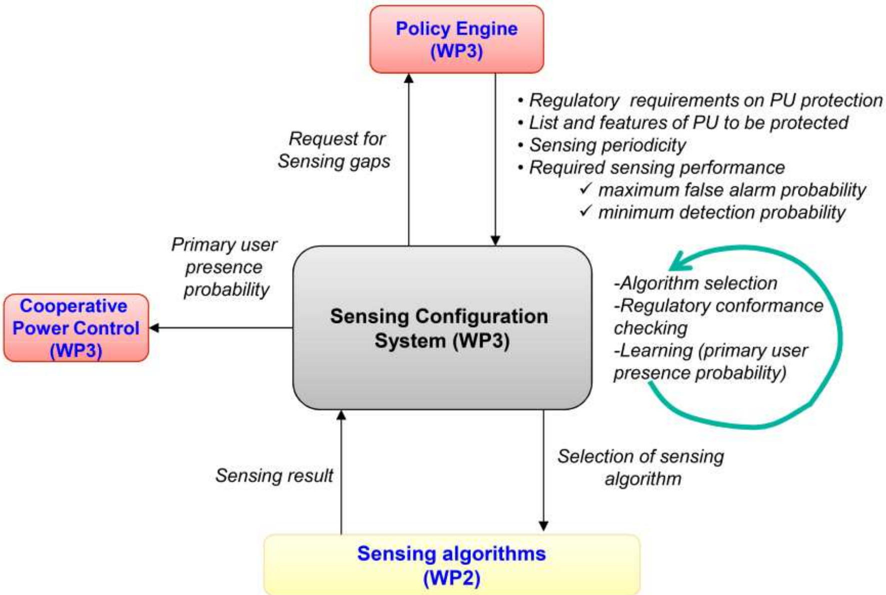

Figure 11: Interaction of the sensing configuration system with the other SACRA functionalities

2.3 USER AND FLOW PARTITIONING ALGORITHM

2.3.1 Description

User and flow partitioning algorithm focuses on solving the problem of spectrum aggregation across multiple bands formulated in SACRA scenarios [2][3]. Indeed, the user and flow partitioning algorithm allocates efficiently resource blocks belonging to the principle component carrier (situated around 2.6 GHz) and the secondary component carrier (situated around 800 MHz) to a set of secondary users while minimizing the probability to interfere with the primary user who is the licensed user on the 800 MHz component carrier. The user and flow partitioning algorithm optimizes jointly two different objectives namely the quality of service of the different secondary users in terms of achieved throughput and the probability to cause interference to the primary user. This algorithm also assumes that the inputs from the SAC (Secondary user Access Control algorithm) and the reported sensed data from the sensing configuration enable estimation of the channel gains. In addition, this algorithm applies only to the resource budget available for opportunistic use and hence excludes already the power budget consumed by the pilots or all other control channels.

Mathematically, the user and flow partitioning problem is formulated using a mixed integer non linear optimization problem with a main objective function which aggregates, using a weighted sum method, the two conflicting objectives mentioned before while satisfying three constraints related to the resource allocation problem. The first constraint states that the sum of transmission powers allocated to the different secondary users must be below the power budget of the cognitive base station. The second constraint states that one resource block is allocated to at most one secondary user. Finally, the third constraint stipulates that the probability to interfere with the primary user must be below a given probability threshold.

The mixed integer non linear problem is solved using a genetic algorithm that can find a near optimal solution that achieves a good compromise between maximizing the percentage of satisfied users in terms of throughput and minimizing the probability to interfere with the primary user. The genetic algorithm uses a chromosome structure that is suitable to the spectrum aggregation problem. Indeed each chromosome in the genetic algorithm is composed by a set of genes whose number is equal to the number of resource blocks belonging to the two aggregated component carriers. The value of a given gene is the identity of the user who will occupy the resource block represented by the gene. The value of the gene is set to zero if the corresponding resource block is left vacant due to a high probability to interfere with the primary user in this current block.

The genetic algorithm is used jointly with a reinforcement learning mechanism which learns the probability of presence of the primary user. The value of this probability is incorporated into the objective function through the confidence parameters in order to improve the efficiency of the genetic algorithm.

2.3.2 Rules and Policies description

At the highest level in the traffic management and applications request levels, in the outer loop, SACRA has to partition flows into sub-bands according to application flows profiles and QoS requirements. The rules and policies will govern this allocation of flows into bands by injecting appropriate behaviours into CRRM in terms of goals and performance objectives.

Key policies, rules and constraints that govern the CRRM allocations originate from providers, stakeholders and applications QoS requirements that can be viewed in fact as constraints and can determine pre-allocation rules for interactive and real time applications, non real time applications and best effort traffic. Applications with stringent QoS requirements will in general be allocated to the stable licensed bands and will not be the subject of migration across bands during the lifetime of a session. While the more flexible non real time and best effort traffic can seamlessly be moved from a set of carrier components to another whenever necessary or to maintain or improve performance. The key policies and rules objet of the assessment for the partitioning algorithm are:

- **Required throughput** (goodput) for the applications or end user service,
- **Protection of primary user**: this is achieved by introducing a constraint on the optimisation problem definition and the additional objectives of minimising collisions with the primary using the learning algorithm of the primary user presence probability,
- **Latency** in making decisions, this is reported by analyzing the number of iterations typically required to converge to a stable solution. This applies to latency assessments for the partitioning into bands (resulting from the allocation of resource blocks to applications in the genetic algorithm) or learning (of the primary presence probability).

2.3.3 Mapping in SACRA Functional Architecture

Figure 12 presents the mapping between the components of the user and flow partitioning algorithm and the SACRA reference architecture. This mapping can be defined as follows:

- Policy Engine: this component will contain all the policies used by the genetic algorithm. These policies can be defined by rules and constraints that govern the CRRM allocations originate from providers, stakeholders and applications QoS requirements that can be viewed in fact as constraints and can determine pre-allocation rules for interactive and real time applications, non real time applications and best effort traffic.
- Cognitive engine: this component will contain the reinforcement learning mechanism that is used to learn the probability of presence of the primary user.
- Cognitive RRM: this component will contain the core of the user and flow partitioning algorithm namely the genetic algorithm.

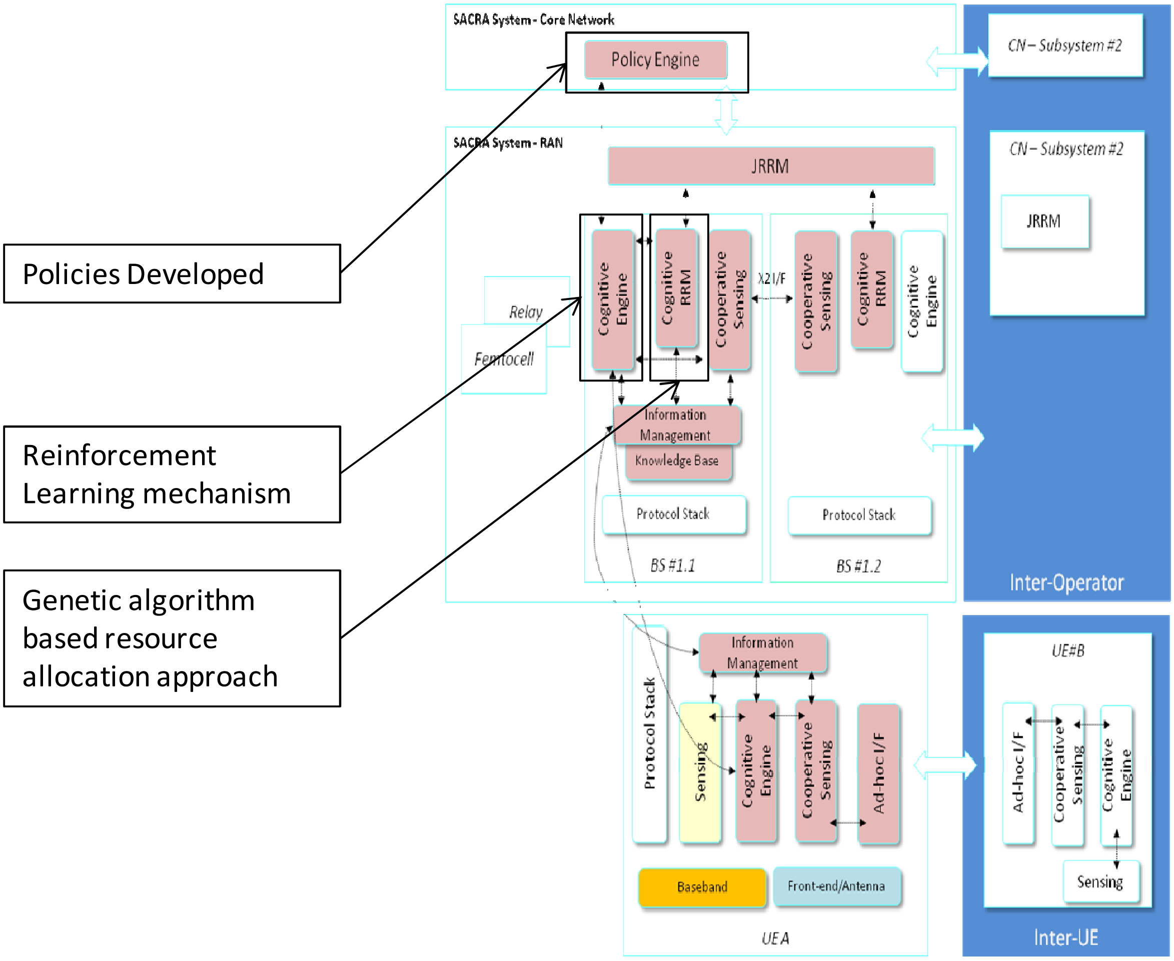

Figure 12: Mapping between the user and flow partitioning algorithm and SACRA architecture

2.3.4 Interaction with other components

Figure 13 shows the relationship among the user and flow partitioning algorithm and the other components in the SACRA project, especially the WP3 components. The user and flow partitioning algorithm is at the heart of the resource allocation mechanism as it distributes resource blocks belonging to different components carriers, to a set of cognitive radio users. To perform this task, the algorithm needs some information from the other WP3 components and the surrounding environment. First, the user and flow partitioning algorithm needs to know the components carriers that it can access opportunistically (non-licensed band), this information is included in the rules and polices introduced by the operator. Second, the algorithm needs a set of parameter values like SINR, ACK, NACK that are given by the MAC and physical layers of the LTE protocol. Finally, the user and flow partitioning algorithm requires some information that can be given by the sensing configuration module, namely the sensing decisions related to each resource block, the estimation of probability of detection P_d and the estimation of the probability of false alarm P_{fa}. On the other hand, the user and flow portioning algorithm can trigger an alarm whose target is the sensing configuration module. This alarm aims at informing the sensing configuration module about the accuracy of the delivered parameters like the estimation of the probability values, namely the probability of detection, the probability of false alarm and the probability of presence of the primary user.

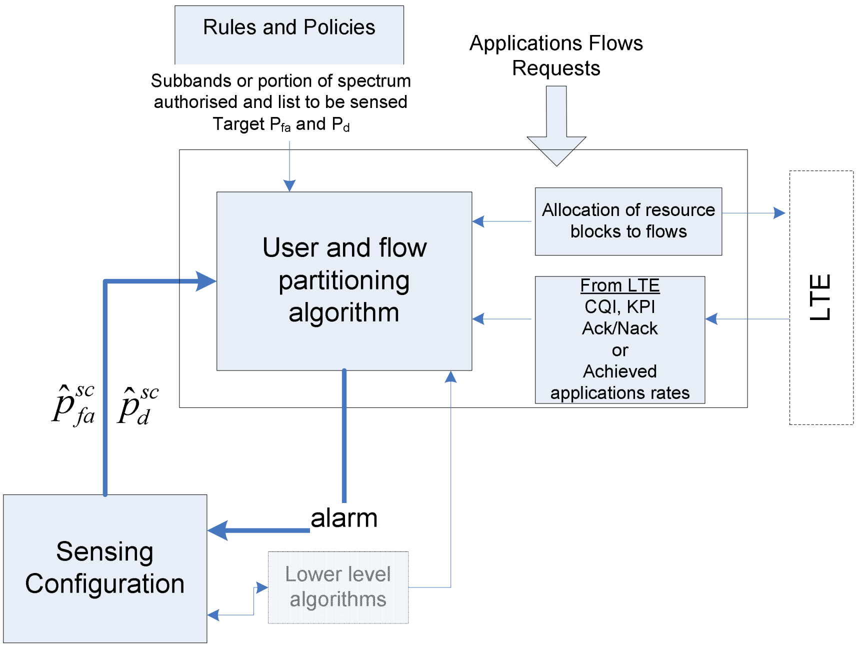

Figure 13: Interaction of the user and flow partitioning algorithm with the other SACRA functionalities

2.4 *ACCESS CONTROL ALGORITHM BASED ON PRIMARY OUTAGE PROBABILITY*

2.4.1 Description

In this work we propose a different way to efficiently protect primary systems from SU interference, based on outage probability [9]. The motivation is that, in any case, the PU will not necessarily need all the features and resources of the multi-rate system [10]. In fact, the CR behaviour can be generalized to allow SUs to transmit simultaneously with PU in the same frequency band. It can be done as long as the level of interference to PUs remains within an acceptable range. In what follows, we consider a CRN in which primary and secondary users both attempt to communicate in a distributed way, subject to mutual interference. We propose a distributed CR coordination that maximizes the CRN secondary rate while keeping the interference to the PU acceptable. Our goal is to realize PU-SU spectrum sharing by optimally allocating SU transmit powers, in order to maximize the total SU throughput under interference and noise impairments, and short term (minimum and peak) power constraints, while preserving the QoS of the primary system. In particular, it is of interest to determine, in a distributed manner, the maximum number of SUs allowed transmitting without affecting the PU's QoS. In such approaches, users individually make a decision on their transmit power so as to optimize their contribution to the system throughput. At the core of the distributed concept lies the idea that the interference is more predictable when the network is dense, and consequently the resource allocation problem of a given user is made more dependent on the average behaviour, thus facilitating distributed optimization [11][12].

In D3.2 [2] we have presented the evaluation criteria and performance metrics chosen to validate the proposed strategies. Particularly, we propose criteria to evaluate the performance of the outage probability based algorithm in terms of SUs and PU desired performance level. We will provide in the following more details about the proposed strategy, especially rules and policies used to define and evaluate this algorithm.

2.4.2 Binary Power Control Strategy

One basic assumption throughout this work is that a SU can vary its transmit power, under short term (minimum and peak) power constraints, in order to maximize the cognitive capacity, while maintaining a QoS guarantee to the PU. For the proposed resource allocation algorithm, we will use a binary power control (nodes transmitting at maximum power Pmax or being silent). The idea of the binary "on"/"off" power control is simple, as well as yielding quasi-optimal results in a number of cases. As such, it constitutes a promising tool for making spectrum sharing a reality. Besides complexity reduction, an important additional benefit of binary power control is to allow distributed optimization. With binary power constraints, power control reduces to deciding if links should be "on" or "off". The power p_m of the m-th SU transmitter is selected from the binary set {0, Pmax}. It is intuitively clear that if the cross-gain is sufficiently low, then all links should be "on". The key idea within the iterative algorithm used in the development of the proposed distributed user selection algorithm is to subsequently limit pm to {0, Pmax}, i.e., to switch "off" transmission in SUs links which do not contribute enough capacity to outweigh the interference degradation caused by them to the rest of the network. We propose an adaptation of the distributed algorithm which allows a subset of controlled size $\tilde{M}$ of the total number of SUs M to transmit simultaneously on the same sub-band. We will give in this section a summary of the presented method.

Let Ψ be the set of indices of all presently active SUs. Denoting the SU which is to be potentially turned off by m, the network capacity with and without SU turned off is given by the LHS and the RHS of this inequality, respectively:

$$\sum_{l\in\Psi}\log_2\left(1+\frac{p_l\mid h_{l,l}\mid^2}{\sigma^2+p_{pu}\mid h_{pu,l}\mid^2+\sum_{\substack{k\in\Psi\\k\neq l}}p_k\mid h_{k,l}\mid^2}\right)<$$
$$\sum_{\substack{l\in\Psi\\l\neq m}}\log_2\left(1+\frac{p_l\mid h_{l,l}\mid^2}{\sigma^2+p_{pu}\mid h_{pu,l}\mid^2+\sum_{\substack{k\in\Psi\\k\neq l\neq m}}p_k\mid h_{k,l}\mid^2}\right)$$

Equation 2: Network capacity with and without SU turned off

We define:

$$\mathrm{SINR}_{l_m} = \frac{p_l\mid h_{l,l}\mid^2}{\sigma^2+p_{pu}\mid h_{pu,l}\mid^2+\sum_{\substack{k\in\Psi\\k\neq l\neq m}}p_k\mid h_{k,l}\mid^2}$$

Equation 3: Signal to interference plus noise (SINR) ratio

After simple manipulation we find:

$$(1+\mathrm{SINR}_m)\prod_{\substack{l\in\Psi\\l\neq m}}(1+\mathrm{SINR}_{l_m})<\prod_{\substack{l\in\Psi\\l\neq m}}(1+\mathrm{SINR}_{l_m})$$

Equation 4: Network capacity with and without SU turned off based on SINR ratio

At High SINR Regime: Assuming all SUs to be in “on” condition for the mentioned CRN, at high SINR regime, we have dense environment with more users within small geometrical area and hence a SU requires higher threshold to be active. After simple manipulation of the last equation and assuming that 1+ SINR = SINR holds, the signal-to-interference ratio (SIR) threshold for high populated regions comes out to be,

$$\mathrm{SIR}_m=\frac{p_m\mid h_{m,m}\mid^2}{p_{pu}\mid h_{pu,m}\mid^2+\sum_{\substack{k\in\Psi\\k\neq m}}p_k\mid h_{k,m}\mid^2}>e=2.718281\ldots$$

Equation 5: Signal-to-Interference Ratio (SIR) threshold for high populated regions

At Low SINR Regime: By definition in the low SINR region Ln(1+x) = x holds with good accuracy, and binary power control is always optimal. We can go from Equation 5, to come up with the active user threshold at low SINR region as,

$$\mathrm{SIR}_m>1$$

Equation 6: Active user threshold at low SINR region

Results given in Equation 6 and Equation 7 confirm, as intuition would expect, that SUs under better SINR conditions would transmit only above a higher threshold than in the low SINR regime.

2.4.3 Access control algorithm description

Outage probability constraint: To proceed further with the analysis of the distributed strategy and for the sake of emphasis, we introduce the PU average channel gain estimate G_{pu} based on the following decomposition:

$$h_{pu,pu} \triangleq G_{pu} * h'_{pu,pu}$$

Equation 7: Decomposition for the PU average channel gain estimate

where $h'_{pu,pu}$ is the random component of channel gain and represents the normalized channel impulse response tap. This gives us the following PU outage probability expression:

$$P_{out} = Prob\left\{ \log_2\left(1 + \frac{p_{pu} G_{pu}^2 \mid h'_{pu,pu} \mid^2}{\sum_{m=1}^{M} p_m \mid h_{pu,m} \mid^2 + \sigma^2} \right) \leq R_{pu} \right\}$$

Equation 8: PU outage probability expression

where Rpu is the primary user transmitted data rate. Let $\tilde{M}$ be the maximum number of SUs allowed to transmit using the distributed method and G_{su} the SU average channel gain estimate. If we introduce these two parameters in the last equation, we obtain

$$P_{out} \simeq Prob\left\{ \frac{p_{pu} G_{pu}^2 \mid h'_{pu,pu} \mid^2}{G_{su}^2 \sum_{m=1}^{\tilde{M}_d} p_m + \sigma^2} \leq 2^{R_{pu}} - 1 \right\} \leq q$$

$$\simeq Prob\left\{ \mid h'_{pu,pu} \mid^2 \leq \left(2^{R_{pu}} - 1\right) \left(\frac{\tilde{M}_d G_{su}^2 P_{max} + \sigma^2}{G_{pu}^2 p_{pu}} \right) \right\} \leq q$$

Equation 9: PU outage probability expression based on $\square_d$ and G_{su}

where q is the maximum outage probability. From now on we assume for simplicity of analysis that the channel gains are i.i.d. Rayleigh distributed. However, the results can be immediately translated into results for any other channel model by replacing by the appropriate probability distribution function. We obtain:

$$P_{out} \simeq \int_0^{\left(2^{R_{pu}} - 1\right) \left(\frac{\tilde{M}_d G_{su}^2 P_{max} + \sigma^2}{G_{pu}^2 p_{pu}} \right)} \exp(-t) dt \leq q$$

Finally, we get the following outage constraint:

$$P_{out} \simeq 1 - \exp\left[-\left(2^{R_{pu}} - 1\right)\left(\frac{\tilde{M}_d G_{su}^2 P_{max} + \sigma^2}{G_{pu}^2 P_{pu}}\right)\right] \leq q$$

and the maximum number $\dot{M}_d$ of active “on” SUs that transmit with P_{max} is given by

$$0 \leq \tilde{M}_d \leq \frac{-\log(1-q)}{\left(2^{R_{pu}} - 1\right)} \cdot \frac{G_{pu}^2 P_{pu}}{G_{su}^2 P_{max}} - \frac{\sigma^2}{G_{su}^2 P_{max}}$$

Equation 10: Maximum number $\dot{M}_d$ of active “on” SUs that transmit with P_{max}

Optimization problem SUs offer the opportunity to improve the system throughput by detecting the PU activity and adapting their transmissions accordingly while avoiding the interference to the PU by satisfying the QoS constraint on outage. We present here a distributed user selection strategy using the binary power allocation policy. The proposed strategy tries to limit the number of SUs interfering with the PU so as to guarantee the QoS for the primary system. Specifically, a SU will be deactivated if its action results in an increase in the cognitive capacity of SUs or if its transmission violates the PU outage constraint. The optimization problem can therefore be expressed as follows:

$$\text{Find } \; p_m|_{m=1,\ldots,M} = \arg\max_{p_m} C_{su}$$

Equation 11: Optimization problem

subject to:

$$\begin{cases} p_m \in \{0, P_{max}\}, \quad \text{for } \; m = 1, \ldots, M \\ 0 \leq \tilde{M}_d \leq \dfrac{-\log(1-q)}{\left(2^{R_{pu}} - 1\right)} \cdot \dfrac{G_{pu}^2 P_{pu}}{G_{su}^2 P_{max}} - \dfrac{1}{\mathrm{SNR}} \end{cases}$$

Equation 12: Constraints for the optimization problem

As we can see, the CR system does not require any knowledge about the PU and SUs channels in the sense that it decides distributively to either SU transmits data or stays silent over the channel coherence time depending on the specified P_{out} threshold (q). On the other hand, the optimization problem in the centralized case using (19) requires all $h_{m,pu}$ and $h_{pu,pu}$ data to compute the outage probability and to select then the SUs able to transmit without affecting the PUs’ QoS.

2.4.4 Mapping to the SACRA Functional Architecture

A resource management algorithm based on outage probability assesses impact on incumbent or licensed users and opportunistic or unlicensed users interference to control initial access to the available bands. This algorithm can be used to decide if users are allowed to enter the system or not based on outage probability estimation prior to any access grant. This algorithm can operate on the output from the previous algorithm in each sub-band at reduced complexity or on all bands independently.

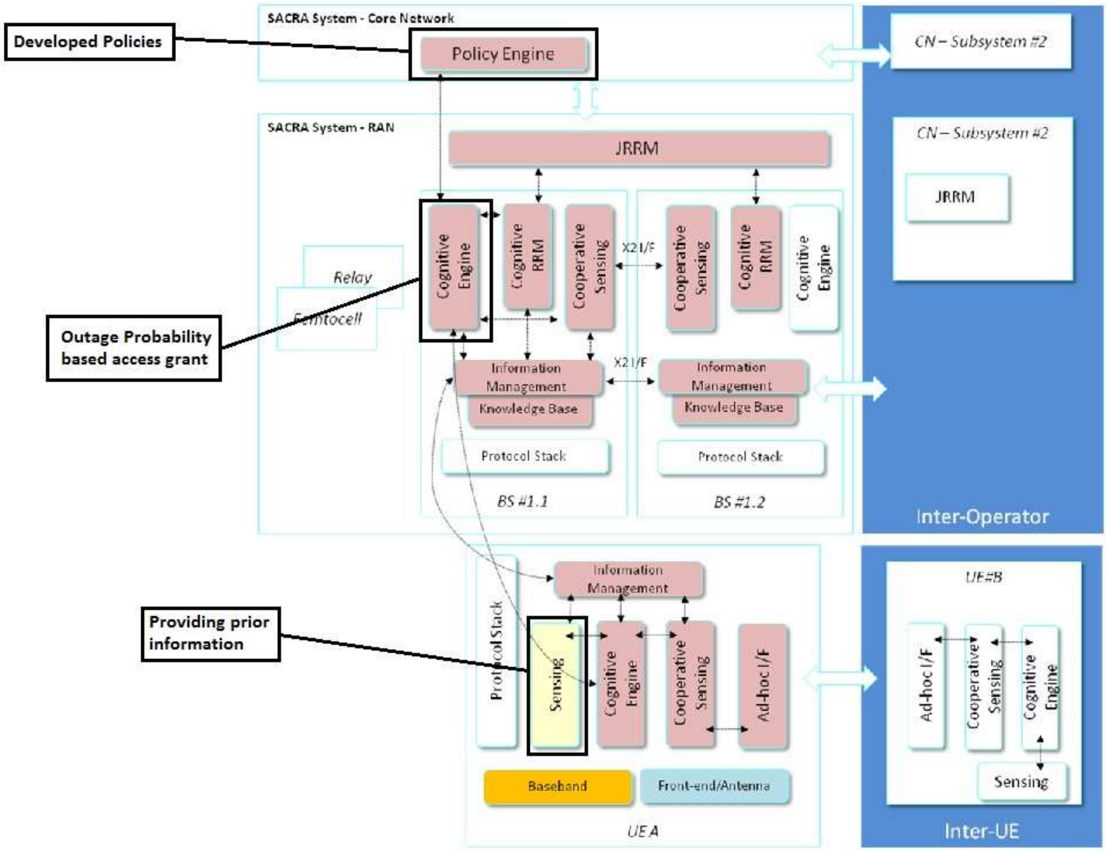

Figure 14: Mapping between Secondary Access Control algorithm and SACRA architecture

2.4.5 Interactions with other components

As a first step, the sensing configuration system controls and configures sensing dynamically according to the collected information by the activated sensing algorithms, to their observed performance and to the estimated signal to interference ratio in the monitored primary bands. Then, the outage probability based algorithm is used to determine if secondary users are allowed or not to enter the white spaces by assessing the impact on primary users first and second by assessing the mutual interference secondary users experience from each other. This algorithms allows access only if all the conditions are fulfilled. It is specialised for both uplink and downlink access to free spectrum. Afterwards, the cooperative power control algorithm actually fine tunes power settings for users that have been granted access already and it relies on shared and exchanged experience instantaneous utility among secondary users to derive the best power settings. As the data gets shared and exchanged and delays as well as uncertainties in received data qualities are experienced, the cooperative power control algorithm introduced fuzzy logic features to handle these doubts and become robust to the unreliable utility reporting.

2.5 OVERALL MAPPING OF RRM MECHANISMS TO THE SACRA FUNCTIONAL ARCHITECTURE

This section summarizes the overall mapping of the RRM system to the SACRA Functional Architecture. Figure 15 provides the functional blocks upon which the RRM components rely, as well as the location of each functionality of the proposed algorithms.

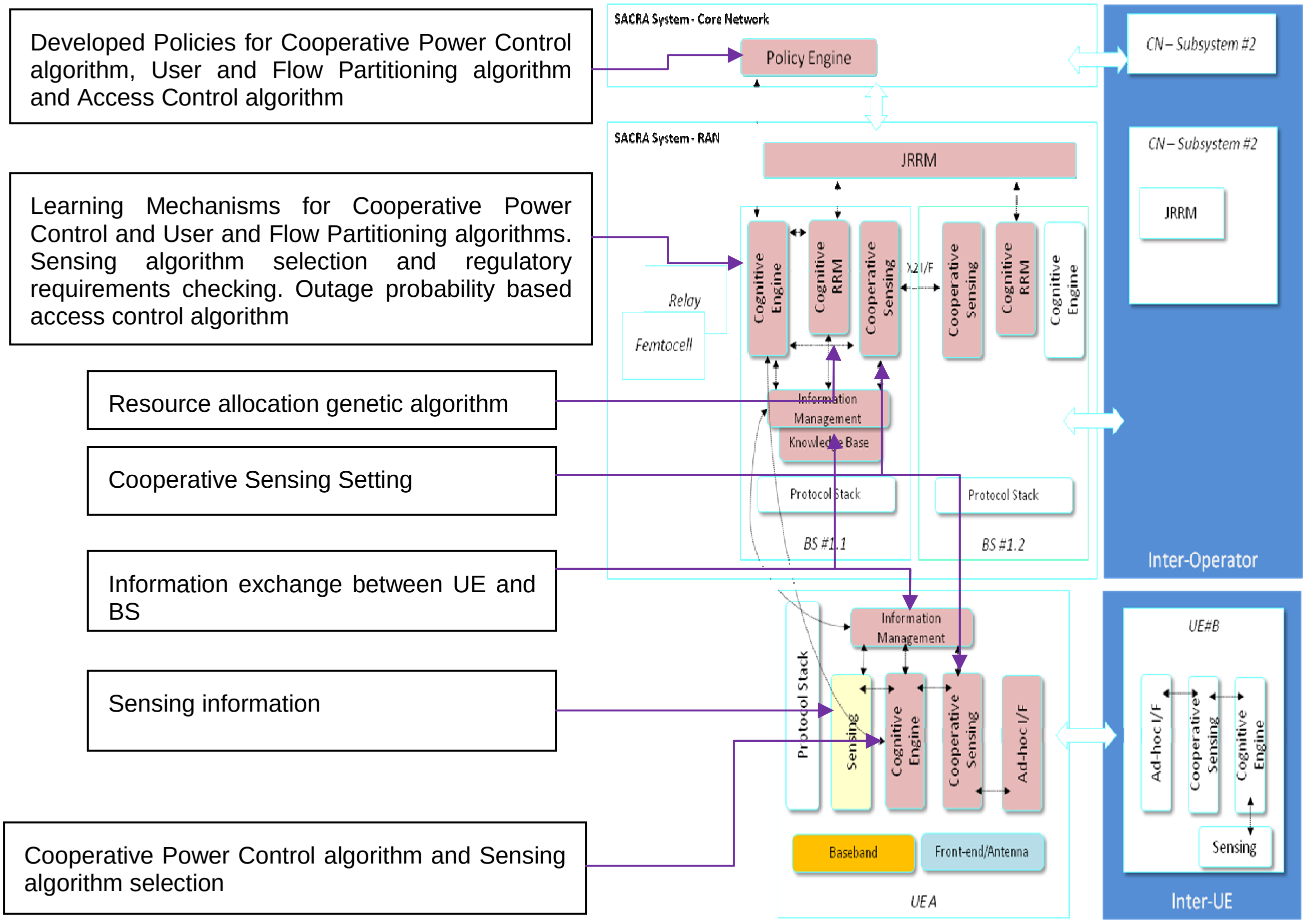

Figure 15: RRM system mapping to the SACRA Functional Architecture

3 SCENARIO DEPLOYMENT

3.1 SPECTRUM AGGREGATION SCENARIO

Spectrum Aggregation has been introduced by 3GPP as an enabler for overall spectrum efficiency, as it will increase the capacity in wireless and mobile communications by providing additional bandwidth. Figure 16 illustrates the Spectrum Aggregation Scenario as in 3GPP. In this 3GPP scenario, the aggregated spectrum component can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz, thus up to five (5) component carriers (i.e., the individual component carriers can be of different bandwidths) can be aggregated leading thus to maximum bandwidth of 100 MHz. The number of aggregated carriers can be different in DownLink (DL) and Uplink (UL).

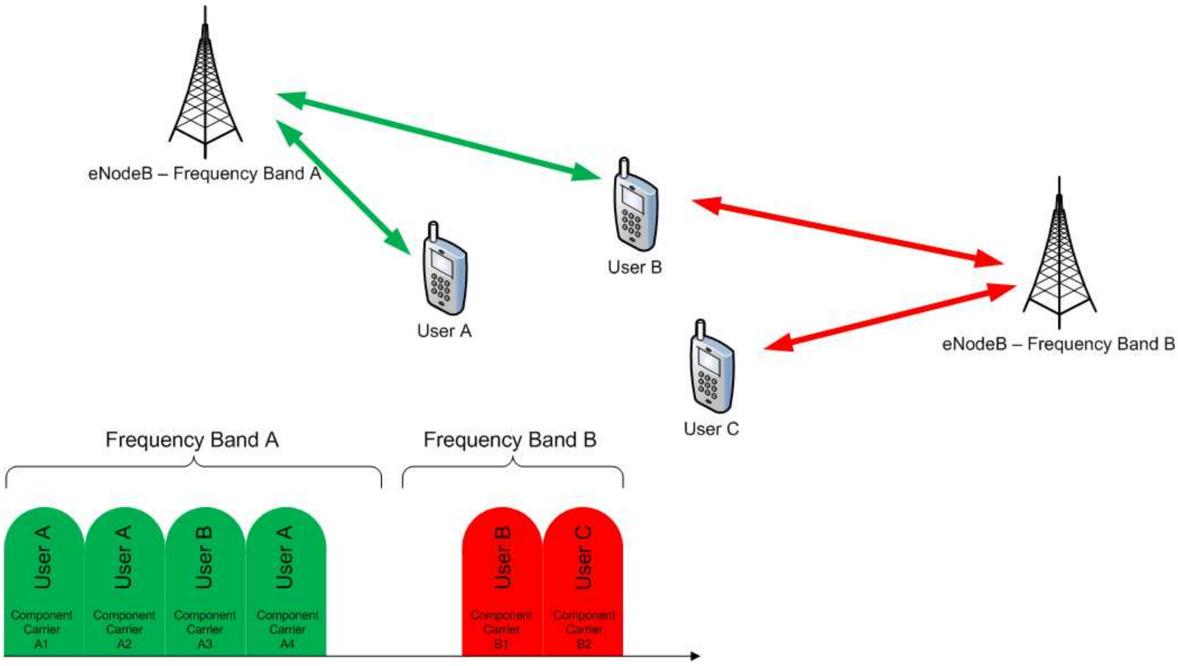

Figure 16: Intra and Inter-band spectrum aggregation

Two ways for Spectrum Aggregation have been incorporated in the LTE-A (Figure 16):

- Intra-band
  - Contiguous allocation featuring use of contiguous component carriers within the same operating frequency band (as defined for LTE – user A with component carriers A1 and A2). Different frequency allocation scenarios may limit applicability of intra-band contiguous Spectrum Aggregation.
  - Non-contiguous allocation; in this scenario the component carriers belong to the same operating frequency band but are separated by a frequency gap (user A with component carrier A4).
- Inter-band non-contiguous allocation; in this case the component carriers belong to different operating frequency bands (user B with component carriers A3 and B1).

As described in D1.1b [8], spectrum aggregation is considered one of the core cases to be taken into consideration in terms of SACRA project. The 3GPP focuses mainly in intra-RAT spectrum aggregation. However, SACRA project goes one step beyond and identifies two spectrum aggregation use cases, the opportunistic intra-cell and the inter-cell one. In the former case, the user equipment uses resources from both licensed and unlicensed bands from the same base station, whereas in the latter user equipment uses resources from different base stations (i.e., the user equipment might use resources from two co-located or distant cells, i.e. two sectors of a single eNodeB or two eNodeBs), regarding the licensed and unlicensed bands. In this analysis we do not consider the usage of Cell-specific Reference Signals (CRS), and consequently we do not take into account the interference introduced to the PUs by these channels. The following subsections describe how the Radio Resource Management components are being materialized in the spectrum aggregation use cases, the intra and inter-cell ones.

3.1.1 Intra-Cell Spectrum Aggregation Storyline

The opportunistic intra-cell spectrum aggregation case considers a user which uses resources from both licensed and unlicensed bands from the same base station. This simplifies the problem regarding the communication among neighbouring base stations. In the remaining of this section, the storyline of the intra-cell spectrum aggregation scenario is being provided. Furthermore, the Radio Resource Management Component invoked in every step of the storyline is being provided, as well as its basic functionality in relation to the scenario. We consider a multi-operator environment where several users exist:

1. Periodically, the sensing configuration system identifies which is the most suitable sensing algorithm for the considered environment. The decision is made locally in the user equipment, using local information and information stemming from the base station as well.
2. A user wants to have access to a specific service. The local sensing algorithm senses the environment in order to detect primary signals in the considered area.
3. The spectrum access control algorithm decides whether a user shall be permitted to operate in TVWS. Considering the fact that no primary users are in the area under discussion, the users will be granted access to the TVWS.
4. The base station, using the user and flow partitioning algorithm, decides the optimal aggregation of the available spectrum, so as to fulfil users’ demands.
5. Then, primary users appear in the environment and are detected by a subset of the opportunistic users using their local sensing algorithms; such information is communicated to the spectrum access control algorithm (operating in the user equipment) from the sensing configuration system.
6. The spectrum access control algorithm executed distributed in each User Equipment decides whether the user will be allowed to transmit in the TVWS taking into account the primary outage probability to ensure that the interference which the primary users perceive will not exceed a maximum allowed threshold.
7. The base station (user and flow partitioning algorithm) decides the optimal aggregation of the available spectrum, so as to fulfil user demands.
8. The base station (using the user and flow partitioning algorithm) perceives delay issues (i.e. degraded QoS) for a subset of the granted users and informs sensing configuration system (i.e. the part located in the base station).
9. The sensing configuration system takes into account this information and modifies the sensing parameters (i.e. sensing frequency etc.), or even selects another algorithm for the sensing procedure. Any modification of the sensing configuration procedure is disseminated to the corresponding part of the sensing configuration system located in the User Equipment.
10. In case primary signal is detected by the sensing algorithm upon the sensing procedure the sensing configuration system (located in the User Equipment) informs the rest of CRRM blocks and steps 7-9 are repeated.

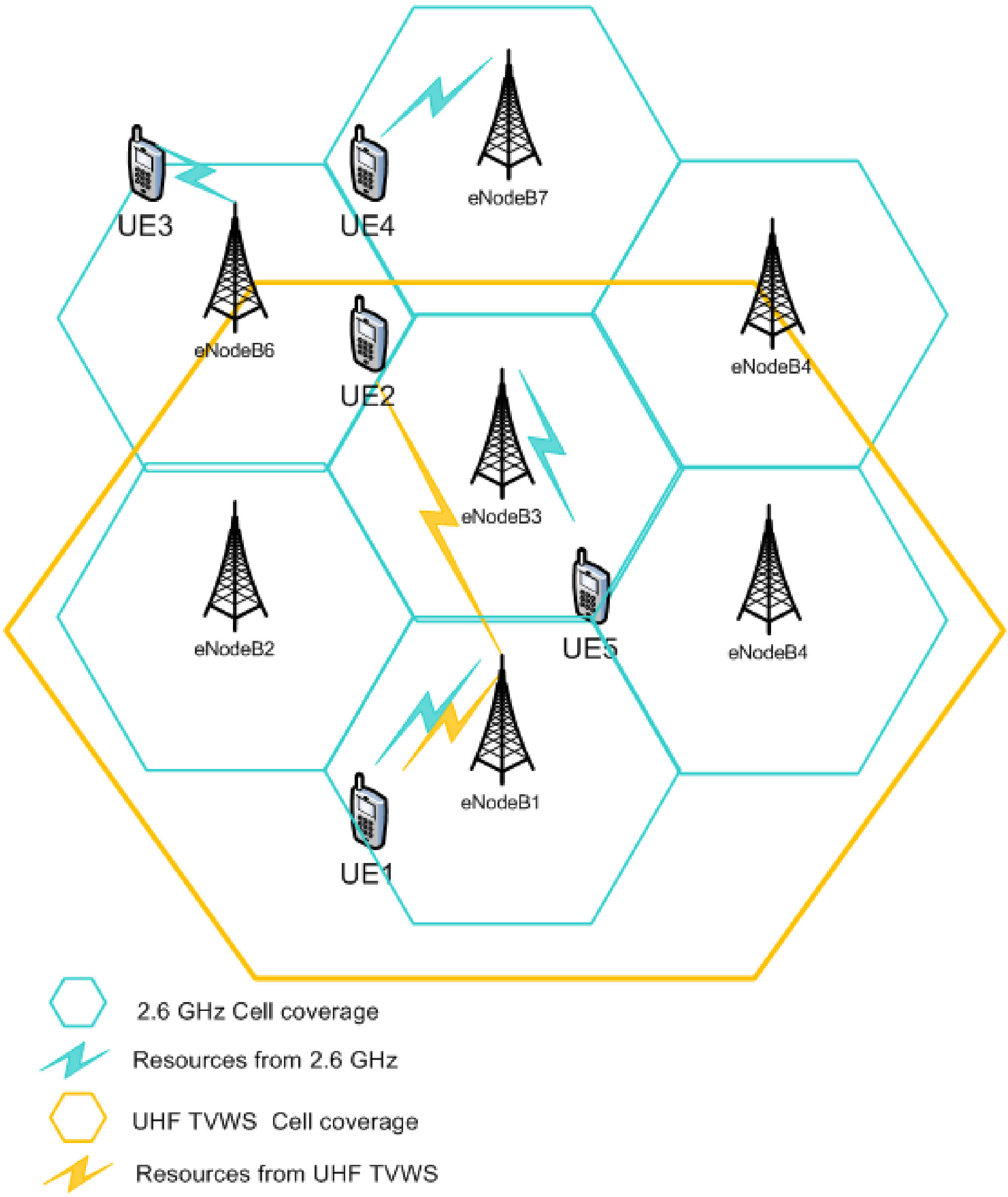

Figure 17: Intra-Cell Spectrum Aggregation

3.1.2 Inter-Cell Spectrum Aggregation Storyline

The storyline regarding the inter-cell spectrum aggregation scenario is similar to the intra-cell one. The main difference is related to the collaboration among neighboring base stations. This is mainly related to the Cooperative Power Control among users accessing TVWS; the users associated to neighboring base stations cooperate for the identification of their optimum transmission power.

The storyline of the inter-cell spectrum aggregation is described by the following steps:

1. Periodically, the sensing configuration system identifies which is the most suitable sensing algorithm for the considered environment. The decision is made locally in the user equipment, using local information and information stemming from the base station as well.
2. A user wants to have access to a specific service. The local sensing algorithm senses the environment in order to detect primary signals in the considered area.

3. The spectrum access control algorithm decides whether a user shall be permitted to operate in TVWS. Considering the fact that no primary users are in the area under discussion, the users will be granted access to the TVWS.
4. The cooperative power control algorithm located in the terminals identifies the transmission power of each device (i.e. user equipment) participating in the scheme. It must be clarified that among the users that are associated to the same base station the operation of a cooperative power control scheme is not required. However, such scheme is necessary for coordination among users associated to neighbouring cells; the base station at this case operates for information fusion among the user equipments in the area under consideration.
    a. Every user equipment belonging in the scheme sets its transmission power and forwards this information to the base station and its interference price as well.
    b. The base station forwards this information to the neighbouring base stations which also forward it to the user equipments belonging in the scheme.
    c. The user equipments identify their transmission powers and repeat the steps 4.a – 4.c.
5. The base station, using the user and flow partitioning algorithm, decides the optimal aggregation of the available spectrum, so as to fulfil users' demands.
6. Then, primary users appear in the environment and are detected by a subset of the opportunistic users using their local sensing algorithms; such information is communicated to the spectrum access control algorithm (operating in the user equipment) from the sensing configuration system.
7. The spectrum access control algorithm executed distributed in each User Equipment decides whether the user will be allowed to transmit in the TVWS taking into account the primary outage probability to ensure that the interference which the primary users perceive will not exceed a maximum allowed threshold
8. The users (using the cooperative power control) proceed in transmission power adjustment, due to the change in the context.
9. The base station (user and flow partitioning algorithm) decides the optimal aggregation of the available spectrum so as to fulfil user demands.

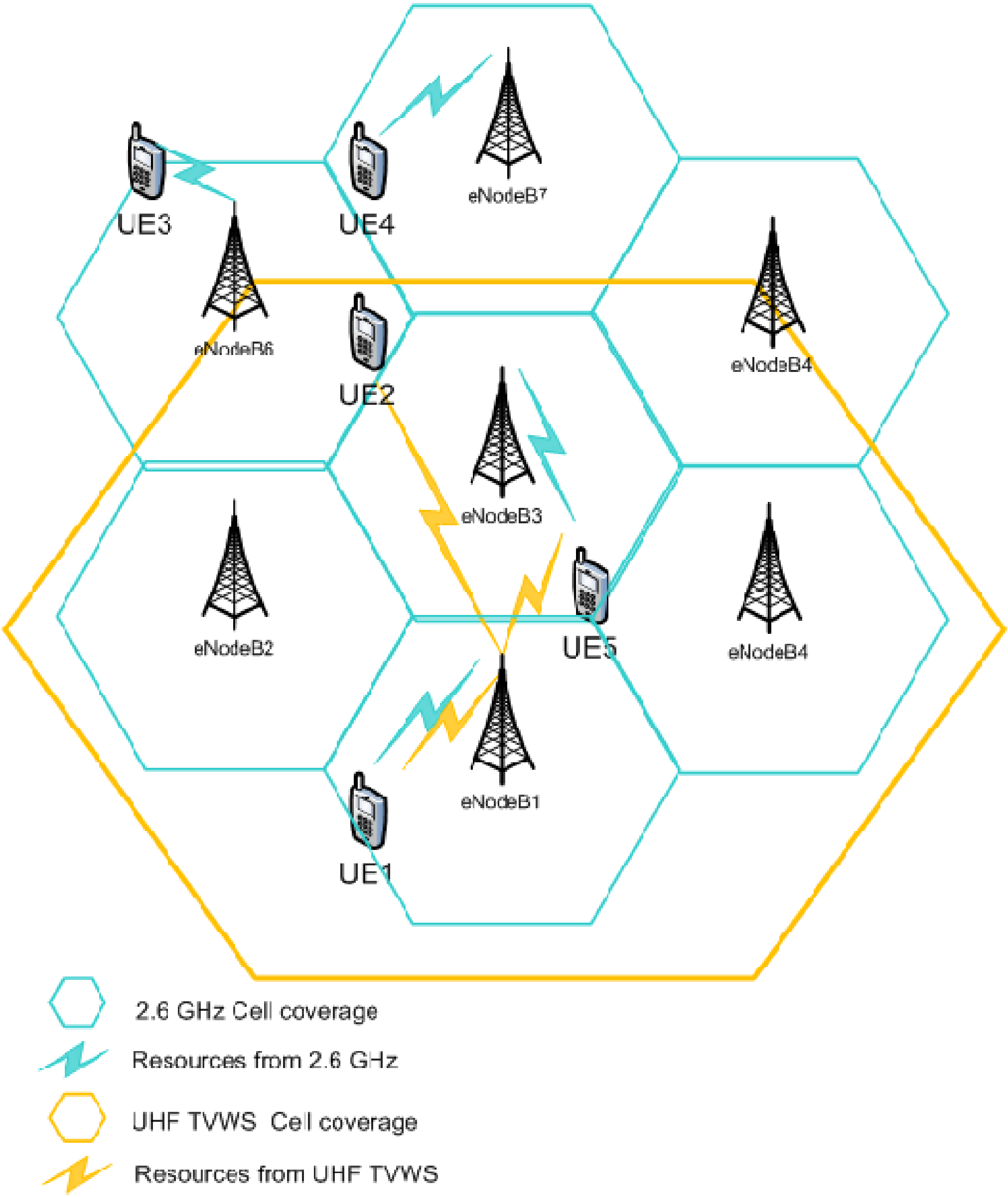

Figure 18: Inter-Cell Spectrum Aggregation

3.1.3 System Architecture

Considering that the previously intra- and inter- cell spectrum aggregation scenarios are focusing on LTE-A environments it is of prime importance to map the identified functionalities in the LTE-A system; Figure 19 provides such mapping. The Cognitive Engine, the Cooperative Sensing, and the Information Management are located both in eNodeBs and UE. The eNodeB also incorporate Cognitive RRM functionalities. All the entities obtain the required policies from the corresponding core network entity. It should be noted the fact that the even though there have been identified two separate scenarios (intra- and inter- cell) the same functionalities are being invoked; the main difference between the two cases is the absence of the Cooperative Power Control because such functionality is not required in the intra-cell scenario.

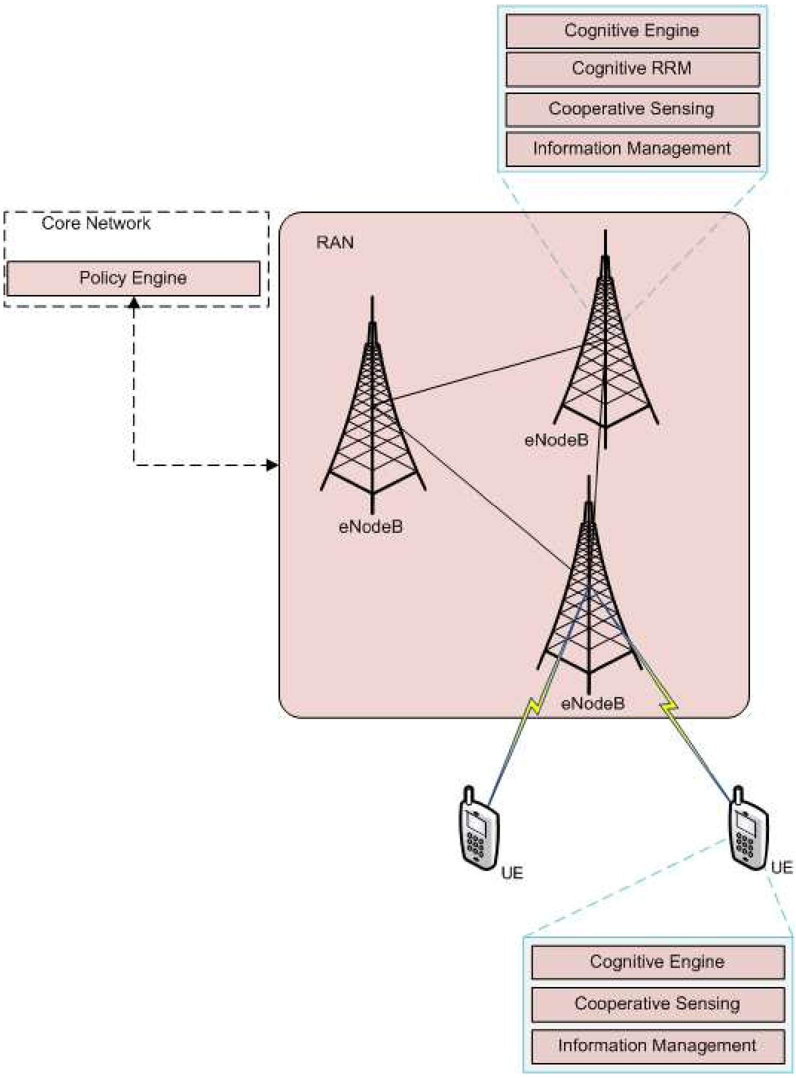

Figure 19: Inter- and Intra- cell Spectrum Aggregation Architecture

3.2 COGNITIVE RELAYS SCENARIOS

The use of Relay Nodes (RNs) is one of the main directions considered by 3GPP as a promising paradigm which is expected to increase spectral efficiency, optimized resource allocation and efficient heterogeneous planning. Relay Nodes are small-sized base stations operating at low power levels; they are used for providing enhanced coverage and capacity at cell edges, or connection to remote areas without fiber infrastructure.

RN is expected to be connected to the eNodeBs via a radio interface whilst the radio resources are shared among the UEs which are served directly by either the Donor eNodeB or the RN [13]. Two types of RNs have been identified, based on whether they use the same frequency as the Donor eNodeB or not. In the former case, it should noted the fact that the RNs could suffer from self-interference issues which could be surpassed with a time sharing scheme between transmitting and receiving, or by placing the transmitter and the receiver at different locations.

Cognitive Relays use case as it has been thoroughly described in D1.1b [8] it can be separated into two sub use-cases; the conventional relays and the cognitive relays with intelligent processing. As this use case has not been evolved in the SACRA context, in this section we provide only two indicative scenarios, one for each sub use-case, and the probable invocation of the mechanisms described in section 2 to these scenarios.

3.2.1 Conventional Relays Scenario and Radio Resource Management Components invocation description

3.2.1.1 Conventional Relays Scenario description

An indicative network topology which involves conventional relays is depicted in the following Figure 20 .We consider 2 operators (A and B) equipped with two eNBs and two RN each. In the case where eNB and RN concurrently serve a UE we assume that eNB provides one carrier from the TVWS band and RN one carrier coming from the licensed bands (2.6GHz / DD bands). UE1 and UE3 are licensed under operator A and receive two separate component carriers form the two frequency bands; one from their serving eNB and one from the RN. Particularly UE1 communicates with RN2A through licensed band and with the donor eNB1A through TVWS. Similarly, UE3 communicates with RN2A through the same licensed band and with the donor eNB2A through TVWS. We assume that UE2 and UE4 have traffic demands that necessitate the use of two carriers: one on licensed band from the RN and one on TVWS from the donor eNB. As TVWS carriers have been allocated for users in the considered scenario, Radio Resource Management mechanisms are required to exploit optimally the available resources. Furthermore, the considered scenario highlights a potential interference problem between UE2, UE4 (operator A) and UE1, UE3 (operator B) which transmit in TVWS. In this scenario cooperative power control between UE2-UE4 and UE1-UE3 must take place. UE5 and UE7 communicate with their serving eNB2B in the licensed spectrum. UE6 is out of the coverage range of operator A eNBs and thus a relaying operation takes place through RN1A. UE8 is served only by eNB1B while UE9 is served concurrently by eNB1B (TVWS) and RN3B (licensed band). The presence of primary users (PU) introduces the need for the secondary Spectrum Access Control (SAC) algorithm.

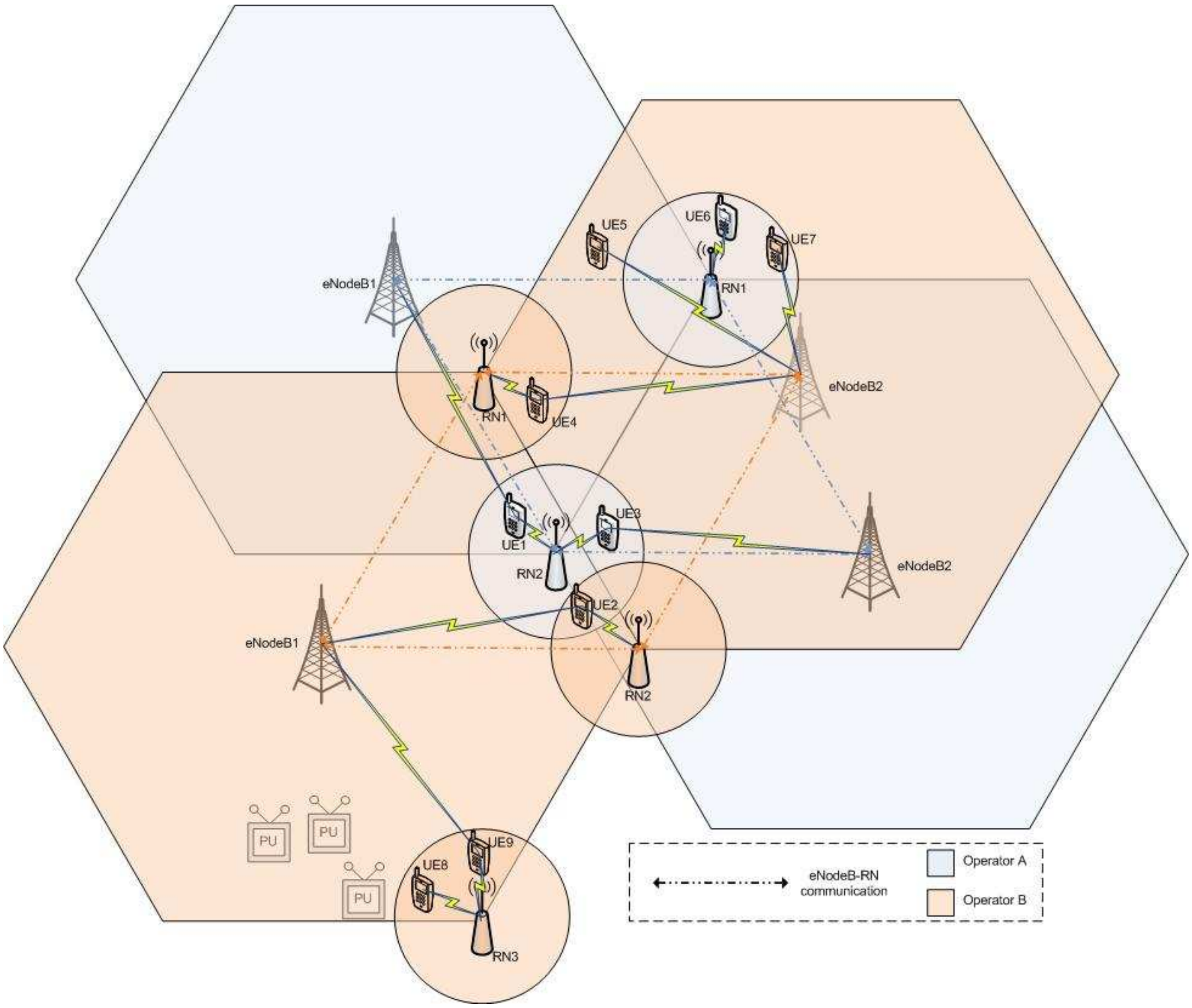

Figure 20: Conventional Relays scenario

In the considered scenario it is assumed that UE2 needs to be assigned with two component carriers in order to satisfy his traffic demand: one through the RN2B (2.6GGHz/DD band) and one directly from the eNB1B (TVWS).

The storyline of the capacity limited scenario for conventional relays is described in the following steps:

1. Periodically, the sensing control and configuration system identifies which is the most suitable sensing algorithm for the considered environment as well as the most appropriate configuration settings. The decision is made in the UE, using both local information and information stemming from the serving RN. The RN is assigned with the tasks of the eNB (i.e. RN selects the parts of the spectrum to be sensed, schedules the sensing task and finally sets the sensing configuration parameters).
2. We consider that UE2 wants to have access to a specific service that necessitates the assignment of two component carriers: one from RN2B (licensed band) and one from eNB1B (TVWS). The local sensing algorithm senses the environment in order to detect PU transmissions over the TVWS in the considered area.
3. The spectrum access control (SAC) algorithm decides whether a UE shall be permitted to operate over the TVWS or not. In the considered scenario the following users have

requested additional resources: UE1, UE2, UE3, UE4, UE8 and UE9. Five out of these six users (i.e. UE1, UE2, UE3, UE4 and UE9) are located far from the PUs and thus, the SAC algorithm will grant permission to transmit over TVWS band to all of them. Regarding UE8, SAC algorithm does not allow its transmission over TVWS, based on the measured maximum outage probability of a neighbouring PU.

4. After secondary users have been granted access to TVWS band, the cooperative power control (CPC) algorithm is executed in order to reduce mutual interference among those users and also to maximize the network utility function (as expressed in D3.3 [3]). In the considered scenario, such interference issues may exist only between UE2-UE4 and UE1-UE3 which belong to different operators and transmit opportunistically over the TVWS. Regarding UE5, UE6 and UE7, CPC execution is not required as these UEs transmit only over a licensed band. The transmission power and interference price updates for every UE are disseminated to all the other UE that participate in the secondary users' cooperative scheme (through their serving RNs and corresponding eNBs). For example UE2 transmits its power and interference price update to RN2B through the LTE interface and then this information is disseminated from RN2B to eNB1B. In turn eNB1B sends this information to its neighbouring eNB1A. In this way every UE gets informed about the power and interference price updates of every other UE. Further details on the information exchange scheme are available in D3.2 and D3.3 [2][3].
5. The final RRM mechanism that participates in the considered scenario is the user and flow partitioning algorithm. The following network entities cooperate to determine the optimal allocation of the available resources: eNodeB1B, RN1B, RN2B, RN3B, eNodeB1A, RN2A which is executed by RN3B. The decision making mechanism attempts to maximize the satisfied opportunistic users while minimizing the probability to occupy a Physical Resource Block (PRB) that is used by a PU.
6. The steps 1-5 are executed in iterative way (similar to the afore described Spectrum Aggregation scenario) so as to capture any changes in the environment (i.e. appearance of primary users, mobility of opportunistic users, deviation of QoS requirements etc.)

3.2.1.2 System Architecture

The purpose of this section is to provide the parts and the way each component is distributed in the considered Network Elements of the Conventional Relays Scenario. As depicted in Figure 21 several Functional Blocks are used over the considered scenario in eNodeBs, RNs and UEs. It is worth noticing that UEs receiving carriers only from eNodeB are not participating in the Cognitive Radio Resource Management system. This is due to the fact that these users receive only LTE carriers as mentioned in the detailed description of the Conventional Relays Use Case in D1.1b [8].

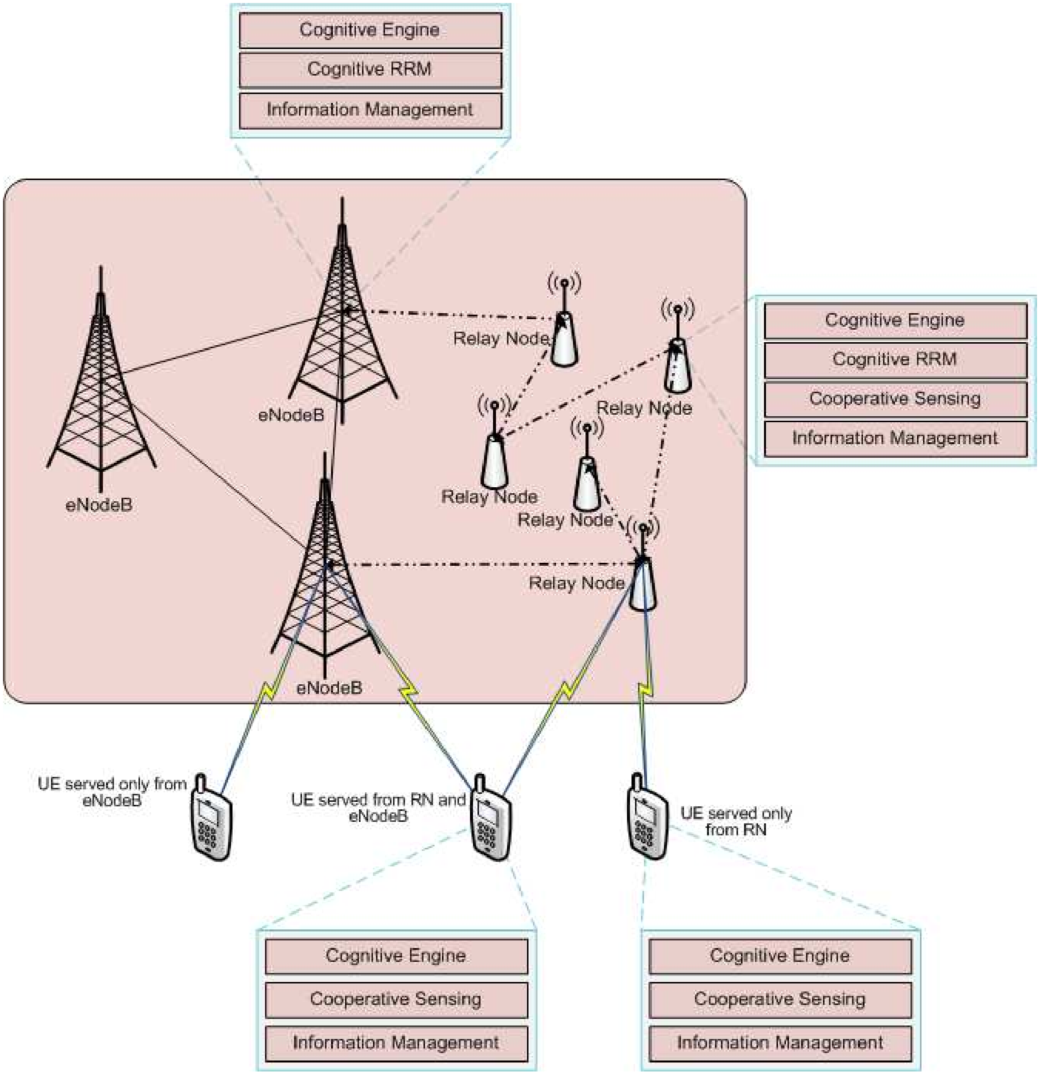

Figure 21: System Architecture for the Conventional Relays Scenario

3.2.2 Cognitive Relays with intelligent processing and Radio Resource Management components invocation

3.2.2.1 Cognitive Relays Scenario description

Similarly to the Conventional Relays in this section we provide a scenario for the Cognitive Relays with intelligent processing. An indicative network topology involving cognitive relays is depicted in the figure below:

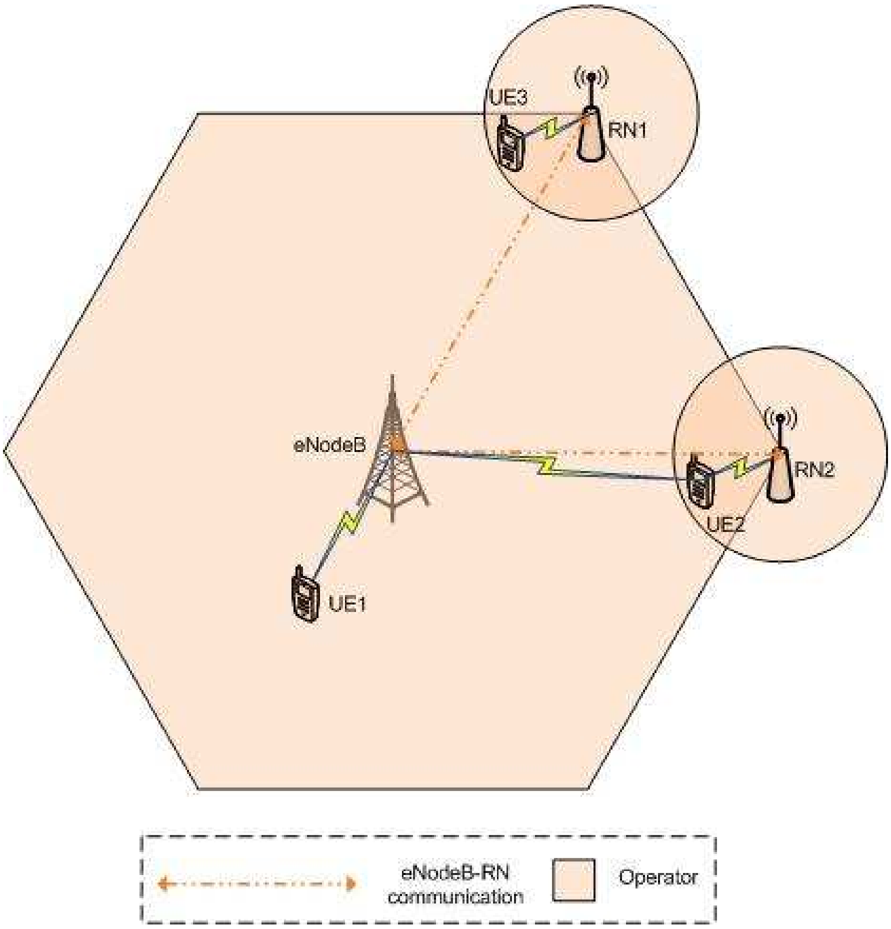

Figure 22: Cognitive Relays with intelligent processing scenario

Cognitive RN have access to the data that eNB is transmitting to a UE (through eNB retransmissions or communication with the core network) and take this information into account for resource planning. From this knowledge capability of RN we can derive the following cases:

- RN2 senses the data destined from eNB to UE2 and assists the retransmission over the same carrier frequency achieving an increase in spectral efficiency.
- RN1 allocates the same carrier to UE3 that BS has allocated to UE1 using appropriate interference cancellation techniques.

Considering a dense and heavy loaded environment, a possible storyline for the second case of cognitive relays is described below:

1. RNs are sensing the spectrum for retransmissions between eNBs and UEs.
2. Based on this information, an adapted version of user and flow partitioning algorithm can be used to assign PRBs to UEs served by a RN. In this scenario primary users are considered the ones served by the eNB. Thus, user and flow portioning algorithm aims to maximize the number of satisfied UEs served by the RN while minimizing the probability that a PRB is used by a UE served by eNB.
3. Due to the considered overload situation scenario two or more users could be scheduled with the same set or overlapping set of PRBs. This necessitates the execution of cooperative power control algorithm in order to mitigate the induced interference (alternatively interference cancellation techniques may take place).

3.2.2.2 System Architecture

The purpose of this section is to provide the parts and the way each component is distributed in the considered Network Elements of the Coognitive Relays with intelligent processing scenario. As depicted in Figure 23 several Functional Blocks are used over the considered scenario in RNs and UEs. As it can be noticed the system architecture is different between the Conventional Relays scenario and the Cognitive Relays scenario. Sensing tasks have been moved from the UE to the Relay Node, so as to detect retransmitted packets. Furthermore, eNodeBs and UEs that are served only from the eNodeB do not participate in the Cognitive Radio Resource Management system in the considered scenario. This is due to the fact that eNodeB serves only users in the LTE carriers as also described in the corresponding use case in D1.1 version 2.0 [8].

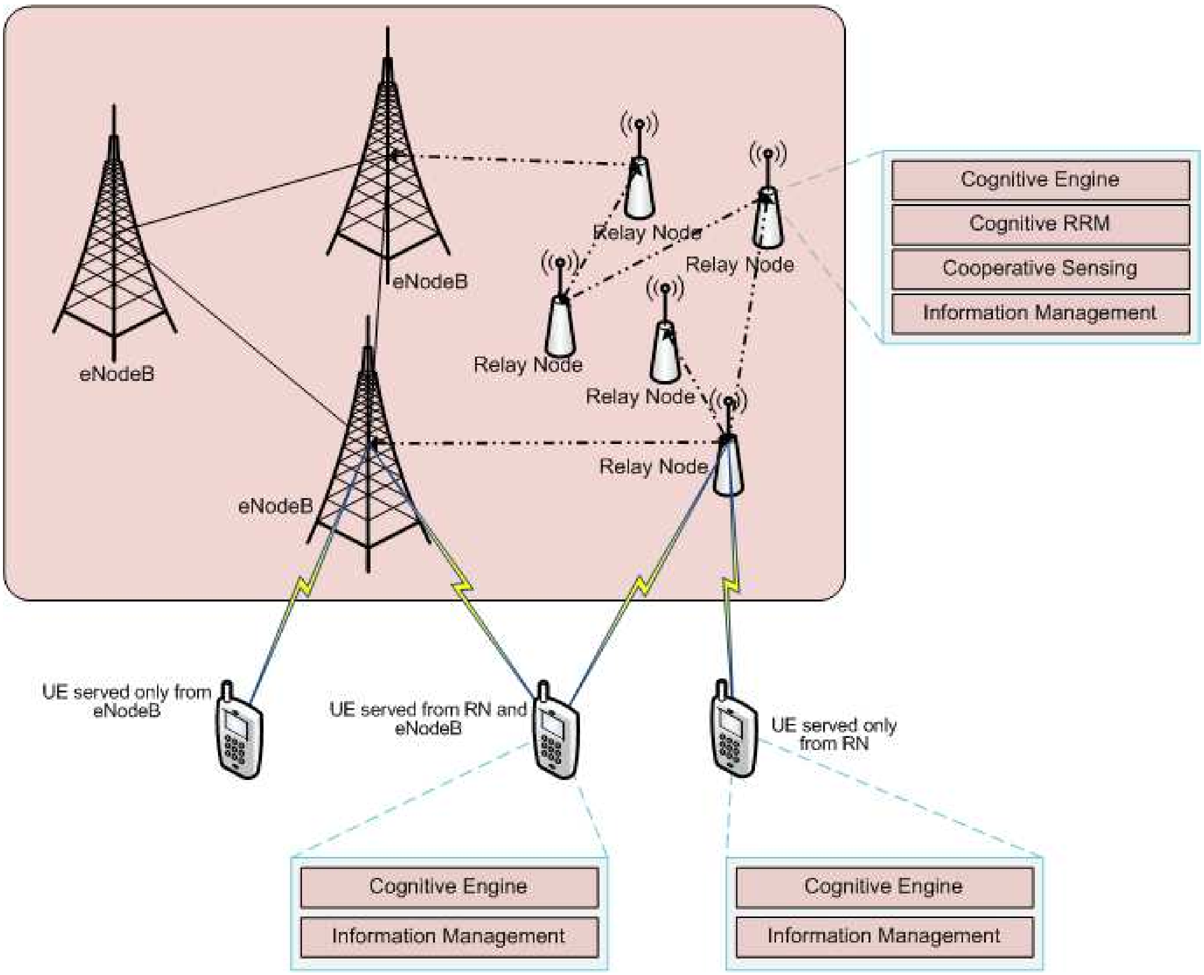

Figure 23: System Architecture for the Cognitive Relays with intelligent processing scenario

3.3 BROADBAND ACCESS AROUND HOME SCENARIO

The broadband access around home scenario aims at providing very high data rates to users who suffer from bad coverage conditions or severe shadowing. The main idea is to deploy special base stations called Home evolved Nodes (HeNBs) in the regions where the coverage provided by the macrocell base station (referred to as MeNB) is weak or unavailable. Based on Release 9 of 3GPP LTE-A, Home eNodeB refers to the deployment of small E-UTRA cells, in domestic, small office or home environments. The Home eNodeB interconnects with the 3G core / Evolved Packet Core (EPC) over a fixed broadband (e.g. DSL, Cable, etc.) access network.

The deployment of Home eNodeB enhances LTE coverage and at the same time ensures that capacity requirements will be met. The most straightforward way to reach the capacity requirements is to reduce the size of the cell; this is performed by deploying HeNBs. Coverage problems are the result of issues such as difficult urban terrain and the poor indoor penetration of high frequency LTE. HeNBs help deliver a rich data experience indoors and at the same time take the load of mobile data off the macro network.

Improved indoor coverage and capacity offload are not the only benefits from the deployment of HeNBs. HeNBs provide the opportunity to the operators to build incrementally their networks and also the flexibility to manage their networks in an efficient manner. Concluding, it should be noted that LTE HeNBs play a key role in enabling a wide spread adoption of LTE, and they will also play a key role in the enterprise and metro deployment areas.

3.3.1 Storyline and Radio Resource Management Components invocation description

As mentioned afore two types of eNodeBs are identified, namely HeNBs and MeNBs. HeNBs are connected directly to the network with a broadband connection, typically a DSL connection. In addition, HeNBs use the same licensed frequency spectrum as the one used by a MeNB which means that interference can occur between them. Figure 24 depicts HeNBs deployment around a principle MeNB. Typically, interference issues occur depending on the scenario as follows [14]:

1. Femtocell UE causes uplink interference to the neighboring femtocell base stations (see arrow 1 in Figure 24);
2. Femtocell base station acts as a source of downlink interference to the neighboring femtocell UEs (see arrow 2 in Figure 24);
3. Macrocell UEs act as a source of uplink interference to the nearby femtocells (see arrow 3 in Figure 24);
4. Femtocell UEs act as a source of uplink interference to the serving macrocell base station (see arrow 4 in Figure 24);
5. Macrocell base station causes downlink interference to the femtocell UEs (see arrow 5 in Figure 24);
6. Femtocells cause downlink interference to the macrocell UEs (see arrow 6 in Figure 24).

However, the above interference scenarios can be avoided if good resource and power allocation strategies are employed. In this context, user and flow portioning radio resource allocation and cooperative power allocation algorithms defined in deliverable D3.2 [2] can be used in order to handle the problem of interference mitigation between neighboring femtocells and between the femtocell and macrocell. First, the user and flow portioning algorithm is executed in order to schedule users in each cell according to channel quality, sensing information (sensing decision, probability of detection and probability of false alarm) and stochastic activity of the surrounding cells (probability of transmission). Second, the cooperative power allocation algorithm can be adapted and utilized in order to find an optimal power allocation strategy for the network formed by the macrocell and the neighboring femtocells. Note that, in the case of radio resource allocation the macrocell and the femtocells consider the surrounding cells as a primary user which means that in addition to user satisfaction, a probability of collision must be minimized (see deliverable D3.2 [2]). Finally it should be noted that cases that the system is getting overloaded and exhaustive reuse causes very strong interference issues could occur. Such cases are identified as the network states that the Cooperative Power Control algorithm will not be beneficiary and interference will exist even after the execution of the algorithm. Under these circumstances, the cognitive SACRA users use their spectrum sensing capabilities and use the spectrum holes in the unlicensed band, thus exploiting the benefits of a Sensing Control system that will fine-grain the sensing procedure.

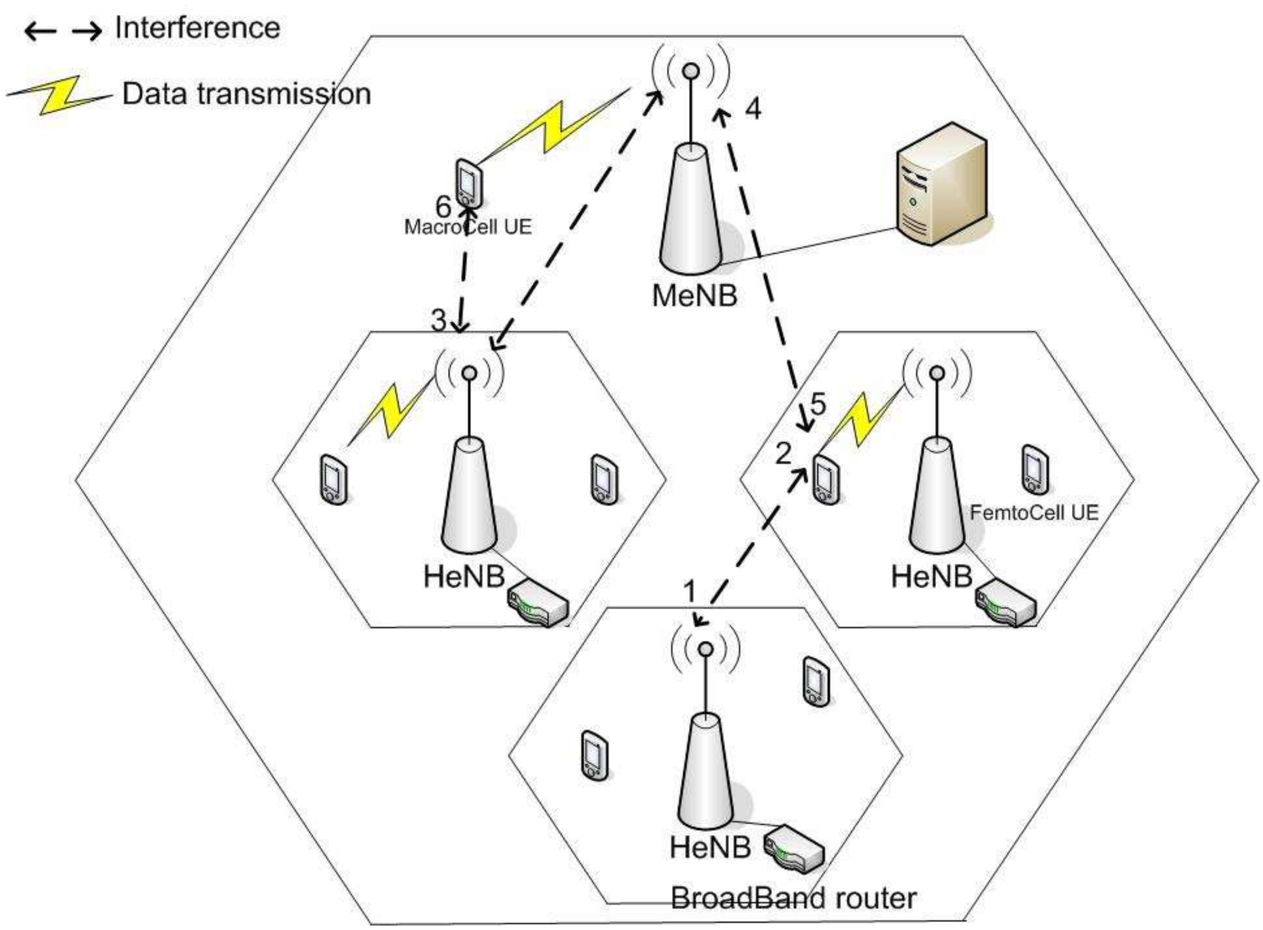

Figure 24: Broadband access around home scenario

3.3.2 System Architecture

In this section the way each Radio Resource Management component invoked in the scenario described above is distributed among the considered Network Elements is given. Figure 25 below highlights the functional blocks that are involved in the Broadband Access Around Home scenario based on the invoked mechanisms described afore in section 3.3.1. As it is shown in the figure sensing capabilities of SACRA cognitive users are exploited in cases of strong interference and the sensing information disseminated to the HeNBs and the MeNB could assist the MeNB to use TVWS to serve its users.

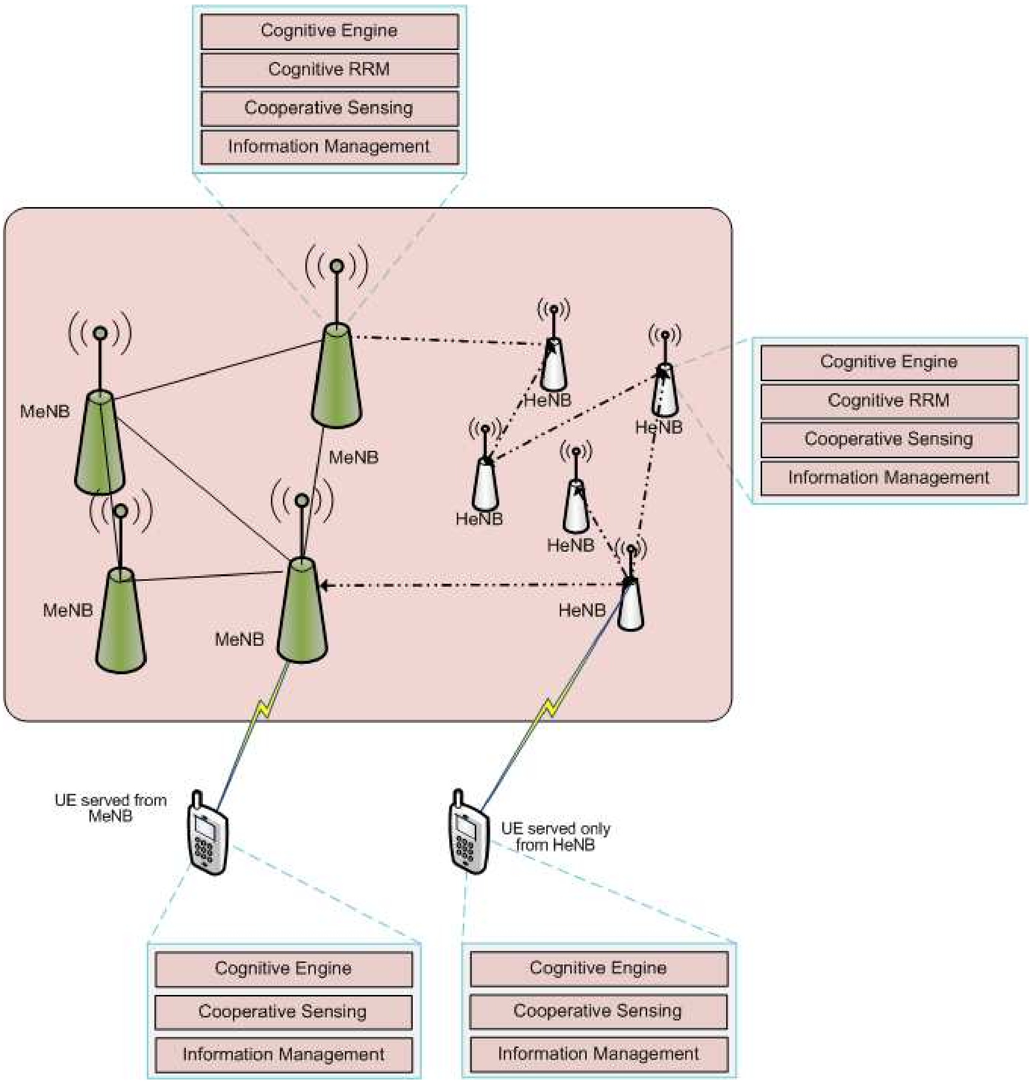

Figure 25: System Architecture for the Broadband Access around home scenario

4 ADVANCEMENTS OF RRM COMPONENTS

This section provides advancements of the Radio Resource Management techniques described in detail in previous WP3 deliverables. The content of this section is twofold. On the one hand additional assessment results that have not been reported in previous deliverables are given in section 4.1. The provided results comprise a combined assessment of the Spectrum Access Control algorithm and the Cooperative Power Control algorithm. On the other hand we present improved problem formulation regarding the user and flow partitioning algorithm. The proposed solution for multi-cell environment is given in section 4.2.

4.1 COMBINED ASSESSMENT OF THE SECONDARY ACCESS CONTROL AND THE COOPERATIVE POWER CONTROL MECHANISMS

In SACRA deliverable D1.1b [8] a series of definitions were given so as to set the directions for WPs further work. Proposed scenarios, use cases and system requirements were also defined in detail in D1.1b [8], in order to be used throughout WPs in conjunction to a set of indicators that capture the targets of the SACRA project. More specifically, an indicator reflects a certain technical feature; each indicator is evaluated by metrics that act as quantitative measures of the degree to which a process possesses a given indicator. As the Radio Resource Management system comprises a set of components (i.e. core mechanisms, learning techniques, rules and policies relying in policy engine etc.) it is important to identify how each process deals with the SACRA indicators. Such analysis has been already provided from WP3 point of view and has been reported in deliverable D3.2 v2.0 [2]. Furthermore, performance assessment of the RRM components has been the main study of deliverable D3.3 [3]. However, all the evaluation outcomes reported in previous WP3 deliverables included only individual assessment of a single RRM component without any interactions with the rest of the RRM system. Thus, it is important to provide combined assessment evaluation of at least a subset of the WP3 mechanisms. Thus, we present here a joint assessment of the Spectrum Access Control algorithm and the Cooperative Power Control algorithm.

4.1.1 Evaluation Environment and Scenario

In this section we provide the evaluation details that have been agreed for the joint assessment of the two Radio Resource Management components as well as the scenario upon the partners relied to evaluate the performance of their components. In the considered scenario we assume a set of N Cognitive Users that request from the system permission to transmit opportunistically in the TVWS band. The Spectrum Access Control algorithm is triggered and the system decides that a portion M of the initial number of users has been granted access to transmit opportunistically in TVWS at maximum power level. The decision taken is based on the primary outage probability approach that was described afore in section 2.4. Following the execution of Secondary Access Control, the Cooperative Power Control algorithm is triggered and the opportunistic users cooperatively decide the optimum transmission power levels taking into account interference caused to neighbouring users (from different operators). The twofold objective of the Cooperative Power Control is depicted in Equation 1 presented afore in section 2.1. Figure 26 shows the flow of execution of the considered scenario.

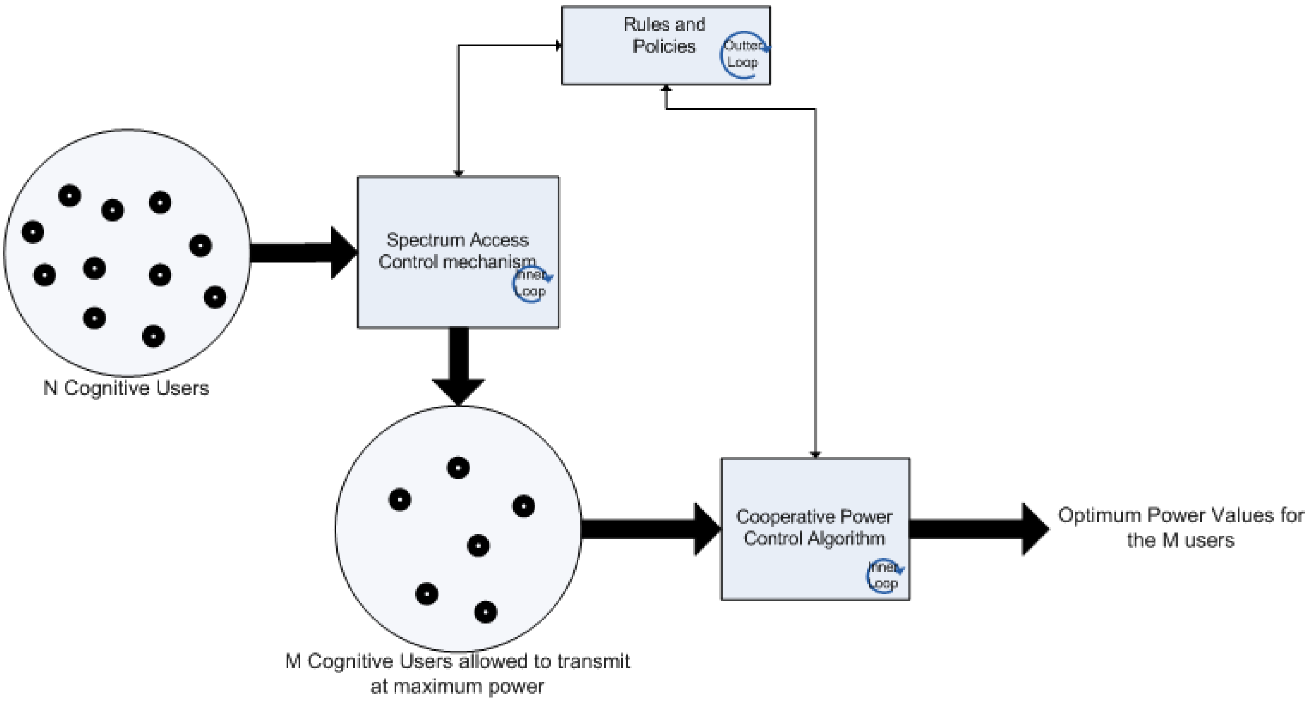

Figure 26: Joint Assessment flow

4.1.2 Spectrum Access Control evaluation

In this section, we present the results of the Spectrum Access Control Algorithm. These results are presented for the 15 randomly generated topologies in terms of per-user capacity.

Secondary transmitters may communicate with their respective receivers of distances $d < R_p$ from the eNodeB. We assume that the PU and the SUs are randomly distributed in a two-dimensional plane. The channel gains are based on the COST-231 Hata model including log-normal shadowing with standard deviation of 10dB, plus fast-fading assumed to be i.i.d. circularly symmetric with distribution CN(0, 1). It is assumed that the maximum outage probability q = 1%. We considered also that the radius of the secondary cell R = 1000 meters and the radius of the primary protection area R_p = 600 meters.

In the figures presented below, we have verified the first goal of the proposed methods, maintaining the outage probability of the PU to an acceptable level and avoiding any degradation beyond a certain interference threshold and showing under this constraint the Capacity achieved by users 2 to 11 for each instance which are the SU users and the primary user is indexed as user 1.

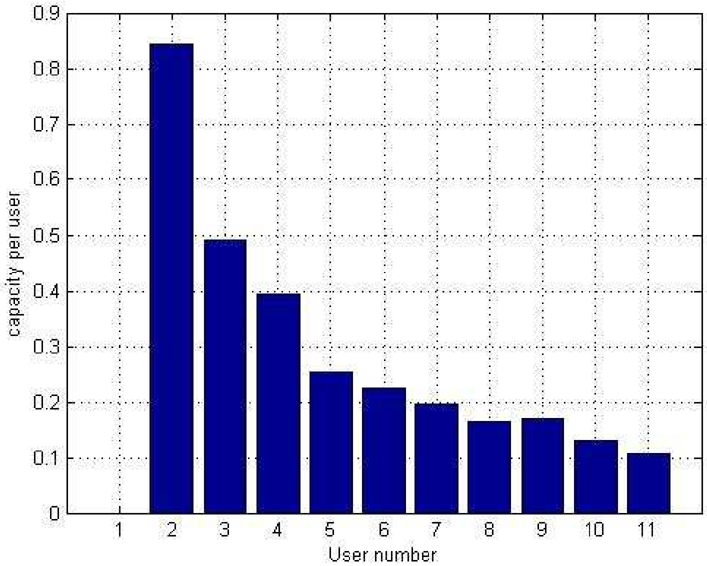

Figure 27: Capacity per user for topology 1

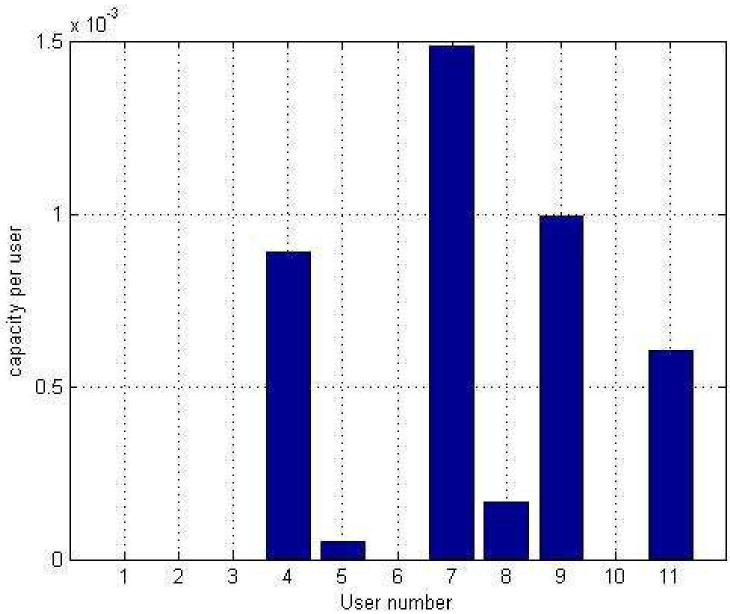

Figure 28: Capacity per user for topology 2

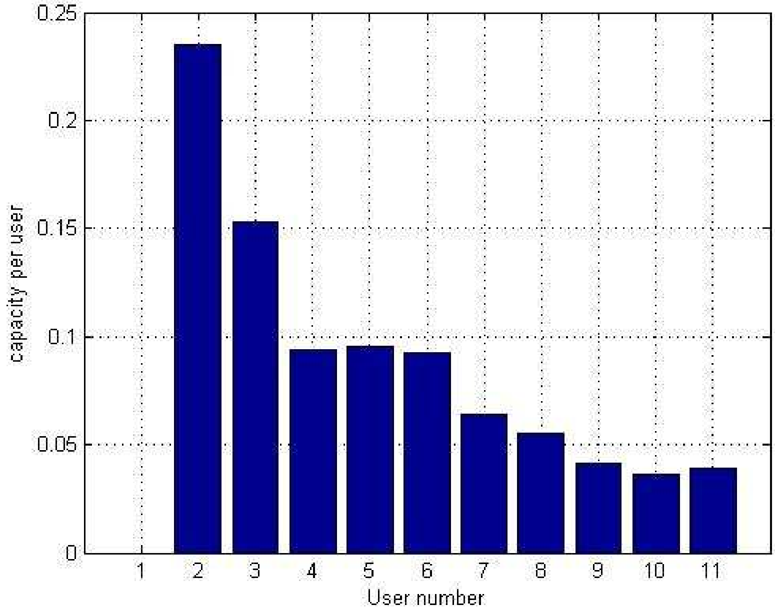

Figure 29: Capacity per user for topology 5

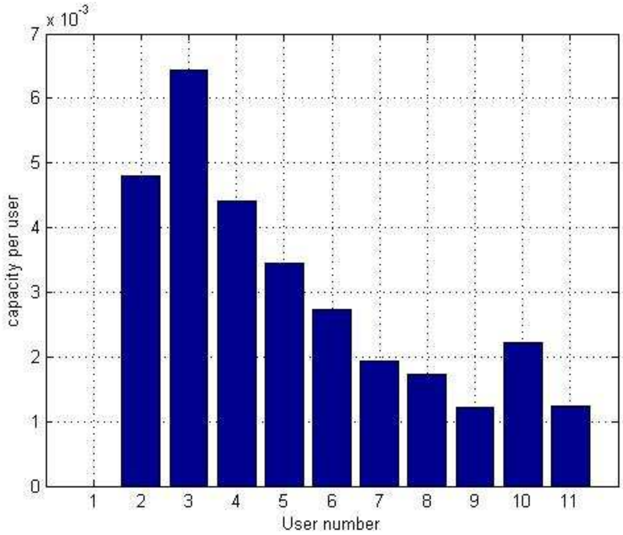

Figure 30: Capacity per user for topology 10

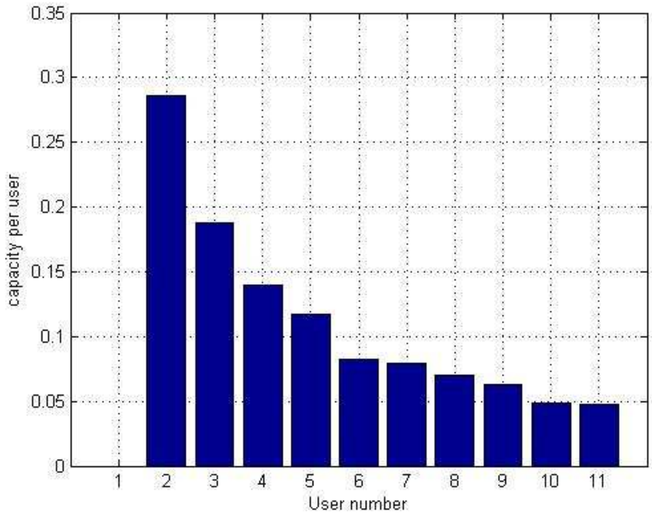

Figure 31: Capacity per user for topology 15

4.1.3 Cooperative Power Control evaluation

The performance of the cooperative power control algorithm is evaluated through extensive MATLAB simulations; as basis for the algorithm's evaluation a scheme of maximum power value assignment is considered as well as a state of the art approach that does not incorporate the fuzzy logic and the α (alpha) factor introduced in our approach in [5] which has been thoroughly described in [1][2]. Regarding the comparison against the Maximum Power approach, the main objective is to evaluate how the proposed solution performs, compared to a simplified scheme of no cooperation between UEs and transmission in arbitrary transmission power values (i.e. in this case maximum power levels). The major difference between these two schemes is that in case of cooperation, UEs choose their transmission power considering both their needs for capacity but also the interference they cause to neighbouring UEs from other operators. Regarding the comparison against the state of the art approach, the main objective is to show that the proposed solution achieves better performance as it improves the situation perception of the UEs and copes with uncertainties that appear in real life systems caused from parameters such as non-ideal message exchange or high user mobility.

As shown in Figure 32 and Figure 33 we have conducted 15 experiments with random topologies of a small number of users (i.e., 5-15). The input for our evaluation is actually the output of the Spectrum Access Control component (i.e. portion of *M* users out of *N* users that initially requested to transmit opportunistically). Figure 32 shows that the Cooperative Power Control algorithm with the fuzzy reasoner selects lower transmission power level for the Cognitive Users while in parallel, it achieves better network utilization in all the 15 cases as shown in Figure 33.

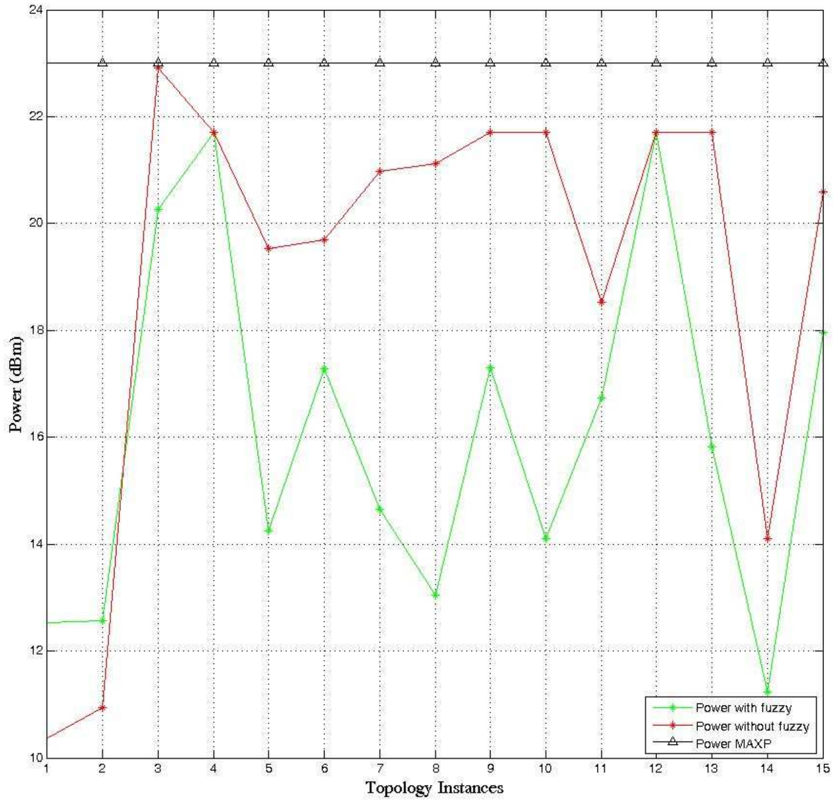

Figure 32: Mean Transmission Power Level for 15 random topologies

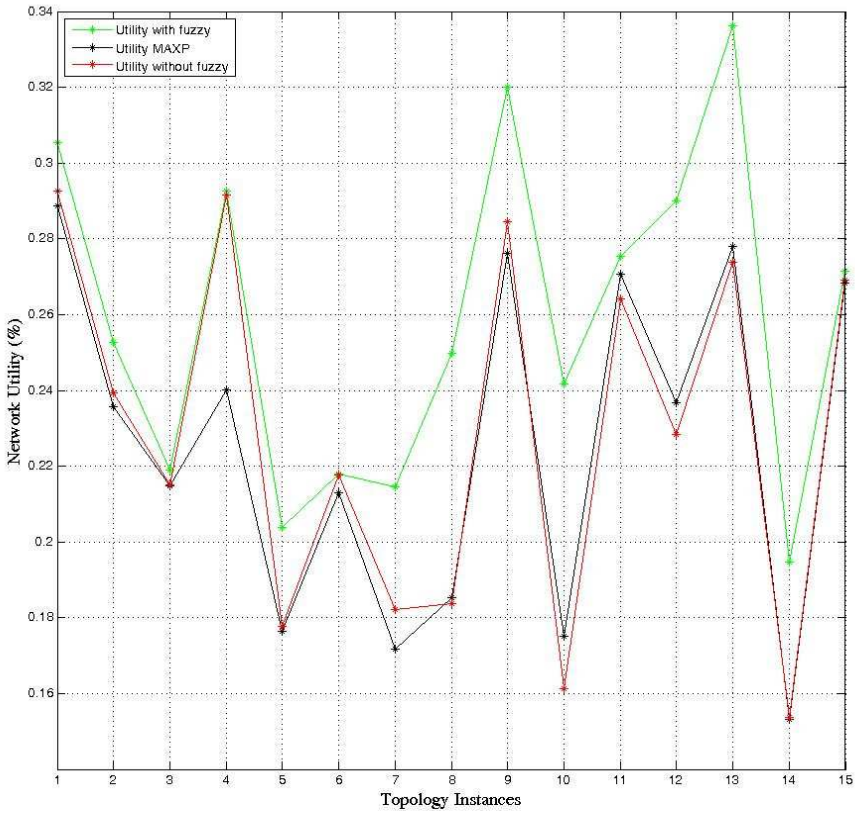

Figure 33: Network Utility for 15 random topologies

4.2 COMMON RADIO RESOURCE ALLOCATION FOR MULTI-CELL LTE-A NETWORK

4.2.1 System Model

In this section we consider the downlink of an LTE-A system with multiple cognitive LTE-A base stations (eNodeBs) serving multiple LTE-A users over frequency selective fading channels (see Figure 34). LTE-A users can communicate with their associated eNodeB using the 2.6 GHz band and access opportunistically the 800 MHz band that can be occupied by a primary user (PU). For downlink communication, we use the OFDM technology which means that each band is divided into M_1 and M_2 resource blocks, respectively. In addition, we assume that each eNodeB has perfect knowledge of the downlink channel state information (CSI) between itself and its associated LTE-A users, and between itself and the primary user (PU). We further assume that the LTE-A users can sense the 800 MHz band and determine, using a sensing algorithm, if a given resource block is occupied or not by a primary user. The sensing decision and the two probabilities of false alarm and detection are transmitted to the eNodeB through a set of dedicated sub-channels. In addition, eNodeB should not use reference signals in the opportunistic band because an interference threshold must be guaranteed to the PU. However, the eNodeB can use the information from the secondary access algorithm (see 2.4) to estimate channel gains towards the primary user. Finally, we assume that primary and secondary Synchronization channels and the Broadcast channel are present in the 2.6 GHz band.

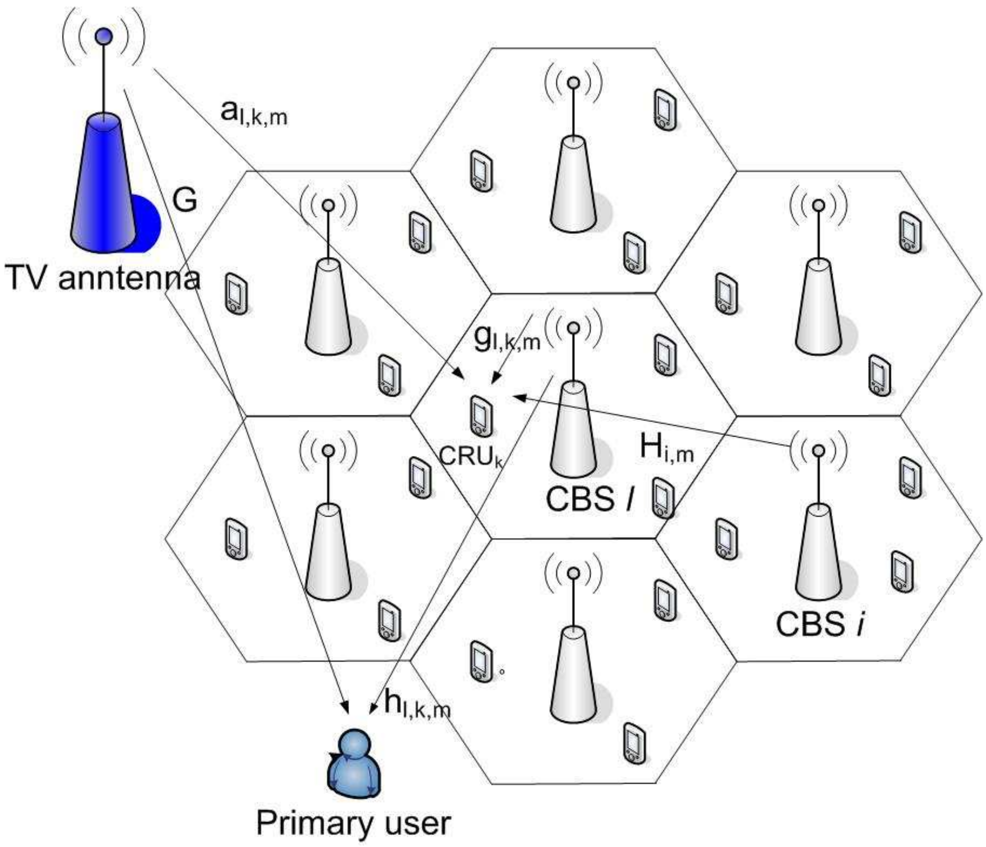

Figure 34: Inter-cell spectrum aggregation problem

Let N, K_l, M_1, M_2 denote the number of eNodeBs, number of LTE-A users served by eNodeB l, the number of blocks in the principle component carrier and the number of blocks in the secondary component carrier, respectively. Let $t_{l,k,m}$ denote the throughput of user k served by eNodeB l using resource block m. $t_{l,k,m}$ is given as follows:

$$t_{l,k,m} = B \log_2 \left(1 + \gamma_{l,k,m}\right)$$

Equation 13: Throughput of user *k* served by eNodeB *l* using resource block *m*

where,

- B is the bandwidth of a resource block (B=180kHz in the LTE-A standard),
- $\gamma_{l,k,m}$ is the Signal to Interference-plus-Noise Ratio (SINR) of user *k* on Resource block *m*.

Its expression is given as follows:

$$\gamma_{l,k,m} = \frac{g_{l,k,m} p_{l,k,m}}{\sigma^2 + I_{l,m}^{PU} + I_{l,m}^{CR}}$$

Equation 14: Signal to Interference-plus-Noise Ratio (SINR) of user *k* on Resource block *m*

where,

- $g_{l,k,m}$ is the channel gain from the target eNodeB *l* to user *k* on resource block *m,*
- $p_{l,k,m}$ is the transmit power used by eNodeB *l* to serve LTE-A user *k* on resource block block *m,*
- σ the noise standard deviation.
- $I_{l,m}^{PU}$ and $I_{l,m}^{CR}$ are respectively the interference power generated by the primary user and the neighbouring eNodeBs.

There expressions are given as follows:

$$I_{l,m}^{PU} = a_{l,k,m} P$$

Equation 15: Interference power generated by the primary user

where,

- $a_{l,k,m}$ is the channel gain from the primary user to the LTE-A user *k* on resource block *m* and
- P is the transmission power of the primary user.

$$I_{l,m}^{CR} = \sum_{i=1, i \neq l}^{N} p_{i,m} H_{i,m}$$

Equation 16: Interference power generated by the neighbouring eNodeBs

where,

- $H_{i,m}$ is the channel gain from the interfering eNodeB *i* to the target eNodeB *l* and
- $p_{i,m}$ is the power used by the eNodeB *i* to transmit on resource block *m*.

The total throughput of user k served by eNodeB *l* is:

$$T_{l,k} = \sum_{m=1}^{M_1} L_{l,k,m} t_{l,k,m} + \sum_{m=1}^{M_2} \left(1 - \alpha_{l,m}\right) L_{l,k,m} t_{l,k,m}$$

Equation 17: Total throughput of user k served by eNodeB *l*

where,

- L is the resource block assignment indicator. $L_{l,k,m}$ = 1 if resource block *m* is allocated to user *k* by the eNodeB *l*. $L_{l,k,m} = 0$ otherwise.
- $\alpha_{l,m}$ is the confidence parameter. It is the probability that a block *m* is truly occupied, given that the sensing algorithm working in the eNodeB *l* identified it as non-occupied. Its expression is given in terms of:
    - o probability of detection p_d^m,
    - o probability of false alarm p_{fa}^m and
    - o the probability of presence of the primary user p_q^m (see D3.2 delivrable).

4.2.2 Problem Formulation

The objective is to maximize the number of satisfied users in the system while keeping the interference caused to the primary user below a certain threshold. We recall that primary and secondary Synchronization channels and the Broadcast channel are present only in the 2.6 GHz band. The constrained optimization problem thus can be formulated as follows:

$$\max \sum_{l=1}^{N} \sum_{k=1}^{K_l} f_k\left(T_{l,k}\right)$$

$$\textit{subject to} \quad C1: \sum_{k=1}^{K_l} \sum_{m=1}^{M} L_{l,k,m}\, p_{l,k,m} \le P_l^{\max}, \forall l \in [1, N]$$

$$C2: \sum_{k=1}^{K_l} L_{l,k,m} \le 1, \forall l \in [1, N], \forall m$$

$$C3: \sum_{l=1}^{N} \sum_{k=1}^{K_l} \sum_{m=1}^{M_2} L_{l,k,m}\, p_{l,k,m}\, h_{l,k,m} \le I_{th}$$

Equation 18: Constrained optimization problem formulation

where,

- C1, C2, C3 are the constraints of the optimization problem. C1 means that the sum of the allocated power to all users in a given eNodeB *l* is below the power budget P_l^{max} of the eNodeB. The constraint C2 means that a given block *m* is allocated to at most one user in a given eNodeB. Finally, the constraint C3 means that the amount of interference caused to the primary user must be below the interference threshold parameter I_{th} of the primary user. Due to the assumptions introduced above, it is difficult to estimate the channel gains $h_{l,k,m}$ between the secondary and primary systems. Indeed since we are not using reference signals in the opportunistic band, it is impossible to estimate these gains. However, we assume that we can derive approximate values form inputs relayed by the sensing and especially the access control algorithms that actually approximate these gains.
- f_k is a satisfaction function: $f_k(x)=1$ is user k is satisfied, $f_k(x)=0$ otherwise. A cognitive user *k* is satisfied if its achieved throughput $T_{l,k}$ is greater than a given threshold. Typically this threshold depends on the type of traffic (or application flow) that is received by the cognitive user *k*.

4.2.3 Proposed solution

The problem described afore is a Mixed Integer Non Linear Programming problem that is known to be NP-hard. Since, we are in a multi-cell case the problem can be treated with a centralized approach. For this, we assume that an elected eNodeB will perform the scheduling of resource blocks belonging to the primary band. Let *t* be the index of the elected eNodeB. Let G_l^{PU} and G_l^{CR} define the set of CR users that will be served by eNodeB *l* in the primary component carrier (800 MHz band) and the secondary component carrier (2.6 GHZ), respectively. G_l^{PU} and G_l^{CR} sets are computed in each eNodeB *l* using a partition criterion such as the distance of each LTE-A user to the eNodeB. Once the partition is performed, each eNodeB *l* will use a local genetic algorithm to perform resource allocation of users belonging to the set G_l^{CR} in the secondary component carrier. In this case each eNodeB *l* will solve the following sub-optimization problem.

$$\max \sum_{k\in G_l^{CR}} f_k\left(T_{l,k}\right)$$

$$\textit{subject to}\quad C1: \sum_{k\in G_l^{CR}} \sum_{m=1}^{M} p_{l,k,m} \le P_l^{\max}$$

$$C2: \sum_{k\in G_l^{CR}} L_{l,k,m} \le 1, \forall m \in \left[1, M_1\right]$$

Equation 19: Sub-optimization problem

On the other hand, each eNodeB *l*, *l≠t* shall send the information related to the LTE-A users that belong to the set $G^{PU,l}$ towards the elected eNodeB *t*. The set of information include the SINR of each user in each resource block ($\gamma_{l,k,m}$) and the channel gains from each LTE-A user to the primary user ($h_{l,k,m}$). After receiving all the information, the elected eNodeB shall perform a resource allocation on the primary band by solving the following sub problem:

$$\max \sum_{k\in G_l^{Cglobal}} f_k\left(T_{l,k}\right)$$

$$\textit{subject to}\quad C1: \sum_{k\in G_l^{global}} \sum_{m=1}^{M} p_{l,k,m} \le P_l^{\max}$$

$$C2: \sum_{k\in G_l^{CR}} L_{l,k,m} \le 1, \forall m \in \left[1, M_1\right]$$

$$C3: \sum_{k\in G_t^{global}} \sum_{m=1}^{M_2} L_{t,k,m}\, p_{t,k,m}\, h_{t,k,m} \le I_{th}$$

Equation 20:Sub-optimization problem followed for resource allocation on the primary band

where, $G_t^{global} = \bigcup_{l=1, l\neq t}^{global} G_l^{PU}$.

5 CONCLUSIONS

Deliverable D3.4 entitled “Cooperative and Cognitive RRM Components and Architecture for the SACRA Scenarios” provides the description of the mechanisms developed in terms of WP3 in relation to the SACRA scenarios (i.e., Spectrum Aggregation, Cognitive Relays, and Home Broadband Access). Furthermore, given the fact that it is the final report of WP3, D3.4 provides the final version of the algorithms and the joint assessment of a set of the mechanisms. All the solutions of WP3 are described briefly with their learning and policy extensions; their mapping to the SACRA functional architecture is provided as well.

The first part of the document contains the mapping of the mechanisms in the functional architecture as it is defined by WP1 in D1.1b. The second part of this deliverable highlights the cooperative and cognitive parts of the RRM system in the SACRA scenarios. Thus, each scenario is being described using detailed storylines for the identification of the steps during the problem solving procedure at each case. Such procedure enables the mapping to the LTE-A system architecture for each scenario from WP3 point of view. Finally, the third part of D3.4 completes the analysis and extends the reported in D3.3 single and partially independent performance assessments of the SACRA CRRM.

This document is the final report provided in terms of WP3; taking into consideration the available inputs from previous reports of this WP (i.e., D3.1, D3.2, and D3.3) as well as other WPs (i.e., WP1, WP2, and WP6) identifies the key points of each mechanism and enables its incorporation in the SACRA system.

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7 ACRONYMS

ACK	Acknowledgement
CPC	Cooperative Power Control
CR	Cognitive Radio
CRN	Cognitive Radio Network
CRRM	Cognitive Radio Resource Management
CSI	Channel State Information
DB	Database
DD	Digital Dividend
eNB	evolved NodeB
HeNB	Home eNB
IID	Independent and Identically Distributed
LTE-A	Long Term Evolution-Advanced
MAC	Medium Access Control
MeNB	Macrocell eNB
NACK	Negative Acknowledgement
OFDM	Orthogonal Frequency-Division Multiplexing
PDP	Policy Decision Point
PEP	Policy Enforcing Point
PR	Policy Reasoner
PRB	Physical Resource Block
PU	Primary User
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RHS/LHS	Right/Left Hand Side
RN	Relay Node
RRM	Radio Resource Management
SAC	Spectrum Access Control
SACRA	Spectrum and Energy Efficiency through multi-band Cognitive Radio
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ration
SU	Secondary User

TVWS	TV White Spaces
Tx Power	Transmission Power
UE	User Equipment