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:	**D3.2**
Document title:	Intersystem networking for sharing & cooperation
Version:	1.0
Due date of document:	M20
Actual submission date:	December 6th, 2011
Lead beneficiary:	Institut Télécom
Participants:	Konstantinos Chatzikokolaki, Roi Arapoglou (UoA), Bassem Zayen (Eurecom), Abdoulaye Bagayoko (NTUK), Farouk Aissanou, Alain Petrowski and Djamal Zeghlache (Institut Télécom)

Project co-funded by the European Commission within the 7th Framework Programme		
DISSEMINATION LEVEL		
PU	Public	**X**
PCA	Public with confidential annex	
CO	Confidential, only for members of the consortium (including Commission Services)	

EXECUTIVE SUMMARY

The scope of this deliverable (D3.2) on intersystem networking for exchanging and sharing information between cognitive nodes or radios (terminals and base stations) has been extended to the specification of the SACRA CRRM algorithms to address concerns about the lack of detailed description of the SACRA CRRM algorithms in the first period. Each algorithm is described in terms of principle, modelling, criteria, objectives and resolution methods and with respect to its contribution to the overall CRRM system and its position in the system hierarchy.

The overall SACRA CRRM system composed of a hierarchy of algorithms is described in this document where each algorithm contributes to a key aspect in the complete cognitive radio resource management framework. The role and purpose of the algorithms are provided with their required inputs, key internal parameters and outputs. The algorithms address:

- the aggregation of carrier components from several bands to fulfil application requirements and achieve user satisfaction in throughput and delay performance while ensuring optimal partitioning of flows, sessions and users onto the aggregated resources;
- an opportunistic users access control to the incumbent spectrum using a probability of outage criterion of the primary users;
- a cooperative power control mechanism to enable opportunistic users to jointly optimise their respective power levels in a distributed and autonomous way relying only on the exchange of utility information among neighbouring nodes.

This is augmented by a sensing configuration module, whose aim is to select the best sensing algorithm based on signal to interference conditions. The module configures the selected sensing algorithm parameters to achieve a trade-off between sensing cost and efficiency.

Performance assessments for some algorithms and the contribution of each algorithm to the SACRA system spectrum and energy efficiency are reported. The analysis is conducted mostly for the spectrum aggregation use case even if the algorithms can be applied to other use cases. A dedicated section of the deliverable hopefully describes candidate LTE logical control channels and interfaces for data exchange and for cooperation between the cognitive terminals and base stations. The algorithms are analysed further to identify variables and portions that can be the subject to learning and reasoning enhancements. Future plans to enhance and consolidate the SACRA CRRM system are also mentioned.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

The original goal of this deliverable is to describe how data and information can be exchanged between SACRA cognitive radio resource management (CRRM) algorithms within or across systems by relying on sensing nodes(user terminals and base stations), including joint RRM when applicable. The document conducts for this purpose an analysis of the logical channel structure of the opportunistic system to identify the most appropriate control channels to exchange information using an in-band approach. The scope of the deliverable has been extended to provide details, beyond the conceptual description reported in the previous period, on the proposed CRRM algorithms to address the SACRA use cases for multi-band operation. The emphasis in this document is on the spectrum aggregation scenarios involving a LTE 2.6 GHz system and TVWS UHF corresponding to one of the central SACRA use cases.

The document describes consequently the proposed radio resource management algorithms meant to operate at different levels of the SACRA CRRM system and a sensing configuration module that interacts with the SACRA sensing algorithms. The algorithms are analysed in terms of input requirements and produced output and their contributions to cognitive radio resource management with emphasis on the spectrum aggregation use cases. The document also explores how the logical channels of the LTE system can be leveraged for exchanging information between nodes (terminals and base stations) to support the cooperative nature of some of the algorithms and supply the required inputs in terms of channel quality indicators and sensing results coming from the SACRA sensing algorithms. For the cooperative algorithms means to exchange information between cooperative nodes is also investigated, especially for a cooperative power control algorithm where nodes share their achieved utilities to set their power levels when opportunistically capturing free carrier components.

The document also describes how the SACRA CRRM algorithms contribute to spectrum and energy efficiency whenever applicable. The possibility of relying and introducing learning and reasoning in the proposed radio resource management algorithms or subsystem, such as the sensing configuration subsystem, is assessed with the objective of embedding these learning and reasoning capabilities in the algorithms. The algorithms have been the subject of independent feasibility tests and assessments that evaluated mainly their performance. This document reports some of the findings and will be used as a basis for the combination of the proposed algorithms, following the project work plan, as they address different aspects of radio resource management, spanning from partitioning of flows to secondary users access control and their cooperative power control.

1.2 DOCUMENT RELATIONSHIP TO TASKS AND RECOMMENDATIONS

This document relates to tasks WP3.1 to WP3.3 that have contributed to its content. These tasks cover the networking aspects for information exchange, the CRRM algorithms and the configuration of sensing to enhance resource usage and improve resource management. Milestone M3.2 on behavioural models, rules and policies specification served mostly as a structuring milestone for the CRRM algorithms and has contributed marginally to D3.2 except for the actual CRRM algorithms that are also reported in this milestone. Deliverable D3.2 acts as one of the preliminary roadblock to D3.3 on SACRA resource management assessment. The documents content has been extended to comply with the recommendations from the first period evaluation which suggested the inclusion of details on the CRRM algorithms. The document addresses the concern of lack of detailed specification of algorithms and the need to elaborate more on learning and reasoning. The algorithms are addressed in section 4 while the learning and reasoning aspects and approaches are discussed in section 7 and will be the object of further investigation in the third period where the CRRM will be combined and strengthened with learning capabilities.

2 ASSUMPTIONS AND SCENARIOS

The goal of this section is to set the stage for the data and information exchange analysis and the cognitive radio resource management for the SACRA envisaged use cases. The resource management algorithms reported in this document rely on the use cases and the spectral bands and systems they address. The emphasis for the use cases is on spectrum aggregation. As LTE is a central component of the use cases, SACRA inherits naturally a number of existing features in LTE that in turn define the scope of the CRRM studies. This also sets the basic assumptions for the proposed algorithms in this document. We review some of these basic assumptions.

SACRA extends the concept of spectrum aggregation defined in the release 10 of 3GPP LTE-Advanced standard, by considering a system capable of spectrum aggregation of:

- licensed spectrum in the 2.6 GHz and in the digital dividend bands;
- available spectrum in the TV white spaces band

SACRA proposes two additional features to allow a more dynamic behaviour of the operating network:

- the capability to use jointly and simultaneously the two bands, taking into account instantaneous conditions, especially the environment, the system state or the communication needs ;
- the capability to perform secondary use of the spectrum in the UHF band, extended to TV white spaces down to 470 MHz.

SACRA also assumes that resource managers in eNodeBs make this dynamic selection and perform spectrum aggregation using the knowledge on the characteristics of the channels in the licensed and the bands available for opportunistic use in the TVWS. Each eNodeB performs individually these operations in the case of intra-cell spectrum aggregation, while it cooperates with other eNodeBs to better serve the users through inter-cell spectrum aggregation.

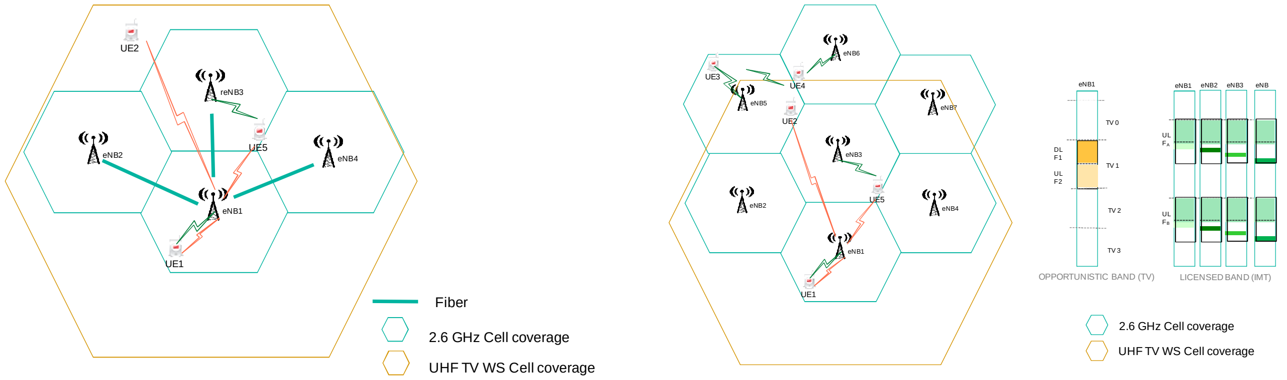
A terminal connected to a first eNodeB over a licensed carrier may also communicate simultaneously with a second one using additional resources in the TVWS, in order to get a better throughput. The UE will have an anchor RRC connection with the network (on the primary cell in the LTE sense[1]). Depending on traffic load and QoS requirements, eNB will add, remove or configure any secondary cells through new RRC signalling (this will correspond to bands that are shared and meant to be used opportunistically and would correspond to secondary cells[2]).

In addition, there will be associated in the coverage area a serving cell [3] that is assumed to provide system information to all the users in coverage range.

[1] **Primary cell** is designated as the Downlink primary Carrier Component and the corresponding Uplink Carrier component, which is the main carrier for the UE. This primary cell is UE specific and could be different between the UEs of the same base station.

[2] **Secondary cell** is designated as the Downlink and Uplink Carrier components corresponding to an additional serving cell for one UE.

[3] **Serving cell** corresponds to a Downlink Carrier component linked with an Uplink carrier component. This serving cell handles its own system information and has an unique ECGI (E-UTRAN Cell Global Identifier)



a) Intra-cell aggregation

b) Inter-cell aggregation

Figure 1: Spectrum aggregation scenarios and deployment examples

The scenarios and use cases targeted by this document meet essentially the requirements for spectrum aggregation with some variants that correspond to contiguous or non contiguous carrier components arrangements as well as intra cell or inter cell aggregation. This is depicted in Figure 1.

In Figure 1.a) the scenario corresponds to a connection established on request from UE1. The eNB1 is establishes a connection with the primary cell in the licensed band (2.6 GHz band) which is the main carrier for the UE. This carrier component is notified on signalling data in the licensed band. Depending on traffic load and QoS requirements of the application for the UE1, eNodeB1 will add a secondary cell through new signalling in the licensed band. Depending on the availability of carrier components in the UHF TV WS band, eNodeB1 configures a second carrier component in the opportunistic band to enhance the throughput for the UE1. As a consequence, eNodeB1 aggregates data in the two carrier components to allow simultaneously communication in the two bands.

Figure 1.b) corresponds to an initial connection established on request by UE5. eNB3 establishes a connection for this purpose with the primary cell in the licensed band acting as main carrier for the UE. Due to QoS requirements of the application for UE5, eNB3 triggers a search for additional resources for this UE. The eNodeBs coordinate their actions to select appropriate CC bands for use by UE5. The eNB1 configures a carrier component in the opportunistic band to enhance the throughput for the UE5. As a result, eNB1 and eNB3 coordinate the scheduling of data through the two allocated carrier components to allow simultaneously communication in the two bands for UE5.

The CRRM algorithms presented in this document assume these two scenarios for their analysis and for the derivation of their models. Hopefully, the proposed algorithms can be extended and applied to other use cases, with marginal changes to their objective functions or optimisation mechanisms.

3 OVERALL CRRM SYSTEM

The overall CRRM system is composed of a hierarchy of algorithms, each contributing a key aspect in the complete cognitive radio resource management framework as illustrated Figure 2.

The proposed CRRM algorithms cover a number of the SACRA target objectives. A genetic algorithm is selected to partition users in the bands and aggregate carrier components (levels 4 and 5) and driven by rules and policies from level 6. For this higher level of cognitive radio resource management working on partitioning flows into sub bands, a genetic algorithm is preferred for its ability to address multiple constraints, multiple objectives and multiple criteria in addition to naturally embedding joint optimisation and learning capabilities.

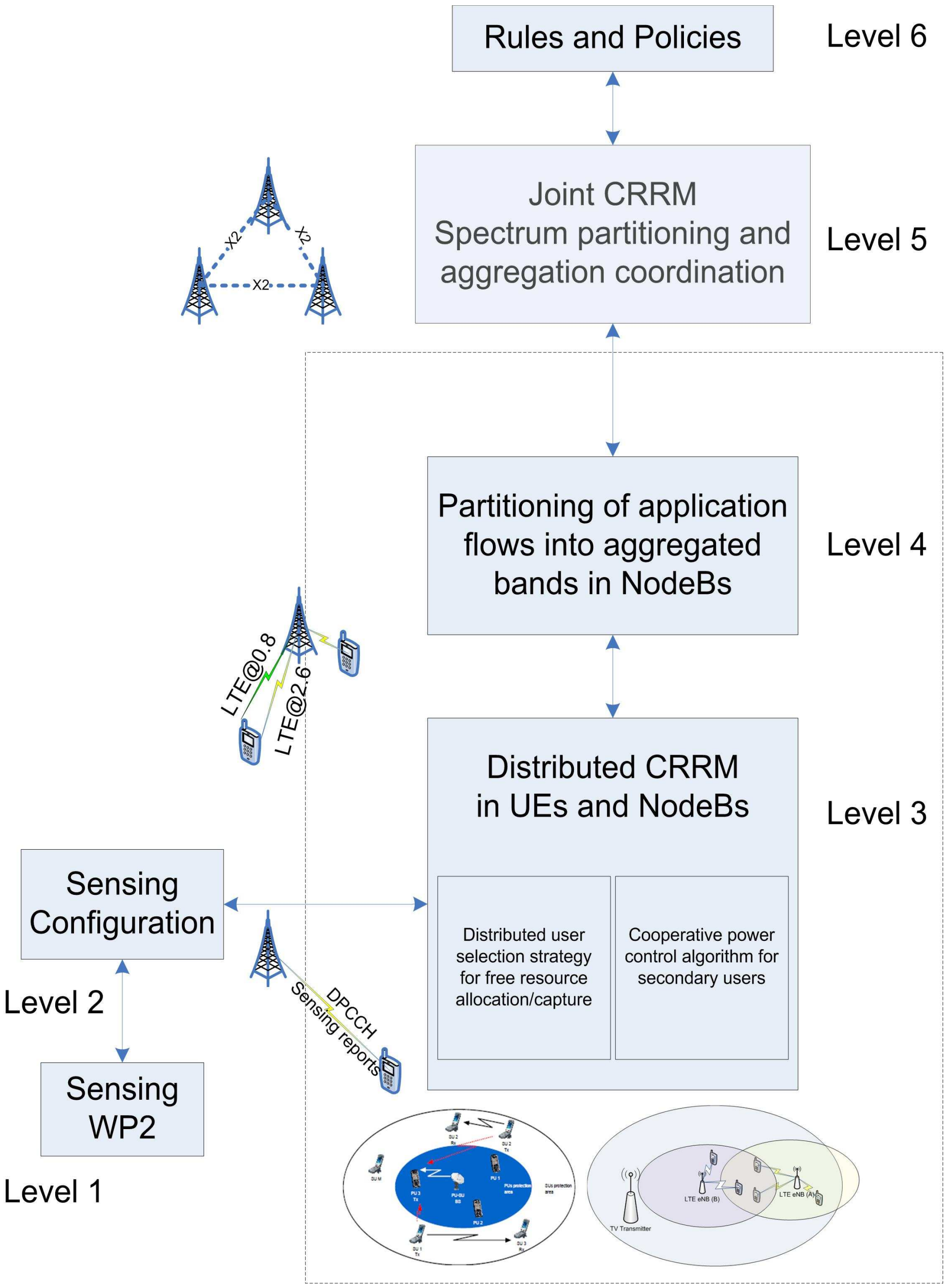


Figure 2: CRRM system and proposed algorithms

A resource management algorithm (at level 3) 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.

Additionally, a second algorithm, at level 3, enables secondary users that have been allowed to enter the system to tune opportunistically and cooperatively their transmission power levels. Learning can be added to the existing cooperative power control optimisation to improve performance when confronted with new conditions or uncertainty.

The SACRA sensing algorithms, implemented and evaluated by WP2 on sensing techniques, serve as key input to all the SACRA CRRM algorithms. The sensing results are injected into the CRRM system in the form of detected presence of primary users across available bands and carrier components for opportunistic use by secondary users. This information comes either as hard decisions indicating presence or absence of primary users without any additional knowledge on the likelihood of error, or as soft information augmented with probability of correct detection and probability of false alarm acting as weights on the reliability of the sensing results. Sensing is performed by the terminals and reported to the base stations for consolidation purposes. The sensing data and results may be shared or not among terminals, depending on the type of sensing used, e.g. in cooperative sensing, or simply gathered at the base stations that may redistribute the information to other nodes (terminals and other base stations)

The sensing data (level1 in Figure 2) is passed primarily onto the sensing configuration system, described in more details in section 4.4, responsible for selecting the most appropriate sensing algorithm according to estimated signal to noise ratio as well as experienced and observed performance of the CRRM algorithms. The sensing configuration module goals are to select the best spectrum and signal sensing algorithms and to tune the parameter configuration for these algorithms in terms of sensing frequency and cost-efficiency-reliability tradeoffs. Sensing configuration (at level 2) in fact adapts the sensing by reducing the amount of sensing or modifying the sensing parameters to ensure deeper inspection of the spectral bands or carrier components if the collected information is insufficient for reliable decisions.

The sensing results are also shared and communicated to the various CRRM algorithms (levels 3, 4 and 5) that will also make use of the available hard or soft sensing information. The terminal centric and the distributed algorithms in the terminals and base stations are described in sections 4.2 and 4.3. The more base station centric and upper CRRM algorithms relying on LTE radio resource blocks maps or resource occupation matrices are described in section 4.1. These algorithms, located in levels 4 and 5 in Figure 2, partition or split the application flows into the available (aggregated) spectral bands depending on the collected primary user presence information collected by the sensing algorithms, processed and interpreted by the sensing configuration as well as the distributed sensing algorithms in the nodes (terminals and base stations) in both uplink and downlink directions and bands. The algorithms in level 3 are dedicated to access control to primary user bands or carriers and the control of the power that will be used by secondary users once they are allowed to enter the system and share or use the primary bands, carrier components or spectrum.

They are the subject of detailed descriptions in sections 4.2 and 4.3. The algorithms are described in terms of access control to the primary spectrum and in terms of power control for secondary users. Section 5 describes the inputs required for the proposed CRRM algorithms at levels 3 through 5 and the outputs of these algorithms, as well as the assumptions under which they operate.

The list of algorithms is given below with the section where they are described respectively:

- sensing configuration (see section 4.4)
- distributed primary users and secondary users spectrum access control and power setting based on a probability of outage criterion in terminals (see section 4.2)
- secondary users cooperative power control in shared bands to optimise secondary users utility subject to primary user interference constraint (see section 4.3)
- and a higher level application and flow partitioning algorithm that aims at partitioning flows across combined or aggregated bands located in levels 4 and 5 of the SACRA CRRM hierarchy (described in section 4.1).

A short description of each algorithm is provided next to prepare the reader to the more detailed descriptions.

- As stated earlier the sensing configuration system controls and configures sensing dynamically according to the collected sensing information by the activated sensing algorithms, to their observed performance and to the estimated signal to interference ratio in the sensed primary bands;
- 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;
- 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
- the user satisfaction algorithm operated at a different level in the SACRA CRRM system and intervened quite early by actually partitioning or splitting flows and resources into sub bands to organise and distribute initially the flow s and applications according to their profiles and operators policies and rules on specific applications or usage of the multiple available bands including the white spaces. This algorithm can run in each base station and in fact aggregates spectrum and consolidates allocations on the basis of currently used resources (busy), free resources within the LTE 2.6 GHz band and based on a collected view form sensed carrier components and sub carriers by SACRA CR, on monitored channels within LTE via CQI and ICIC reports. This algorithm can also be reused for JRRM and combined with the same algorithm decisions running autonomously in each base station.

4 CRRM ALGORITHMS

This section will describe the CRRM algorithms and the planned integration of the algorithms into the overall CRRM system. The idea is to describe each algorithm and describe how they will be combined into a coherent and cohesive system. It will start by setting the stage with the spectrum portioning and allocation policies at a rather high level in order to specialise the description to each algorithm fist and afterwards look at the algorithms jointly for integration.

4.1 SPECTRUM PARTIONINING AND HIGH LEVEL ALLOCATION POLICIES

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 CRMM in terms of goals and performance objectives. The methodology and approach are those of the well known Policy Based Management (PBM) framework. The key process in PBM is the MAPE loop (Monitor, Analyse, Plan and Execute). Depending on detected events and sensed conditions policy decision points will determine what action to plan and executed through the injection of rules into policy enforcement points that will make sure the rules are respected and the objectives met. PBM is by now well known. There is no need to dwell on its principles. The focus will be instead on the distribution of application flows across bands and on the evaluation of a genetic algorithm to achieve the partitioning and aggregation of carrier components when conducting the management of the sub-bands and their associated carrier components.

The analysis will in addition focus on a key and central SACRA use case and scenario; the carrier aggregation scenario. The 2.6 GHz band and an 800 MHz band will serve as a basis for the study. The scenario assumes an LTE-A system operating in the 2.6 GHZ band taking opportunistically advantage of available spectrum in the 800 MHz bands in a TVWS context.

The SACRA sensing algorithms are assumed to provide soft information on the availability of primary users in the 800 MHz band. Probability of detection and false alarm compose this soft information. The partitioning algorithms will use the primary user sensing information to address the LTE resource block allocation across the bands. A genetic algorithm is proposed to allocate the data flows to LTE radio resource blocks selected across the available carrier components in the 2.6 GHz and 800 MHz band.

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. Some of these policies and rules are:

- authorised bands and carriers
- maximum number of carriers allowed for a single user or application (limit per sub-band or limit in total resource aggregated from all bands)
- QoS requirements or equivalently user satisfaction assuming a criterion is selected to define such satisfaction

- a maximum acceptable interference or degradation by primary and secondary users such as acceptable outage probability of primary users, SINR targets for primary and secondary users, etc.
- application required throughput and maximum delays
- fairness across users in terms of mobility patterns, applications and coverage range (in terms of QoS such as SINR, Throughput, delays)

In order to capture most of these rules and policies into a set of constraints or target objectives, concrete performance measures for the optimisation algorithms, SACRA elected to use a combined metric that lumps most of these criteria into one measure: the user satisfaction. The advantage of such an approach is the design of an algorithm that would work irrespective of the selected or retained criteria in the combination. Designers need only change the expression of the utility function or the overall user satisfaction definition.

A genetic algorithm was also selected to naturally handle the multi-criteria, multi-constraints and multi-objectives nature of CRRM. Genetic algorithms have also an inherent resilience to uncertainty as they embed learning and adaptation capabilities in their evaluation, selection, crossover and mutation steps. Genetic algorithms find near optimal solutions to NP-Hard problems and are suitable for complex problems with many local optima. The CRRM problem addressed by SACRA exhibits all these characteristics.

The formal evaluation of the user satisfaction criterion embedding several policies and rules for CRRM partitioning of traffic flows into sub-bands and carrier components is described in 4.5.

4.2 LOCAL PER BASE STATION OUTAGE PROBABILITY CENTRIC ALGORITHM FOR OPPORTUNISTIC SPECTRUM ALLOCATION TO SECONDARY USERS

This algorithm operates at level 3 and uses outage probability protection on incumbent to control access to the TV white space or any band subject to opportunistic use. The algorithm can be used to decide if users are allowed to enter the system based on outage probability estimation prior to any access grant [1][2]. This algorithm has been modified, adapted and implemented to address and fulfil SACRA scenarios' requirements. Policies and constraints are applied to the outage probability-based algorithm. Two policies are considered: PU policies including the primary capacity, the outage probability and the interference outage, and, SU's policies including SU's capacity, SU's sum capacity, the interference power and fairness. Throughout this section, we will use the following notation:

- the index of SUs j lies between 1 and M,
- $h_{pu,n}$ denotes the channel gain from the PU indexed by pu to a desired SU n,
- $h_{\mathrm{pu,pu}}$ denotes the channel gain between the base station (BS) and the PU,
- $h_{j,n}$ denotes the channel gain from SU j to a desired SU n,
- the data destined from the primary system is transmitted with power p_{pu}.
- the data destined from SU j is transmitted with power p_j.

4.2.1 Primary users policies

Primary Capacity: In most of resource allocation strategies, algorithms must ensure that the maximum capacity of the PU resulted from the SUs transmission is no greater than some prescribed threshold. The PU instantaneous capacity C_{pu} is given by

$$C_{pu} = \log_2\left(1 + \frac{p_{pu}|h_{pu,pu}|^2}{\sum_{j=1}^{M} p_j|h_{j,pu}|^2 + \sigma^2}\right) \quad (1)$$

where σ^2 is the ambient noise variance. Clearly, the primary capacity is directly related to the PU transmission as well as the SUs transmission.

Outage Probability: The notion of information outage probability, defined as the probability that the instantaneous mutual information of the channel is below the transmitted code rate, was introduced in [3]. Accordingly, the outage probability can be written as:

$$P_{out}(R) = P\{ I(\mathbf{x}; \mathbf{y}) < R\} \qquad (2)$$

where I($\mathbf{x}$;$\mathbf{y}$) is the mutual information of the channel between the transmitted vector **x** and the received vector **y**, and R is the target data rate in (bits/s/Hz). Reliable communication can therefore be achieved when the mutual information of the channel is strong enough to support the target rate R. Thus, a cognitive transmitter can adapt its transmit power p within the range of [0; P_{max}] to fulfill the following two basic goals:

- *Self-goal*: Trying to transmit as much information for itself as possible,
- *Moral-goal*: Maintaining the primary users' outage probability unaffected.

The outage probability can be written as:

$$P_{out}(R) = Prob\{ C_{pu} < R_{pu} \} \quad (3)$$

where R_{pu} is the PU transmitted data rate. The information about the outage failure can be carried out by a band manager that mediates between the primary and secondary users, or can be directly fed back from the PU to the secondary transmitters through collaboration and exchange of the Channel State Information (CSI) between the primary and secondary users.

QoS control: The main contribution within the proposed outage probability based algorithm is the QoS management of the CR system [1][2]. The originality in the proposed method is that we guarantee a QoS to PU by maintaining the PU's outage probability unaffected in addition to a certain QoS to SUs and ensuring the continuity of service even when the spectrum sub-bands change from vacant to occupied. Thus by the outage probability control, if we have a vacant spectrum holes in the PU band, we set the outage probability P_{out} = 1 to exploit the available spectrum band by SUs, and if we have occupied sub-bands, the outage probability is set to $P_{out} = q$ depending on the PU's QoS.

Interference Outage: The CR specific metrics relate to how well the CR is able to avoid PU and the efficiency in using available spectrum. This will require a model for PU dynamics, such as disappearance and reappearance time intervals, the amount of spectrum being used and the strength and location of the PU. In addition to the primary capacity and the outage probability, we define the interference outage meaning when the power of interference at a receiver PU exceeds a pre-defined absolute limit. Let q be this absolute limit (i.e. the maximum outage probability).

4.2.2 Secondary users policies

Secondary User's Capacity By making SUs access the primary system spectrum, the j^{th} SU experiences interference from the PU and all neighbouring co-channel SU links that transmit on the same band. Accordingly, the j^{th} SU instantaneous capacity C_j is given by:

$$C_j = \log_2\left(1 + \mathrm{SINR}_j\right); \quad \text{for } j = 1, \ldots, M \qquad (4)$$

where

$$\mathrm{SINR}_j = \frac{p_j |h_{j,j}|^2}{\sum_{\substack{k=1 \\ k \neq j}}^{M} p_j |h_{k,j}|^2 + p_{pu} |h_{pu,j}|^2 + \sigma^2}. \qquad (5)$$

Secondary User's Sum Capacity: SUs need to recognize their communication environment and adapt the parameters of their communication scheme in order to maximize the cognitive capacity, expressed as

$$C_{\mathrm{sum}} = \frac{1}{\tilde{M}} \sum_{j=1}^{\tilde{M}} C_j, \qquad (6)$$

while minimizing the interference to the primary users, in a distributed fashion. The sum here is made over the $\tilde{M}$ SUs allowed to transmit. Moreover, we assume that the coherence time is sufficiently large so that the channel stays constant over each scheduling period length. We also assume that SUs know the channel state information (CSI) of their own links, but have no information on the channel conditions of other SUs. No interference cancelation capability is considered. Power control is used for SUs both in an effort to preserve power and to limit interference and fading effects [1][2].

Fairness: In addition to the SU instantaneous capacity and the global sum capacity, other functions of SU rates are useful, as an example the fairness. Specifically, every station in the CRN transmits as much data as possible and the throughput is calculated for each of them. Both the total throughput and fairness (differences in the throughput achieved by individual stations) are of interest.

4.3 COOPERATIVE POWER CONTROL BASED ON FUZZY LOGIC

The focus of the proposed power control algorithm is:

- Cooperative power control between the nodes of different secondary systems (e.g. in the case of different operators in the TVWS bands) in order to maximize network efficiency and minimize interference;
- M spectrum areas with same width.
- Every node selects its transmission power level trying to maximize a utility function defined to ensure algorithm convergence to a maximum within a finite number of steps.
- Asynchronous message exchange ("interference prices" [4]) required for cooperation between the nodes;
- Fuzzy logic is utilized to enhance situation awareness by compensating for uncertainties that cause underestimation of the interference.

Since this algorithm was described in great details in D3.1 [15], only the algorithm key principles are needed in this section that focuses on the algorithm usability and its combination with other overall CRRM system algorithms.

In the cooperative power algorithm proposed in D3.1 [15], the users exchange information about their interference levels, using for this purpose appropriate message exchange mechanisms. Each secondary user sets its power level by considering its own Signal to Interference plus Noise Ratio (SINR) information and the negative impact on the utility of other users [18]. This serves as counter-motive that discourages nodes from setting consistently their transmission power to the maximum allowable level. Assuming that there are a total of *L* pairs in a spectrum band with *k* available channels, the SINR of the i*th* user in channel *k* is given by the equation:

$$\gamma\left(p_i^{\,k}\right)=\frac{p_i^{\,k}\cdot h_{ii}}{n_0+\sum_{j\neq i} p_j^{\,k}\cdot h_{ji}} \qquad (7)$$

where γ_i is the SINR of the ith transmitter as described in [15] and [18]. Variable p_i^k is the transmission power for the node *i* on channel *k,* h_{ii} is the link gain between i*th* receiver and i*th* transmitter, p_j^k is the transmission power for all other users on channel *k,* $n_0=10^{-2}$ is the noise level and h_{ji} is the link gain between i*th* receiver and j*th* transmitter. It is important to underline that $h_{ij} \neq h_{ji}$ since the first expresses the gain between i*th* transmitter and j*th* receiver and the second depicts the gain between j*th* transmitter and i*th* receiver.

In the following analysis we assume that the environment causes average to high loss and as a consequent the path loss exponent is three, therefore the channel gain can be expressed as $h_{ji} = d_{ji}^{\ -3}$, where variable *d* denotes the distance between the j*th* transmitter and i*th* receiver. Furthermore, in general, the carrier frequency of a signal varies and consequently the magnitude of the change in amplitude will also vary. The coherence bandwidth defines the separation in frequency after which two signals will experience uncorrelated. Specifically, in the case of frequency-selective fading, the coherence bandwidth of the channel is smaller than the bandwidth of the signal. Thus, different frequency components of the signal experience uncorrelated fading. On the other hand, in the case of flat fading, the coherence bandwidth of the channel is larger than the bandwidth of the signal. Therefore, all frequency components of the signal will experience the same magnitude of fading. In our case we assume a flat-faded channel without shadowing effects [4]. For a flat-faded channel there is no frequency selectivity and no delay spread, as elaborated previously. This implies that a single coefficient is used for channel attenuation. The described channel is static, thus the coefficient is fixed, and therefore the path loss is the only attenuation affecting it. Consequently, in this particular case h is strictly the channel gain or attenuation.
In order to model the impact in utility for node *i* caused by the transmission of all other nodes, we adopt from [4] the notion of interference price. Interference price π_i^k is defined as:

$$\pi_i^{\,k}=\frac{\partial u_i\left(\gamma\left(p_i^{\,k}\right)\right)}{\partial\left(\sum_{j\neq i} p_j^{\,k}\cdot h_{ji}\right)} \qquad (8)$$

It is clear that the interference price expresses the marginal loss in utility due to a marginal increase in sustained interference. Interference prices are exchanged between the users in a completely asynchronous way. Furthermore, not only the updates of interference price between users are asynchronous, but also every node can proceed to update at different times its own price and power level values. Each node subsequently selects an appropriate level for its transmission power in order to maximize the difference between the “increase” in its own utility minus the reduction in utility of other nodes caused by the increased interference as expressed by the interference price. Specifically, the mathematical formula that [4] is trying to maximize is:

$$u_i\left(\gamma_i\left(p_i^{\,k}\right)\right) - p_i^{\,k}\sum_{j\neq i}\pi_j^{\,k}\cdot h_{ji} \qquad (9)$$

The first part of the last equation is related to the Shannon capacity for user i (the constant term is omitted in order to have a form that can be proved to converge in all cases). Increasing user i Shannon capacity part translates to a direct increase in the maximum bit rate. However, since the transmission of every node is potentially seen as noise by the other nodes in the secondary system, the second term expresses what the other users will lose if user i increases its transmission power level. The algorithm consists of the following three steps:

- **Initialization:** For each node $i \in L$ that is transmitting in channel k select a valid transmission power level p_i^k and a positive value for the interference price π_i^k
- **Power Update:** For every node i update its transmission power level p_i^k trying to maximize the surplus in equation (1), after a time interval $t_{ai} \in T_i$, where T_i is a set of positive time instances in which the user i will update its transmission power level and $t_{a1} \neq t_{a2} \neq \ldots \neq t_{ai}$,
- **Interference Price Update:** For every node i calculate and announce the updated interference price π_i^k and notify the rest of the users for the updated value, after a time interval $t_{bi} \in T'_i$, where T'_i is a set of positive time instances in which the user i will update its interference price and $t_{b1} \neq t_{b2} \neq \ldots \neq t_{bi}$

The last two steps are asynchronously repeated for all the nodes until the algorithm converges to its final steady state. Due to the nature of equation (1) it can be proved that the algorithm will converge within a finite number of steps, provided that no external parameters will disturb the system. Moreover, if the problem is partitioned so that there is a single available spectrum area or if the algorithm is executed only for subgroups selecting the same spectrum area M, then it can be proved that the algorithm converges to a global maximum under arbitrary asynchronous updates [4].

In order to perform the power update in step 2, users select p_i^k from the set TP of the allowable transmission power levels, so that the surplus of equation (1) is maximized. Provided that the allowable power levels are equidistant values (meaning that they can be derived from the previous value by adding a constant increment) then the algorithm will converge, as long as the increment is sufficiently small. In order to execute the algorithm, every user in the network requires knowledge of its own SINR and channel gain, as well as the channel gains and the interference prices announced by other users. The SINR and the channel gain between a user pair can be calculated at the receiver and forwarded back to the transmitter. The channel gains between users can be calculated if receivers periodically broadcast a beacon [4]. This information can also be provided on demand through a specially defined message sent from the receiver. Thus, in case the transmitter requires channel gain information before the reception of the next scheduled beacon, it can request this information from the receiver who will respond with the relative measurements. Finally, interference price values can be also conveyed in the same manner. Every user announces a single interference price, therefore the delay that is introduced by the algorithm scales linearly with the number of users.

However, in the original version of the algorithm from [4], without coefficient α in (1), an underestimation of interference prices is likely in some cases (e.g. due to problems in message exchange or increased update time intervals for the interference prices) and the effect of the underestimation is the convergence of the algorithm in a non optimal solution. Therefore, coefficient α is introduced in our work in order to improve situation aware decision making in the presence of uncertainties such as large update time intervals from the previous interference price update (considering that updates are asynchronous for all users) and potential problems in message exchange due to high mobility. In such cases the relative impact of the subtracted term should be enhanced, otherwise the first term usually dominates and this results to all users selecting the maximum valid power level. In both cases there is a danger that the impact of the interference to others due to the increase in transmission power will be underestimated as explained above, thus factor α needs to avert this scenario by increasing the weight of the second term. In such cases factor α compensates for the underestimation of interference and if it is defined appropriately it can result in a system that approximates the case of “perfect” message exchange. Fuzzy logic is well suited for this since it can handle vague and unclear requirements efficiently and the system can be easily fine-tuned to exhibit the desirable behaviour. Therefore, if coefficient α is included as a “weight” factor that is multiplied with the subtracted interference term then we derive the following equation that is the objective we are trying to maximize:

$$u_i\left(\gamma_i\left(p_i^{\ k}\right)\right) - \alpha \cdot p_i^{\ k} \sum_{j \neq i} \pi_j^{\ k} \cdot h_{ji} \qquad (10)$$

The coefficient α sets the weight of the subtracted interference-related term in equation (1) and is determined before the initiation of the optimization phase by executing a Fuzzy Logic reasoner.

4.4 SENSING CONFIGURATION SUPPORTING THE SACRA CRRM SYSTEM DESIGN FOR OPPORTUNISTCI MULTI-BAND OPERATION

4.4.1 General context description

Acting as a secondary user in the TVWS (470 - 790 MHz), SACRA system has lower priority using the spectrum allocated to the DTV. Therefore, a fundamental requirement is to avoid interference to the primary licensed users (DTV and PMSE) in their vicinity. Besides, there is no requirement, for the DTV networks and PMSE devices, to change their infrastructure in spectrum sharing with SACRA system. Therefore, SACRA system should be able to independently detect DTV and PMSE presence. To enable such an opportunistic access to licensed spectrum, different access methods have been proposed. Sensing-based access where a cognitive radio transmits if it senses the licensed band to be free is particularly investigated due to its low deployment cost and its compatibility with the primary licensed systems [5]. Several techniques have been previously proposed to sense a licensed spectrum in seeking a primary user signal (Cf. [6]-[11], SACRA D2.1). In single-node sensing, a cognitive radio performs sensing and provides one single decision about the frequency band occupancy. However, this technique is somewhat inefficient in some situations when deep fades and shadowing are encountered. Cooperative sensing has being proposed to enhance single-node sensing (see for instance [8] and references therein). Furthermore, implementation issues have being widely addressed over last years (see for instance [12]).

The sensing configuration aims at

- specifying the frequency band to be sensed and the primary signal features,
- defining the sensing time, duration and periodicity,
- selecting the UEs to participate in the cooperative sensing task,
- setting a sensing target performance: maximum allowed false alarm probability, minimum allowed detection probability, noise estimation time.

Besides, the regulatory conformance should be checked for each sensing task. Regulatory bodies (e.g., FCC) provide the detection threshold for specific primary signal [13]. The detection threshold corresponds to the minimum received signal at which primary signal should still be accurately (e.g., with probability 90%) detected by the Cognitive Radio.

Therefore, we propose the following sensing structure for SACRA system:

- The master node (e.g., eNodeB) defines the sensing configuration and scheduling strategy and it sends the configuration settings to UEs (selected sensing nodes).
- Given the configuration settings, the selected UEs process the sensing tasks and check the regulatory conformance related to the current sensing. Furthermore, the UEs report the results to the master node together with the regulatory conformance indicator.
- Each UE has various sensing algorithms performing capability. Depending on the configurations settings, the UE selects, among the available algorithms, the best algorithm to perform the current sensing task.

In this deliverable, we propose a new approach to configure and to enhance single-node sensing by selecting among various sensing algorithms, and by verifying regulatory body conformance related to primary users protection in licensed bands. We assume that the sensing node is able to perform various sensing algorithms (developed in SACRA WP2). During a sensing period, depending on the configuration settings (frequency band to be sensed, primary signal type, sensing duration, maximum allowed false alarm probability, minimum allowed detection probability, noise estimation time etc.), an algorithm is selected to perform the sensing task while regulatory conformance is checked regarding the current environment and the selected sensing algorithm. The goal of this research is therefore to optimize local sensing and to provide a regulatory conformance indicator. As a result, processing sensing results is helped by the regulatory conformance indicator and the cooperative sensing performance is enhanced.

We do not investigate the master node sensing configuration and scheduling strategy in this deliverable (this could be the next step of this study). We assume that the configuration settings are already available in the UEs.

4.4.2 System architecture and description

The proposed architecture is depicted in Figure 3. The sensing node is assumed to be able to perform K different sensing algorithms. The algorithms could be software-implemented, so the circuit can be optimized. The sensing node is composed of a short-term process, that is performed more often, and a long-term process that is performed occasionally.

The short-term process consists in choosing the right sensing algorithm, to perform the sensing task, using the current configuration settings, and in testing the regulatory conformance regarding the current environment and the selected sensing algorithm.

The long-term process consists in finding, depending on the configuration settings, the sensing algorithm that should be used to perform the sensing task. The long-term process also provides the required SNR, for all the sensing algorithms, to reach a target sensing performance. Finally, a knowledge base is fed, for all possible configuration settings, with the selected algorithms and their required SNR.

The short-term process is performed in each sensing period while the long-term process is performed only if there are new configuration settings.

The master node is responsible of the following tasks:

- Defining the sensing configuration, sensing scheduling and the sensing nodes selection strategies.
- Learning to adjust strategies in order to achieve target sensing performance.
- Processing sensing results and making decision about the band occupancy.

The sensing configuration and sensing scheduling strategy should be defined in a network context taking into account the radio access technology (see SACRA use cases) and the regulatory body requirements. The learning function of the master node should allow learning the sensing performance through consecutive sensing results. Therefore, sensing configuration and sensing scheduling strategy could be adjusted to achieve given target sensing performance. Different sensing durations could be envisaged: for example, when short sensing durations are not sufficient to achieve a given detection performance, the strategy function could adjust the sensing durations to meet the expected target.

In this deliverable, we focus on the sensing configuration and processing for single sensing nodes. The sensing configuration and scheduling strategy (available in the master node) is currently under investigation and it will be presented in the next deliverable.

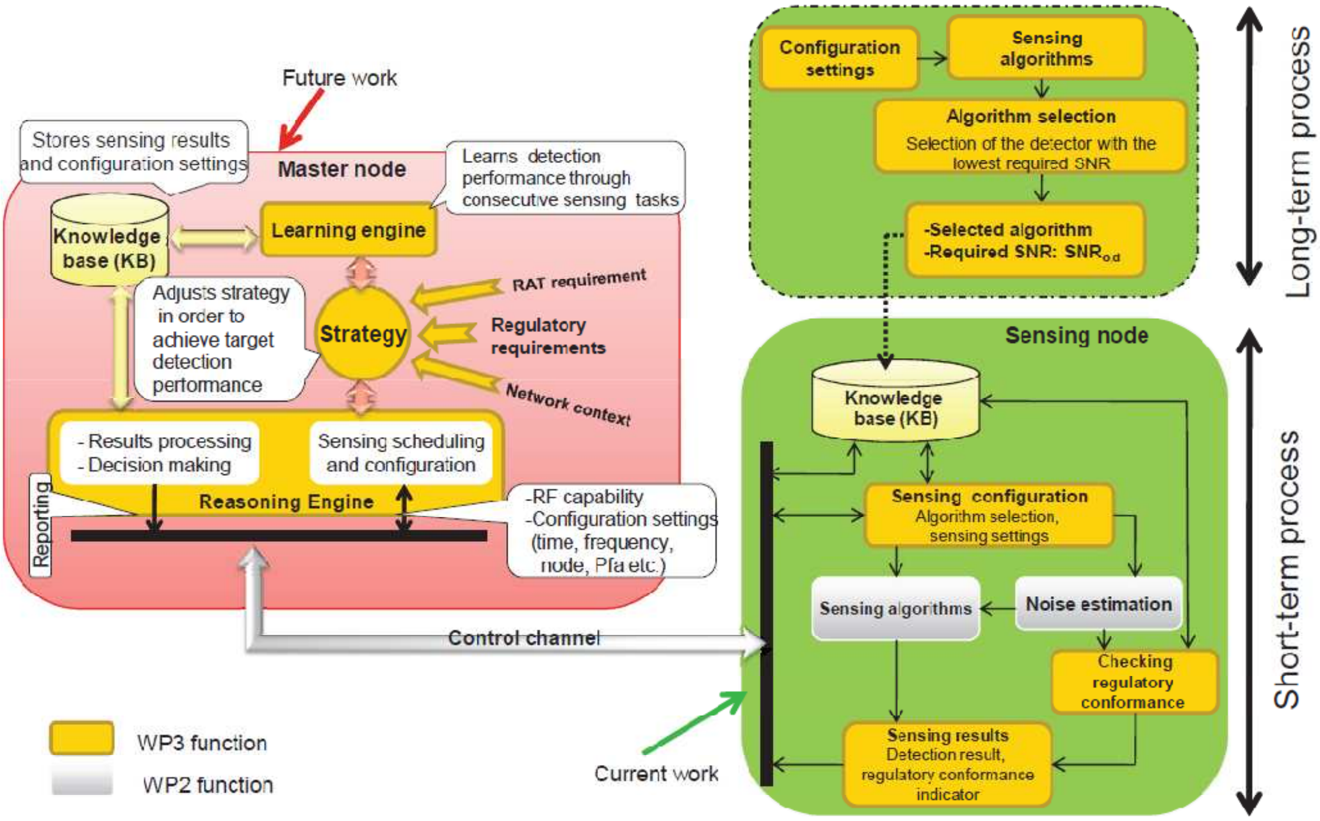


Figure 3: Proposed sensing configuration architecture

4.4.3 Single-node sensing configuration and processing

This section describes the sensing configuration and processing in a single cognitive radio node. We assume that the following sensing settings are available in UEs:

- frequency band to be sensed
- primary signal features,
- sensing duration,
- maximum allowed false alarm probability,
- minimum allowed detection probability,
- noise estimation time (duration).

The above configuration settings are sent by the master node to the sensing nodes (UEs). The tasks assigned to the sensing nodes are the following:

- Select the “best” sensing algorithm for the current configuration settings.
- Estimate the sensed frequency band noise power level.
- Perform the sensing task with the selected algorithm.
- Check the regulatory conformance with regard to the noise level and the selected sensing algorithm.
- Send to the master node the sensing results and the regulatory conformance indicator.

The above tasks comprise both a short-term process and a long-term process.

4.4.3.1 Short-term process

The short-term process is the main component of the UE sensing task and runs in each sensing period. The main steps are as follows:

4.4.3.1.1 Sensing configuration settings

The selected UE receive the configuration settings from the master node (e.g., base station). The current sensing configuration settings include the selected UEs identity, the frequency band to be sensed, the primary signal features, the sensing duration Ts, the maximum allowed false alarm probability Pfa,max, the minimum allowed detection probability PD,min, the noise estimation time.

4.4.3.1.2 Sensing performing

The following tasks are performed.

- For each sensing node, the sensing configuration function reads the knowledge base to get the selected algorithm corresponding to the current configuration settings.
- Noise power estimation, for the current frequency band, is performed. Noise power estimation can be performed directly in the current frequency band, [14], or in another frequency assumed to have the same noise level as the current frequency band, [9].
- The sensing is performed using the selected sensing algorithm which could use the noise estimation if necessary.
- The regulatory requirement, related to the detection threshold [13] is checked for the selected detector and the current noise level. Using the noise power estimation $\hat{\sigma}^2$, one can derive the SNR required by the regulatory body, to reach $P_{D,min}$, as follows

$$\mathrm{SNR}_{rb} = \frac{\text{Detection Threshold}}{\hat{\sigma}^2} \qquad (11)$$

For selected detector *d,* let $\mathrm{SNR}_{0,d}$ be the required SNR, to achieve in the same time $P_{D,min}$ and $P_{fa,max}$, for a given sensing duration T_s. To ensure that the current detection result conforms to the regulatory requirement, the regulatory SNR_{rb} must be higher than the selected detector $\mathrm{SNR}_{0,d}$ (Cf. Figure 4). Therefore, the regulatory conformance indicator, stating either $\mathrm{SNR}_{rb} > \mathrm{SNR}_{0,d}$ or $\mathrm{SNR}_{rb} \leq \mathrm{SNR}_{0,d}$, measures the confidence on the detection result (in regulatory body point of view).

- Finally, the detection result and the regulatory conformance indicator are sent to the master node that is responsible of processing the results coming from the selected UEs and of taking the final decision about current frequency band occupancy.

4.4.3.2 Long-term process

The goal of the long-term process is to feed the knowledge base with necessary information allowing the selection among various sensing algorithms. Moreover, the selection depends on the set of possible configuration schemes which must be known in advance. The long-term process is depicted in Figure 5. For given configuration scheme, we have the following steps.

- For all the available detectors, compute the mean detection probability versus the SNR.
- For each detector *d,* determine the required signal-to-noise ratio $\mathrm{SNR}_{0,d}$ to reach $P_{D,min}$ and $P_{f,max}$ for sensing duration T_S .Therefore, when current SNR is higher than $\mathrm{SNR}_{0,d}$, the detection probability is higher than $P_{D,min}$; otherwise, the detection probability is lower than $P_{D,min}$ (Cf. Fig. 3).
- Select as the best detector, the detector with the lowest required $\mathrm{SNR}_{0,d}$. The motivation of such a selection is that all signal with SNR higher than $\mathrm{SNR}_{0,d}$, for given detector, are sensed with probabilities of detection greater than $P_{D,min}$. Therefore, the lower $\mathrm{SNR}_{0,d}$ is, the more reliable the detector is (at least for higher SNR). Configuration information, selected detector and $\mathrm{SNR}_{0,d}$ are saved into the knowledge base (Cf. Fig. 4).

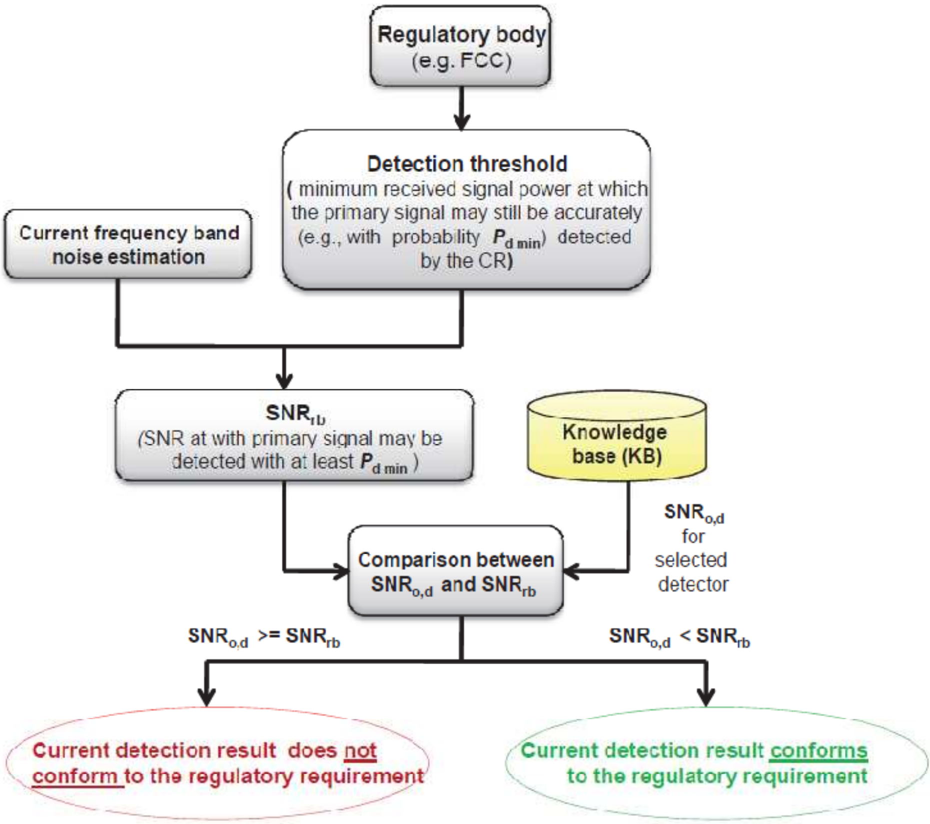


Figure 4: Regulatory conformance checking

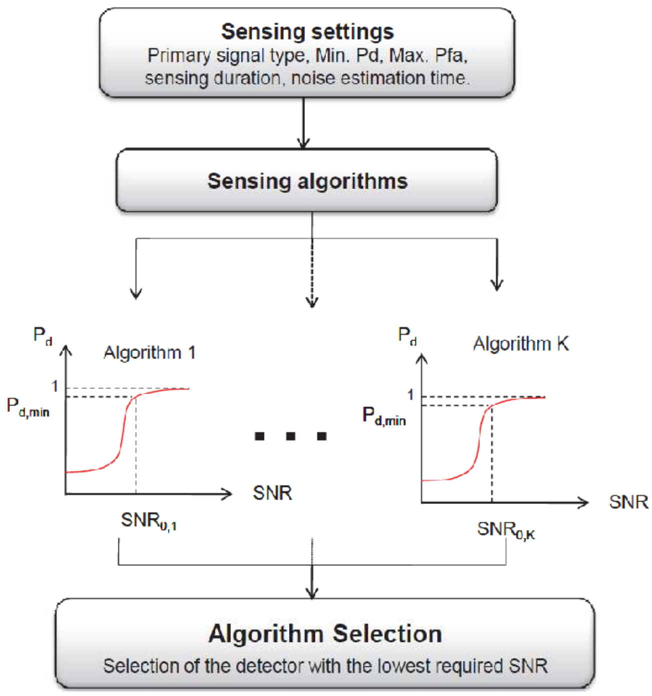


Figure 5: Framework for the long-term process

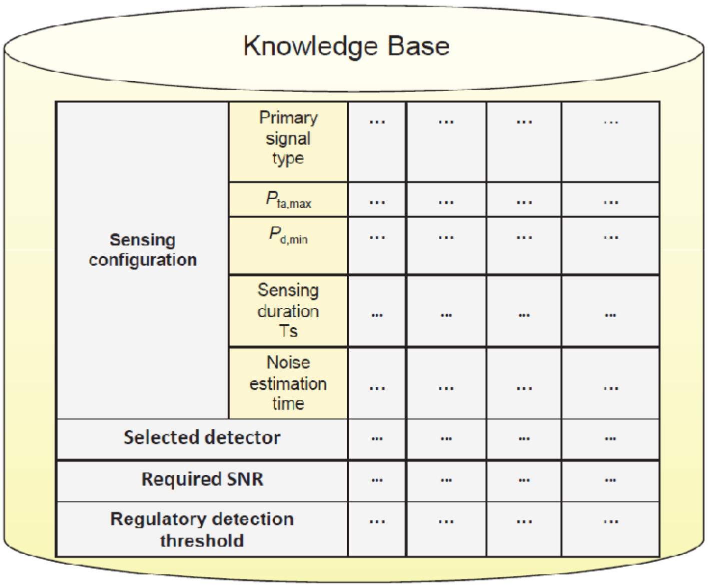


Figure 6: Example of knowledge base for algorithm selection

4.4.3.3 Numerical examples

Let consider a sensing node with two sensing algorithms: the energy detector and the Maximum Cyclic Autocorrelation Selection based detector (MCAS) [10]. MCAS in a detector that achieves closer performance to the conventional cyclostationary feature detector with much less computational complexity. We assume that the energy detector uses noise power estimation in another frequency band known to be free [9]. The licensed frequency band width is set to W = 7.61 MHz (e.g., the DVB-T in Europe). The sampling frequency is set to $f_s = W$. The primary system uses an OFDM modulation with 1024 subcarriers, 224 ms useful symbol duration and 224/4=56 ms cyclic prefix length. The sensing duration Ts, the noise estimation time, the minimum allowed detection probability $P_{D,min}$, and the maximum allowed false alarm probability $P_{fa,max}$ are set in Table 1. In Fig. 5, we have plotted the detection probability versus the SNR for an energy detector with noise estimation times 5 ms and 5/30 ms, and for the MCAS detector. As one can see, the required $SNR_{0,d}$ to reach $P_{D,min}$, $P_{fa,max}$ and T_s for the MCAS is equal to -12 dB. Further, the required SNR is equal to -16 dB for the energy detector using 5 ms noise estimation time, and it is equal to -9.58 dB when noise estimation time is 5/30 ms. Therefore, the energy detector is selected when noise estimation time is 5 ms, while MCAS is selected when the noise estimation is less or equal to 5/30 ms. The table 1 is an example of knowledge base that could be stored in the sensing node. One example of regulatory conformance, related to the detection threshold, is -114 dBm for ATSC digital TV signals, averaged over a 6 MHz bandwidth, as specified is the FCC draft [13] . However, for larger bandwidth (e.g., 7.61 MHz), the detection threshold has to be normalized accordingly (and it should be higher than -114dBm). It can be easily computed that for a 7.61 MHz bandwidth, the detection threshold should be around -112.967 dBm. As stated above, to ensure that the current detection result conforms to the regulatory requirement, regulatory SNR_{rb} (which is dynamically calculated, in each sensing period, using the noise power estimation) must be higher than the selected detector $SNR_{0,d}$. Considering a cooperative sensing scenario, each sensing node should report to the master node its own sensing result together with the regulatory conformance indicator. In processing the various sensing results, the master node should rely more on the results which conform to the regulatory requirement than on the others.

$P_{D,min}$	**90%**	**90%**
$P_{fa,max}$	**10%**	**10%**
T_S	**5 ms**	**5 ms**
Noise estimation time	**5 ms**	**5/30 ms**
Selected detector	**ED**	**MCAS**
Required $SNR_{0,d}$	**-16 dB**	**-12 dB**
Regulatory detection threshold	**-112.967 dBm**	**-112.967 dBm**

Table 1: Knowledge base for the energy detector (ED) and the MCAS-based detector.

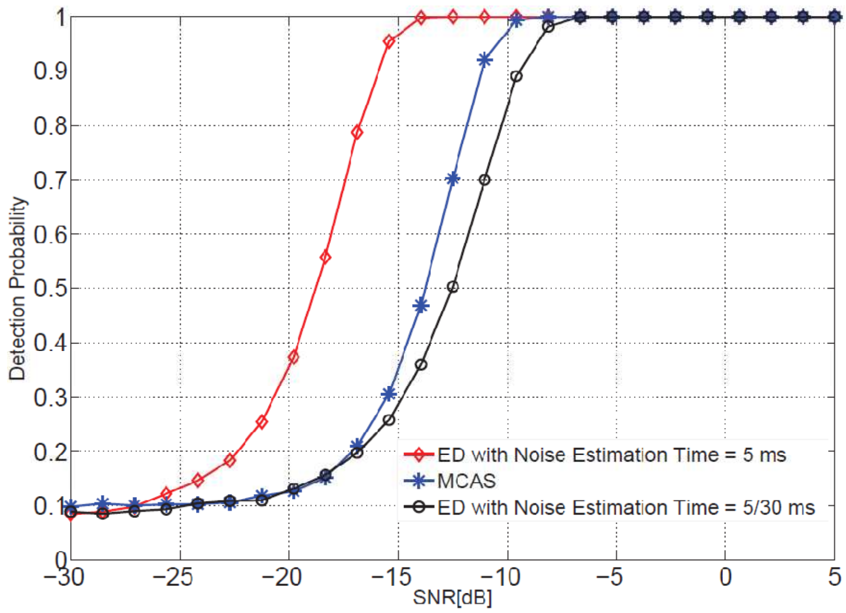


Figure 7: Probability of detection versus SNR for the energy detector, with two different configurations (noise estimation times 5 ms and 5/30 ms), and for the MCAS.

4.4.4 Conclusions

We proposed a new sensing configuration scheme to enable dynamic selection between various sensing algorithms. The proposed selection is based on a long-term process (that is occasionally performed) to allow selecting the best sensing algorithm for given configuration settings. Besides, we proposed a dynamic regulatory body conformance checking method: the SNR required by the regulatory body is compared to the SNR required by the current selected detector to reliably detect the primary signal. The proposed solution allows helping cooperative sensing results processing and decision making by the way that each sensing node could perform the sensing with the most reliable algorithm, among various, and could report, to the master node, a regulatory conformance indicator together with the sensing result.

4.5 *USER AND APPLICATION SATISFACTION BASED ALGORITHM FOR HIGH LEVEL PARTIONING OF APPLICATION DEMANDS ONTO AVAILABLE/SENSED BANDS*

This algorithm operates at a higher level in the CRRM hierarchy and addresses spectral bands allocation to users or applications or equivalently the partitioning of application and traffic flows to the most appropriate bands according to current resources occupancy and reported free carrier components via the SACRA sensing. The sensed data can be enhanced with soft and hard decision indicators on probability of false alarm and correct detection of primary users presence.

To achieve partitioning of application requests based on high level policies and rules injected from level 6 in Figure 2, a genetic optimisation approach has been preferred for its inherent learning capabilities and robustness to dynamic variations and uncertainties in spectral band sensing and access grant errors that may occur in levels 3 and 5. The algorithm assesses user satisfaction, used as the central and combined criterion embedding most of the policies and rules in one metric to ensure appropriate allocation of traffic flows into bands. The scenario used for this preliminary assessment is the SACRA carrier aggregation use case.

4.5.1 User or applications flows partitioning across bands algorithm

Let us first start with a description of the genetic algorithm proposed to partition users in the bands and aggregate carrier components for allocation to their applications flows.

The algorithm assumes as depicted in Figure 8 that the SACRA sensing modules will detect and a report the primary user presence either in the form of a hard indication (user present or absent) or of a soft information containing estimated Pd and Pfa. The sensing configuration module is not emphasised as it focuses on the selection of the most appropriate algorithms based on SINR conditions and overall perceived interference levels and hence controls and sets the sensing algorithm parameters and objectives.

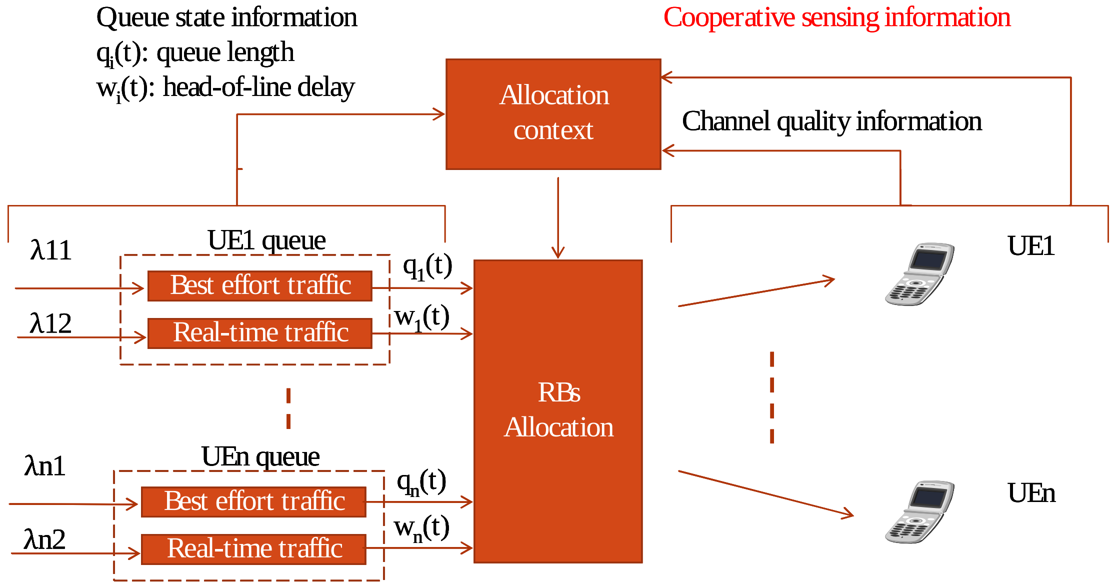


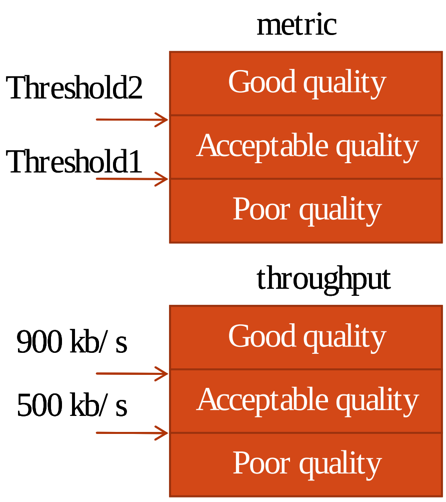
Figure 8: Radio blocks allocation with band selection and carrier aggregation

Figure 8 is a generic representation of the context for the CRRM radio resource blocks allocation algorithm in a base station. The scenario corresponds to a base station that has access to a privileged licensed band (2.6 GHz) for LTE-A users and opportunistic access to another band used by other users, reserved for primary users (e.g. 800 MHz or TVWS). There are n terminals involved: $\{UE_1, UE_2, \ldots, UE_n\}$.

The genetic algorithm running in each base station uses the cooperative sensing information to decide the radio resource block allocations and a user satisfaction criterion that reflects the rules and policies imposed by a policy engine in the outer loop. The algorithm is described for completeness and evaluated in 4.5.2 to assess its conformance to the policies.

The algorithm consists in allocating and aggregating carriers to applications so as to satisfy the users in terms of application throughput and message reception delay. The idea is to use user satisfaction instead of QoS requirements. This metric can be tuned and customised to include multiple QoS parameters. The satisfaction is measured using a score related to the application checked against a set of thresholds. The thresholds correspond to three levels of satisfaction: poor quality, acceptable and good quality.

The global objective is to maximise the number of satisfied users. They are pleased if they achieve acceptable or good quality for instance. More stringent users may impose a good or excellent quality. An arbitrary set of application throughput values, 500 Kbps and 900Kbps, are selected for the assessment.



These criteria concern of course the secondary users. The primary user are protected by setting a interference threshold as a hard constraint on the carrier allocation, aggregation and secondary user power levels optimisation or objective functions. The objective function is indicated below:

$$\max \sum_{k=1}^{K} f_k(Throughput_k, Delay_k) \quad (12)$$

The function $f_k(.)$ represents the satisfaction of user k. For example, for a VoIP application, $f_k(x,y)=1$ if y or delay < 150ms and $f_k(x,y)=0$ otherwise.

In order to address a specific scenario, the assessment is conducted for the downlink with simultaneous presence of terrestrial TV and LTE systems. This is depicted in Figure 9.

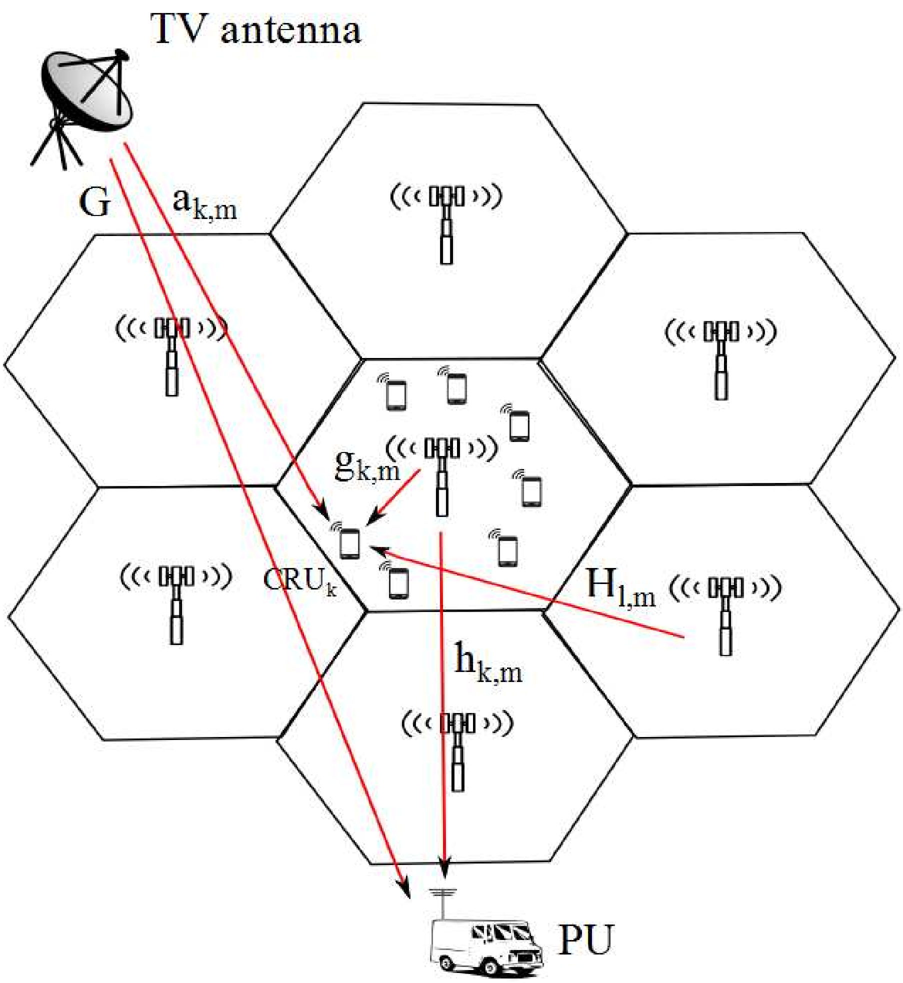


Figure 9: Downlink carrier aggregation use case (algorithm at LTE station for PMSE)

The variables are defined as follows:

- *G* is the channel gain from the TV tower to the TV broadcaster (PU)
- $g_{k,m}$ is the channel gain from the Cognitive Base Station (CBS) to the Cognitive Radio User (CRU) k on radio block (RB) m.
- $h_{k,m}$ is the channel gain from the CBS to the primary user (PU).
- $H_{l,m}$ is the channel gain from an interferer CBS *l* to the target CBS on RB m.
- $a_{k,m}$ is the channel gain from the TV antenna to the CRU k on RB m as specified previously.

The problem to solve is formulated by expressing the throughput for this specific downlink use case:

$$\begin{cases} \max \sum_{k=1}^{K} f_k \left(\sum_{m=1}^{M} (1-\alpha_m) B L_{k,m} \log_2 (1 + \frac{g_{k,m} p_{k,m}}{\sigma^2 + a_{k,m} P + \sum_l P_{l,m} H_{k,m}}),\ Delay_k \right) \\ \sum_{k=1}^{K} \sum_{m=1}^{M} L_{k,m} p_{k,m} \leq P_{\max} \\ \sum_{k=1}^{K} \sum_{m=1}^{M} L_{k,m} p_{k,m} h_{k,m} \leq I_{threshold} \\ \sum_{k=1}^{K} L_{k,m} = 1, \forall m \in [1, M] \end{cases} \quad (13)$$

where:

- K is the number of users and M is the number of blocks,
- $P_{k,m}$ is the transmission power of the target CBS towards user k on block m,
- P is the transmission power of the TV tower,
- f_k is a satisfaction function for user k, $L_{k,m}$ the block affectation matrix,
- P_{max} is the power budget of the CBS,
- $I_{threshold}$ the maximum interference level tolerated by the primary user.,
- $Delay_k$: The head of line delay of user k,
- α_m is a measure of the confidence the sensing system has on the presence of the primary user,
- $L_{k,m}$ is the radio block allocation matrix,

and where α_m is evaluated as follows:

$$\alpha_m = E\left[S_m = 1 \middle/ \hat{S}_m = 0 \right]$$

$$\alpha_m = \frac{P(S_m = 1) P(\hat{S}_m = 0 / S_m = 1)}{P(S_m = 1) P(\hat{S}_m = 0 / S_m = 1) + P(S_m = 0) P(\hat{S}_m = 0 / S_m = 0)} \quad (14)$$

$$\alpha_m = \frac{p_q^m (1 - p_d^m)}{p_q^m (1 - p_d^m) + (1 - p_q^m)(1 - p_{fa}^m)}$$

with

- S_m = 1 if block m is occupied, S_m = 0 otherwise,
- $\hat{S}_m$ = 1 when the sensing algorithm (after aggregation in the base station) believes that block m is occupied,
- $\hat{S} = \{\hat{S}_1, \hat{S}_2, ..., \hat{S}_M\}$,
- p_d^m the probability of detection and p_{fa}^m the probability of false alarm on block m,

- p_q^m is the inherent likelihood or probability that block m is being used by the primary.

An alternative that will be evaluated at a later stage in D3.2 is to modify the constraints and objective function to avoid having to estimate or evaluate the path gains among all POU and SU receiver and transmitter pairs. These values often cannot be estimated in a non cooperative primary systems or TV broadcast situations where knowledge of exact receiver locations is not feasible. Only bounds on performance can be assumed. The modified or new approach would eliminate the needs to drive path gains as follows:

$$\max \sum_{k=1}^{K} f_k\left(\sum_{m\in N_v} (1-\alpha_m) BL_{k,m} \log_2 (1+\frac{g_{k,m} p_{k,m}}{\sigma^2 + a_{k,m}P + \sum_l P_{l,m} H_{k,m}}), d_k \right)$$

$$\min \sum_{k=1}^{K} \sum_{m\in N_v} L_{k,m}\alpha_m$$

$$s.t. \begin{cases} \sum_{k=1}^{K} \sum_{m\in N_v} L_{k,m} p_{k,m} \le P_{\max} \\ \sum_{k=1}^{K} \sum_{m\in N_v} L_{k,m}\alpha_m \le \alpha_{threshold} \\ \sum_{k=1}^{K} L_{k,m} \le 1, \forall m \in N_v \end{cases} \quad (15)$$

The optimisation problem is solved using a genetic algorithm by searching for best genes in a properly selected chromosome structure to solve the carrier aggregation problem. The algorithm allocates contiguous carriers to users and their applications assuming that contiguous carrier components and radio blocks are desired. If this constraint is removed from the policies, the algorithm can be modified and tuned accordingly. For the time being, a maximum packing policy will be assumed by the genetic algorithm and embedded in its optimisation goals.

The algorithm in addition to achieving packing efficiency will minimise the total number of radio blocks allocated to a given user to increase the number of available radio blocks for future allocations. The algorithm evidently aims simultaneously at satisfying the maximum number of users.

To implement the constraints and ensure packing efficiency, the chromosome structure that was introduced is composed of N genes corresponding to the active secondary users in the cell. Each gene is comprised of the user ID (or number) and the number of blocks allocated to the said user.

The chromosome forms in fact an ordered user chain placed in the available carrier components from the two frequency bands. The users are packed one after the other according to their positions in the chromosome

The chromosome structure is depicted on the left portion of Figure 10. The goal is to build the chromosome structure so maximum packing in allocated radio block per user is achieved and user satisfaction is met.

The right side of Figure 10 indicates the actual radio resource blocks per carrier allocated to each user as a result of optimisation using the genetic algorithm. User 3 is allocated 2 contiguous resource blocks on one 2.6 GHz carrier component. User 8 is assigned 4 resource blocks on the same carrier component. The 800 MHz resource is not used yet in this example but would if the load on the system increases or additional criteria, such as range, force the use of 800 MHz carriers.

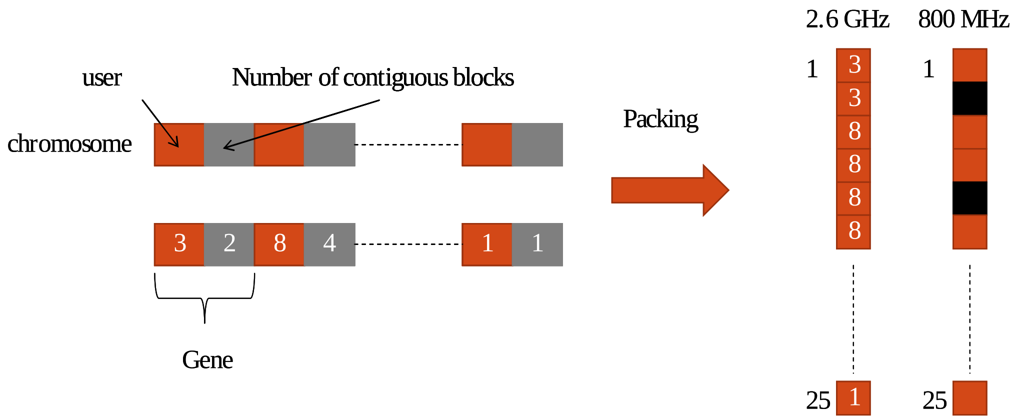


Figure 10: Chromosome structure for the carrier aggregation use case

The chromosome structure on the left side reflects these allocations through the tuple (user number, number of allocated blocks to the user). User 3 is shown as first in the chromosome sequence through the tuple (3, 2). User 8 corresponds to the pair (8, 4) in the chromosome. The tuple (1, 1) for user 1 closes the 2.6 GHz chromosome sequence or structure for this specific carrier. Note that each carrier contains 25 radio blocks as per the LTE specification. Other features that can be used to find the best genes or carrier component allocations and aggregations using the genetic algorithm are mutation and cross over. Our first experience with the carrier aggregation us case indicates that mutation is sufficient to fulfil the goals. The mutation operator is shown in Figure 11. Swapping alone helps finding better allocations and good solutions and satisfying a maximum number of users.

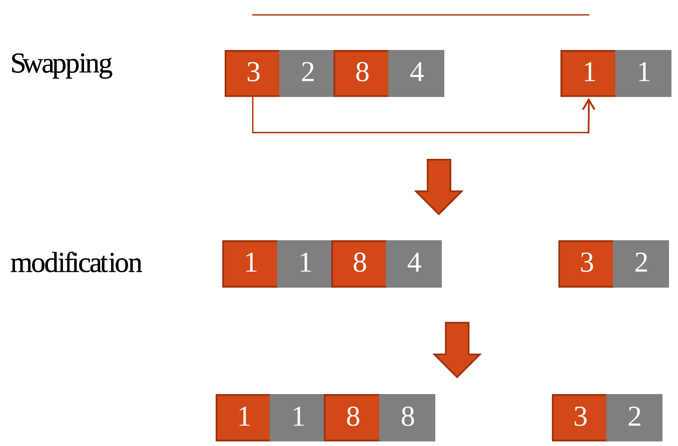


Figure 11: Mutation operation

4.5.2 Assessment of user satisfaction policy

To assess the user satisfaction policy for the high level (outer loop) CRRM, a simulation of a sample network was used. The genetic algorithm selected for assigning traffic flows using user satisfaction as an equivalent criterion reflecting the lumped effect of several criteria, is evaluated to assess the policy. The application flows are partitioned across bands and carrier components are aggregated to construct contiguous resources in frequency and time to allocate 2.6 GHz and 800 MHz LTE blocks to requests.

The simulation consists of a network with 16 users and 7 base stations, 1 target BS and 6 interfering base stations. There are 25 resource blocks in the system. The genetic algorithm described in section 4.1 is used to explore the search space and compared to proportional fair policy or algorithm to verify that there are real benefits using the proposed genetic algorithm.

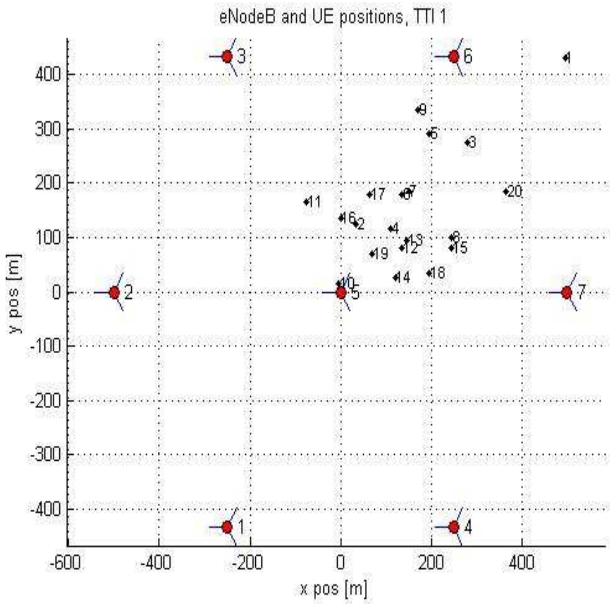


Figure 12: Scenario to assess user satisfaction policy for partitioning of flows across bands

The scenario considers video applications that have stringent throughput and rate requirements. Three levels of quality are considered for the evaluation: good, acceptable and poor. Two cases are considered in the simulations:

- Maximize the number of users experiencing “Good” communication quality corresponding to a throughput higher than 900 Kbps or
- Minimize the number of users with throughput below 500 Kbps considered as “Poor” quality for video applications.

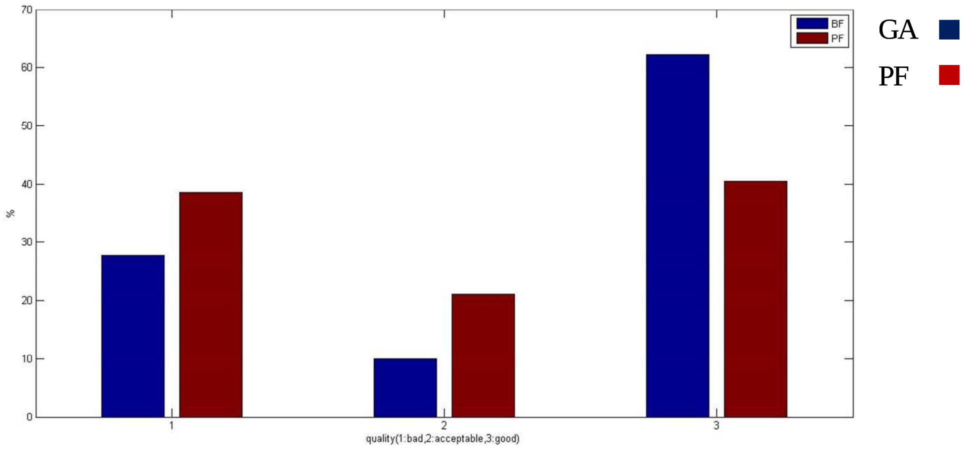
The satisfaction criterion remains the achieved throughput while keeping the delay below a given threshold using for the expression presented previously and repeated here for convenience:

$$\max \sum_{k=1}^{K} \left(f_k \left(\sum_{m=1}^{M} (1-\alpha_m) B L_{k,m} \log_2 \left(1 + \frac{g_{k,m} p_{k,m}}{\sigma^2 + a_{k,m} P + \sum_l P_{l,m} H_{k,m}}\right), Delay_k \right) \right) \quad (16)$$

In parallel all constraints on Primary User impact must be respected. the maximisation must be achieved subject to the specified constraints on power budget on the downlink, interference on the primary user and the allocation of a block to only one user at a time:

$$\begin{cases} \sum_{k=1}^{K}\sum_{m=1}^{M} L_{k,m}\, p_{k,m} \le P_{\max} \\ \sum_{k=1}^{K}\sum_{m=1}^{M} L_{k,m}\, p_{k,m} h_{k,m} \le I_{threshold} \\ \sum_{k=1}^{K} L_{k,m} = 1, \forall m \in [1, M] \end{cases} \tag{17}$$

Maximizing the number of "Good" quality communications



Quality (1:Poor, 2:Acceptable and 3:Good)

Figure 13: Results for maximisation of "Good" quality aggregations and assignments

Both Figure 13 and Figure 14 indicate that the genetic algorithm can achieve improved performance compared to a proportional fair allocation policy. The number of users experiencing "Good" quality when maximising the number of users with "Good" satisfaction or minimising the users subject to "Poor" quality leads to noticeable improvements. The genetic optimisation approach appears as a viable way to increase performance and a good candidate for additional improvements through fine tuning of the criteria and the algorithm parameter control and configuration. Some trade-offs depending on desired "Poor", "Acceptable" and "Good" performance proportions need to be exercised to extract all the benefits from the proposed approach. Additional investigations are required to consolidate the findings. These results also corroborate the findings of section 4.3 on ad hoc cooperative power allocation distributed in the terminals in the inner loops. These approaches need to be ultimately combined and coordinated for increased benefits and performance enhancements.

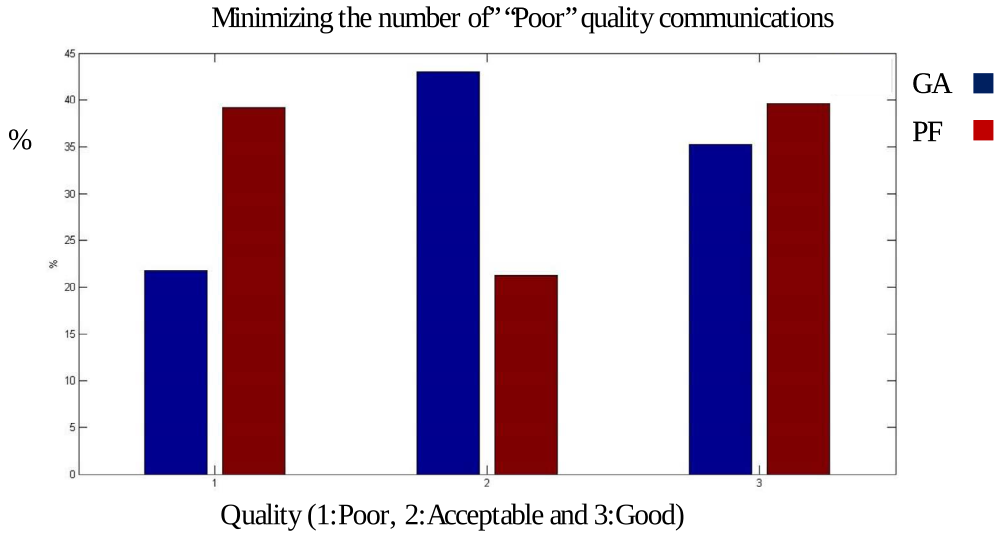


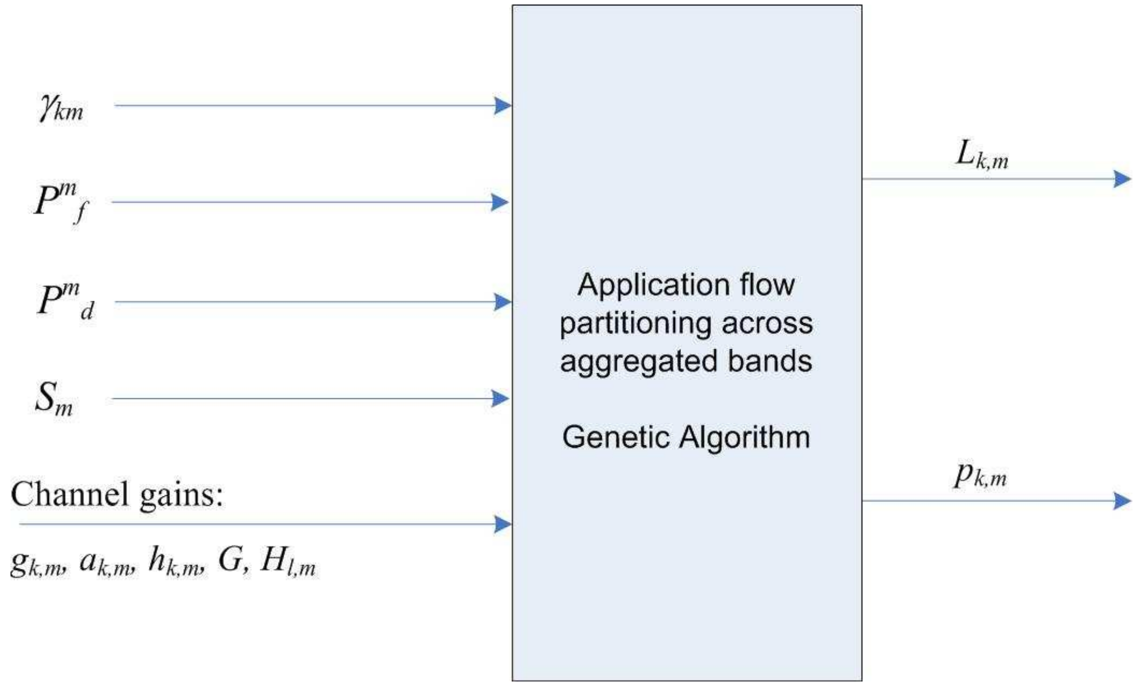
Figure 14: Results for minimisation of “Poor” quality aggregations and assignments

5 INPUT AND OUPUTS OF CRRM ALGORITHMS AND INTEGRATION IN CRRM SYSTEM

This section focuses on the input information or parameters required by each proposed CRRM algorithm and their outputs. The section also explores how the algorithms can be combined to contribute to the overall SACRA CRRM framework.

5.1 INPUT AND OUTPUT OF THE HIGH LEVEL CRRM PARTITIONING OF TRAFFIC AND APPLICATIONS FLOWS INTO AGGREGATED BANDS

Inputs/outputs for the high level traffic/application flow partitioning (2.6 GHz and 400to 800 MHz bands) algorithm in SACRA CRMM. This algorithm splits the requests according to applications quality of service requirements integrated in an objective function aiming at maximising user satisfaction as defined in M3.2. The diagram is meant to identify possible combinations with algorithms from WP3 partners.



Description of the parameters

Inputs:

- S_m : Decision of the sensing algorithm (S_m = 1 if the sensing algorithm believes that the resource block m is occupied by a primary user, S_m = 0 otherwise).
- $P^m{}_{fa}$: Probability of false alarm
- $P^m{}_d$: Probability of detection
- G: Channel gain from the TV tower to the TV broadcaster (primary user).
- $g_{k,m}$: Channel gain from the cognitive base station to the cognitive radio user (CRU) *k* on block m.
- $h_{k,m}$: Channel gain from the cognitive base station to the primary user.

- $H_{l,m}$: Channel gain from an interferer cognitive base station *l* to the target cognitive base station.
- $a_{k,m}$: Channel gain from the TV antenna to the cognitive base station *k*.
- γ_{km} : Signal to Interference-plus-Noise Ratio of user *k* on block *m*

Outputs:

- $L_{k,m}$: Allocation matrix ($L_{k,m}$ = 1 if block m is allocated to cognitive radio user k, $L_{k,m}$ = 0 otherwise).
- $p_{k,m}$: Transmission power that will be allocated to cognitive user k on block m.

Assumptions

In this scenario we consider the downlink of a cognitive radio system with one target cognitive base station (CBS) and *K* cognitive radio users (CRUs) over frequency selective fading channels. Cognitive radio users can communicate with the target base station using the 2.6 Ghz band and access opportunistically the 800 MHz band that can be occupied by a primary user (PU). For communication, we use the OFDM technology which means that each band is divided into *M* resource blocks. In addition, we assume that the target CBS has perfect knowledge of the downlink channel state information (CSI) between itself and the CRUs, and between itself and the primary user (PU). We further assume that the CRUs 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 CBS through a set of dedicated sub-channels.

5.2 INPUT AND OUTPUT OF THE SECONDARY USERS COOPERATIVE POWER CONTROL ALGORITHM

Inputs/outputs for the cooperative power control algorithm in SACRA CRMM. The algorithm is described in detail in D3.1 and further extensions are described in M3.2. The diagram is meant to identify possible combinations with algorithms from WP3 partners.

Scope

The proposed solution concerns a cooperative power control algorithm. The objective of the proposed scheme is to achieve a balance between the achieved bit rate and the negative effect a node has to its neighboring ones. The algorithm has been described in details in D3.1. Extensions of the algorithm so as to treat users in a fair way have been provided in M3.2. Potential extensions regarding introduction of learning capabilities (by using data mining techniques) in the cooperative power control scheme may be provided in D3.3. The rest of this document describes the inputs and outputs, as well as the assumptions of the proposed cooperative power control scheme.

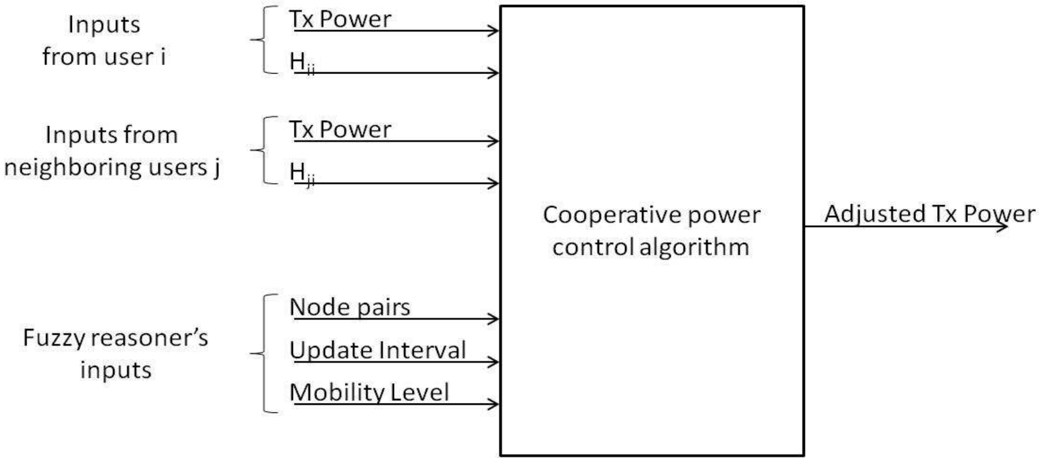


Figure 15: Input/output Diagram for deliverable D3.2 as per agreement during last WP3 audio

Description of the parameters

Inputs:

- Tx Power : Transmission power level of a user
- H_{ii} : link gain between i^{th} transmitter and i^{th} receiver
- H_{ji} : link gain between j^{th} transmitter and j^{th} receiver
- Node pairs, Update interval and Mobility Level are the inputs for the fuzzy reasoner that is utilized to avoid the underestimation of interference prices.

Outputs:

- Adjusted Tx Power : The new Tx Power of the user i

Assumptions

In the proposed scheme we assume the presence of several user equipments. The scenario examined and the assumptions taken into account regarding LTE operation over TVWS are described here. LTE UEs act as secondary users in the TVWS. The purpose of this opportunistic extension is to ensure higher cellular coverage and capacity. Therefore, the network extends its capacity by upgrading its base station (LTE eNB) to support the TVWS band. More analytically, a mobile operator opportunistically utilizes TVWS for expanding its operation. However, in the future it is expected that multiple mobile operators will share TVWS for their opportunistic operations. For example, as depicted in Figure 16, operator LTE (A) extends its operation band in (vacant) TVWS and so does another mobile operator, named LTE (B). Therefore, two operators share TVWS for secondary usage.

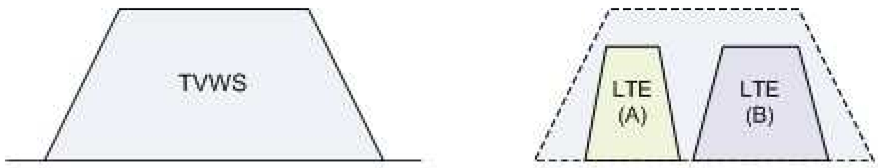


Figure 16: Two LTE operators sharing TVWS

The scenario examined is depicted in Figure 17. Two different LTE operators (served by eNB (A) and eNB (B) with three and two serving UEs respectively) are assumed to operate in TVWS in a specific geographical area where no primary (TV transmitters) users are found. Since no primary users are found in this area, the cooperative power control algorithm aims at:

- Optimally managing the (limited) power resources of UEs
- Limiting interference caused to (possible) other cognitive radio networks in the area
- Ensuring that aggregate interference is not harmful for adjacent channels (with primary users)
- Securing a lower bound of QoS (in terms of SINR) for the LTE UEs

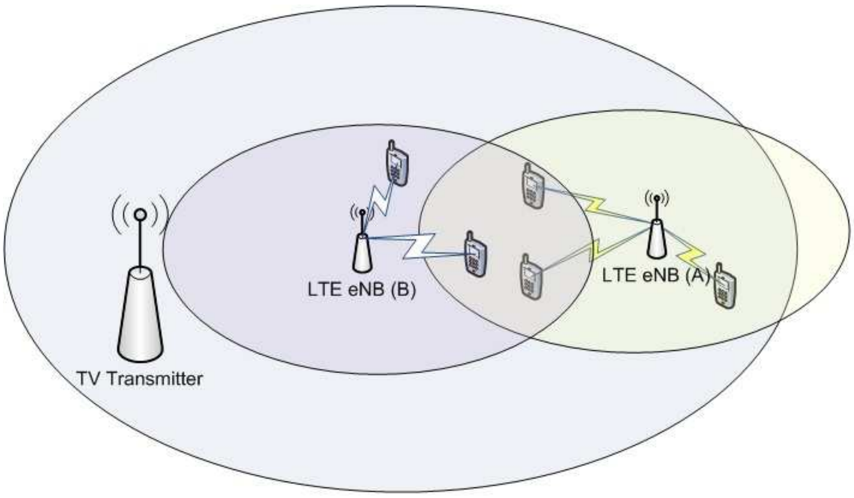


Figure 17: Examined Scenario

In other words, the main scope of the proposed power control scheme in LTE uplink is to limit inter-cell interference while respecting minimum SINR requirements based on QoS constraints and UE power capabilities. Uplink is the main focus since we examine the optimal power required for transmitting the interference prices in the network. It is worth mentioning that no interference is assumed for the UEs belonging to the same operator and are located in the same cell, due to orthogonal channel allocation. However, the use of the same channel in different cells is possible and could lead to Inter Cell Interference (ICI). This means that when a UE that belongs in a certain cognitive group (LTE cell of an operator) transmits, its signal is not interpreted as interference for the rest UEs of that cell, but only for the neighboring UEs belonging to different cell areas-cognitive groups. This is due to the fact that LTE uplink is orthogonal and therefore no intra-cell interference is caused, although a margin is still needed for the other cell interference (inter-cell interference).

5.3 INPUT AND OUTPUT OF THE DISTRIBUTED USER SELECTION ALGORITHM

The distributed secondary user selection and access control algorithm of section 4.2 assumes a number of parameters to be available as inputs to produce a resource allocation ensuring minimum experienced outage probability by primary users. A number of inputs are actually required to configure and set the values and variables of the algorithm itself. The input data needed for the algorithm initialisation and calibration are:

- Primary users transmitted data rate
- Maximum outage probability
- Tx antenna gain
- Rx antenna gain
- Thermal noise power
- Maximum transmission power

- Ambient temperature
- Equivalent bandwidth
- Signal to noise ratio
- Average gain over all users
- Channel gain between the base station and users
- Maximum number of cognitive users

Inputs from sensing unit are also required for the algorithms to run. These are key parameters and variables that need to be made available to most if not all the algorithms in the SCRA CRMM levels depicted in Figure 2. These central parameters are the:

- False alarm probability
- Detection probability

that originate from the sensing algorithms and pass through the sensing configuration unit where pre-processing may occur. The algorithm required access to the raw and pre-processed data to confirm or infirm the sensing configuration control.

The outputs of the outage probability based resource allocation algorithm are the

- Active secondary users
- Received power from all possible transmissions
- and the outage probability that determines if the target objective is fulfilled or not.

6 INFORMATION EXCHANGE AND COOPERATION

The exchange of information and cooperation between the terminals and the base stations in the SACRA carrier aggregation use case will rely on the 2.6 GHZ LTE-A band physical and logical channel structure. The cognitive SACRA terminals will use the WP2 algorithms to sense a specific list of sub bands received either through the broadcast or the multicast channels. The initial list is decided by the higher level rules and policies at the very start. This list can be tuned or modified through the sensing configuration system or as a result of CRRM decision making if a need arises.

Hence, we expect the overall CRRM system to interact with the LTE RRC and RRM and MAC to achieve in-band exchange of information between terminals themselves, terminals and base stations.

The terminals will use existing LTE channels to report their measurements on the uplink just like they conduct Channel Quality Indicator (CQI) Reports in LTE. Except that additional bands, carrier components and sub carriers need to be scanned in the potentially free bands in the 800 and 400 MHz bands.

Periodic CQI data is carried over the PUCCH (Packet Uplink Control CHannel). The PUCCH uses few bits to ensure swift and immediate decoding when the UE is not scheduled for transmission. Scheduled UEs can send their CQI reports over the PUSCH (Packet Uplink Shared Channel) that uses more bits and is decoded over several transmissions. The CQI reporting channels have a flexible structure and have been left deliberately open to implementers to enable differentiated and future use. This flexibility provides SACRA with the opportunity to find or select the most appropriate organisation for reporting sensing dedicated to the sensing of free bands and unused resources for resource aggregation by the algorithms presented in section 4.

Using the PUCCH and PUSCH structure from the LTE band means that all terminals actually report sensing results to the base station. The results are sent to the SACRA sensing configuration and control system for further processing. The actual data that needs to be sent to each component of the block diagram in Figure 2 are described in section 5. The main data that needs to be sent to these blocks are the probability of correct detection of primary user presence in the shared and white bands and the probability of false alarm both derived from the reported sensing results coming from the sensing unit.

Other parameters listed in section 5 are essentially internal to the SACRA CRRM system, the exception is the cooperative power control algorithm proposed to tune secondary users' power setting that have been allowed to enter the system and selected to benefit from carrier aggregation to achieve their throughput. Since this algorithm assumes that the terminals will actually exchange their observed or experienced utility a periodic and regular transmission on the downlink for these terminals will be required. Even if piggy backing on the downlink control and notification channels is possible, this may require an overlay of a logical channel organisation on the actual LTE-A downlink logical channels organisation. For the time being it is assumed that a dedicated physical channel need not be set aside to enable this exchange of information and that it is possible to multiplex the transmissions on available downlink control channels.

Obviously the amount of data that needs to be exchanged will generate overhead on these channels and additional physical channels provisioning may be required. A channel dimensioning study is required to assess more exactly the amount of resources that need to be set aside for this dedicated signalling for this specific algorithm. Another alternative is to isolate a subset of the

OFDM carrier and sub carrier structure for this dedicated cognitive radio signalling. The amount of needed resources to enable this exchange of information has to be estimated and removed from the available resource budget for data plane or user plane information exchange. Another possibility for sending sensing results from each terminal to the base stations is the HS-PDCCH that sends CQI information to eNodeB if HSPA is targeted for carrier aggregation.

Terminals that have established a link on the 2.6 GHz band and are active that may seek additional resources to achieve their target rates or performance can also benefit from the allocation of a dedicated control channel to exchange information with their base stations. So for UEs that are in RRC Connected mode a signalling radio bearer is already established with variants that can be used by SACRA CRRM to ensure exchange of information over the downlink.

For UEs or terminals that have not established any RRC connection and are relying on uplink shared channels or uplink random access channels to transmit their sensing reports there is no dedicated signalling possible. These terminals are in RRC-idle mode and there is no signalling radio bearer established. Hopefully, the availability of the DL-SCH enables the base stations to communicate with the cognitive terminals since the DL-SCH can be used to broadcast data in entire cell. A multicast channel is also available to address these terminals as well.

As of now, SACRA assumes that the terminals will send the sensing measurements to the base stations and will do the same for data that needs to be exchanged for cooperative power control and setting of secondary users. The same applies for terminal estimated channel gains between the base station and users.

Beyond the autonomous decision making, resource allocations and carrier aggregations that may be attempted or sought by each base station independently, there is a need to coordinate the base stations and exchange information between the base stations to control the inter cell interference and avoid collisions in their attempt to opportunistically capture unused carrier components in bands of primary users.

This type of data exchange occurs over the X2 interface that will also be used by SACRA in a multiplexed or piggy back mode to exchange data and views between the base stations for coordinated or joint CRRM. This will typically occur with the use of higher level algorithms located in levels 4 and 5 of Figure 2. The genetic algorithm proposed in 4.5 for resource allocation in a base station based on application and user satisfaction in the outer loop can easily be duplicated in a joint RRM (JRRM) module to coordinate a set of geographical co-located or adjacent base stations or cells. This algorithm relies on knowledge of resource blocks matrices providing availability status of each block indicating if a resource block is currently used by a primary user either in a hard or soft decision manner. Indicating that the block is believed used or not for the hard decision case or weighted by metadata containing soft information (the probability of false alarm and the probability of primary user detection estimates reported by WP2 sensing algorithms augmented possibly by the sensing configuration system assessment of ambient noise floor for the sensing algorithms).

The X2 interface already plays a key role in LTE and provides valuable functions that SACRA will rely upon and investigate to reuse. The list of functions on the X2 interface is the following:

- Intra LTE-Access-System Mobility Support for ECM-CONNECTED UE ensuring:
    - Context transfer from source eNB to target eNB;

  - Control of user plane transport bearers between source eNB and target eNB;
  - Handover cancellation;
  - UE context release in source eNB.

- Load Management

  - Inter-cell Interference Coordination
  - Uplink Interference Load Management;
  - Downlink interference avoidance

and application level data exchange between eNBs.

It is sufficient clear from this list that the X2 interface is the appropriate vehicle for the SACRA cognitive and cooperative sensing and resource management data exchange across base stations and across systems. When such an interface is not in place between different operators and systems, each domain must rely on their internal S Interfaces to reach the other domains via the core network and the backbone. This would apply over much larger time scales of the orders of tens of seconds to coordinate base stations belonging to different providers and are out of the scope of SACRA WP3.

7 SACRA CCRM COORDINATED DECISION MAKING, LEARNING AND REASONING

Learning and reasoning combined with optimisation is also a viable approach for some of the SACRA RRM algorithms, especially the cooperative power control algorithm that can learn the most appropriate power setting through reinforcement techniques. As decisions are taken through the use of the algorithms, the effect can be observed and classified to tune future decisions. Q or H learning can be used for instance to make future decisions based on past outcomes resulting from past explorations and decisions. This knowledge can be mined for reasoning and exploitation on the next encountered events that can be recognized as past patterns and can lead to faster decision and shortening the decision time and cycle. The use of learning can also be valuable for the sensing configuration module that can derive patterns for future dynamic and on the fly or on line sensing algorithm selections. The genetic algorithm described in section 4.5 embeds inherently learning and can operate on multiple criteria and constraints and will naturally adapt its decisions during exploration and exploitation phases while searching for good genes. Adding learning to these algorithms does not provide any benefits in genetic or bio-inspired techniques. Both have embedded learning in their inherent optimisation process.

For the cooperative power control, learning and reasoning added to the current version of the algorithm can improve performance. The introduction of learning is justified and briefly described in this deliverable to give an idea of plans to add learning to the current version.

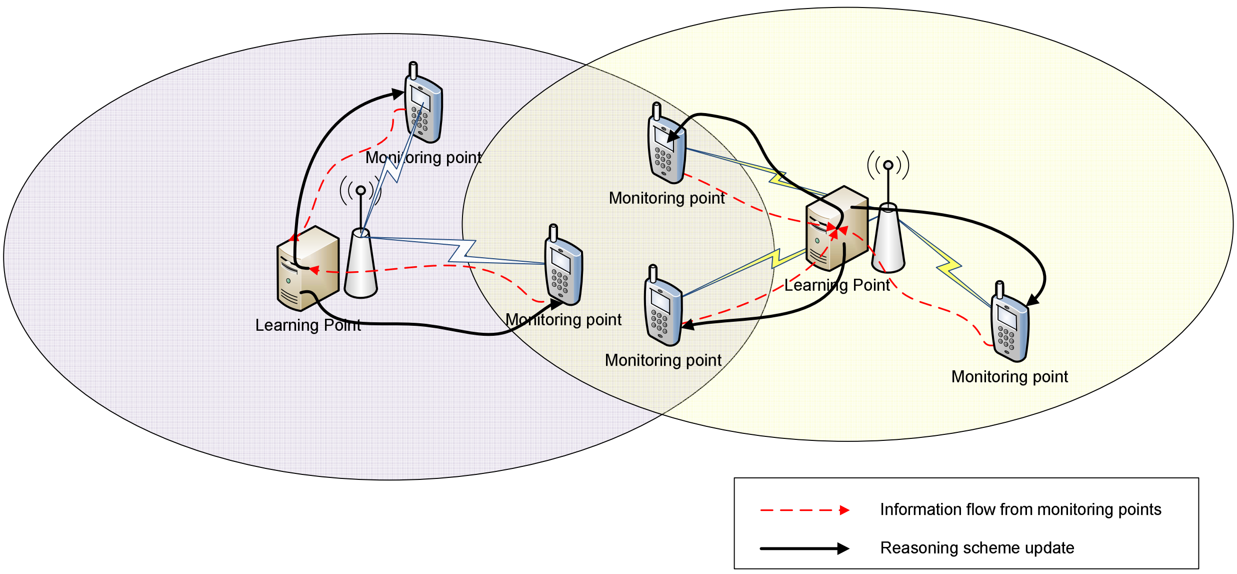


Figure 18: Overview of the learning scheme

The simultaneous presence of autonomous CR as in SACRA scenarios for dense and home environments underlines the necessity for interference mitigation schemes to harness or control performance. In [15], we have introduced an algorithm which deals with interference mitigation in uncertain environments under specific capacity and energy constraints. The proposed scheme in [15] does not capture, however, the different situation perception that each network element should have for optimal performance. The introduction of a learning-based adaptation mechanism is required to provide this required situation assessment capability. The aforementioned learning capabilities should benefit the network by providing better QoS levels on a user perspective and improved utility to the overall network.

Cooperative interference mitigation techniques are mainly based on the communication of peering nodes in order to inform their neighbours about their state (i.e. transmission power, interference, frequency etc) [16]-[17]. In the proposed scheme, the transmission power is extracted by identifying a trade off between the capacity and the interference caused to the neighbouring nodes but since a highly distributed approach can usually result in chaotic decisions, a supervised learning scheme is proposed. The learning capabilities of the mechanism try to have the more suitable situation perception of the environment based on the evaluation of the previous actions. Thus a network device will have more precise power adjustments and thus achieve higher benefits for the overall network utility.

To overcome the static characteristics of the aforementioned decision making and learning processes, a data mining mechanism should be integrated to exploit the feedback from the network and adjust the mechanism according to the interpretation of the environment (Figure 18). More specifically, clustering techniques could be incorporated in order to enhance the situation perception by extracting the correlations of the monitored instances and calibrate the decision making parameters so as to adapt the power levels according to the environmental changes. This learning technique will be combined with the proposed cooperative power control algorithm to enhance performance through improved power settings.

8 CRRM ENERGY AND SPECTRUM EFFICIENCY CONSIDERATION AND SACRA INDICATORS

Energy efficiency and number of components are the two indicators that are considered in the SACRA energy efficiency assessment. SACRA CRRM does not deal with number of components and their energy consumption as it involves mainly optimisation algorithms in software deployed in terminals and base stations. The SACRA CRRM system contributes to the energy efficiency of the overall SACRA system at the user admission control and user power setting control levels. All algorithms aim at allocating resources in the most efficient way in terms of energy consumption even if no explicit energy attributes are directly included in the objectives functions of the proposed solutions. At all levels of the SACRA CRRM system (levels 2 through 5 in Figure 2) the minimum interference and minimum power allocations are sought. This is obtained via the objective functions and the constraints associated to each algorithm. Spectrum efficiency is achieved through better usage of the available spectrum in the incumbent bands as well as the flexibility gained through the opportunistic carrier aggregations conducted by the flow and user partitioning algorithm (levels 4 and 5 in Figure 2) across all available bands and free carrier components from all the bands. The energy and spectral efficiency are measured instead via overall achieved capacity and the amount of reduced interference thanks to carrier aggregation and cooperative and cognitive power control.

The genetic algorithm presented in section 4.5 aims at splitting traffic flows into sub bands while ensuring incumbent protection in the white spaces as well as allocating the LTE OFDM resource blocks to achieve best secondary users satisfactions. This algorithm contributes indirectly to better spectrum usage and spectral efficiency. This is achieved via better spectrum occupation and sharing by using vacant frequency bands and aggregating carrier components with packing and consolidation of contiguous or non contiguous bands for application session flows. The spectrum occupancy is the aspect that is dealt with for this algorithm and to some extend the amount of overall required power to improve system capacity. The energy efficiency is not addressed in terms of number of components in the case of the SACRA CRRM. The algorithm can be either centralised or distributed and in both cases induces marginal impact from the number of components standpoint and has no impact on energy consumption in this respect. Like all the algorithms in SACRA CRRM, it just requires the integration of the algorithm as software running on any operating system in the base stations. Spectral occupancy is however taken into account. The indicator is the amount of bandwidth consumed by the system to serve a given number of users.

This genetic algorithm, even if aiming primarily at user or application satisfaction in throughput and delay performance to handle tolerant as well as stringent delay requirements, achieve indirectly minimum power levels for secondary users or LTE users through inequalities 15 and 16 and conditions and constraints expressed within these equations and equation 17. They are repeated here for convenience:

$$\begin{cases} \sum_{k=1}^{K}\sum_{m=1}^{M} L_{k,m}\, p_{k,m} \le P_{\max} \\ \sum_{k=1}^{K}\sum_{m=1}^{M} L_{k,m}\, p_{k,m} h_{k,m} \le I_{threshold} \end{cases} \qquad (18)$$

These constraints in fact indirectly lead to a minimum power or equivalently minimum mutual (opportunistic users' interference) and cross interference (between opportunistic users and incumbents). This is not as explicit as in the other algorithms operating at level 3. Indeed, the minimum power is obtained as a by product of the genetic algorithm whose goal is to find the best chromosomes or resource block allocations. These allocation lead to minimum power levels for the users and minimum usage of the available LTE resource capacity as specified by the constraint in equation 15:

$$\min \sum_{k=1}^{K} \sum_{m \in N_v} L_{k,m} \alpha_m \quad (19)$$

All these goals and constraint lead to minimum power usage. For the minimum incumbent outage probability protection algorithm and the cooperative power control, this is far more explicit in the algorithm formulations themselves and the minimum power goal or objective is immediately visible.

For the minimum outage probability criterion algorithm, described in section 4.2, deployed in base stations and handling both uplink and downlink LTE opportunistic users access control, the minimum power criterion is embedded in equations 1 through 3 that jointly aim at keeping the PU capacity above a threshold rate R_u with high probability (1- P_{out} (R)). For secondary users the criterion, beyond maximising the sum capacity as indicated in equation 6, consists of controlling power of the SUs both in an effort to preserve power and to limit interference and fading effects [1][2]. The overall system is also governed by admission control based on a capacity bound that sets the maximum number of users that should enter the system at a given power level including the maximum allowed power for secondary users. The bound from [1] provides the maximum number of opportunistic users that should be allowed to enter the system. The bound is given by the following equation:

$$0 \le \tilde{M} \le \frac{-\log(1-q)}{(2^{Rpu}-1)} \cdot \frac{G_{pu}^2 p_{pu}}{G_{su}^2 p_{\max}} - \frac{1}{SNR} = \tilde{M}_{tn} \quad (20)$$

This bound controls the maximum number of users that may enter the system at maximum power. This provides a worst case condition corresponding to all secondary users operating at their maximum allowed power setting. This bound guarantees that even in this case, the interference induced on incumbent users will remain below the protection threshold and their outage probability will not drop below the acceptable limit.

The users allowed to enter the system can hence use the available carrier components at these power levels without causing unacceptable outage probability to the incumbents or violating their protection thresholds. Actually in SACRA, the approach consists of entering the system at lower power levels first and then fine tuning the levels to the minimum required power for each SU that gained access to the free carrier components. Access grant is consequently first given but no actual transmission takes place. The minimum power levels are next found and only once each SU gets its minimum required power setting to achieve its target QoS, he is finally allowed to enter effectively the system. This can be achieved either by the Minimum Outage Probability algorithm itself when SUs make decisions autonomously or via the cooperative power control algorithm when the SUs exchange information and cooperate.

The cooperative power control algorithm described in section 4.3 aims at finding the minimum required power level for each SU based on the computation of their respective utilities and their achieved utility values. The algorithm assumes that the SUs exchange their currently achieved utilities to make future decisions. As described in section 4.3 this algorithm is specifically addressing minimum power requirements and leads to minimal power transmission levels and minimum overall interference. This algorithm achieves significant power gains whether it is used independently or in tandem with the minimum outage probability criterion algorithm. The latter decides on access control and access grant. The cooperative power control algorithm determines precisely the lowest power level needed for each and every SU.

Spectrum occupancy and efficiency are not dealt with by the Cooperative Power Control Algorithm. The algorithm considers only energy efficiency and number of components as the key indicators. This algorithm introduces an efficient power control mechanism so terminals operate at minimum transmission power settings. This reduces the amount of consumed battery power in the terminals. More specifically, cooperative power control algorithm improves the terminal's energy efficiency, as it optimally calculates transmission power levels in a finite number of iterations. As a consequence, not only unlicensed users transmit at significantly enhanced power levels, but also signaling overhead is limited. The number of involved components is reduced, since the algorithm is fully distributed and each user will autonomously decide its transmission power level based on information received by the eNB regarding interference other users experience.

The flow partitioning algorithm into the available sub bands for carrier component aggregation can be used prior to these two algorithms to partition flows into bands according to minimum power budget consumption goals. This partitioning algorithm splits flows across bands but also aggregates carrier components into contiguous or non contiguous fashion to serve the traffic flows and results in more efficient use of the spectrum. Both carrier packing and consolidation are embedded in the proposed genetic algorithm that aggregates carriers and saves consequently spectral resources. A formal assessment is actually needed to quantify precisely the gains. This is currently out of scope of this deliverable that conducts only an intuitive and qualitative analysis.

The WP3 CRRM algorithms address energy efficiency by targeting minimum power levels for secondary users in all the selected algorithms. Hopefully, the sensing configuration system can also optimise the sensing configuration and parameter settings and sensing cost based on energy efficiency criteria as well.

The SACRA sensing configuration in fact enhances single node sensing by allowing selection of the most reliable detector according to ambient noise conditions. This achieves better and more accurate detection probabilities (than in the state of the art) of spectrum holes for secondary use. When combined with optimal resource allocation contributes positively to optimal occupancy of the spectrum. This results in better spectrum usage. Sensing configuration is not directly impacting and does not involve spectrum efficiency that will be mostly the duty of radio Link Control that ensures adaptive modulation and coding. Sensing configuration also aims at achieving a trade-off between accuracy and cost and this also leads to a parsimonious use of the resource in computation and signalling load that in turn improves overall system efficiency and to some extent energy efficiency as less processing will be needed. Energy efficiency will rather be achieved from for example better spectrum occupancy of the lower frequency bands.

In the future plans, the partners in WP3 are preparing an adaptation and simplified version of the cooperative power control algorithm and the outage probability based algorithm for the WP6 demonstrator. The algorithms studied in WP3 require the availability of or assume the implementation of the entire LTE MAC/RRC/RRM pile, while the demonstrator will be mainly integrating the WP2 and WP3 PHY layer algorithms in the WP5 platform library and boards. So far, independent feasibility analysis and partial performance evaluation has been conducted for each algorithm. Joint feasibility tests need to be conducted for algorithms that can be combined and merged in a cohesive fashion in the CRRM system for integration since they operate at different levels in the system hierarchy.

Alternate approaches for secondary users' access to free spectrum will be explored. A resource management method based on game theory is envisaged or foreseen. The idea is to maximize a defined utility function subject to minimization of the mutual interference caused by secondary users with protection for primary users. We will adopt in this work the same method proposed in section 4.2 to protect primary users by using the outage probability constraint. In fact, a utility function will be formulated to reflect the needs of primary users by verifying the outage probability constraint, and the per-user capacity by satisfying the signal-to-noise and interference ratio constraint, as well as to limit interference to primary users.

At the spectrum sensing scheduling and configuration level in the base station (eNodeB), work will be devoted for integration of the sensing configuration module in the SACRA CRRM system by through interactions and interfacing with the resource allocation and optimisation algorithms. The sensing configuration in the base station aims at setting and controlling the sensing parameters (e.g., maximum allowed false alarm and minimum allowed detection probabilities, sensing duration) for cooperative sensing. To set and control the sensing parameters, learning should be introduced to take into account previous results and fine tune decisions. The same effort is expected for the cooperative power control algorithm that can introduce learning next to improve decision and optimisation. At the higher levels, 3, 4 and 5, the user satisfaction based algorithms will be deployed in multiple base stations and will run concurrently on their own resource block management budget but will cooperate with joint RRM in a multi-cell and multi-user context in order to monitor local and autonomous allocations and their potential mutual interference by sharing ICI data across the X2 interface. The JRMM in the base station acting as central controller and coordinator will intervene only when required by reacting only if conflicts are detected or foreseen and will bar any resources accordingly and force decisions into the autonomous base stations. The objective is to have the base stations operate as autonomously as possible with no intervention from Joint RRM unless deemed necessary. These investigations have been initiated and will be the subject of future reports and deliverable.

9 REFERENCES

[1] B. Zayen, M. Haddad, A. Hayar and G.E. Øien. Binary power allocation for cognitive radio networks with centralized and distributed user selection strategies, Elsevier Physical Communication Journal 1(3): 183–193, 2008.

[2] B. Zayen and A. Hayar, "Primary Outage-based Resource Allocation Strategies", Chapter book in "Cognitive Radio Systems", Intech, November 10th, 2011, Ed. Samuel Cheng, ISBN 978-953-307-643-0.

[3] L. H. Ozarow, S. Shamai and A.D. Wyner, “Information theoretic considerations for cellular mobile radio“, IEEE Trans. Veh. Technol., 43(5):359–378, May 1994.

[4] J, Riihijavi, M. Petrova and P. Mahonen, “A Common Application Requirement Interface for Cognitive Wireless Networks”, in IEEE 6th Annual Sensor, Mesh and Ad Hoc Communications and Networks Workshops, 22-26 June 2009.

[5] A. Ghasemi and E. S. Sousa, “Spectrum Sensing in Cognitive Radio Networks: Requirements, Challenges and Design Trade-offs”, IEEE *Communications Magazine*, Avril 2008, vol. 46, pp. 32-39.

[6] H. Urkowitz, “Energy detection of unknown deterministic signals”, *Proceedings of the IEEE*, vol. 55, pp. 523-531, April 1967.

[7] A. Dandawate and G. B. Giannakis, “Statistical tests for presence of cyclostationarity” *IEEE Trans. Signal Process,* 42, 2355-2369 (1994).

[8] A. Ghasemi and E. S. Sousa, “Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments”, *Proc. of IEEE DysPAN*, pp. 131-136, Dec. 2005.

[9] Z. Ye, G. Memik and J. Grosspietsch, “Energy Detection using Estimated Noise Variance for Spectrum Sensing in Cognitive Radio Networks”, *Proc. of IEEE WCNC*, pp. 711-716, March 31-April 3, 2008.

[10] K. Muraoka, M. Ariyoshi, “A Robust Spectrum Sensing Method Based On Maximum Cyclic Autocorrelation Selection for Dynamic Spectrum Access” *IEICE Trans. Commun.*, Vol. E92-B, No.12, Dec. 2009.

[11] S. Maleki, A. Pandharipande and G. Leus, “Two-stage spectrum sensing for cognitive radios”, *In Proc. IEEE ICASSP*, pp. 2946-2949, Mar. 2010.

[12] D. Cabric, S. M. Mishra, R. W. Brodersen, “Implementation Issues in Spectrum Sensing for Cognitive Radio” , *Conference Record Thirty-Eighth Asilomar Conference on Signals, Systems and Computers*, 7-10 Nov. 2004, vol. 1, pp. 772-776.

[13] FCC 10-174, In the Matter of “Unlicensed Operation in the TV Broadcast Bands and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band”, SECOND MEMORANDUM OPINION AND ORDER, Sept. 23, 2010.

[14] M. J. Ready, M. L. Downey and L. J. Corbalis, “Automatic noise floor spectrum estimation in the presence of signals” , Proceedings of Thirty First Asilomar Conference on Signals, Systems and Computers, vol. 1, pp. 877 - 881, Nov. 1997.

[15] Deliverable D3.1 of SACRA project, “Cognitive RRM outer & inner loop architecture”.

[16] Chun-Gang Yang, Jian-Dong Li, Zhi Tian, “Optimal Power Control for Cognitive Radio Networks Under Coupled Interference Constraints: A Cooperative Game-Theoretic Perspective”, IEEE transactions on vehicular technology, vol. 59, no. 4, pp. 1696-1706, May 2010.

[17] Mariana Dirani, Zwi Altman, “A Cooperative Reinforcement Learning Approach for Inter-Cell Interference Coordination in OFDMA Cellular Networks”, 8th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2010.

[18] A. Merentitis, D. Triantafyllopoulou, "Transmission Power Regulation in Cooperative Cognitive Radio Systems Under Uncertainties" in the Proceedings of the International Symposium on Wireless Pervasive Computing, (ISWPC), 5-7 May 2010, Modena, Italy.