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PCA	Public with confidential annex	
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EXECUTIVE SUMMARY

This document presents the key achievements of the SACRA project on the design of a cognitive multi-band terminal and advanced RRM mechanisms that have been developed for its exploitation. This terminal is designed to communicate with eNodeBs in the licensed bands at 2.6 GHz and in the digital dividend, and has also the capability to benefit from more bandwidth using additional channels in the TV white spaces. New mechanisms for a flexible management of the resources have been designed to benefit from the cognitive and multi-band capabilities of the SACRA terminal, and then improve the system performance in terms of capacity, range and energy consumption.

This document starts with a summary of the SACRA use cases, the main one being related to the aggregation of carriers with an access to the spectrum which can be licensed and potentially opportunistic. The global objectives of the project and the approach followed to achieve them are presented.

The architecture and information model of SACRA that were detailed in the previous WP1 deliverables have been updated. They have been designed to support sensing and classification for protection of the primary users, and to manage an opportunistic access to the TV white spaces on top of the operation in the licensed bands. The description of the terminal architecture, of its modules and of its interfaces, is also revised. A final view on these topics is given here.

Then this deliverable presents the main technical achievements of the project, and provides the outcomes and recommendations for each enabling technique that has been investigated in the framework of SACRA. The main techniques are listed below:

- Antenna sub system for mobile cognitive terminals;
- Radio Frequency Front-End for mobile cognitive terminals;
- Digital Predistorsion and PAPR reduction algorithms to improve the performance of the power amplifier;
- Baseband approach for cognitive operation, applicable to terminals but also to other radio access equipment;
- Sensing and classification techniques for protection of the primary users: those techniques can be implemented on mobile terminals but also on eNodeBs;
- Flexible Radio Resource Management and Cognitive Engine mechanisms to control the licensed and opportunistic use of the resources.

The motivation, the position vs SOTA, the design approach and the conclusions on the performance evaluation are given for all techniques. Recommendations for future cognitive systems, and the impact on key performance indicators, are also provided.

In addition to these technical results, this document includes the main economical achievements of the project, and in particular an overview of the SACRA business architecture reference model.

Last the regulatory context in which SACRA studies have been conducted is presented, and conclusions for future communications systems are given.

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1 INTRODUCTION

This document reports the activities that have been performed in SACRA to build a terminal for mobile communications with multi-band capabilities to address both the licensed spectrum in the 2.6 GHz and Digital Dividend bands, and the TV white spaces with a secondary access to this spectrum band. This document also presents the mechanisms that have been developed for the dynamic management of these bands by a network operator.

D1.3 compiles the technical and economical achievements of the project, and provides the outcomes and recommendations that are valuable for the future deployment of cognitive radio systems. This document is meant to be a standalone one, thus providing a quick overview of the project scenario, use cases and objectives, and then an extended summary of the whole study of each building block. The main results of the project are gathered in D1.3 whereas the research activities have been detailed in the technical reports of WP1 to WP5. Another report of the project, D6.4, will present the results and conclusions from the validation and trial activities.

Chapter 2 summarises the scenario and use cases of SACRA. It reminds the objectives of the project and the approach that has been specified and followed to achieve them. It is important to design the enabling techniques in a consistent way so that the system objectives, such as the communication in the TVWS and the protection of the primary users, can be achieved.

This chapter is followed by the presentation of the reference model of SACRA and the architecture of the terminal in chapter 3. The role of the interfaces between the building blocks of the terminal is also presented. This chapter is completed with the SACRA information model.

The study of the enabling techniques (antennas, RF-FE, ADC, DPD, baseband, sensing/classification, MIMO, RRM) is reported in chapter 4. An extended summary of the design of each SACRA component is provided, from the analysis of the state of the art to the design and evaluation of the solution, and to the conclusions and recommendations for future systems. Chapter 4 ends with the impact of these studies on the global indicators of the project.

The economic studies are addressed in chapter 5 with a short analysis of the market of mobile communications and an overview of the reference model of the business architecture of SACRA.

Finally regulatory aspects are considered in chapter 6 to put the SACRA results into perspective, in particular in terms of incumbent detection, and final conclusions are given in chapter 7.

2 SACRA OVERVIEW

2.1 SACRA SCENARIO AND USE CASES

The regulation in several European countries is currently attributing the 800 MHz (790 to 862 MHz) band, also called Digital Dividend, to radio mobile communications (LTE and following) and considers a joint license to operators with the 2.6 GHz (2.5 to 2.69 GHz) band. The initial intent is to have a full coverage using the lower band for large coverage, typically for rural areas, while the 2.6 GHz band would be used in high density areas.

Such a static use of the two bands may appear inefficient in some conditions, depending on the traffic load, the propagation environment and the terminal positions. Thus SACRA develops the means to exploit jointly and simultaneously these licensed bands with optimization of the network operating parameters to take into account instantaneous conditions, especially the environment, the system state or the communication needs.

Besides SACRA goes further in the exploitation of the UHF band by performing, when relevant, a secondary use of the spectrum in the TV white spaces until 470 MHz. Combined with the dynamic features provided to the network, the joint management of the resources in the 2.6 GHz, 800 MHz and TVWS bands will provide some gains in terms of spectrum efficiency and occupancy, energy efficiency…

In this context, SACRA designed enabling techniques for multi-band cognitive operation as illustrated on Figure 2-1. This includes the investigation of dynamic resource allocation strategies based on the development of optimized radio resource management mechanisms and the derivation of advanced sensing and classification techniques, combined to the design of the advanced software and hardware components required to build a SACRA terminal.

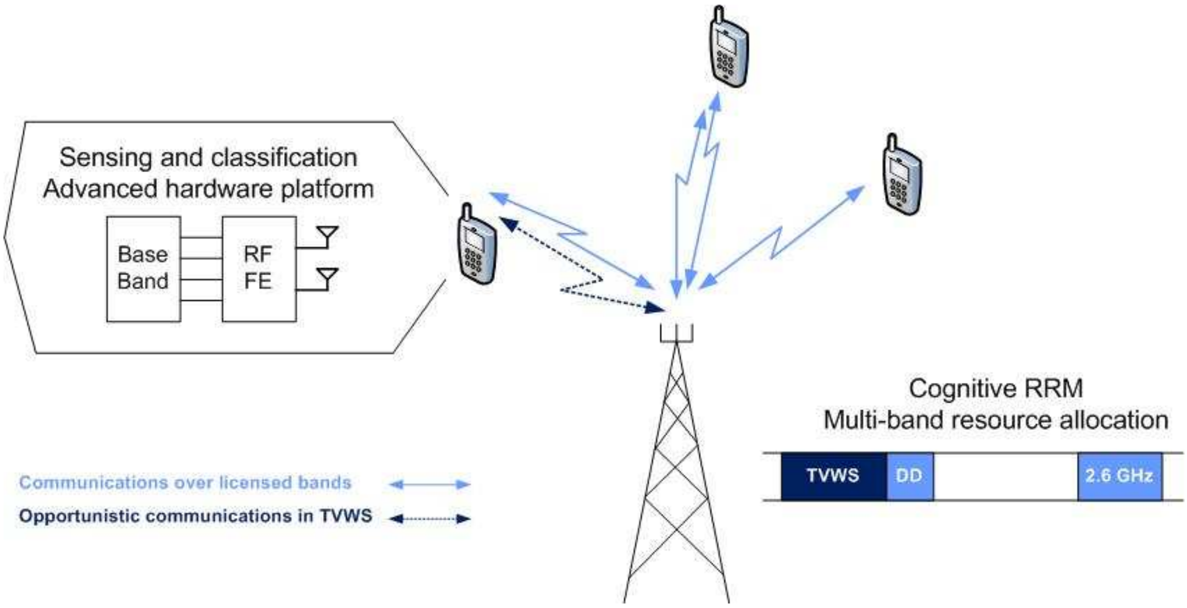


Figure 2-1: SACRA scenario

Based on this general framework, use cases of interest for SACRA have been selected in D1.1 [1] for their interest considering the current standardisation context, the technical challenges to be addressed, and their commercial potential which has been further investigated in D1.2 [2].They are briefly reminded in the following.

2.1.1 Spectrum aggregation

In 3GPP Release 8/9, various carriers' bandwidths of 1.4, 3, 5, 10, 15 and 20 MHz are supported. 3GPP release 10 is introducing carrier aggregation which is the feature to expand the bandwidth delivered to a user terminal thanks to the aggregation of different bandwidths in multiple carriers. It allows aggregating two and up to 5 component carriers (CC) in the DL and UL between the E-UTRAN Node B (eNB) and the user equipment (UE). This aggregation mechanism will provide up to 100 MHz bandwidth.

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

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

Operating in the TVWS will improve the throughput experienced by the users of a given cell, in particular at the border of the cell, provided that the network has the capability to detect and protect the incumbent users from a noticeable degradation of their QoS.

The second main differentiator of the SACRA spectrum aggregation use case compared to the current status of the LTE-A standard is the dynamic selection of the licensed/unlicensed spectrum to optimize the use of the spectrum in relation to the user needs. The resource managers of the eNodeB make this dynamic selection and perform the spectrum aggregation using some knowledge on the characteristics (capacity, range …) of the channels of interest: the licensed ones and the available ones for an opportunistic use in the TVWS. Each eNodeB performs individually these operations in the case of intra-cell spectrum aggregation, but the eNodeB can also cooperate to better serve the users thanks to inter-cell spectrum aggregation, as illustrated in Figure 2-2.

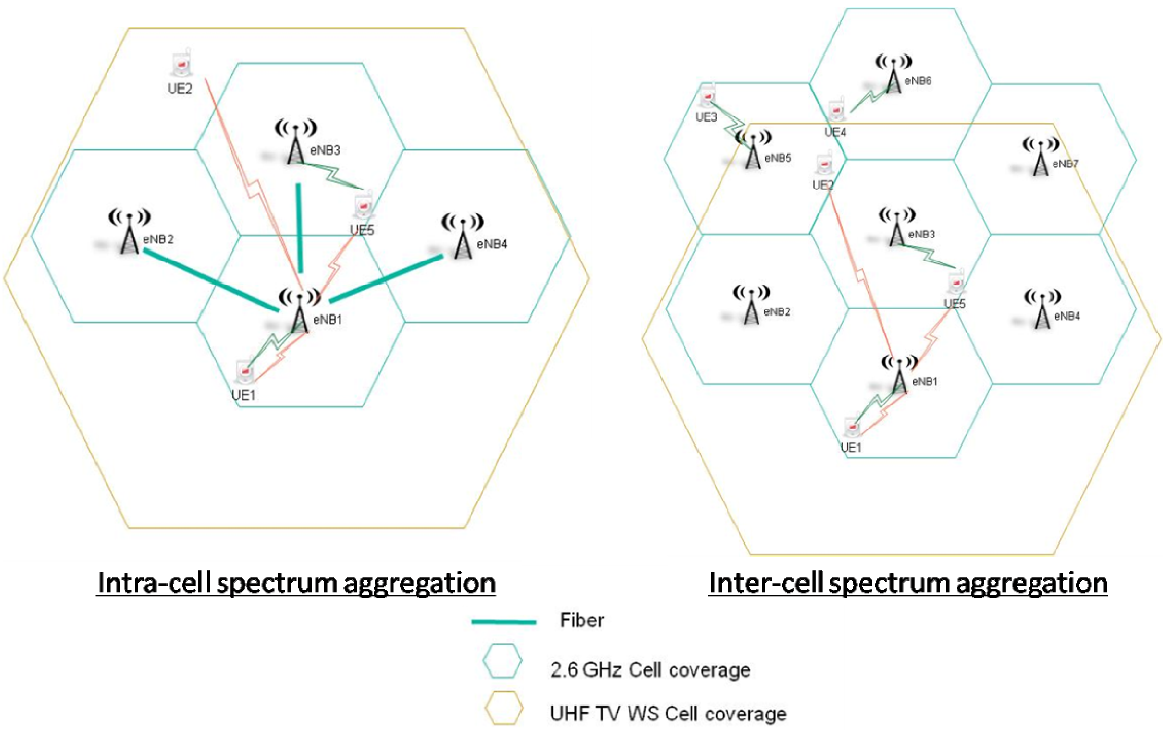


Figure 2-2: Examples of spectrum aggregation deployment

Intra-cell spectrum aggregation relies on the concept of an upgraded eNodeB using carrier components in both licensed and TVWS bands:

- to provide an higher throughput to the users nearby the eNodeB,
- to allocate new resources, in the TVWS, to users at the cell edge or beyond, which suffer from a bad QoS in the licensed band,
- to manage more efficiently the load of the cell thanks to the flexibility in the management of the resources.

In the case of inter-cell spectrum aggregation, which can be applied to co-located or distant cells, i.e. to two sectors or eNodeBs, 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. This mechanism of inter-cell spectrum aggregation also provides new degrees of freedom in the management of the load of the network.

2.1.2 Cognitive relaying

Users lying closer to the cell edges suffer from performance degradation due to two reasons, they not only receive weak signal power as compared to the users lying closer to the BS due to path loss effects, but also receive the strongest interference from neighbouring cells due to their proximity. In such cases, relays could be deployed at the cell edges to provide reasonable service to cell edge users. On the other hand, the relays can be used as a means to increase the cell coverage. These relays could also be deployed in the areas where a better quality of service is required for users.

Two types of relay are considered in SACRA.

<u>Conventional relays using a different frequency band</u>

The network deploys L3 relay nodes to improve its radio coverage in indoor or shadowing areas. This use case enhances the basic LTE-advanced use-case by applying to relays an operating frequency band different than for the donor cell. Thus, the network jointly manages the two frequency bands for allocating resources to terminals with less complexity in interference control process.

<u>Cognitive Relays with Intelligent Processing</u>

In this case, relays coexist with the main network in the same frequency bands (one user in relay area may use the same frequency as one user in main network), as illustrated on Figure 2-3. The BS and relay are connected over the air. Relay performs cognitive operation meaning that it is doing sensing and resource planning for its own users. Relay is aware of transactions on the main network and takes this information into account for resource planning.

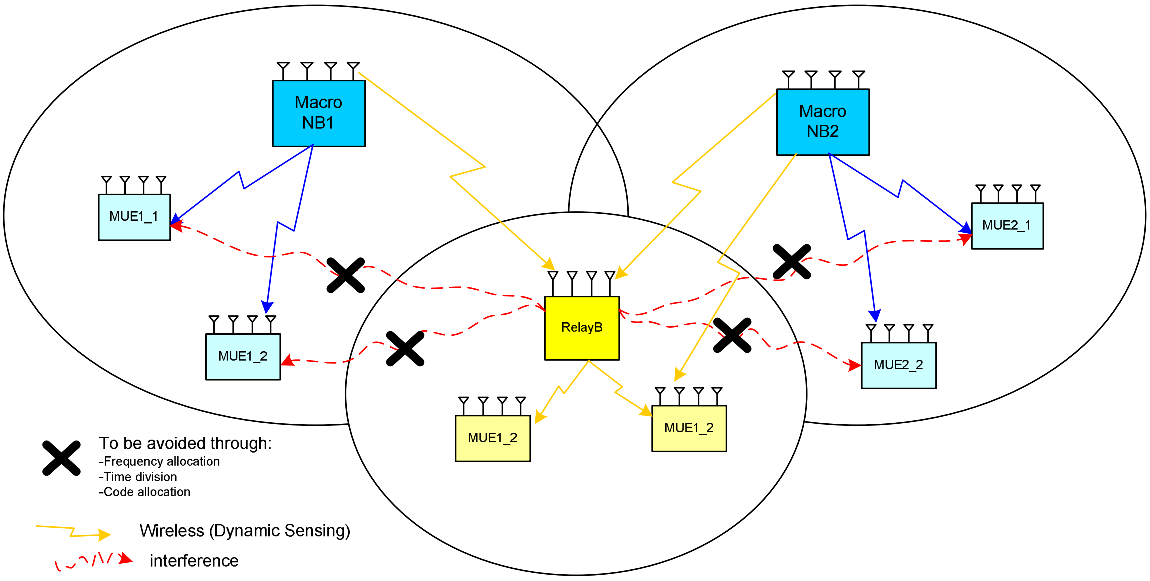


Figure 2-3: Cognitive relaying with coexistence mechanisms

2.1.3 Broadband access around home

Very high data rates can be provided to the users around femto base stations (BSs). These femto BSs can be further deployed in the areas where users suffer from bad coverage conditions or severe shadowing. Although femto BSs are being standardised in 3GPP LTE-Advanced, SACRA considers them at a very different and dynamic level where femto BSs and home BSs sense the frequency and/or spatial “holes” in the spectrum and transmit over those “holes”. In SACRA another significant step compared to current 3GPP standardisation is the possibility of co-coordinated transmission where macro and home BS join hands to provide high data rates to the users. This use case is illustrated on Figure 2-4.

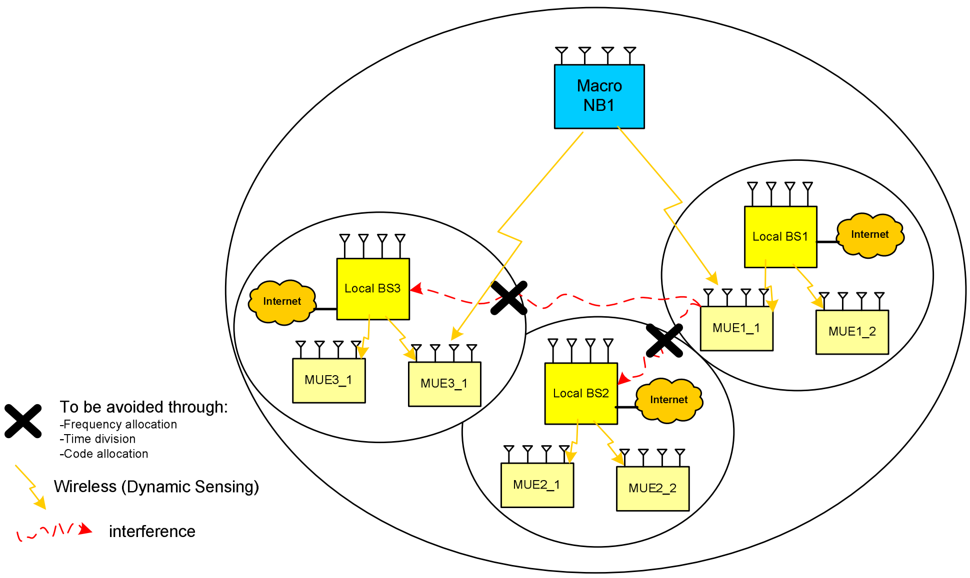


Figure 2-4: Broadband access around home

Femto cells may provide performance enhancement in two scenarios:

1. Deployment in non or badly covered areas.
2. Deployment of femtocells in already covered areas to enhance the users' throughput.

It is to be noted that the second setup with deployment of femtocells for better user experience is of particularly interest.

The proposal is to use dynamically the licensed spectrum among the macro and femtocells. In case, the system is getting overloaded and exhaustive reuse offers very strong interference, the cognitive SACRA users use their spectrum sensing capabilities and use the spectrum holes in the unlicensed band. We also consider the cases where multiple femtocells or a combination of femtocells along with macro cell serve the user.

2.2 OBJECTIVES

2.2.1 Project objectives

In relation with the use cases reminded in the previous subsections, the SACRA project has targeted the design and demonstration of enabling techniques for energy efficient multi-band cognitive operation. This includes:

- the investigation of new cognitive radio resource management strategies, combined to advanced sensing and classification techniques to manage a secondary use of the spectrum in the TVWS;
- the development of a SACRA platform that supports multi-band communications, based on the design of flexible baseband and wideband hardware components (RF front-ends, antennas);
- the demonstration of the project concept using the SACRA platform for communication in real time over the air, with a real IP application on the top of the protocol stack;
- the dissemination and the exploitation of SACRA results through various actions.

2.2.2 Technical objectives

The SACRA system is based on cognitive radio mechanisms, to gain in adaptability thanks to the combination of several advanced techniques in context awareness, decision-making and associated reconfigurable hardware capabilities. The capacity to allocate dynamically the transmission opportunities to each radio terminal of the system including the band, power, modulation and coding scheme, ensures a more optimal use of the spectrum resources than a static solution.

To allow both an optimal distribution of load between the 800 MHz and the 2.6 GHz bands, and an opportunistic operation in TV White Spaces (TVWS), the SACRA system requires measurements and especially knowledge of the spectrum occupancy in the considered bands. Therefore, certain detection/management techniques are required. The collected information is then conveyed through the network to the decision point(s) where resource allocations and interference management techniques are running. Multi-band Radio Resource Management techniques have been developed to take optimal decisions at system level. Decisions are then conveyed on the network and each radio terminal receives instructions on how to behave: what band at what time, what power, modulation, coding scheme, and polarisation.

To allow such a strategy to be applied by the SACRA system, the terminals must be flexible enough to provide sufficient options to the decision process. For this reason the system relies on an advanced hardware platform design. The following points have been considered: (i) the implementation of flexible radio base band architecture, (ii) the implementation of an advanced Radio Frequency modem, and (iii) the implementation of dual-band antenna. All this hardware is designed to maximize capabilities while minimizing the number of components and the energy consumption. All system parts have been designed in a coherent manner using the methodology presented in the following section.

2.3 SACRA APPROACH

2.3.1 WP breakdown

The activities of SACRA have been divided into eight work-packages, as reminded on Figure 2-5.

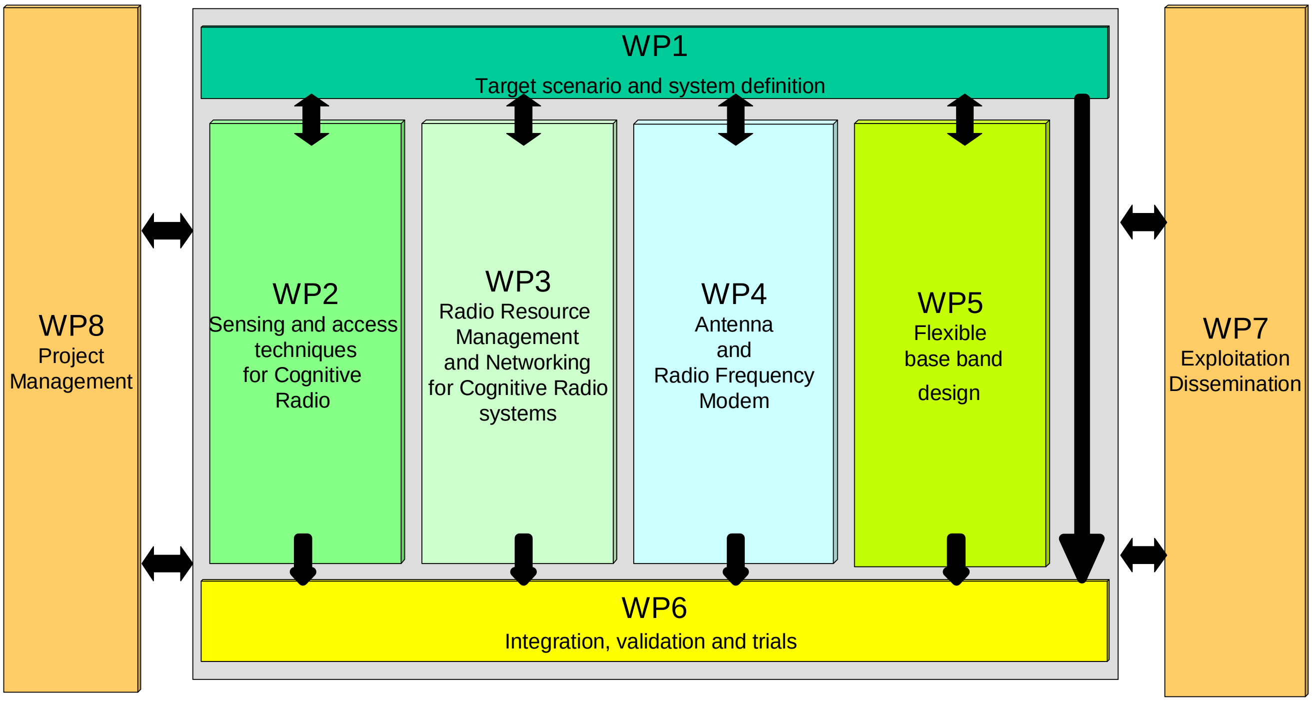


Figure 2-5: SACRA WP breakdown

In order to achieve the objectives of SACRA, the work-packages have worked and interacted according to the methodology presented in the next subsection.

2.3.2 Methodology

The activities of SACRA have started in WP1 with the definition of the use cases of interest for the project from the target scenario. Initial system requirements have been derived from these use cases in order to allow the different technical work-packages to work on common assumptions and parameters. A feedback from the technical studies performed in WP2/3/4/5/6 has contributed to progress iteratively with WP1 on the specification of requirements to design the SACRA system and on the definition of the reference architecture. The main use cases have then been considered from a business perspective to propose a reference model for SACRA business architecture, and to evaluate the economical benefits of the main features of the project.

The requirements and the system defined in WP1 have set up the scope to design the enabling techniques for cognitive multi-band communications. New concepts and components have been designed and assessed in the fields of sensing, RRM and networking, antennas/RF and baseband, taking into account the interactions between these blocks. The final results and conclusions of these studies are a key element of the recommended system definition presented in this document with an overall presentation of the project.

In parallel and in close relation with these design and evaluation tasks, use cases and related requirements have been selected for the demonstration of SACRA concept. The building blocks of the SACRA terminal are integrated to form the demonstration platform and system for cognitive multi-band real time communications. The information provided by the validation and trial activities will be reported in a specific report at the end of the project.

The overall methodology followed in the project is illustrated in Figure 2-6.

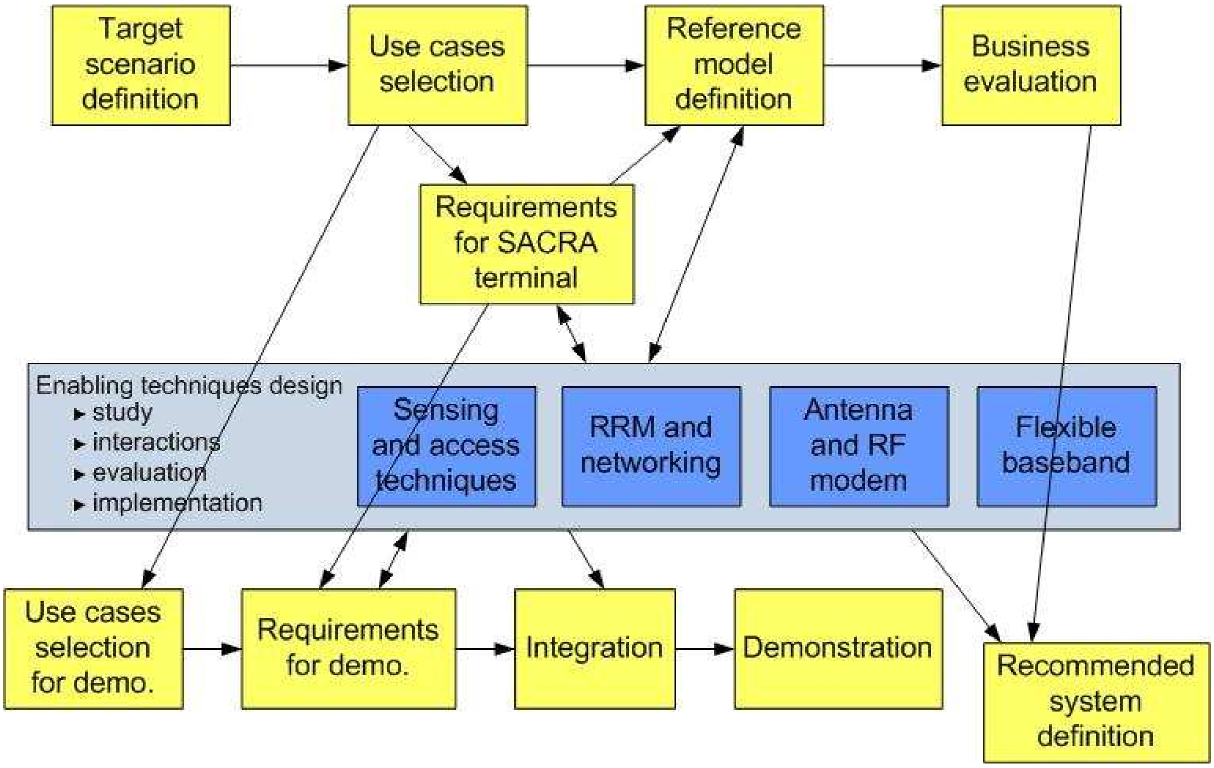


Figure 2-6: SACRA methodology

3 REFINED ARCHITECTURE AND INFORMATION MODEL

3.1 REFINED TERMINAL ARCHITECTURE

The overall SACRA system architecture is depicted in the figure below incorporating different elements (Core Network, RAN, User Equipment) of a SACRA system.

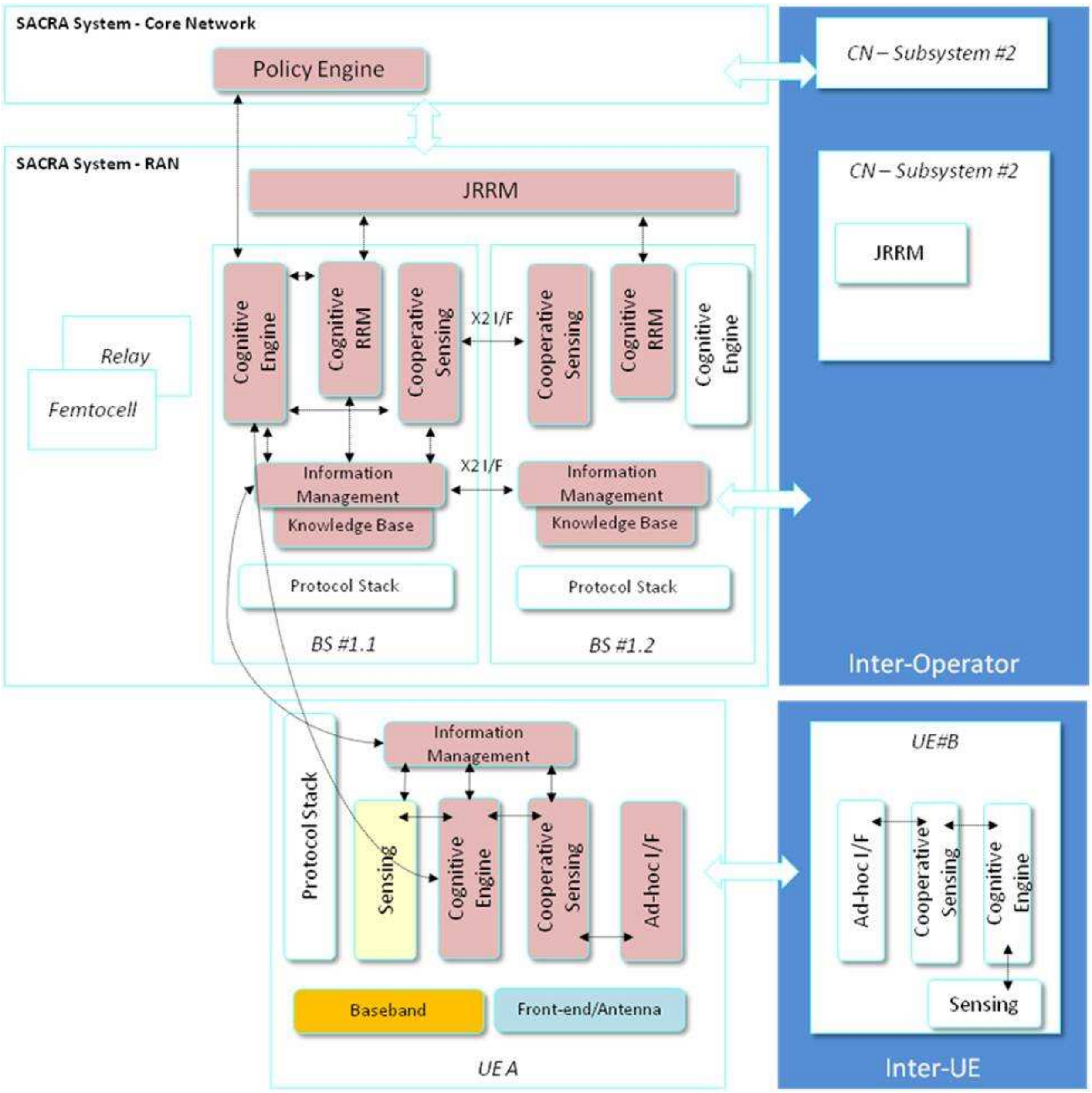


Figure 3-1: SACRA reference model

The overall functional architecture has been elaborated and presented in the second issue of the SACRA Deliverable D1.1 [1], where an initial version of the internal structure of architectural block internal structure is has provided as well.

The following functionalities had been identified internal to UE model:

- Information Management responsible for collecting, storing and distributing information related to spectrum, network, and area measurements, as well as constraints and local policies;
- Sensing responsible for primary and secondary users detection based on a combination of spectrum and interference sensing as well as incumbent protection;
- Cooperative Sensing aiming at evaluating all area sensing measurements targeting primary user and neighbour detection as well as sensing performance management;
- Cognitive Engine performing the actual decision making and policy learning based on measurements monitoring.

Among the SACRA entities, the terminal is the main scope of the project. A more detailed architecture is provided in Figure 3-2. The terminal (or UE) architecture comprises the following building blocks:

- Antenna sub-system: in order to enable the SACRA scenarios (spectrum aggregation, cognitive access), several antennas are needed (here we illustrate the case of 4 antennas). Each antenna is multi-band, in order to address several frequency bands.
- Radio Frequency Front End (RF/FE) part: for each antenna a RF/FE section is needed to process the signal. The RF/FE contains of digitally tuneable bandpass filters, ultra flexible transceivers, amplifiers, mixers, and ADAC (Analog to Digital and Digital to Analog Converters) in order to address several frequency bands and bandwidths.
- Baseband processing: it comprises mainly 2 parts, the physical layer processing for each modulation type/standard (LTE, 3G …), and the sensing/classification algorithms for incumbent detection purpose.
- Higher layers (L2 and above) processing: it comprises 2 parts, the protocol stack, the Cognitive Engine and the RRM block.

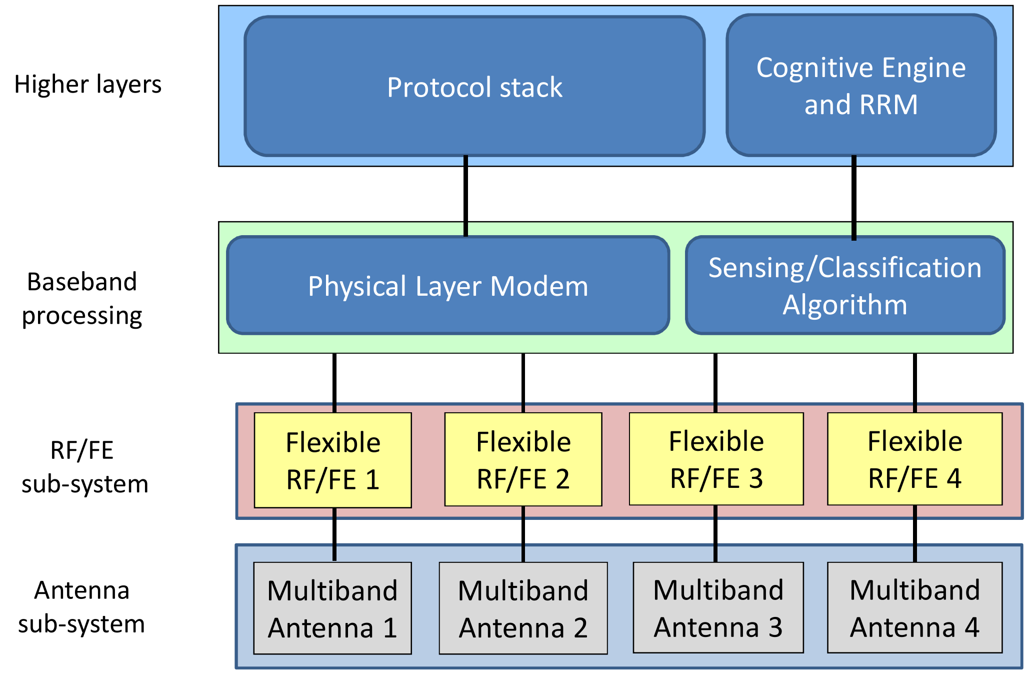


Figure 3-2: UE detailed architecture

Based on the presented UE architecture as well as the specific considerations and progress related to certain functional blocks of Figure 3-2 (i.e. Cognitive Engine and RRM, Sensing / Classification Algorithm) the refined “internal structure” of each block is presented, in terms of supported functions, algorithms and operations. Specifically, the following considerations apply:

- Cognitive Engine and RRM
    - Work-Package: WP3
    - Functions
        - Cooperative Power Control (not to be implemented)
            - Information fusion, among UEs from neighbouring cells
            - Conformance to policies
            - Tx Power adjustment of the UEs - Learning capabilities
        - Sensing Configuration - Control (to be implemented)
            - Select the UEs to act as sensing nodes
            - Select the most appropriate sensing algorithm
- Sensing/Classification Algorithm
    - Work-Packages:WP2, WP3
    - Functions
        - Sensing Task (TBI)
            - SNR Estimation and Report

  - Tx Classification and Report
- Noise Estimation (TBI)
- Check Regulatory Requirements (TBI)

Based on the above summarised functions, the UE detailed functional architecture is refined as in the following figure.

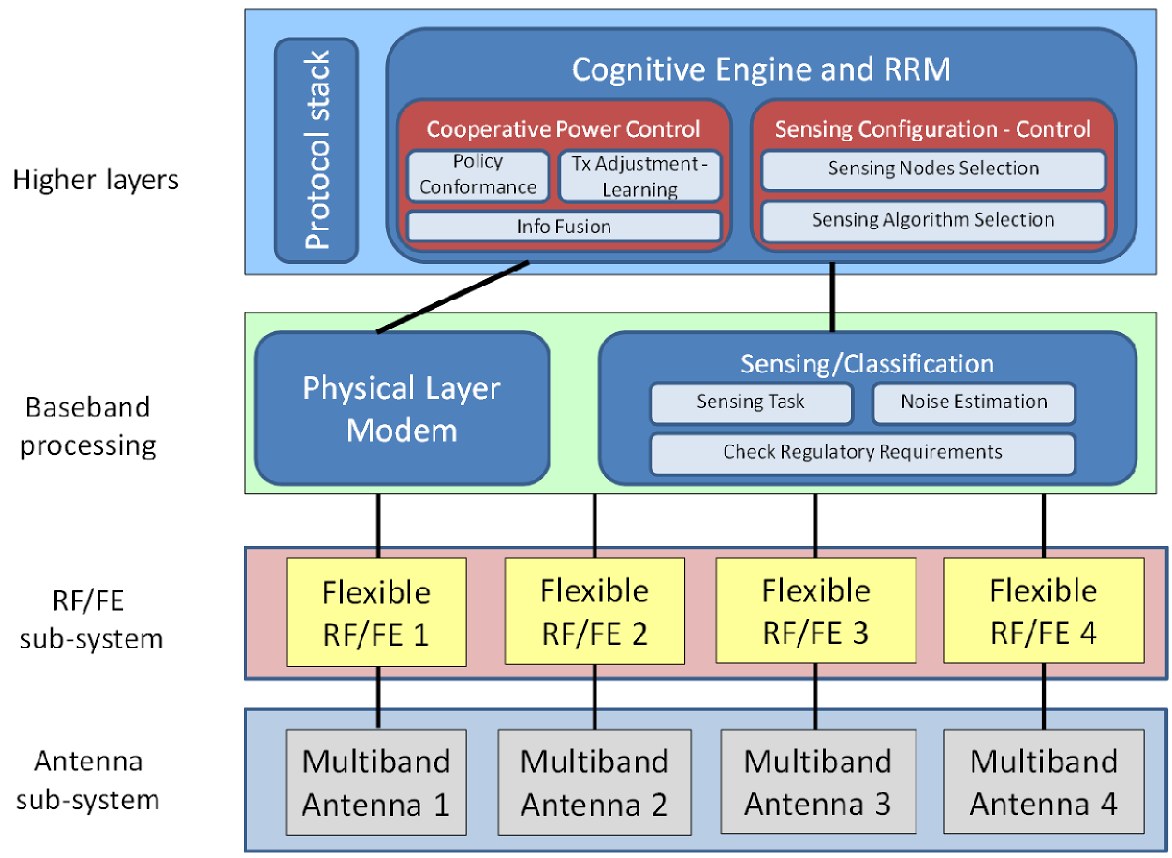


Figure 3-3: UE Detailed Architecture - internal structure.

3.2 DEFINITION OF THE INTERFACES BETWEEN THE BUILDING BLOCKS

3.2.1 Interface between antennas and RF/RE modules

In the case of purely passive multi-band antennas (with no active component), the interface is very simple, and consists of a connector (SMA type for example). In some recent designs for 4G systems (see for instance http://mobiledevdesign.com/tutorials/4g-devices-demand-active-antenna-solutions-0216/), antennas integrate active components. In this case, the interface with the rest of the modem includes a control interface (voltage control for example) in order to match the antenna to the desired frequency band.

3.2.2 Interface between RF/RE modules and the BB processing

This interface comprises:

- A data interface: typically, RF/FE modules include ADDACs, and samples are exchanged between the RF/FE and the BB processing unit. On the transmitter side, the digital samples in the BB to be transmitted are sent to the RF/FE transceiver (an example of such a transceiver can be found in http://www.limemicro.com/lms6002d.php). On the receiver side, the digital samples in the RF/FE transceiver are sent to the BB processor.
- A control interface: RF/RE modules comprise many active components such as switches, frequency synthesizers, voltage gain amplifiers (VGA), power amplifiers (PA), and low noise amplifiers (LNA). Those active components are controlled through a control interface. Typically, this interface includes binary voltage controls (0/+5V for example) for the switches, and Serial Peripheral Interfaces (SPI), see http://en.wikipedia.org/wiki/Serial_Peripheral_Interface_Bus) for the control of active components such as the frequency synthesizers. The overall control interface is controlled by the Spartan 6 FPGA.

3.2.3 Interface between the BB processing and the higher layers

As already mentioned above, BB comprises mainly 2 parts, the physical layer processing for each modulation type/Standard (LTE, 3G, …) and the sensing/classification algorithms.

Concerning the physical layer processing, the interface is compliant with the implemented standard. In SACRA, the main focus is on LTE rel. 10 and beyond. A description of the physical layer and the corresponding interfaces can be found in the 36 series included in the 3GPP web (http://www.3gpp.org/ftp/Specs/html-info/36-series.htm).

Concerning the sensing/classification algorithms, sensing control information (i.e. threshold for the Signal to Noise ratio) is being communicated by the higher layers (i.e. Policy Engine and Cognitive Engine blocks) to the UE in order to perform sensing/classification tasks. After the execution of the algorithm, sensing information (i.e. decision on whether a primary user is present or not based on the measured Signal to Noise ratio or the interference level) is sent in return back to the BS. Therefore, we can distinguish:

- the data interface: it is mainly a bottom-up interface, in which the sensing and classification algorithms send to the cognitive engine the algorithm output;
- the control interface: it is mainly a top-down interface in which the cognitive engine provides control information to the algorithms.

3.3 INFORMATION MODEL

3.3.1 Introduction

This section provides an updated view of the SACRA Information Model which was presented in the two versions of deliverable D1.1 [1] and [2]. The scope of this contribution is mainly the information exchange in (i) UE-UE and (ii) UE-RAN interactions as they have been presented in [11]. The objective of this section is twofold:

1. To capture additional or modify existing information items based on the mentioned interactions;
2. To elaborate on a small set of message sequence charts thus to showcase the usage of information model in SACRA RRM scenarios.

3.3.2 Updated Information Model – RRM operations

The following concepts have been identified in order to abstract the entities which are present in RRM scenarios and operations. The hierarchies below include the entities (e.g. UE) as abstracted by a set of attributes.

- UE
    - access to frequency band,
    - Tx Power Level,
    - Max Tx Power Level,
    - Interference caused,
    - Interference causing,
    - Max accepted threshold – interference to primary user,
    - Throughput requirements.
- Frequency band
    - Type (LTE, TVWS),)
    - Is aggregated,
    - Is primary user detected,
    - Detection probability,
    - Carrier component
        - Is aggregated,
        - Is Primary user detected,
        - Detection probability.
- Base Station
    - Assigned Frequencyspectrum bands,
    - Number of served UEs.

The overall Information Model has been updated accordingly as in the following Figure.

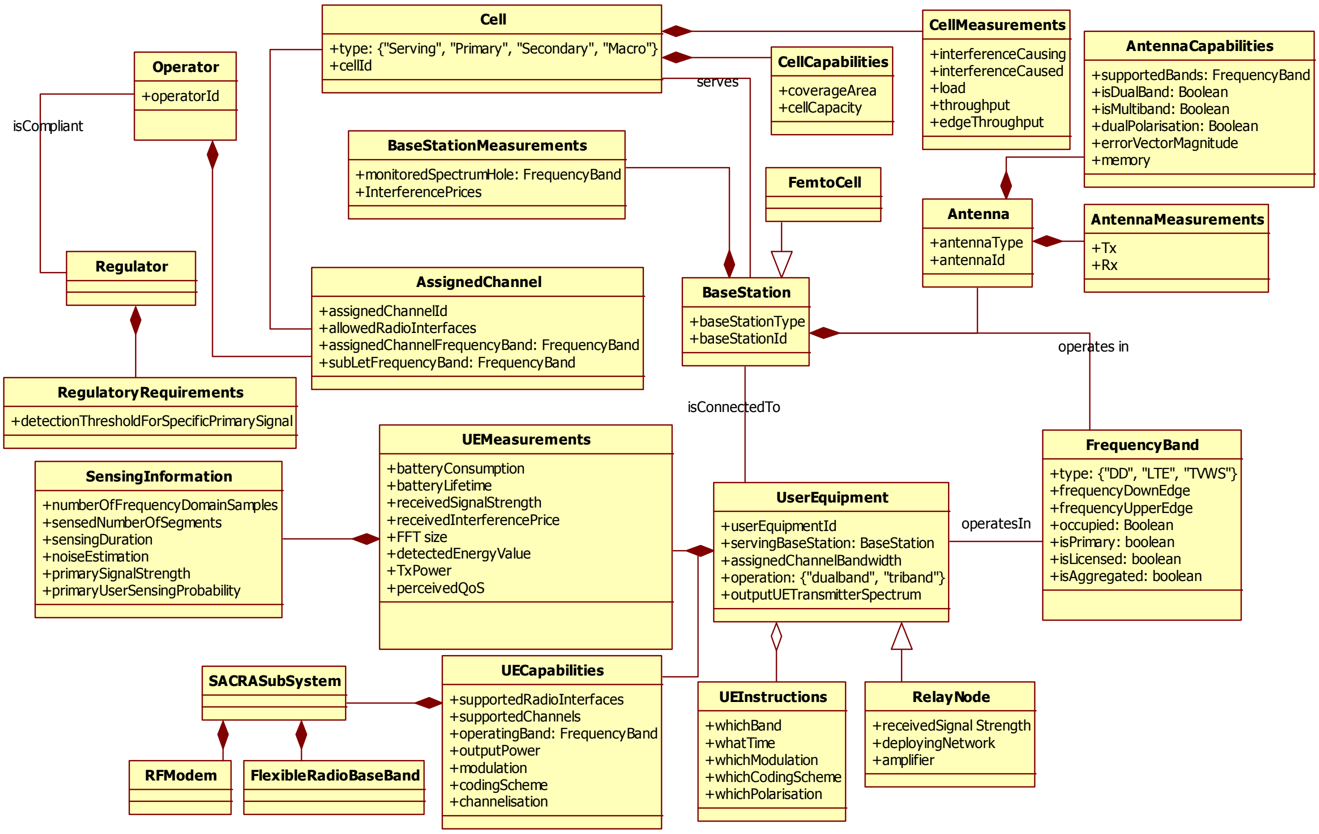


Figure 3-4: SACRA Information Model

It must be noted that a Policy Model has been also developed mainly in the context of the SACRA RRM operations and mechanisms abstracting the various policy concepts which have been identified for cognitive RRM scenarios. Figure 3-5 presents SACRA Policy Model which has been presented in details in SACRA Deliverable D3.2 [10].

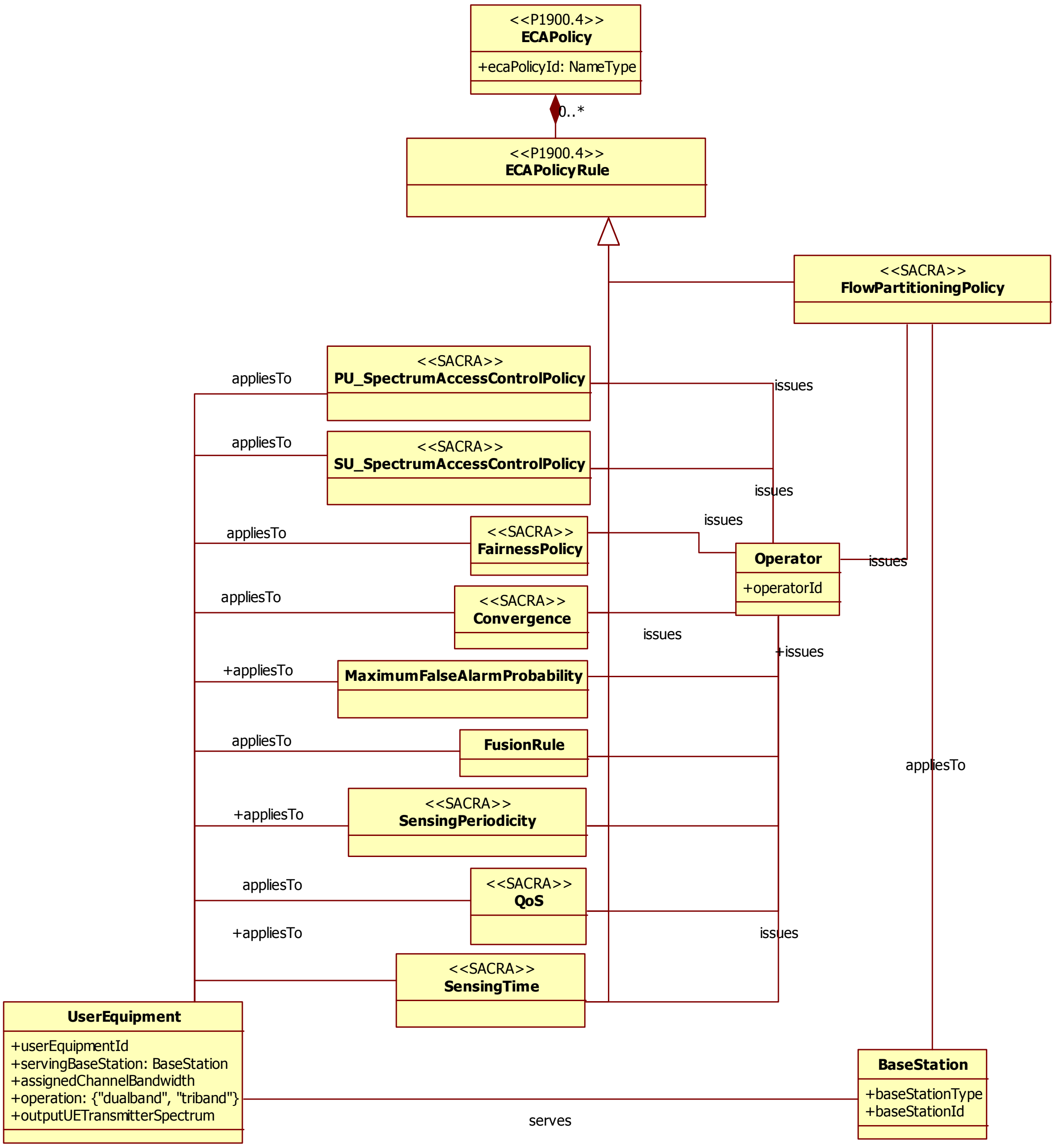


Figure 3-5: SACRA Policy Model.

The remaining of the section presents a set of message sequence charts (MSCs) illustrating the sequel of processes and the information exchange for corresponding scenarios which have been identified in the context of WP3. Both the SACRA Functional Architecture (FA) and the Information Model are used for the elaboration of the presented MSCs.

Sensing Configuration and Secondary Users Access Control

Figure 3-6 illustrates the WP3 scenario for sensing configuration and secondary users access control. The scenario is rolled out around a SACRA Cognitive Base Station (CBS), a SACRA User Equipment (UE), and the SACRA Policy Engine. In this:

- Policy Engine issues Regulatory requirements to the Cognitive Engine (SACRA CBS),
- The Cognitive Engine identifies the sensing nodes (i.e. some of the UEs served by the CBS) and configures corresponding sensing parameters (e.g. sensing duration, thresholds etc) thus forming the Forming Strategy which is then communicated to the Cooperative Sensing (SACRA CBS),
- The Cooperative Sensing elaborates on the sensing strategy by e.g. setting the needed metrics to be sensed; the sensing strategy is then communicated to Cooperative Sensing at the SACRA UE,
- Cooperative Sensing (SACRA UE) identifies the sensing algorithm and task to be invoked based on the received sensing strategy, thus forming the sensing configuration which is then communicated to Sensing (SACRA UE),
- Sensing is checking conformance to regulatory requirements and performs the actual sensing as imposed by the sensing configuration; corresponding measurements are then communicated to Cooperative Sensing (SACRA CBS) which, in turn reports the sensing information to Cooperative Sensing (SACRA CBS); eventually the sensing reports is communicated to Cognitive Engine (SACRA CBS),
- Cognitive Engine identifies the UEs being granted access to secondary spectrum access and notifies the Cognitive Engine of the SACRA UE accordingly.

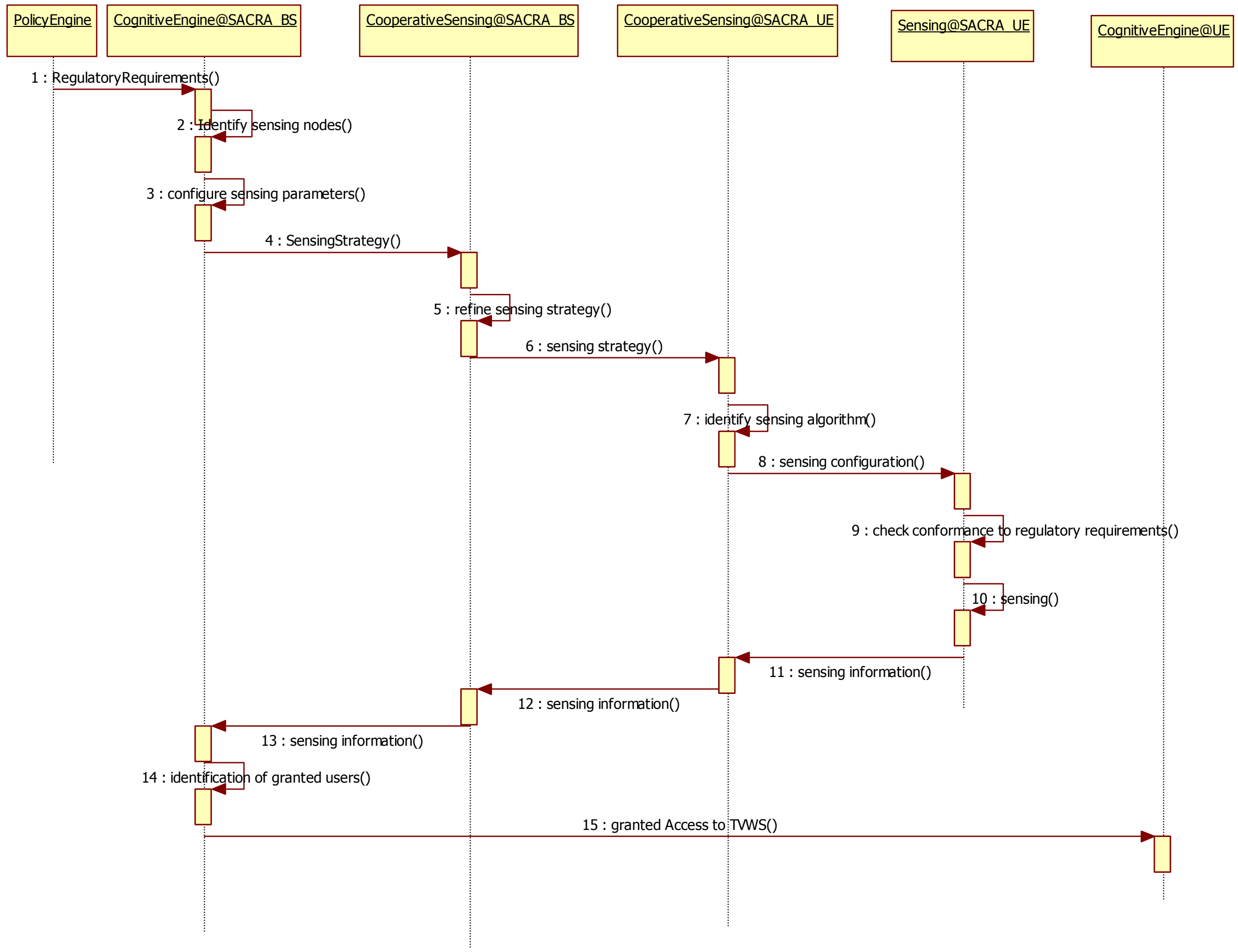


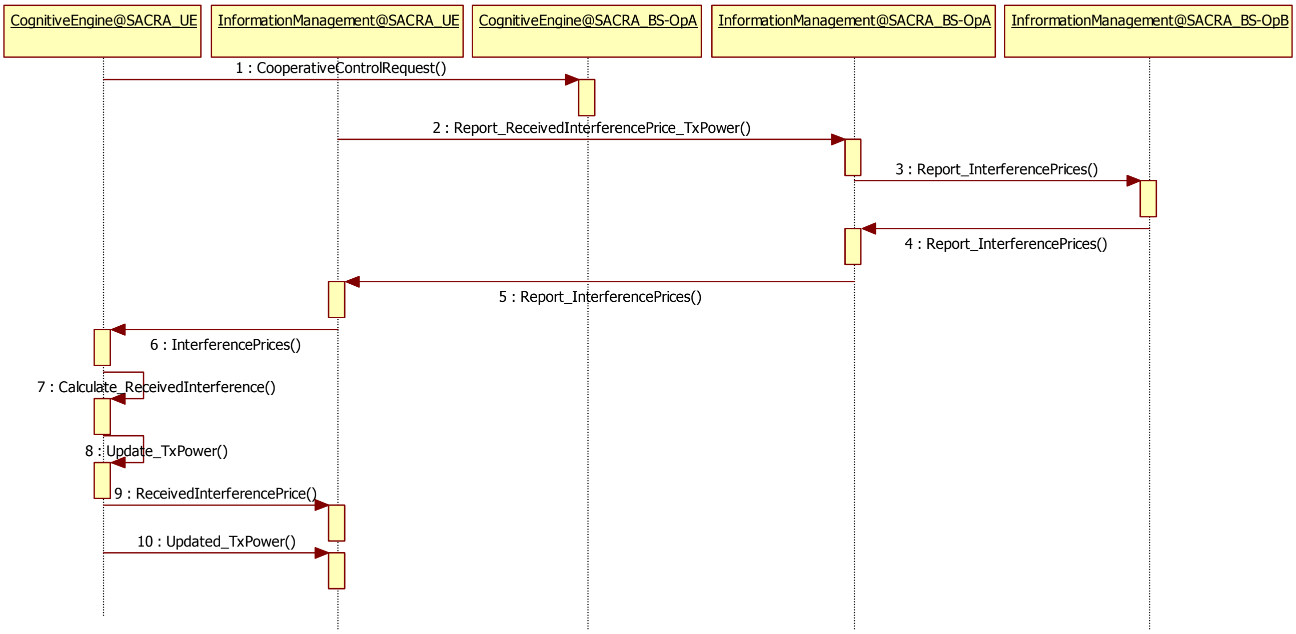
Figure 3-6: RRM operation (Sensing Configuration and Secondary Users Access Control).

Cooperative Power Control

Figure 3-7 presents the interactions and information exchange for the cooperative power control in the context SACRA RRM operations. It must be noted that CBSs belonging to two different operators are assumed in the scenario - OpA, OpB. In this:

- Cognitive Engine (SACRA UE) sends a request for power control to the Cognitive Engine at the serving SACRA CBS belonging to OpA (i.e. due to high interference or QoS degradation),
- In parallel, UE reports the interference price received by neighbouring UEs as well as own Tx Power level (the procedure is asynchronous and triggered between some time intervals) in the communication interfaces between the Information Management at the UE and the Information Management at the CBS,
- CBS (OpA) reports the interference prices (received for served UEs) to the Information Management (CBS, OpB) in a consolidated way. CBS (OpB) reports corresponding interference prices to CBS (OpA) which, in turn, communicates them to the UEs,

- The UE Cognitive Engine re-calculates the interference price and update own Tx Power based on the received information; updates are reported to Information Management (Knowledge Base).



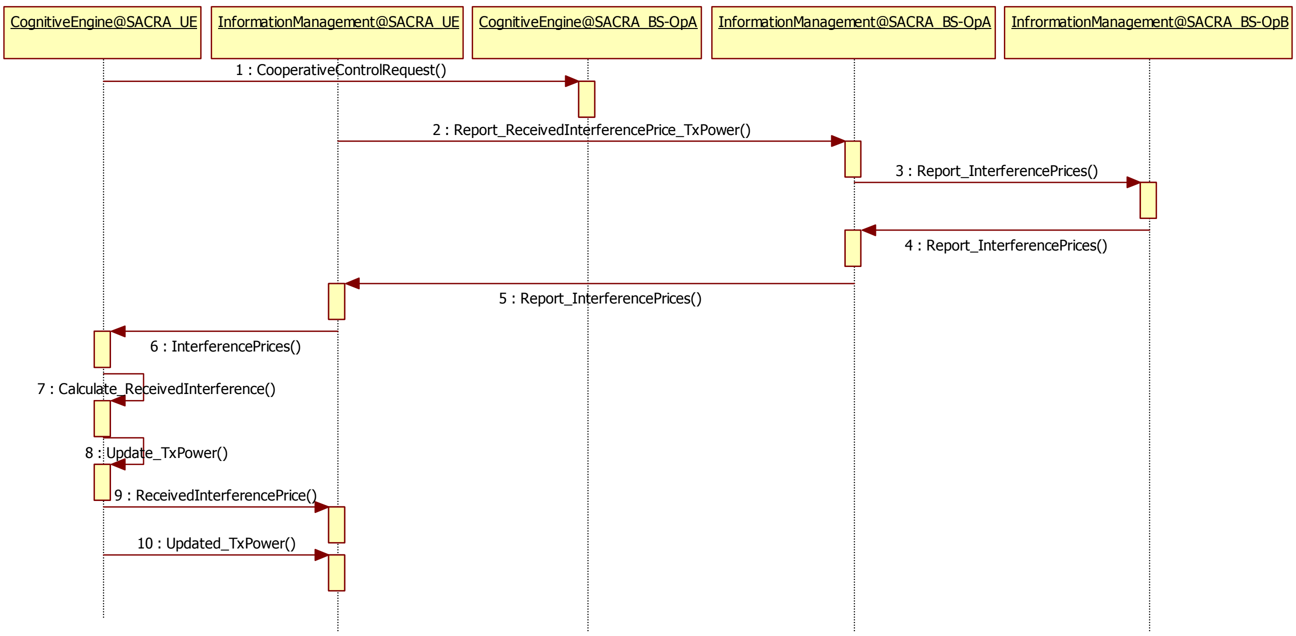


Figure 3-7: RRM operation (Cooperative Power Control).

Spectrum Aggregation

Figure 3-8 concludes the WP3 operation by presenting the interactions among SACRA FA for spectrum aggregation scenario, using the identified SACRA Information Model.

- The scenario is initiated by the Cognitive Engine (UE) notifying own Information Management regarding QoS degradation; in turn, Information Management (UE) reports to Information Management (CBS) and, eventually the CBS Cognitive Engine is notified on the perceived QoS,
- The CBS Cognitive Engine checks whether the UE in question has been granted access to TVWS spectrum as secondary user,
- After the confirmation the CBS Cognitive Engine retrieves corresponding flow partitioning policy from Policy Engine and communicates the policy to CBS Cognitive RRM,
- The Cognitive RRM executes the User and Flow partitioning algorithm and reports the aggregated spectrum band to Information Management,
- Finally, the CBS Information Management communicates the aggregated spectrum band to the UE Information management.

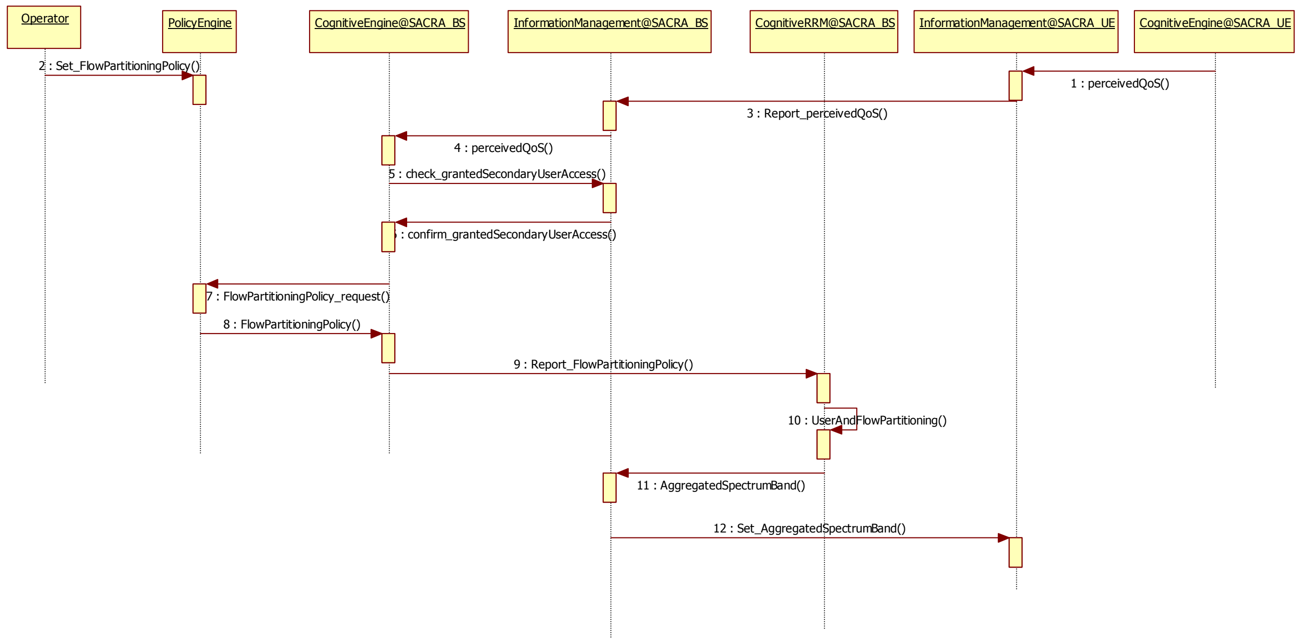


Figure 3-8: RRM operation (Spectrum Aggregation)

4 TECHNICAL ACHIEVEMENTS

Exploiting the TVWS, one of the main SACRA use case, raises high demands on the RF Transceiver, the RF Front-End and the antenna sub system. The need of parallel RX/TX chains to connect to the TVWS and a licenced LTE band, non-compressed mode monitoring for sensing the TVWS and low operating frequencies are challenging RF features especially when taking BoM and power efficiency into account.

The main RF objectives are the following:

1. Carrier aggregation
2. Exploiting unlicensed frequency bands
3. Power efficiency
4. Bill of material

The main RF objectives defined at the beginning of the project are not only SACRA objectives, from today's point of view these objectives are part of upcoming as well as next generation cellular standard releases. Some 3GPP examples are:

- the 4x4 MIMO feature of LTE-A, LTE carrier aggregation
- the additional assigned LTE frequency bands (Digital Dividend, for some time a unlicensed band)
- DC-HSDPA, DB-DC-HSDPA and 4C-HSDPA carrier aggregation 3G features of 3GPP release 8,9 and 10
- the downlink dual carrier (DLDC) feature of 2G

The SACRA RF results will have a major impact on upcoming products, the ideas and first prototypes of SACRA can be improved to products for next cellular standards and the developed demonstration platform enables early system analysis of future cellular concepts like carrier aggregation. The most important results of the antenna sub system and the RF Front-End are summarised and highlighted in this section.

4.1 ANTENNA SUB SYSTYEM

The antenna sub system is the link enabler for all wireless communication standards and unfortunately an antenna cannot be matched to all frequency bands supported by modern user equipment. Antenna sub systems also consume a high percentage of the available area. Further, for multi-band, multi standard support several antenna sub systems are usually necessary. This is an issue for world engines and state of the art mobile phones.

The iPhone 5 for example needs to support:

- UMTS/HSPA+/DC-HSDPA 850, 900, 1800, 1900, 2100 MHz
- GSM/EDGE 850, 900, 1800, 1900 MHz; LTE Band: 1, 3, 4, 5, 13, 25 and17
- CDMA EV-DO Rev. A und Rev. B 800, 1900, 2100 MHz;

On top of the band support, MIMO features additionally increase the antenna area consumption of a mobile device. Recently, active antennas have been developed for 4G systems [http://mobiledevdesign.com/tutorials/4g-devices-demand-active-antenna-solutions-0216/]. But the devices involve the use of active components, which introduce concerns over nonlinearity, stability, response time, power handling capability and test methodology.

In SACRA, an alternative approach has been chosen. Indeed, passive antennas have been developed working over two bands covering LTE, Digital Dividend and the upper part of TVWS (700-862 MHz) and (2.5-2.69 GHz). The reduction of the number of components has been addressed through the design of dual band antennas. To bring diversity in a limited area, polarization and patterns diversities have been exploited. Thus dual polarized dual band antennas have been developed. The two ports ensure flexibility, with either the same band at each port to benefit from the dual polarization feature or a different band at each port to improve the communication link.

Antenna performance further significantly scales with its building size, a crucial design parameter for mobile devices. Therefore all antenna sub system results as well as recommendations of SACRA are divided among two main applications: mobile phones and mobile PCs.

Figure 4-1: trade-off between size and performance in mobile devices

4.1.1 Application: mobile phones

Mobile phones did not only significantly scale in performance and number of features during the last years, but also in terms of building size. Nevertheless, the available area for antennas is limited. Popular high end smart phones like the iPhone from Apple or the Galaxy Series from Samsung are consuming approximately 12x6 cm. The antenna sub system developed by the SACRA project respects this area requirement also taking the need of additional antennas for WLAN or GNSS applications into account. The overall area including the ground plane is 10x5 cm and meets typical requirements for handsets in terms of matching, isolation and radiation pattern.

4.1.2 Application: mobile PCs

Mobile PCs represent a wide spread field of applications from notebooks, netbooks to tablet PCs. A typical dimension of a mobile PC is impossible to estimate but it can be assumed that a mobile PC antenna sub system can exceed the area requirements of mobile phones. A clear SACRA target is to minimize the required antenna sub system area for mobile PCs but compared to mobile phones the focus is still on antenna performance.

Thus the antenna sub system developed in SACRA occupies 15x9 cm, which is compatible with tablet PCs. It reaches good performances in terms of matching (return loss less than -10 dB), isolation between ports (less than 10 dB). Diversity performances have also been evaluated through the envelope correlation coefficient ρe and the Mean Effective Gain (MEG) ratio for several antennas' positions in different environments. For most configurations, it is found that the system satisfies the condition ρe < 0.5 and MEG ratio > 0.5. Thus, the presented design is suitable for MIMO communication applications. SACRA antenna for mobile PC goes beyond the State of The Art. A variety of dual-polarized antennas has been reported recently in which good dual-polarized radiation over a wide bandwidth [3] and high isolation between the feeding ports [4] have been achieved. However, these antennas are mainly designed for single-band operation [5] or for frequencies above 800 MHz [6]. Most of dual-band dual-polarized antennas proposed in literature exploit harmonics frequencies [7] or use techniques to generate additional resonances such as insertion slot [8]. But generally, it leads to a ratio between frequency bands below or equal to 2 and implies dependence between the two frequency bands. Today, very few designs are reported for dual-band dual-polarized operations for the following bands: 700-862 MHz and 2.5-2.69 GHz.

4.1.3 Conclusion

The two antenna sub systems developed in SACRA have demonstrated that it is feasible to design passive antennas offering diversity within a limited area with good performances at 700 MHz. Thanks to their small complexity, we believe that passive antennas designs have to be considered for future developments in LTE and TVWS in parallel with active devices.

4.2 RF FE

The developed SACRA RF Front End does not only combine existing state of the art components to enable the necessary RF access, SACRA goes one step further with a clear focus on beyond state of the art architectures. In addition to the necessary RF components for radio access, two tuneable / programmable FE components have been developed increasing system flexibility, targeting next generation cellular systems and reducing BOM.

4.2.1 Digitally Tuneable Filter

To guaranty a good sensitivity and a good selectivity in the midst of strong interference signals, reconfigurable RF components were used in the RF analogue front-end. A state of the art research shows (for tuneable pre-selection filters) that voltage controlled filters above 1 GHz are available on the market, but additional voltage regulators are needed in order to tune the center frequency. They also show a high insertion loss and low linearity. RF-MEMS tuneable filter technology is "very" young. Thus, RF-MEMS tuned filters are hardly available on the market. Therefore a need existed to design a digitally tuneable pre-selection band pass filter (tBPF). The developed tBPF meets the requirements given by SACRA and Ofcom. Moreover the tBPF can be tuned digitally with SPI control bus, which exists on the SACRA motherboard. That simplifies the integration of the tBPF.

The tBPF has been integrated in the SACRA analog front-end and provide good selectivity for the DVB-T, TVWS and LTE-800 frequencies. Further, the used filter bank now can be reduced from 3:1 filter according to energy efficiency (reducing the bill of material).

4.2.2 MIMO Antenna Switch

MIMO is a very important aspect of SACRA as well as upcoming RATs and cellular releases. MIMO can be divided among up and down link MIMO and upcoming standards as well as today's products already support various down link MIMO schemes: 1x2, 2x1, 2x2, 4x4.

Typically an eNodeB is able to adapt to the MIMO capabilities of a mobile and in order to evaluate a dedicated MIMO scheme the proper engine is required. To analyse all MIMO schemes specified, one needs to design several analogue Front-End solutions: 1 x Front-End per scheme. This approach guarantees the best engine performance but slows down general system analysis and is overall a very expensive approach.

The solution for system analysis is to use a more flexible / reconfigurable approach. Within the SACRA project a configurable antenna switch for up to 4x4 MIMO systems has been developed targeting next generation cellular LTE-A networks. This switch is an extension to any RF FE and enables different switching scenarios usually handled by different front end designs.

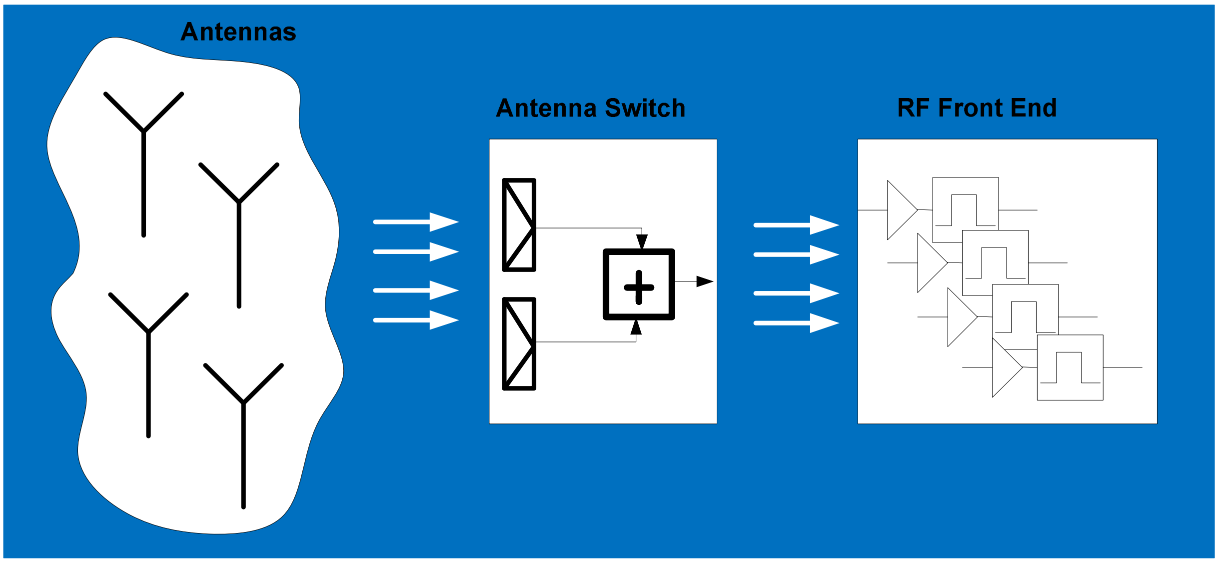


Figure 4-2: MIMO antenna switch

This PCB adds the needed RF Front End flexibility, enabling evaluation of different MIMO schemes and Front End scenarios like single antenna carrier aggregation, dual antenna carrier aggregation; at the cost of RF performance / insertion loss.

4.3 ADC

In SACRA, a dedicated Analogue to Digital Converter has been designed for the Rx path. The added value of the proposed architecture compared to prior state of the art realisations is the low power consumption.

A first prototype has been fabricated in a 65nm CMOS process. The measurement results of this first prototype did not match with the expected results. After correcting the bug of the first version, the design of a second prototype is on-going. It must be sent to the manufacturer (ST Microelectronics) the 13th of February 2013.

As shown in Figure 4-3, if the measurement results of the second prototype match with simulation results, it will be the first ΣΔ ADC with 12-bit resolution up to 40MHz bandwidth.

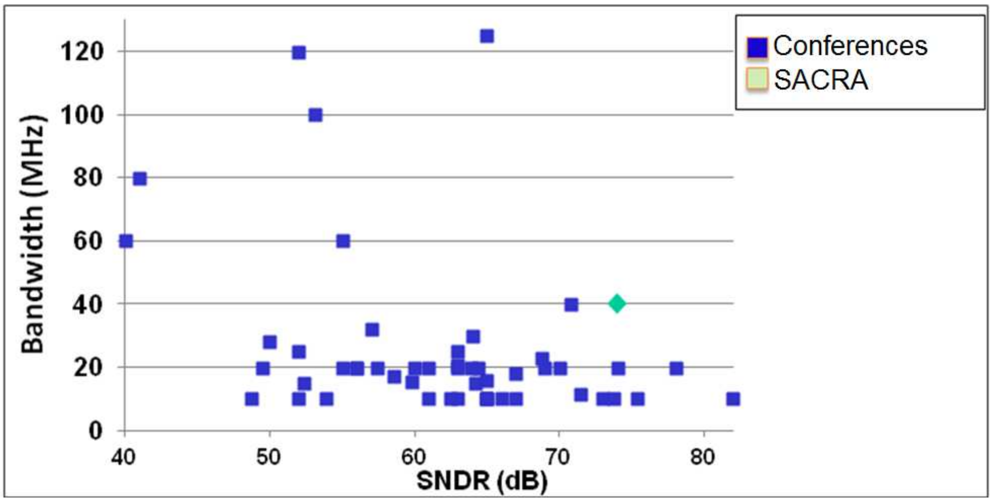


Figure 4-3: Comparison with state of the art of wideband ΣΔ ADCs presented @VLSI, ISSCC, CICC, ESSCIRC conferences between 2005-2011

4.4 DIGITAL PREDISTORTION AND PAPR REDUCTION

The linearity and the power consumption of the transmission part of the SACRA terminal are mainly dictated by the power amplifier. The role of the digital Predistorsion is to enhance the linearity of the transmitter, whereas the goal of the PAPR reduction is to limit and control the instantaneous power distribution of the signal to be transmitted.

According to the objective, the impact of the joint use of the digital Predistorsion and the PAPR reduction could be different:

- Power efficiency objective:

  The power amplifier linearity and its power efficiency are antinomic metrics. If one wants to design a very efficient power amplifier, the linearity of such a device is really poor, and inversely. In SACRA, we propose to relax the linearity and power efficiency trade-off during the PA design phase. In order to keep the terminal performance at the specification level (in terms of EVM and out of band radiation for instance) for a given mean output power, the digital Predistorsion can be used with a more efficient and less linear power amplifier. In addition, the use of the PAPR reduction algorithm allows designing a power amplifier that has a lower peak power value, decreasing the power amplifier power consumption.

- System performance objective:

  For a given terminal (i.e. power amplifier) and if the power efficiency is not the critical objective, one can imagine that the performance of the network could be improved thanks to the joint use the digital Predistorsion and the PAPR reduction. Indeed, the interference level (i.e. out of band radiation) within the network due to the user equipment non linearity could be drastically decreased.

We define the global power consumption of the joint use of the digital Predistorsion and PAPR reduction as the ratio between the saved power amplifier power consumption and the power consumption dedicated to the processing. It is worth mentioned that for any objective described above, the global power consumption shall be positive. Unfortunately, it seems that nowadays, the global power consumption is not necessarily positive for the user equipment due to the amount of processing required (see D5.2 [12] for further details). Nevertheless, one can imagine that thanks to the Moore's law, the approach that we propose for SACRA will be easily implementable and with significant positive global power consumption.

The computational capacity of the SACRA platform does not allow to perform a demonstration of the Predistorsion capabilities with all SACRA features. However, the assessment of Predistorsion techniques on the platform developed in SACRA is being prepared and is planned by the end of the project.

4.5 BASEBAND

The digital baseband processing is a key element of agile SACRA-like terminals. It is in charge of classical modem processing, sensing, classification and all extra digital processing dedicated to RF optimization for energy efficiency and/or spectrum efficiency. In traditional terminals the processing is mainly limited to modem processing. As only a small, fixed number of radio technologies are supported, the digital baseband processing is implemented in a small collection of modules, each dedicated to one particular technology and each comprising:

- hardwired processing engines for the most demanding operations (usually at least Fourier transforms and channel decoding),
- general purpose Digital Signal Processors (DSP) for less demanding but less regular operations,
- a general purpose micro-controller for the control of the module.

This classical architecture has some advantages (simplicity, isolation of radio technologies one from the others, reusability of designs and validation efforts) but it also exhibits several severe drawbacks that render it quite inefficient in the context of the SACRA objectives:

- The lack of flexibility: it is very difficult and frequently impossible to implement sensing, classification, RF optimization algorithms on a module dedicated to the modem processing of a single radio technology.
- The number of components: year after year it is getting more and more inefficient to pile up dedicated modules while the list of supported radio technologies increases. Most of these modules embed very similar basic operators that could be shared among technologies instead of being customized for one and used for this one only. Fourier transforms are the same for WiFi, LTE, DVB,...
- The energy inefficiency: because the most demanding operators are not shared among radio technologies the Dynamic Frequency and Voltage Scaling (DVFS) strategy cannot be used globally across technologies but only locally. The local power optimization is less efficient than a global one. Moreover, some processing request a limited processing power that do not justify dedicated hardware engines in a single technology but would if all technologies were considered. Consequently they are implemented in general purpose DSPs while a hardware engine would be more energy efficient.

4.5.1 The hardware baseband processor

The recommended SACRA terminal embeds a baseband processor, EMBB, that intends to solve these issues. The EMBB processor is designed to be the single DSP of the terminal (not mentioning application-oriented DSPs: multimedia, gaming...). One of the SACRA main indicators, reduction of the number of components, asks for this. Of course, EMBB is just an example of a new family of baseband processors. Other solutions exist or will in the near future with similar goals. In order to fulfil the requirements of all radio technologies plus the sideband functions, and to be ready for new radio technologies and functions, the baseband processor has to be flexible. Yet, it has to be energy efficient, even if the continuous improvement of the microelectronics manufacturing processes continuously reduces the contribution of the baseband to the total power budget. Flexibility and energy efficiency are mostly antinomic: the most flexible General Purpose Processor (GPP) is about ten times less energy efficient than an optimized DSP which is itself about ten times less energy efficient than a hardwired dedicated processing engine. The optimal solution is thus a trade-off between flexibility and energy efficiency. The recommended baseband is a collection of dedicated DSPs, optimized for a given class of operations, sufficiently flexible to handle all the possible variants of these operations but sufficiently dedicated to be energy efficient. In EMBB terminology these are the DSP units and the instance of EMBB in the SACRA terminal embeds the following DSP units:

- AD/DA interface (ADAIF): interfaces the baseband processor with a set of four analogue to digital converters and four digital to analogue converters. ADAIF performs synchronization between the baseband clock frequency and the converters sampling frequencies, assembles samples in frames, synchronizes transmission (Tx) and reception (Rx) in TDD mode,...
- Pre-Processor (PP): applies several transforms to the incoming and outgoing samples (I/Q imbalance compensation, carrier frequency offset compensation, digital resampling).
- Front-End Processor (FEP): vector operations and time-frequency conversions.
- Interleaver (INTL): hard bits and soft bits permutations, rate matching, frame equalization.
- Channel Decoder (CHD): Viterbi and turbo channel decoding.
- Mapper (MAPPER): modulation from BPSK to QAM 65536.

This list is the result of a deep study of a large collection of radio technologies, sensing, classification and RF optimization techniques. The similarities have been identified and the classes of processing have been defined based on these similarities. The DSP units have then been designed to handle one of the identified classes. Each DSP unit is involved in all radio technologies and other activities requiring its services in a time-sharing manner. FEP, for instance, serves almost all modem, sensing, classification and even RF optimization applications. Thanks to this sharing of computing resources a DVFS strategy would operate a DSP unit under the most appropriate frequency and voltage for its current load and the energy optimization would be optimal. And thanks to the specialization of the DSP units they are by themselves energy efficient while flexible in their specific domain. They are interconnected by a network on chip (a partial, Advanced Virtual Component Interface (AVCI)-compliant, crossbar in the case of EMBB) that allows all possibly useful communications between two DSP units. Each unit embeds a local memory in which it fetches its input data and stores its output results, a Direct Memory Access (DMA) engine that transfers data in and out, and a small 8-bits microcontroller which can be used to chain sequences of operations.

The whole EMBB processor is controlled by a GPP that runs software applications on top of an embedded operating system. The operating system is equipped with software drivers of the DSP units and abstracts the hardware to application designers.

We believe that this baseband architecture is a very promising one and that most of its characteristics are or will be shared with similar, next generation, baseband processors.

4.5.2 The software design environment

The programming of such a processor is very challenging: heterogeneity, parallelism, complex distributed memory management, hard real time constraints, shared resources between different radio technologies and other applications, all this makes the software design extremely delicate and error prone. In the context of the SACRA project we developed a complete software design and verification environment and used it effectively to implement sensing and classification applications. We also proposed a prototype high level design entry methodology based on a dedicated UML profile. Again, we believe that these approaches are promising and that a significant part of the effort when designing new baseband processors should be dedicated to the companion software design tools. They should offer the following to algorithms and software designers:

- A way for algorithms designers to quickly evaluate whether their algorithm proposal can be efficiently implemented on the target processor and also to emulate the implementation in order to assess pure algorithmic performance. In the SACRA project this is done through an emulation software library.
- A way for software designers to solve the memory management issues before entering the asynchronous design (parallelism). In SACRA a synchronous version of the software library provides the Programmer's View (PV) that can be used for this purpose.
- A way for software designers to design and validate a scheduling of the shared resources in a parallel version of the application. In SACRA a bit-accurate, cycle-approximate virtual prototype of the whole processor allows this.
- An underlying operating system and runtime library to abstract as most as possible the hardware details. In SACRA a customized version of the MutekH operating system, altogether the software drivers of the DSP units, has been designed for this purpose.

Finally, high level design entry would be a plus as it would free software designers from the most challenging tasks: memory management and scheduling. In SACRA we propose a prototype UML based environment but it is a very preliminary version, far from being deployable on a large scale. In the future it will be progressively equipped with memory management and scheduling synthesizers. We believe that this kind of advanced tools will probably emerge on the medium to long term and will allow much shorter design cycles and a much better quality of software applications.

4.6 SENSING/CLASSIFICATION/MIMO

4.6.1 Sensing

4.6.1.1 Motivation and Objectives

Spectrum sensing is a key enabling technology for cognitive radios. Sensing allows for identifying spectrum opportunities and avoiding interference with the licensed primary users (PUs). A key task in spectrum sensing is to decide whether a primary signal is present or not. The efficiency of the sensing can be assessed using the probability of detection ($P_{D)}$ and the probability of false alarm (P_{FA}).

On 23rd September 2010 FCC published a report 10-174 with the scope of finalizing rules to make the unused spectrum in the TV bands available for unlicensed broadband wireless devices. The scope of the SACRA WP2 study is to allow Secondary User (SU) access in the TVWS band (470-790 MHz) occupied by licensed PUs. Primary user is a device that is the rightful owner of a given frequency band. A sensor device, which is located within the secondary system, has to be able to detect the presence of the primary user in order to avoid any harmful interference with the primary user.

The challenge in distributed sensing, learning and optimization is that channel variations and uncertainties make local observations not reliable. Users have typically a partial view because of hidden nodes for example. Cooperative spectrum sensing among users is therefore required and needs to be supported by fusion using hard or soft combining.

Here we first discuss single node spectrum sensing starting by introducing classical sensing techniques and continuing with more advanced sensing methods. Performance and complexity comparisons of the sensing algorithms are considered. Then at the end, we extend the studies for the cooperative sensing.

4.6.1.2 Classical Sensing Techniques

Energy detector: Instead of relying on the a priori knowledge of the signal, energy detectors are independent of the signal's nature. The energy detector performs an energy computation, compares the energy value to a threshold and decides whether the useful primary signal is present or not.
Pros: Energy detection is a well-known detection method mainly used because of its simplicity.
Cons: It can be shown that the performance of the energy detector decreases when the noise variance increases (for low SNRs). Subsequently, a precise knowledge of the noise variance is necessary to determine the threshold value. Under noise uncertainty the performance of the energy detector may be very low.

Cyclostationary detector: The cyclostationary feature based detection methods use periodic characteristics of the transmitted radio signals. Indeed, modulated signals are generally coupled with wave carriers, pulse trains, repeating spreading, hoping sequences, or cyclic prefixes which result in built-in periodicity.
Pros: Such processing can deal with low SNR signals and are less sensitive to background noise.
Cyclostationary detectors can provide signal classification capabilities of the detected signal such as the number of detected signals, their symbol rate, modulation type, and so on.
Cons: However, the disadvantage of such detectors is their computational complexity which is very high and therefore a quick detection is not achievable.

Matched Filtering: The matched filter is the optimum detector of a known signal in the presence of additive Gaussian noise.
Pros: It is the linear filter that maximizes the SNR of the output.
Cons: The major drawback behind using such a technique is that it is based on the use of high a priori knowledge of the received signal, which is totally unrealistic for PMSE signals.

Welch Detector: is an energy detection method based on discrete Fourier transform (DFT). It is a modified version of a basic periodogram. The idea of the Welch periodogram is to divide the data sequence into several segments to reduce the large fluctuations of the periodogram estimates.
Pros: Using overlapping of the segments, the total number of the samples needed in one sensing period is reduced and still the reduction of estimate fluctuation through averaging over the segments is achieved.
Cons: Just the same as in ED case, to work properly, Welch detector needs to get accurate noise level estimation. The performance of WD suffers a lot from noise uncertainty. Therefore, in practice, WD should be implemented with noise level estimation. To efficiently use Welch detector, a priori knowledge about the PU signals has to be known. For example, the center frequencies and widths are essential to be known to achieve good performance. This information could be obtained from a pre-existent database.

4.6.1.3 Advanced Single Node Spectrum sensing techniques

This section presents and describes improvements of sensing algorithm with respect to current state of the art. Chapter presents several advanced single node spectrum sensing techniques which have been developed by SACRA.

Pilot based detection: In order to estimate the channel conditions, some predefined pseudo-noise sequences are integrated in the transmitted signal. These are known as “pilot” sequences. Alternatively, in multicarrier transmissions such as DVB-T some subcarriers may be dedicated for transmitting pilot signals. Pilot signals may be scattered over the subcarriers and over the time depending on the coherence time and coherence bandwidth of typical channel. The PU standards are usually known and these sequences are defined correspondingly. Based on the knowledge of these sequences various detection algorithms can be defined.

Compressed sensing: Each single radio sends the compressed observations to the fusion centre. In the fusion centre the observations from each radio are processed separately by an algebraic approach to produce the detection result from each radio. The proposed detection technique in [21] is a linear algebraic algorithm.

Algebraic Algorithm:
This technique uses the Fourier transform of the observed signal to detect the occupied frequency bands in the observed spectrum. By using the form of sensing matrix proposed in [21] we obtain the opportunity to use the compressed measurements from each radio directly as input to the algebraic detection algorithm in the fusion centre and thus avoiding the computation complexity of reconstructing the original signal.

Welch periodogram with noise estimation: In addition to sensing simultaneously several sub bands, WD can also be used for noise energy estimation in the same way. The noise level estimation can be performed in the regions where the signal is less predominant. As mentioned above, the PU signals are known a priori. Therefore, the noise level can be estimated from the regions between the bands of the PUs. I.e. in the frequency domain regions where the PU signal power is very low compared to the noise power.

4.6.1.4 COMPLEXITY COMPARISON OF SENSING ALGORITHMS

The complexity analysis of sensing algorithms determines the clock cycles and energy consumption by the algorithm when in operation. In SACRA, the complexity requirements are analysed in a real-time environment. The analysis in a real-time environment sets a stringent constraint on the computation capacity required for each of the algorithms. In a real-time environment, the decisions are always obtained at certain pace and the required resources are quite well defined.

In the context of SACRA project, three selected spectrum sensing algorithms are executed in the Front End Processor (FEP) component of the ExpressMIMO architecture. FEP is the vector processor of ExpressMIMO and it also computes Fourier transforms. We use the ExpressMIMO software library (libembb) which is the 100% accurate model of the functional behaviour of the ExpressMIMO hardware baseband processor.

The complexities of the algorithms are compared based on the required operations needed to obtain the detection statistic. Area requirements and power consumption are approximated based on the required operations. All the comparisons are based on the real-time constraint. However, not all algorithms are suitable for a real-time implementation as the algorithms have excessive amount of calculations that cannot be pipelined feasibly.

Comparison results can be summarised as follows. The Energy Detector can be seen as the least complex sensing method. It needs least of all computing operations for processing, and therefore the processing time is the shortest. The second one is the DVB-T Pilot detector followed by the Welch Detector. The Cyclostationary Detector and Algebraic Detector are the most complex methods requiring a lot of computing operations and computing time.

4.6.1.5 PERFORMANCE SIMULATIONS

Two different scenarios with different properties have been chosen to evaluate the detection performance, subject to provide different attributes, so that the performance can be assessed under different conditions, aiming to provide fair conditions before making conclusions.

- Scenario 1 utilizes DVB-T OFDM signal in the presence of Rayleigh multipath fading and shadowing.
- Scenario 2 utilizes also a DVB-T OFDM signal in Rician multipath fading with shadowing.

Results of simulations show that the proposed detectors lost its detecting ability when decreasing the SNR. Results also show that the DVB-T Pilot detector outperforms all detectors under the same interference condition. It was also found that WD and ED have comparable performance. The worst performance is displayed by the AD and CD detectors. Thus, results of simulations infer that the most performing detector is the DVB-T Pilot detector followed by WD and ED that best meet the FCC requirements in reasonable simulations time.

4.6.1.6 COMPRESSED SENSING FOR COOPERATIVE NETWORKS

The compressed observations from each radio are processed separately at the fusion centre with an algebraic approach. The algebraic detection is a new approach based on advanced differential algebra and operational calculus. In this method, the primary user's presence is rather casted as change point detection in its transmission spectrum.

The proposed algorithm is implemented as a filter bank composed of P filters mounted in a parallel way. In order to infer whether the primary user is present in its sub-band, a decision function is computed and the decision is made by comparing the threshold to the mean value of the decision function over the detected subbands. In the cooperative sensing the final decision is made by applying a rule on the decisions from all the radios for each detected subband.

4.6.1.7 WELCH PERIODOGRAM FOR COOPERATIVE SENSING

Examples of the sensing performances in situations where the WD is used with hard cooperative sensing are presented in [21]. These examples show that already three users' cooperation improves the performance a lot comparing to the single user case. When increasing the number of the cooperative users from 15 to 20, the performance improvement is not anymore so high. Also the signalling overhead over the network becomes a crucial issue when the number of the cooperative users is high. In addition, examples with AND, OR and MAJ (majority) rules are shown. Results show that OR and MAJ rules are reasonable for cooperative sensing while AND gives only a little bit improvement.

4.6.1.8 WIDE-BAND COOPERATIVE SENSING METHOD

Wide-Band Cooperative Sensing is cooperative spectrum sensing method for a cognitive radio that is attempting to opportunistically access a wide-band licensed spectrum. Sensor Nodes (SNs) perform spectrum sensing using energy detection paradigm. Physical channels are used to deliver sensing results to the master node (MN). If primary user signal is not present SNs receive only noise whereas if PU signal is present SNs receive attenuated signal and noise.

A SN has to perform sensing over the entire frequency band of interest W. This band W can be very wide and thus it can be very difficult to obtain good detection performance. If SNs are sensing in $W_{DVB\text{-}T}$, PMSE signal power might be completely masked by the noise captured in such a wide band. Another issue is that since PMSE are narrowband PUs and can be located anywhere inside a wide-band TV channel, MN has a difficult task of deciding in which sub-bands these PMSE are.

A distributed sensing method which tries to mitigate the problems described is proposed. The proposed method also improves system detection performance by dividing W into set of sub-bands $\{B_i\}$ and ordering to different SNs to perform sensing in each B_i. The detection performance of method could further be improved by creating clusters of SNs which are expected to have correlated sensing measurements.

The main advantage of proposed method is the gain in terms of SNR, which leads to improvement of detection per sub-band, and which means that PMSE PUs are more easily detected. This kind of sensing allocation does not hinder the system's potential to detect DVB-T PUs since narrowband detection results can be appropriately combined in order to decide the presence of a DVB-T signal. This technique would be especially beneficial in the case of few PMSE present inside one TV channel. A standard wideband detection technique can either declare a positive or a negative decision for the entire TV channel, without verifying if there are unused frequency gaps that normally should be exploited by an opportunistic system. The proposed method is therefore useful in order to increase the total opportunistic spectrum through a better white space resolution. One more advantage is that SNs can be of more simple design; SNs that need to perform sensing in several MHz of bandwidth need to have more complex electronic circuitry. The proposed method also allows less complex SN circuitry.

Simulations of proposed method show that, for a fixed number of sensors, the PD is increased when the number of sub-bands is increased. Simulations prove that this technique improves detection performance when the spectrum might be occupied by both wideband and narrowband transmitters.

4.6.2 Classification

4.6.2.1 Motivation

The chapter 4.6.1 describes sensing methods which are used by SU to check if a frequency band is available for opportunistic access. If band is found free SU may decide to use it for his own purpose. However, since a primary user may start transmitting anytime, the identification becomes very difficult if the SU system continues to transmit, because a secondary receiver could detect its own secondary system rather than the primary user. The SACRA project therefore supposes that SU system embeds classification capabilities, allowing primary user discrimination from SU transmissions. In other words, reason for using signal classification algorithms is to distinguish PU transmitters in the same time as the SU system is communicating in the non-licensed TVWS band.

It is important to mention that an alternative for classification is to use a technique employing Quiet Periods (QPs) and the advantage of this method would be that it requires sensing algorithms which are faster and less complex. However, such a technique using QP is very disadvantageous for Quality of Service (QoS).

We describe two approaches for incumbent detection when LTE system is transmitting:

- Separation combined with classification.
- Simple classification techniques using cyclostationarity PU properties

4.6.2.2 CLASSIFICATION COMBINED WITH SEPARATION AND CLASSIFICATION WITHOUT QUIET PERIOD

In SACRA two different classification algorithms are presented in [20]. The first proposed algorithm combines signal classification with signal separation. This proposed algorithm for signals classification in CRN contains three steps: a frequency edge location, via algebraic estimation of spectrum edges, and the separation process exploiting blind signal separation techniques followed by a final classification step using DVB-T signals cyclostationarity features. Second algorithm proposed is a less complex LTE signal classification technique without Quiet Period, which does not impact the SU QoS. The later method also shows that classification using cyclostationarity properties is possible and in agreement with the FCC requirements. The detailed comparison between the two classification techniques is presented. It can be noticed that the direct classification technique over-performs the one proceeded after separation technique as the separation step introduces some distortions and noise to will be added to the simulated noise level as signal to signal plus interference noise.

4.6.2.3 RELIABLE CLASSIFICATION BASED ON EXCLUSION OF SENSING NODES

The classification without quiet period has been further considered. It is the exclusion of sensing UEs for reliable cooperative PU classification. Only UEs that meet the classification requirements are used. The idea is to exclude nodes that receive high SNR_{LTE}.

The solution can be divided into design-time process and run-time process as presented in Figure 4-4. The design-time process uses simulations to obtain database indicating the probability of detection with respect to Signal to Noise Ratios of the PUs. Depending on the received SNR of the SU the database will contain multiple set of data. In the run-time process LTE SNR is estimated or received from the network and signal classification is done using selected classification method. Those are then used together with database, obtained by design-time process, in reliability checking module to check if classification devices meet the requirements. If requirements are not met the unreliable SNs could be decided to be excluded or the acquisition time could be modified in order to exclude less unreliable SNs. Another option would be to directly use the decision of reliable SNs for a decision fusion. 3 advantages of the proposed solution can be identified. The first advantage is that the solution excludes nodes which are not reliable. Other advantages are that the proposed method increases the classification reliability and of course the incumbent protection.

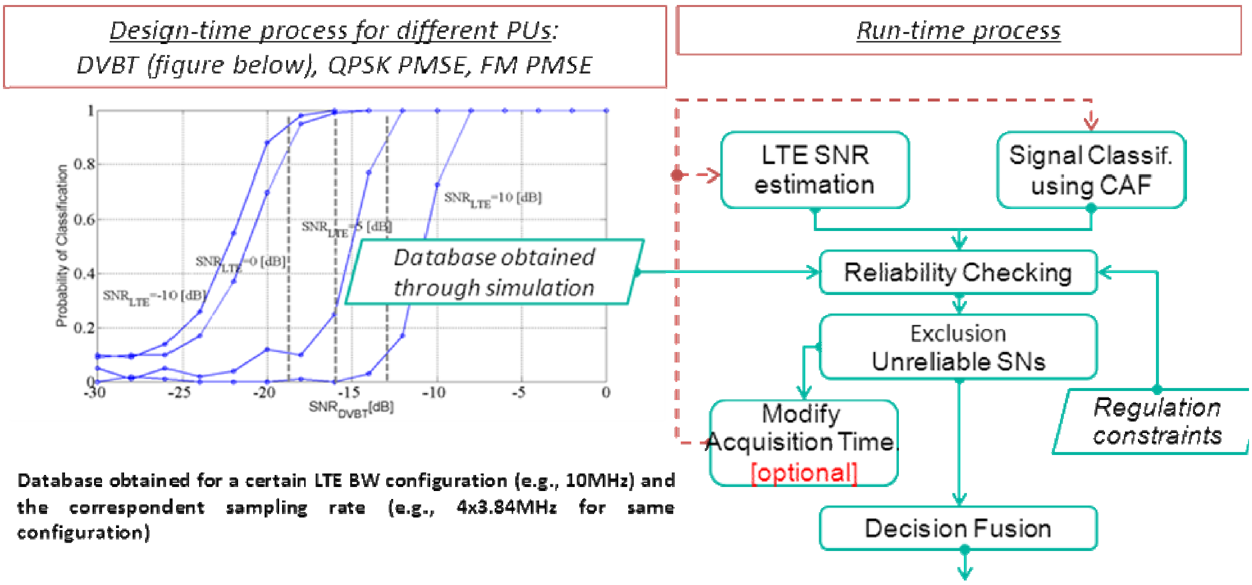


Figure 4-4: Design-time process and Run-time process representation for reliable classification.

4.6.2.4 Classification of PMSE based on Higher Order Cumulants

When an LTE system operates in TVWS, it must detect PMSE Tx while continuing transmitting in the concerned channel. The energy variations are not sufficient to decide if the sudden environmental change is from SU or PU. As a solution, we propose to use feature variation given by High Order Cumulant (HOC) in order to decide if the sudden environmental change is from PMSE PU.
Cumulants are known statistical tool, however orders higher than 4 are difficult to compute. The literature does not even provide exact expressions for higher order cumulants. Thus, description for higher order cumulants is presented.

The proposed method can work only to classify non-OFDM signals mixed with noise and OFDM. However, the advantage of this method is that it is less complex and completely blind.

Implementation example is presented comparing the HOC computed for a certain classification period with a previous HOC computed during another classification period. The comparison process can be further resumed in two parts:

1. The time-domain (sampled) signal is normalized in order to alleviate the impact of power variation on HOC value (the variance of the normalized signal equals 1).
2. HOC is applied on time-domain normalized signals from step 1. HOC of LTE (OFDM) is not dependant on the received power while HOC of PMSE (xPSK, RM or n-QAM) depends on the received power.

4.6.3 MIMO

4.6.3.1 Space time frequency polarization codes

We focus on space time frequency coding schemes and to extend the code design criteria to include the polarization as a new component. The performance of orthogonal space time block codes (OSTBC) is studied with the additional constraint consisting of reducing interference toward neighbouring users or primary users. Moreover, achieving spatial diversity in the low band TVWS is an issue in terms of antenna size and of antenna separation since an antenna separation distance of half a wavelength is necessary to avoid signal correlation and electromagnetic antenna coupling. This justifies the study of polarization based diversity as an alternative to spatial diversity for the SACRA use cases.

We propose signalling and channel estimation using superimposed pilots in a polarised MIMO system in which Alamouti coding was utilized over polarization dimension. Results show that using the superimposed pilots higher data rate and bandwidth efficiency can be achieved than conventional multiplexed pilots. The difference is even larger when the number of the antennas is high. Due to the use of the superimposed pilots, some performance degradations were noticed. For example, it was not seen reasonable to use the superimposed pilots with 64QAM. However, the difference between the superimposed and multiplexed pilot schemes was insignificant with the small modulation orders. In addition, the optimal power allocation factor β was seen to be dependent on the used modulation order. Finally, it was noticed that it is reasonable to utilize the superimposed pilots in a low mobility scenario because the channel stays almost constant during the frame (and so the channel estimates can be averaged over the frame).

One of the main contributions is to provide prefiltering technique allowing the use of conventional OSTBC in a cognitive radio scenario. The prefiltering technique has been optimized for the purpose of minimizing the interference that a secondary system may introduce on an existing primary system. Results have shown powerful interference avoidance capability of the proposed prefiltering technique. Polarization diversity has been used to allow achieving better SNR on the secondary link while keeping the induced interference below threshold. Threshold setting on SP link has been shown to be the main limiting factor when only two antennas are used by the secondary transmitter, despite the appreciable gain that is brought by polarization selection.

4.6.3.2 MIMO COGNITIVE TRANSMISSION AND RECEPTION TECHNIQUES

We propose various MIMO transmission and reception strategies for cognitive radio systems. A special attention is paid to the overlay regime of cognitive radios which is the most challenging and consequently most rewarding of the cognitive regimes. A novel practical interference cancellation receiver design is considered which brings very attractive gains at the cost of reasonable complexity.

We present a scheme for a simple case of two user Gaussian fading Cognitive Radio (CR) interference channel. It has two pairs of communication terminals, one representing single antenna primary pair and the other as unlicensed multi-antenna cognitive pair. The study is conducted with the availability of partial CSIT where each transmitter knows its channel to the PRx and has no

information about its channel to the CRx. Two transmission strategies are proposed for this partial CSIT cognitive radio channel focusing the so-called “overlay paradigm” where the CTx not only transmits its own message but helps as well transmitting the primary message. Results show that the strategy with same primary message encoding shows significantly larger rate regions over the strategy where the primary message is independently encoded at the two transmitters.
We focus also on interference mitigation in an uplink of cognitive network based on dual stage reception strategy and centralized processing. The categorization of interferences into weaker and stronger groups is proposed. In the proposed multistage receiver, the first stage is linear which reduces the system dimension by attenuating weaker interferences. After the adaptation of system dimension, the subsequent stage is a non-linear ML receiver which exploits the structure of dominant interferences in the detection process. The simulation results with the proposed strategy show near ML performance with much reduced complexity making the proposed dual stage receiver a suitable candidate for implementation into practical systems.

4.7 RADIO RESOURCE MANAGEMENT COMPONENTS AND COGNITIVE ENGINE

4.7.1 Radio Resource Management Techniques

SACRA use cases and especially the spectrum aggregation concept which is also planned to be demonstrated, imply that a set of novel radio resource management techniques are required to optimize the way opportunistic users transmit in unlicensed bands, given the fact that a fundamental requirement for SACRA system is to avoid interference to the primary licensed users (DTV and PMSE) in their vicinity. These techniques comprise a set of mechanisms so that the secondary users will be capable to dynamically select a sensing algorithm to detect the presence of primary users, adapt their transmitting and receiving parameters accordingly and choose the optimal resource allocation of the available resource to the opportunistic users. Furthermore as the environmental conditions could change rapidly (i.e., users mobility, presence of primary users, need for additional resources etc.) it is required to introduce functionalities that adapt the aforementioned mechanisms in order to capture better the environmental changes and consequently exploit optimally the available resources. Therefore in this section we provide a brief description of the advancements of the Radio Resource Management as have been reported in WP3 deliverables [9][10][11]. The approaches adopted in the SACRA system are compared against state of the art approaches and the beneficial outcomes of the performance assessment are presented.

As also mentioned in section 4.6 a spectrum sensing mechanism is necessary as it is required from opportunistic users to perform real-time monitoring of the licensed spectrum they intend to use. As also mentioned in section 4.6 there are a variety of available methods to perform spectrum sensing. Besides the advantages and the disadvantages of each method, there is also one additional obstacle that these techniques cannot overcome. Factors such as noise uncertainty, multipath effect and shadowing effects, reduce significantly the detection performance of a single user. Therefore, cooperative sensing has been considered as a potential solution that will improve the detection accuracy due to the spatial and multi-user diversity. Cooperative spectrum sensing could follow a centralized approach where a secondary base plays the role of the central controller that aggregates information received from the users and based on decision making process determines which channels could be accessed from opportunistic users and informs them accordingly. On the other hand, this process could be applied in a distributed manner; in that case a message exchange scheme among users is required. All the aforementioned techniques are sensitive to the environment and very careful selection of their parameters is needed. Furthermore, none of those approaches outperforms the rest in all circumstances. Therefore, in a Cognitive Radio device (where more than one sensing mechanisms are available) a sensing algorithm selection and configuration mechanism is required. The aim of this functionality is to specify the frequency band to be sensed and the primary signal features, define the sensing parameters (i.e., the sensing time, duration and periodicity) and set a sensing target performance (e.g., maximum allowed false alarm probability, minimum allowed detection probability, noise estimation time). Additionally, in case cooperative sensing may be used, the sensing configuration and sensing selection mechanism will select the UEs that will participate in the cooperative sensing task. Further details of this mechanism are available in [10] This mechanism is considered part of the Radio Resource Management and interacts with the sensing algorithms and the admission control as shown in the following Figure 4-5.

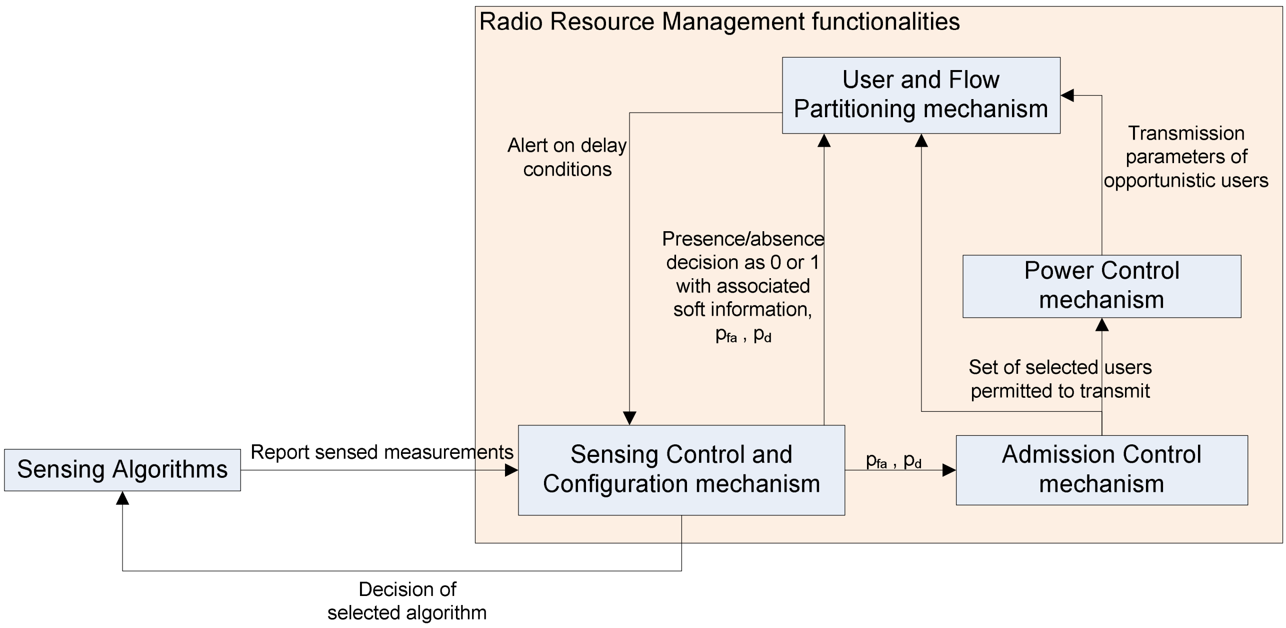


Figure 4-5: Spectrum Sensing and Radio Resource Management interactions

Each of the opportunistic users, based on the sensed environment, decides whether he should transmit in the unlicensed band or not. As the number of opportunistic users increases the problem of accessing the unlicensed spectrum becomes more complex and necessitates the usage of access control mechanisms that will maximize the number of opportunistic users allowed to transmit. This decision could be based on the maximum interference that the user will cause to the primary users present in the area, as well as the corresponding decisions of other opportunistic users present in the area. Therefore, various approaches are available in the literature and can be classified based on the network architecture (i.e. centralized or distributed), the collaborative behaviour of the nodes (i.e. cooperative or non-cooperative), the spectrum management principle (i.e. spectrum overlay or spectrum underlay) and the spectrum bands the secondary users are using (i.e., open spectrum sharing or licensed spectrum sharing) [13]. The considered approach is based on outage probability protection on incumbent in order to control the access to the TV White Spaces or any other band subject to unlicensed use. The proposed algorithm decides if users are allowed to enter the system based on outage probability estimation prior to any access grant [9] and has been adapted so as to conform to policies enforced from the Policy Engine block and to the constraints imposed by SACRA scenarios requirements [10].

Following the access control algorithm, a power control mechanism is required. This aspect has not received similar attention over the past years. Such a mechanism is required as its functionality is twofold; on the one hand energy (that would be spent by the User Equipment if it transmitted always at the maximum allowed level) is conserved and on the other hand interference among the users is mitigated. The latter functionality could be further split into two categories; interference mitigation among primary-secondary users and interference mitigation only among secondary users. The first category is well investigated and many approaches based on game-theoretic solutions or function optimization techniques are available in the literature. On the other hand, the latter category is an open research area and SACRA approach aims at minimizing the mutual interference among the opportunistic users in a cooperative manner. The algorithm introduced in [14] has been adapted in SACRA context and aims at mitigating mutual interference among opportunistic users. The mechanism has been extended in [15] with the capability to conform to high level policies coming from the Policy Engine. Furthermore, the Cooperative Power Control algorithm has been enhanced with learning capabilities so as the UEs do not underestimate the mutual interference among them. The Cooperative Power Control mechanism has been evaluated under various environmental conditions and the results show that the algorithm outperforms the state of the art approach presented in [22] as well as the simplified technique of allowing users to transmit at the maximum Tx Power level.Further details of the core algorithm, the rules and policies that drive it and the learning enhancements, as well as a detailed performance assessment has been provided in WP3 deliverables [9][10][11].

At the highest level of the RRM hierarchy (presented in D3.3 [11]) a resource allocation mechanism is responsible to decide the optimum distribution of users and flows to the available spectrum. The resource allocation problem is a NP-hard problem that has been investigated extensively over the past years and a series of greedy-like methods that model the problem as a knapsack problem have been proposed [16][17][18][19]. On the other hand, as this is a NP-hard problem, heuristic methods, such as Evolutionary Techniques seem to be suitable not only for their ability to find near optimal solution, but also due to the fast convergence they tend to have. Thus, in the SACRA context, a genetic algorithm that achieves the optimum solution of a multi-objective problem concerning the maximization of satisfied users and the minimization of the collisions with primary users has been developed.

All the aforementioned techniques have been adapted and extended so as to incorporate learning techniques and conform to the identified rules and policies developed by the Network Operator. The functional block of SACRA architecture that comprises these learning techniques and the designed policies is the Cognitive Engine and the following section provides a brief description of this block.

4.7.2 Cognitive Engine description

The Cognitive Engine is the functional block that is responsible to initiate the decision-making mechanisms described above; measurements of the external inputs are used so as to extend optimally initial cell coverage depending on radio environment. Moreover this block is responsible to provide local policies to the autonomous nodes [1]. Thus, a subset of the aforementioned mechanisms have incorporated learning capabilities so as to be capable to adjust their operational parameters based on the environment and a set of policies that the mechanisms conform to has been identified. These advancements as well as performance assessment of those techniques has been reported in WP3 deliverables. Table 4-1 summarises the identified policies for each of the aforementioned RRM mechanism.

Regarding the learning enhancements of the RRM mechanisms the genetic algorithm based resource allocation has been extended with a reinforcement learning mechanism that learns the primary user probability of presence; this is combined with the sensing algorithm outputs in order to have more confidence on the decisions. The evaluation outcomes of this work has been reported in D3.3 show that the genetic algorithm enhanced with learning resource allocation is able to balance the two objectives in order to find a good trade-off between maximizing the number of satisfied users and minimizing the collisions with the primary user. Furthermore, the Cooperative

Power Control algorithm has been extended with a learning scheme that improves the situation perception of each Cognitive User. Finally, learning capabilities have been identified and integrated in the sensing configuration mechanism in order to take into account previous results and fine tune decisions of the sensing task.

RRM mechanism	Policies
Sensing Configuration	• Sensing Time • Sensing Periodicity • Maximum False Alarm Probability • Fusion Rule
Spectrum Access Control	• PU policies o primary capacity o outage probability o interference outage • SU's policies o SU's capacity o SU's sum capacity o the interference power o fairness
Cooperative Power Control	• Fairness • Convergence Time • QoS
User and Flow Partitioning	• Flow Partitioning

Table 4-1: Policies identified for the RRM mechanisms

4.8 TOP LEVEL GLOBAL INDICATORS IMPROVEMENTS

TVWS exploitation

In multi-band radios, energy efficiency can be improved by selecting the most suitable frequency band that minimizes the transmitted energy. This is a criterion of choice for the SACRA radio resource manager (RRM) to use as much as possible the secondary lower band, thus improving spectrum occupancy in this band.

MODEM

Two global indicators are related to the modem, and all developments and decisions made during the SACRA project are taking those indicators into account:

- energy optimization for wireless communication terminals by optimizing architecture design and algorithms implementation (3rd global indicator: energy efficiency);
- minimisation of electronic component number in wireless systems (4th global indicator: number of components).

The following architectural and design decisions optimizing the energy consumption have been taken:

- Common Control Units for dual TX and RX;
- TX Diversity Gain;
- Optimized Antenna Gain;
- PAPR reduction (digital pre distortion);

They improve the power efficiency of SACRA modem.

The following architectural and design decisions minimizing the Bill of Material have been taken:

- Tuneable BPF;
- Dual Port Antennas;
- Dual Up-link Transmitter;
- Dual Down-link Receiver.

They reduce the number of external components required for SACRA modem.

5 ECONOMICAL ASPECTS

5.1 ANALYSIS OF MARKET IN THE SEGMENT WE ARE ADRESSING

According to the analysis of the market potential for 3G LTE (Long Term Evolution) [23], the number of cellular subscribers will reach the 5 billion mark by 2015.

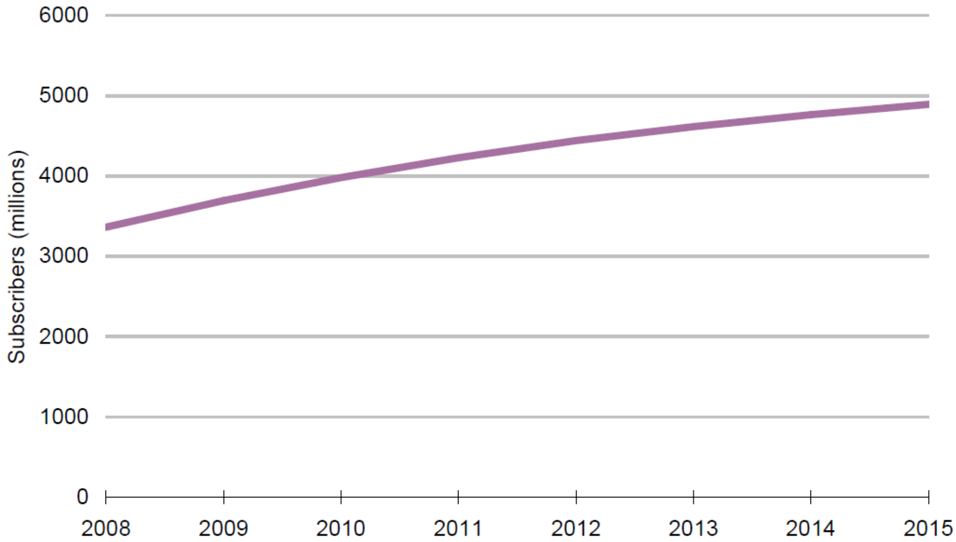


Figure 5-1: Forecast global mobile subscribers, 2008–15 [Source: Analysys Research, 2007]

LTE will already address about 10% of the cellular business by 2015. LTE only supports data services and packet switched applications (Voice over LTE, VOLTEn is still not fully specified) with high bandwidth consumption per users to reach high data rates. SACRA is addressing the LTE segment and therefore about 500 million users by 2015, enabling exploiting additional frequency resources.

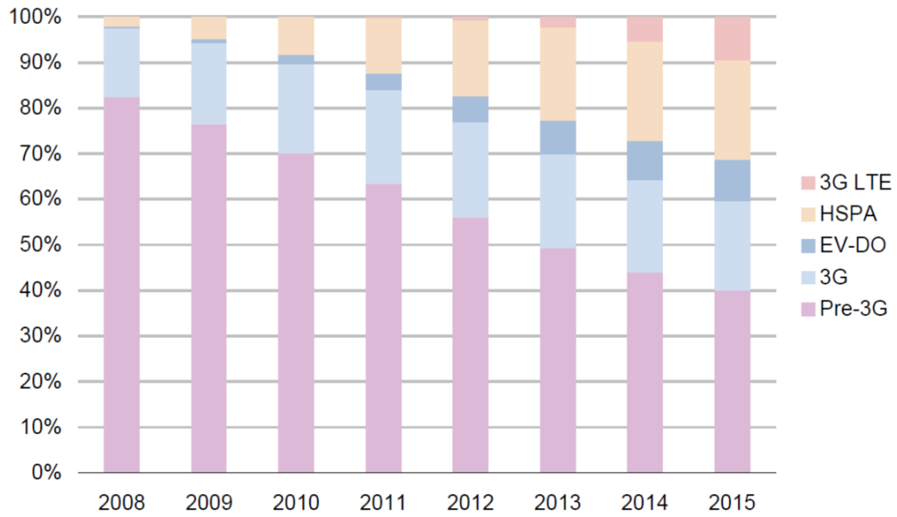


Figure 5-2: Forecast share of global mobile subscribers by technology, 2008–2015 [Source: Analysys Research, 2007]

The revenues from bandwidth-hungry non-voice services are expected to increase rapidly with LTE. In total, it is expected that LTE non-voice services will provide revenues of over EUR50 billion globally by 2015. SACRA is proposing some solutions for an efficient and dynamic management of several bands, including the TVWS, and combined to spectrum aggregation, thus providing the means to access to higher bandwidths as expected to meet the demand of the users.

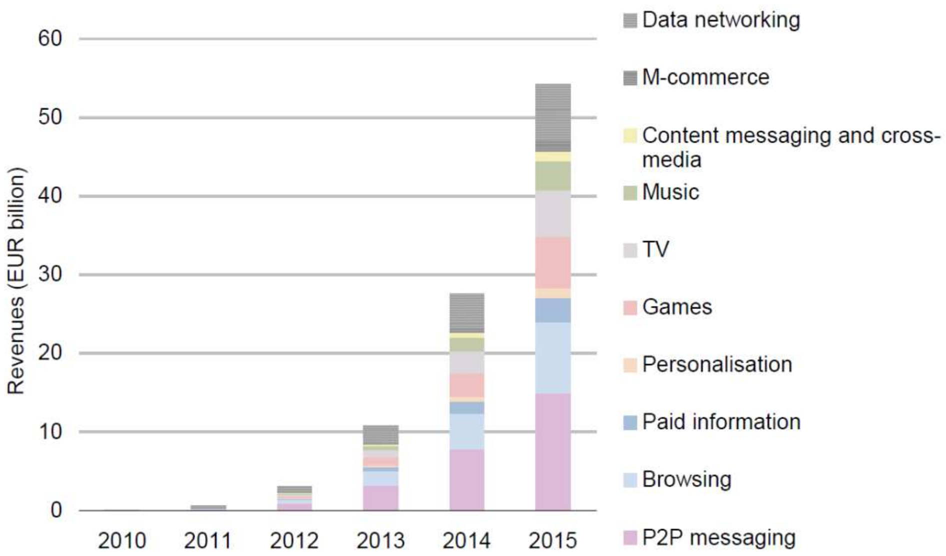


Figure 5-3: Forecast share of global mobile subscribers by technology, 2008–2015 [Source: Analysys Research, 2007]

5.2 BUSINESS ARCHITECTURE REFERENCE MODEL

This section summarises the SACRA business architecture reference model as developed within SACRA T1.3 and presented in [2]. Business architecture reference model incorporates:

- The identified business roles. Two types of roles have been identified:
    - Discrete roles sell their produced value (i.e. products or/and services) to customers,
    - Embedded roles support discrete roles and get funded by them.
- The value propositions of each role, i.e. the product, service or support action provided by the role to interrelated roles,
- The corresponding revenue flows and sharing among involved roles according to the scenarios.

Moreover, the business architecture reference model development has been based on:

- The project reference scenarios and the elaborated business cases, respective motivation has been already presented in the market analysis section,
- The available information regarding regulatory framework around the SACRA cases,
- Standardisation trends.

The (slightly refined) business architecture reference model is presented in Figure 5-4.

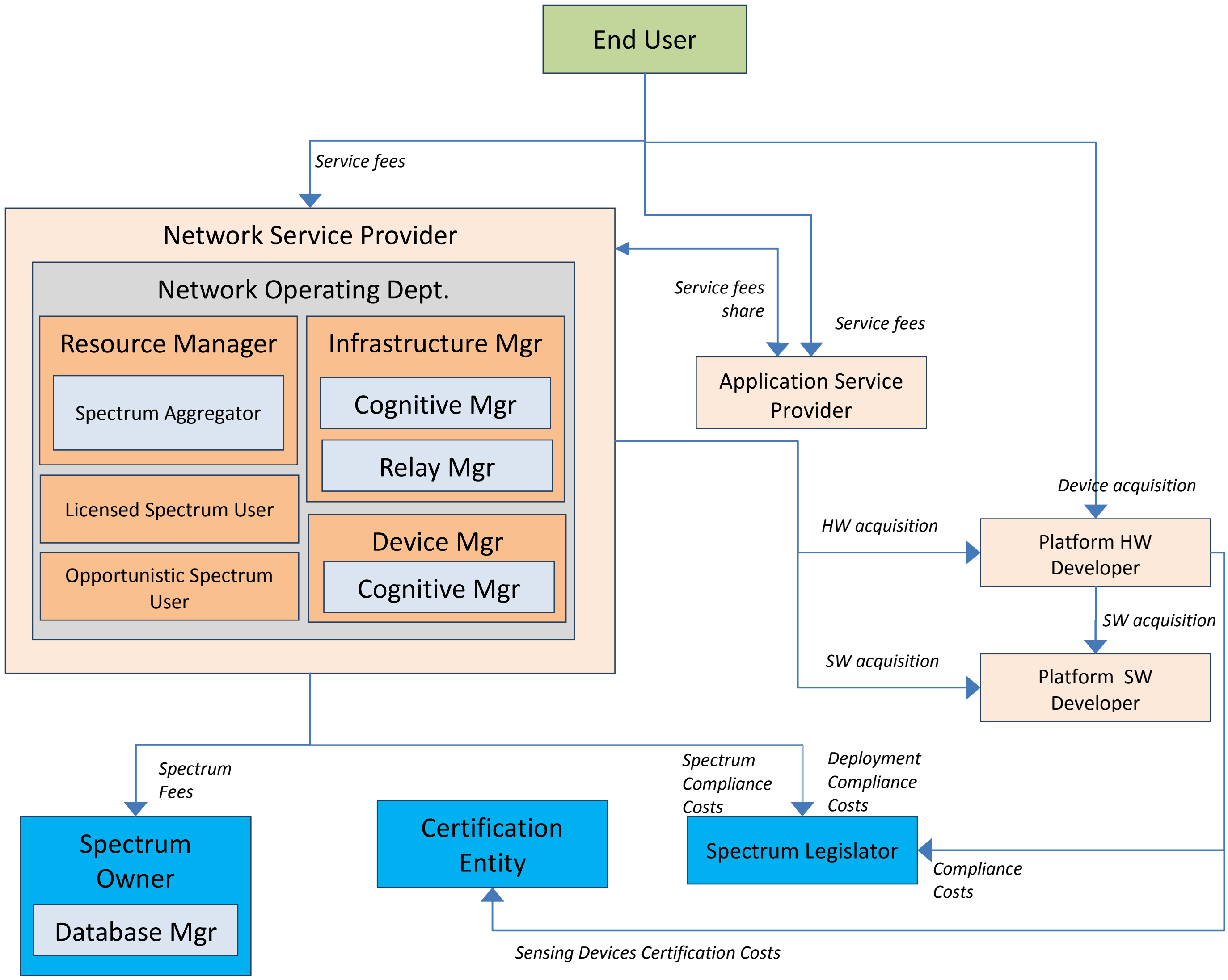


Figure 5-4: Updated SACRA Business Reference Architecture

Table 5-1 summarises the business roles providing a concrete description of each role as well as the proposed value(s) in terms of products, services, capabilities etc, and the corresponding revenue flows.

Business Roles	**Roles description**	**Revenue flows**
End-User (EU)	Utilises user device for service provision purposes in an area and pays corresponding subscription fees, product and service costs.	To NSP To ASP To PHD
Network Service Provider (NSP)	Provides mobile or fixed network services to customers.	From EU and ASP

		To SO and SL To PHD and PSD
Network Operating Department (NOD)	Provides wireless or fixed geographic coverage, manages and operates the infrastructure.	Funded by NSP
Resource Manager (RM)	Performs joint management of the different frequency bands (portions),	Funded by NSP
Spectrum Aggregator (SA)	Performs aggregation of different portions of bandwidth in multiple carriers	Funded by NSP
Licensed Spectrum User (LSU)	Holds the spectrum license; can assign usage rights to others.	Funded by NSP
Opportunistic Spectrum User (OSU)	Detects occupancy in parts of the spectrum, and communicates over spectrum holes with controlled interference to the licensed spectrum users.	Funded by NSP
Infrastructure Manager (IM)	Performs the overall network management within a Network Operating Dept. domain	Funded by NSP
Device Manager (DM)	Performs management of end-user devices within the Network Operating Dept. domain	Funded by NSP
Cognitive Manager (CM)	Performs tasks to cognitive access to TVWS band	Funded by NSP
Relay Manager (RM)	Performs management tasks applicable to relay nodes operating in frequency bands different than the donor cell.	Funded by NSP
Application Service Provider (ASP)	Provides application services to End-Users.	From EU To/From NSP
Platform Hardware Developer (PHD)	Develops and distributes the hardware components and devices related to SACRA system: flexible radio baseband, RF modem, and, dual-band antenna.	From EU and NSP To PSD, SL and CE
Platform Software Developer (PSD)	Develops software for the identified functionality,	From PSD and NSP
Spectrum Owner (SO)	Provides licenses, assigns regulated spectrum rights and collects spectrum fees.	From NSP
Database Manager	Manages the databases on the spectrum holes and available channels	Funded by SO
Certification Entity (CE)	Carries out the certification of sensing-only devices as applied.	From PHD
Spectrum Legislator (SL)	Declares regulated and unregulated spectrum and sets spectrum use policies.	From NSP and PHD

Table 5-1: Summary of roles and revenue flows within SACRA Business Reference Architecture

6 REGULATORY ASPECTS

A number of approaches to spectrum sharing have been proposed in the area of broadband communications in order to increase efficiency and flexibility in the use of spectrum. There are still uncertainties with regard to decisions relating to TV White Space regulation in Europe and to the attractiveness for different stakeholders of associated business models. Nevertheless, in both Europe and the US, significant progress has been made for the use of cognitive radio devices in co-existence with incumbent users in the UHF TV White Spaces band.

The US Federal Communications Commission (FCC) has already taken regulatory steps for the use of CR technologies in the area of TV White Spaces. On November 4, 2008, the FCC approved the rules for the unlicensed use of white space. In this report, devices must both consult a regulated database to determine which channels are available for use at a given location, and must also monitor the spectrum locally once every minute to confirm that no legacy wireless microphones, video assist devices or other emitters are present. If a single transmission is detected, the device may not transmit anywhere within the entire 6 MHz channel in which the transmission was received.

On September 23rd 2010, the FCC released a Memorandum Opinion and Order that determined the final rules for the use of white space for unlicensed wireless devices. The new rules removed mandatory sensing requirements. While FCC eliminates spectrum sensing for TVWS Devices that use geo-location database access, FCC continues to believe that this technology offers significant promise for improving spectrum access and efficiency both in the TV bands and in providing access to other spectrum. FCC therefore leaves open the opportunity to submit applications for certification of sensing-only devices.

As a consequence, the Sept 2010 rules give the following mode of operation:

- Fixed TV Band devices (TVBDs) are installed at a fixed location and their geo location coordinates are known to themselves and to the public.
- Mode II device is portable and has internal geo location capabilities, along with the access capability to the spectrum database.
- Mode I is a portable device with no geo location capability and no direct access to the database. This type of device must contact its neighboring Mode II or Fixed devices to obtain the list of available TV channels.
- Sensing-only is a FCC certified portable device unable to access the spectrum database through either a Fixed or Mode II device, and must rely on local spectrum measurements.

The Commission released in April 2010 a Third Memorandum Opinion and Order (3rd MO&O) due to petitions for reconsideration of September 2010 decision. The latest revision does not represent any wholesale changes, but will make it easier for some devices to operate. Finally, FCC requested comment on whether it may be possible to integrate sensing techniques with the techniques that FCC recently authorized for unlicensed Television Band Devices that include geo-location and database functions as a means for accessing other spectrum bands. As previously noted in September 2010, FCC permitted devices operating in the TV bands to rely only on geo-location and a real-time database to determine if a channel is available. However, it remains to be seen whether such an approach would be sufficient for providing access to other spectrum bands that may present a more variable spectrum environment as compared to the relatively constant-state operation of TV stations. FCC believes that as sensing technology matures it may be combined with geo-location database functions to enable access to other spectrum bands. SACRA project has opportunity to indicate that sensing techniques will become sufficiently mature to enable this concept.

As far as Europe is concerned, OFCOM, UK regulator, published a consultation entitled “Digital dividend: cognitive access. Consultation on license-exempting cognitive devices using interleaved spectrum” on 16 February 2009. This report gave the sensing threshold levels that would be needed for license-exempt devices making use of sensing alone. In a subsequent statement entitled “Digital dividend: cognitive access. Statement on license-exempting cognitive WSDs using interleaved spectrum” published on 1 July 2009 6 (the “July 2009 Statement”), OFCOM noted that there were three mechanisms that could be used by a license-exempt device operating in these bands to determine which frequencies it could use to make transmissions. Sensing (also known as detection) was one of them among the two others, geo location database and beacon transmission. Devices monitor frequencies for any radio transmissions and if they do not detect any, assume that the channel is free and can be used. OFCOM noted that there were advantages and disadvantages to both sensing and geo location database. While sensing does not require any form of infrastructure, and hence devices could be autonomous, sensing to very low signal levels is costly and possibly not achievable. Geo location database does not have the inconveniences of sensing but requires a database to be established and kept up to date. OFCOM decided to proceed with regulation to enable both. However, in the short to medium term, OFCOM concluded that geo location database would be the most important mechanism, given the expected cost and complexity of making WSDs that are sufficiently sensitive to sense the very low level signals of licensed users. Geo location approach is sufficiently flexible to accommodate sensing if it is subsequently required. Therefore, OFCOM concluded that this could be accommodated when it was thought necessary. Again, SACRA project has opportunity to show that sensing techniques are mature and could be combined with geo location database approach in order to improve the current solution.

7 CONCLUSION

As highlighted in this document, the SACRA project has provided key outcomes to design the future cognitive systems, and especially to build a cognitive multi-band terminal which is flexible enough to combine the licensed bands with the available resources in the TVWS, thus benefitting from more bandwidth. Advanced techniques and mechanisms have also been designed to manage the dynamic use of these bands and the secondary access to the TVWS. A reference model of the SACRA business architecture has been proposed from the identification of the business roles and revenue flows.

In this document, a refined architecture and information model for SACRA have been presented. In particular, a detailed architecture for cognitive mobile terminal has been provided, including the description of the components and of their interfaces. In SACRA, we have obtained a very significant amount of results of deep interest to design the enabling techniques for the next generation of cognitive communication systems. Those results are:

- Antenna sub system for mobile cognitive terminals: the multi-band and multi access antennas developed in SACRA exhibit good performance in several bands and in a size compatible with a terminal device. It is clearly a key enabler for efficient cognitive terminals.
- Digitally tunable filters for the RX path of terminals: in order to decrease the amount of components on the RF Front End, there is a need of flexibility in the filtering, and the developed filters bring such flexibility. This activity could be pursued in the future in order to cover more bands, for example the new 3.5 GHz LTE band.
- Digital Predistortion and PAPR reduction is a very promising technology for power consumption reduction. Unfortunately, it seems that nowadays, the global power consumption is not necessarily positive for the user equipment due to the amount of processing required. Nevertheless, one can imagine that thanks to the Moore’s law, the approach that we propose for SACRA will be easily implementable and with significant positive global power consumption.
- Flexible base band processing: the developed architecture is based on the parameterization of the base band processing. All the processing blocs (coder, decoder, mapper…) are generic blocs and can be used for a wide range of standards. The developed platform is a proof of concept that one can implement a wide range of standards (existing and new) in the same hardware target. It is a key enabler for cognitive radio and Software Defined Radio in general.
- Sensing and classification techniques for cognitive radio applications: the developed algorithms enable the deployment of cognitive systems with low impact on primary systems.
- Sensing and classification: It has been shown that primary and secondary systems have different properties that can be used for signal detection and classification. In SACRA it has been also considered LTE extension in TVWS and therefore UEs and/or eNBs have sensing capabilities in order to detect the primary system, and classification capabilities in order to differentiate own LTE system from incumbent system. The choice of the LTE bandwidth impacts on both UE Rx sampling rate and amount of captured noise power. These two parameters together with the sensing or classification time are important as they are affecting the detection and classification probabilities respectively. In the case of classification, it has been also shown that the received LTE power affects the classification probability. It has been therefore presented using performance graphs and by taking into account the received LTE SNR that if the received secondary signal power is too high, the classification is less reliable. Simulation results also described the efficiency of the proposed sensing and classification algorithms with respect to regulatory requirements.

The necessary sensing and classification requirements in terms of duration, efficiency and complexity have been therefore computed and delivered.

- Radio resource management techniques: a set of novel radio resource management techniques has been developed to optimize the exploitation of the available resources. The aforementioned techniques comprise cognitive and cooperative characteristics, and incorporate learning mechanisms. The scope of such mechanisms is to adapt the solutions' operation based on the sensed environment on the one hand and allow the cooperation among the UEs on the other. Finally, those techniques are flexible and comply with policy rules and objectives enforced.

The technical results of SACRA illustrate that many enabling techniques, including the proposed solutions to design RF, antennas, and sensing, are mature for a commercial and wide range development. However, some steps remains in term of regulation and availability of cognitive resources for a wide deployment of cognitive systems. The main challenges for this deployment are indicated below:

- The regulation process is relatively slow versus the technical progress, and is not harmonized from one country to another one. There is not a single view on the access to the TVWS: databases and the access to the databases could vary from one country to another one, thus limiting the development of cognitive systems.
- The cognitive resource (in term of capacity) is time and location dependent. This is a problem to guarantee the minimal Quality of Service which is requested for some applications. Specific mechanisms must be developed to manage these constraints, and then to enable the implementation of cognitive systems. This is out of scope of SACRA activities, but is addressed by other ICT FP7 projects such as QoSMOS (http://www.ict-qosmos.eu/).

8 ACRONYMS

3GPP	3rd Generation Partnership Project
ADAC	Analogue to Digital, Digital to Analogue Converter
ADAIF	Analogue to Digital, digital to Analogue InterFace
ADC	Analog/Digital Converter
ARCEP	Autorité de Régulation des Communications Electroniques et des Postes
AVCI	Advanced Virtual Component Interface
BB	Baseband
BER	Bit Error Rate
BS	Base Station
CBS	Cognitive Base Station
CHD	CHannel Decoder
CEPT	Conférence Européenne des Postes et Télécommunications
CN	Core Network
CPU	Central Processing Unit
CR	Cognitive Radio
DAC	Digital/Analog Converter
DD	Digital Dividend
DMA	Direct Memory Access
DPD	Digital Predistortion
DSP	Digital Signal Processor
DTT	Digital Terrestrial Television
DVFS	Dynamic Voltage and Frequency Scaling
ECC	European Communications Office
eNB	Enhanced Node B
E-UTRA	Evolved-UMTS Terrestrial Radio Access
EVM	Error Vector Magnitude
FA	Functional Architecture
FDD	Frequency Division Duplexing
FE	Front-End
FEP	Front-End Processor
FER	Frame Error Rate
GPP	General Purpose Processor

HSPA	High Speed Packet Access
i/f	Interface
INTL	INTerLeaver
KPI	Key Performance Indicators
LNA	Low Noise Amplifier
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MSC	Message Sequence Chart
OFCOM	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OMC	Operation Maintenance and Control
OMG	Object Management Group
OP	Operator
PA	Power Amplifier
PAPR	Peak To Average Power Ratio
PDP	Policy Decision Points
PEP	Policy Enforcement Points
PMSE	Programme Making and Special Events
PP	Pre-Processor
PV	Programmer's View
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RRC	Regional Radiocommunication Conference
RRM	Radio Resource Management
RRS	Reconfigurable Radio Systems
RT	Real Time
Rx	Reception
SA	Situation Awareness
SPI	Serial Peripheral Interface
SotA	State of the Art
tBPF	tunable Band Pass Filter
TDD	Time Division Duplexing
TVWS	TV White Spaces

Tx	Transmission
UE	User Equipment
UHF	Ultra High Frequency
UML	Unified Model Language
UMTS	Universal Mobile Telecommunications System
VGA	Voltage Gain Amplifier
WP	Work Package
WRC	World Radiocommunication Conferences

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