



Quality Of Service and MObility driven cognitive radio Systems

FP7-ICT-2009-4/248454

QoS MOS

D7.2

Platform Architecture Definition (2/2)

Contractual Date of Delivery to the CEC:	31-Dec-2011
Actual Date of Delivery to the CEC:	29-Dec-2011
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Work package:	WP7
Est. person months:	14 PM
Security:	PU
Nature:	R
Version:	0
Total number of pages:	71

Abstract:

The main objective of WP7 is to demonstrate, assess and validate, through proofs of concepts, selected cognitive radio functionalities and building blocks developed in the different work packages. This document thoroughly analyzes the set of different setups that have been proposed in D7.1 and properly described in the diverse PoC reports.

Keyword list:

Demo, Cognitive Radio, Scenario, System architecture, Proof of concept.

Abbreviations

AC	Access Control
ACLR	Adjacent Channel Leakage Ratio
ADC	Analog- to-Digital Converter
AL	Adaptation Layer
AP	Access Point
API	Application Program Interface
ARM	Advanced RISC Machine
ASN.1	Abstract Syntax Notation One
BB	BaseBand
BER	Bit Error Rate
BS	Base Station
BW	BandWidth
CBR	Connection Blocking Rate
CCDF	Complementary Cumulative Distribution Function
CDR	Connection Dropping Rate
CE	Cognitive Engine
CF	Cognitive Functions
CM-RM	Cognitive Manager for Resource Management
CM-SM	Cognitive Manager for Spectrum Management
CMOS	Complementary Metal-Oxide Semiconductor
COM	Communication Services
CORBA	Common Object Request Broker Architecture
CP	Cyclic Prefix
CR	Cognitive Radio
DAC	Digital-to-Analog Converter
DC	Direct Current
DSP	Digital Signal Processor

DTT	Digital Terrestrial Television
DVB	Digital Video Broadcasting
DVB-T	DVB - Terrestrial
DVI-D	Digital Visual Interface - Digital
EDGE	Enhanced Data Rates for GSM Evolution
EMG	Entity management Functions
F	Functions
FBMC	Frame Buffer Memory Controller
F _c	Characterization Frequency
FCC	Federal Communications Commission
FD	Fixed Device
FFT	Fast Fourier Transform
FIFO	First In First Out
FM	Frequency Modulation
FPGA	Field Programmable Gate Array
GNU	Gnu's Not Unix
GSM	Global System for Mobile Communications
HDMI	High-Definition Multimedia Interface
IDL	Interface Description Language
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IOP	Internet Inter-ORB Protocol
IU	Incumbent User
LNA	Low Noise Amplifier
LTE	Long Term Evolution
LVDS	Low Voltage Differential Signalling
MAC	Medium Access Control
MM	Measurement, Modelling
MME	Measurement, Modelling and Emulation

MSC	Message Sequence Chart
MSR	Multi-Standard Radio
NC	Networking Cognition
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
OTG	On-The-Go
OU	Opportunistic User
PMSE	Programme Making & Special Event
PoC	Proof of Concept
PPD	Personal Portable Device
PPN	PolyPhase Network
PROM	Programmable Read-Only Memory
PSD	Power Spectral Density
RAM	Random Access Memory
RE	Resource Exploitation
RF	Radio Frequency
RISC	Reduced Instruction Set Computing
RPC	Remote Procedure Call
RS	Resource control Support
RX	Receiver
SAP	Service Access Point
SAW	Surface Acoustic Wave
SD	Secure Digital
SDRAM	Synchronous Dynamic Random Access Memory
SNR	Signal to Noise Ratio
SR	Sample Rate
TLV	Type, Length, Value
TV	TeleVision

TVWS	TV White Space
TX	Transceiver
UART	Universal Asynchronous Receiver-Transmitter
UHF	Ultra High Frequency
UK	United Kingdom
US	United States
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral
VSA	Vector Signal Analysis
WB	WideBand
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network
WP	Work Package
XML	eXtensible Markup Language

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1 Executive Summary

The objective of this deliverable is to give a detailed description of the QoS MOS tests that are planned to be carried out in order to demonstrate some of the system characteristics and main functionalities, as well as some of the building blocks that the model comprises. This way, there will be a real-world assessment and validation of the theoretical concepts tackled within the rest of work packages.

These trials will consider a collection of proof of concepts (PoCs) that will help to determine the usefulness of the ideas exposed within QoS MOS project. It has been agreed to put into practice a total of four test setups, each one of them dedicated to exhibit different concepts.

The first one is built around the sensing engine and helps to evaluate the achievements of WP3. A second setup has the flexible transceiver as central point, following the developments of WP4. For its part, the third proof of concept introduces a collaborative spectrum sensing demo as is previously introduced in WP3. Finally, the fourth setup is considered an integrated proof of concept and covers several concepts of the overall system, beginning with diverse aspects of the cognitive resource and spectrum managers, incorporating themes developed within WP5 and WP6, and combining in a certain way advances discovered in the rest of test setups to demonstrate a true cognitive radio system.

This document is organized as follows: Section 2 gives an introduction and first look to the general objectives and overall architecture that has been envisaged in WP7. The link between the activities in WP7 and the tasks in WP1 is also provided. Section 3 provides a deep insight into the different PoC categories, explaining in detail the respective demonstration tests that will be carried out to evaluate every concept. Finally, Section 4 is devoted to introduce and explain the conclusions derived from this work and provide a hint to the work that comes next.

2 Introduction

The main goal of this deliverable is to provide a detailed definition of the different platform architectures designed with the intention of helping in demonstrating various cognitive radio (CR) concepts developed in the QoS MOS project. These platform architectures, which consist of a number of components and sub-systems developed by different partners in their respective technical work packages (from 3 to 6), are expected to provide close-to-real-world conditions and will further help in testing and validating the CR technology enablers. All those components and sub-systems have been developed based on different use-case scenarios and the reference model considered in WP1 [D1.2] and WP2 [D2.2] [D2.3] respectively. This deliverable is the second in a series of two deliverables in charge of defining the deployment plan for different platform architectures or proof-of concept (PoC) demonstrations.

The PoC demonstrations, initially classified into five categories [D7.1], have been changed to four. The reasons to do so have been diverse, being the most noticeable the consideration that it will be quite more useful to focus efforts on design and evolve an integrated system test setup than dividing works into two separate proof of concepts.

These categories are based on inputs obtained from work packages 2 to 6 and their associated tasks. Every PoC category may involve more than one demonstration with inputs obtained from different partners. The four categories of demonstrations are summarized below.

- The *first category* of PoC demonstrations will aim at showcasing the radio environment and the sensing engine modelled in WP3.
- The *second category* of PoC demonstrations will test the concept developed for flexible transceiver architecture in WP4.
- The *third category* will then validate the data fusion and distributed algorithms developed for cooperative sensing in WP3. This category of demonstrations will also validate the flexible transceiver architecture developed in WP4 for the distributed environment.
- The *fourth category* of PoC demonstrations is envisaged to validate the various CR concepts that have been developed for link and upper layers. Thus, the initial input for this set of demonstrations will come from WP5 and WP6. The demonstrations in this category will also include the validation of the Adaptation Layer along with other upper layer concepts such as spectrum management and decision-making efforts. The distributed smart entity defined and simulated in WP5 will be part of the demonstration activity along with other software functionalities such as networking mechanisms. In the end, the integration among these concepts and others coming from the previous three categories will aim to showcase a live cognitive radio system.

This definitive set of four PoCs, along with the interactions among them, is depicted in a rough and illustrative way in Figure2-1 below.

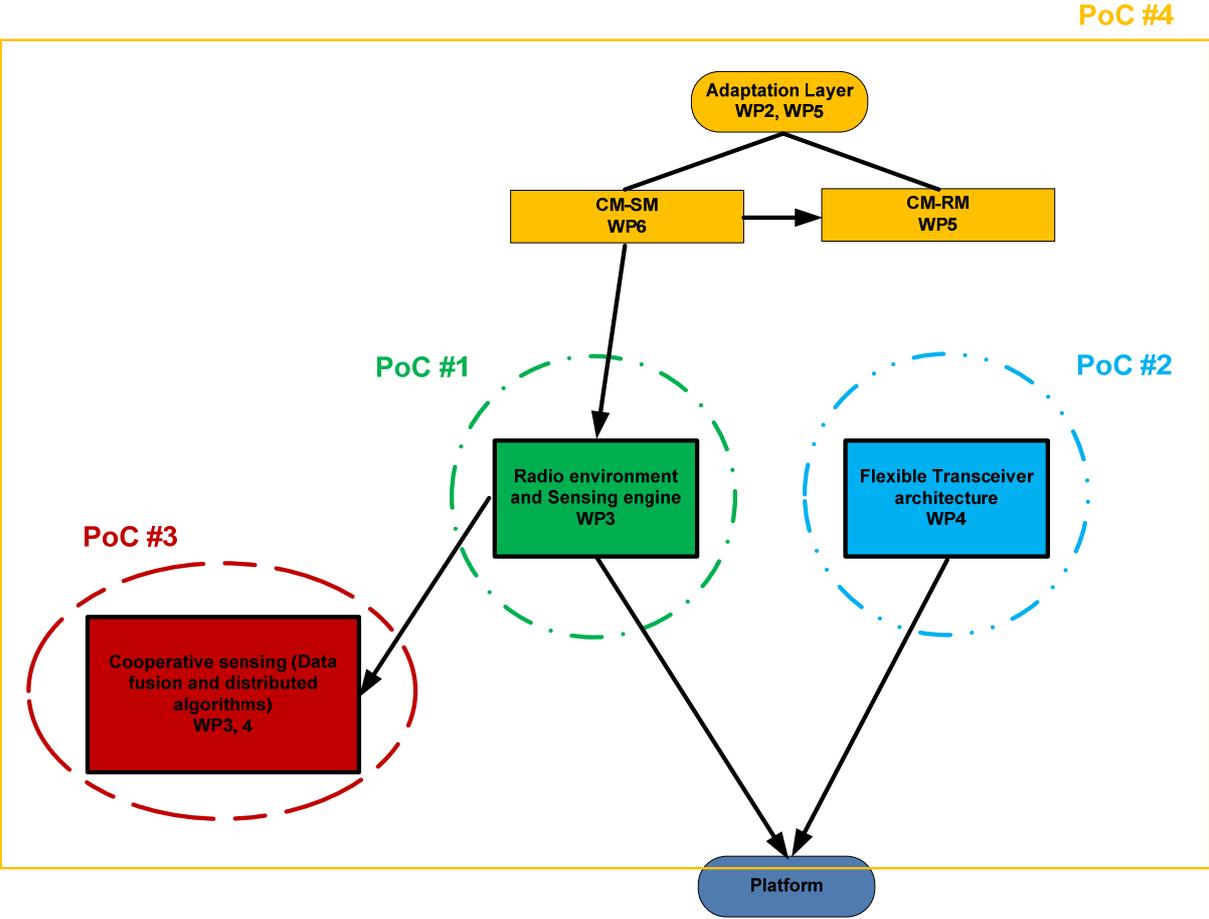


Figure 2-1: Definitive general PoC architecture

3 Proofs of Concepts description

3.1 Proof of Concept #1: Primary scene and sensing engine

3.1.1 Motivation

The PoC will play a critical role in the overall integrated PoC #4. It is important that the basic elements from this PoC function as expected before they can be included in the integrated approach. This test setup will give us important analysis related to the study of different detection schemes and their performances as used by the sensors.

3.1.2 Requirements

This PoC has two basic elements: the primary radio scene emulator and a set of sensors. The requirements for these elements are given below.

3.1.2.1 Primary radio scene requirements

The objective of the primary radio scene emulator is to produce the primary radio scene that will be experienced by sensors in the real environment. Thus the engine has several requirements:

- The engine should be able to mimic close to real-life conditions while providing additional controllability and reproducibility.
- The engine should support wide bandwidth (typically much larger bandwidth support than the sensors).
- The engine should be able to generate the selected waveforms of interest, typically digital terrestrial television (DTT), Programme Making & Special Event (PMSE) or Wireless Local Area Network (WLAN) and cellular signal, within the required bandwidth.
- Different scenarios such as urban/rural, peak/off-peak hours may also be required to be emulated by the engine.
- The engine should provide the dynamic radio scene for as long as needed to appropriately test the performance of the sensors.
- The engine should be controllable, that is the user should be able to precisely control the emulation scenario.
- The engine should be repeatable, that is the user should be able to repeat any desired sequence of events in the emulation scenario.
- The engine should be representative; that is the emulated RF scene should represent as best as possible the real environment that the CR system will experience.
- The engine should also provide a deep enough memory for emulation in order to accommodate a wideband system.
- In an integrated demonstration an important consideration from primary radio scene will be to have a tighter interface with partners related to sensors. This is needed so that there is a harmonious assembly of different isolated developments, in order to shape together a valid test. Thus, a quite concrete and detailed definition of interfaces is mandatory, since the different blocks involved must be able to communicate to the primary engine. The interface requirements will be further developed with the partners in the forthcoming year.
- In addition, it is highly recommended to provide a common hardware platform that makes it possible the mutual interaction of the diverse components. In order to address this, two common platforms have been suggested for the primary scene engine: a multiple baseband

signal generator such as Agilent PXB platform [PXB] and a single baseband signal generator along with RF up-converter such as the Agilent MXG system [MXG].

3.1.2.2 Sensing engine motivations and requirements

The main purpose of vacant channel detection provided by the sensing engine is to protect TV bands incumbents: these are DTT and PMSE signals. Different approaches have been envisaged by regulators to determine whether spectrum is free: spectrum sensing, geo-location and beaconing, although the latter has not been identified as a suitable option [Ofcom2009][ECC_159_2011].

With sensing, opportunistic radios can be autonomous in the assessment on spectrum vacancy without any help from the infrastructure, but the hidden device problem may result in some residual probability of interference [Cabr2006]. This has convinced regulators to consider very conservative scenarios pushing sensitivity requirements to levels very difficult to reach by low-cost hardware technology. Indeed, cognitive devices will need to detect incumbent signals at very low levels, all in the presence of signals in adjacent channels and fluctuating signal levels. This is an extremely challenging task and several blind and signal specific feature-based sensing schemes have been proposed. They include spectral correlation based sensing, time domain cyclostationarity based sensing, eigenvalue based sensing, pilot based sensing and higher order statistics based sensing [Nogu2009].

In the UHF bands IV and V (typically 470 to 862 MHz), the primary system is the DTT broadcast. Since the DTT waveform is known *a priori*, the detector had better use this knowledge. It was shown that better sensitivity at low SNR could be achieved whenever *a priori* knowledge is exploited by the detector [Jall2008]. The DVB-T waveform is used for DTT in many countries including Europe, India, Australia, Russia, and some Asian, African and American. The DVB-T signal is based on the Orthogonal Frequency Division Multiplexing (OFDM) modulation which has strong cyclostationary features stemming from the presence of the Cyclic Prefix (CP). For this reason, cyclostationarity detector has been proposed as one of the most promising technique for DVB-T signal sensing. Theoretical aspect of cyclostationary detection has been thoroughly addressed in the literature [Gard1988][Gard1991][Gard1992][Gard1994], and more recently in the context of cognitive radio [Jall2008][Lund2007][Ye2007][Ghoz2006][Bouz2008]. Then implementation of cyclostationary detectors have been proposed in [Turu2009_1][Turu2009_2]. In [Nogu2009], a hardware architecture for OFDM Wi-Fi waveform has been proposed, and the detector's parameters are traded against their architectural and implementation complexity impact. It was also highlighted in [Nogu2009] that Wi-Fi and DVB-T systems claim for different architectures as the latter can benefit from longer integration time thanks to the broadcast nature of the DTT signal. Yet, [Nogu2009] shows a new approach to determine the detector threshold that does not rely on calibration, but exploits specific harmonics where the second order statistics of the signal is zero. The hardware architecture for DVB-T presented in [Nogu2009] was further implemented on a complete test bed. This hardware platform and measurements have been performed on real broadband signals [Gaut2011]. The DVB-T standard defines different Fast Fourier Transform (FFT) sizes (2048, 4096 or 8192) and different cyclic prefix length (1/32, 1/16, 1/8, 1/4), in practice, implementation considers a smaller set of parameters depending on the country. The proposed architecture is tuned to the DVB-T parameter set used in France, but could be adapted to other profiles also. Thus, the size of the FFT is 8192 (8k) and a CP ratio is 1/32.

Using these measurement results and the complexity/latency evaluation of [Nogu2010], the performance of the cyclostationarity detector are computed and compared to the requirements defined in [Ofcom2009] (see [D1.4]). Figure 3-1 gives the sensing sensitivity of this detector as a function of the sensing time. It is compared with the sensitivity obtained by simulations under perfect channel conditions as in [Jall2008]. Simulation shows that the -120dBm sensitivity could be reached in 150ms. The gap between simulation and measurements is approximately 10 dB and comes from implementation issues discussed in [Gaut2011], which shows the sensitivity of the architecture to RF and digital impairments of the platform. It is very likely that the main contribution comes from the

noise figure of the receiver. This includes the noise figure of the amplifiers, but also the impairments introduced by the digital-to-analog conversion.

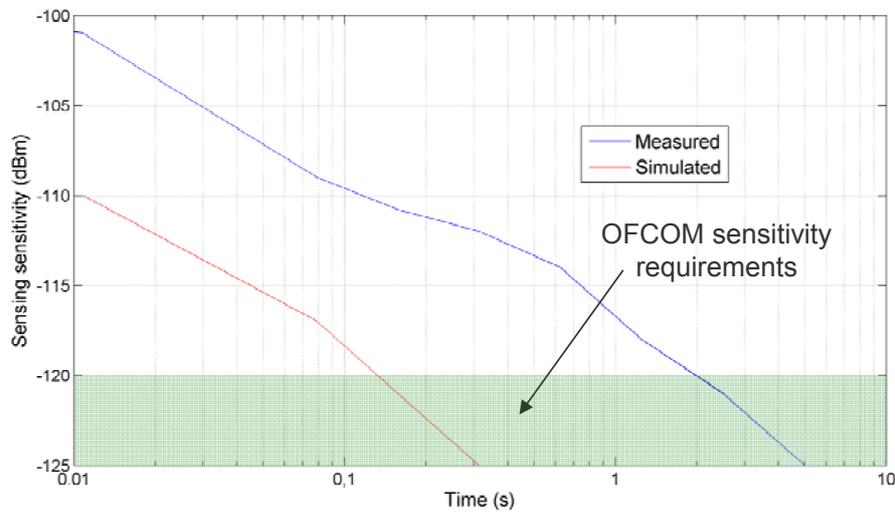


Figure 3-1: Sensitivity vs. sensing duration of the cyclostationary detector

Consequently, measurement results show that at least 2 seconds are needed to reach the sensing sensitivity required by Ofcom's recommendation. Then, the proposed architecture fits relaxed requirements of the FCC but needs to be improved in order to reach the Ofcom recommendations.

Furthermore, performance results of Figure 3-1 only consider one set of DVB-T parameters which is a favourable scenario of DTT deployment in France. In other countries, DVB-T broadcast can use several parameter sets and the sensor must be able to detect each of these configurations. Scanning several parameter sets would increase the complexity of the detector or would lead to longer sensing time.

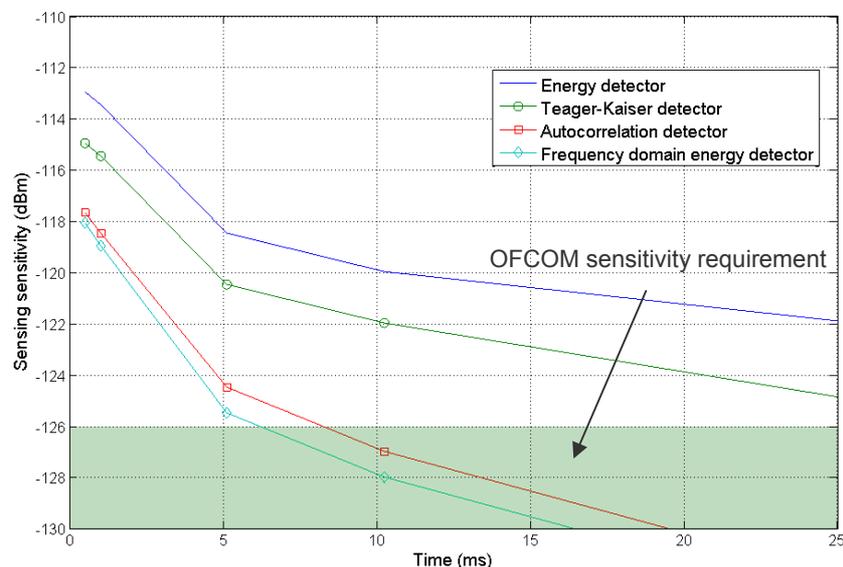
Wireless microphone spectrum sensing is difficult due to the few specific features of its signal. Most of the literature references use a blind detection in the specific case of the wireless microphones [Chen2008]. These studies are based on eigenvalue decomposition, spectral correlation or energy detection. Another issue is that the detector has to search a narrow band signal of 200 kHz in 8 MHz channels. In [Gaut2010], a semi-blind detector is proposed; it uses the Frequency Modulation (FM) characteristics of the wireless microphone signal. This method is based on the Teager-Kaiser energy operator [Kais1990] which takes into account the non-linear model of an FM signal energy. This operator allows an accurate estimation of the energy. Another promising solution performs energy calculation in the frequency domain on the microphone actual bandwidth [Neih2007]. It uses an FFT in order to compute the frequency response of the signal. Once the FFT is performed, the 8 MHz band can be decomposed into sub-bands and the energy can be computed on each sub-band. This algorithm is called the "frequency domain energy detector".

The Teager-Kaiser energy detector allows a 2 dB detection gain compared to the energy detection while the frequency domain energy detector allows a 5.5 dB detection gain and outperforms the autocorrelation detection. The choice of the detector is also a trade-off between its performance and its complexity. Table 1 gives the complexity of each detector in terms of number of multiplications. The Teager-Kaiser energy detector does not induce an important increase of the computational complexity compared to the energy detector while the frequency domain energy detector and the autocorrelation detector have a much more significant complexity.

Table 1: Complexity evaluation of the wireless microphone detectors for N_s samples

	Complexity in number of complex multiplication
Energy detector	N_s
Teager-Kaiser detector	$2*N_s$
Autocorrelation detector	N_s*N_s
Frequency domain energy detector	$N_s*\log_2(N_s)+N_s$

Of course, meeting the regulation requirements remains the main goal. Using the simulated performance, Figure 3-2 gives the sensing sensitivity as a function of the sensing time for each detector. The sensitivity requirement in [Ofcom2009] is quoted for 200 kHz channels. These results have been obtained in perfect conditions with no fading channel and no radio and hardware impairments. As for the DVB-T signal detection, this performance is expected to be degraded in a real system with hardware implementation of the algorithms.

**Figure 3-2: Sensing sensitivity versus sensing duration of several wireless microphone detectors**

From these results it can be understood that sensing is not going to be straightforward to deploy. The issue is even more complex in the case of PMSE which are inherently more dynamic than DTT transmitters. One option is to have a harbour channel for PMSE transmission and to prohibit the opportunistic use of this channel. This solution has been adopted in the UK where the channel 38 is already dedicated to PMSE transmission (see [D1.4]). However, it is unlikely that this option will be generalized, as in some countries, PMSE are allowed to use all the UHF bands. This solution would therefore induce deep modifications for the PMSE manufacturers and users.

It is therefore considered that one crucial aspect of the sensing engine is to demonstrate and validate the capabilities of the simulated PMSE performance. As the frequency domain energy detector promises the best performance in simulation, this algorithm is going to be particularly interesting. As part of PoC #1, a proposed set of requirements may be summarized by the level of sensitivity and a detection time given.

Table 2: PMSE Sensing Engine system requirements

Requirement	Value
Minimum sensibility Level of PMSE detection (in 200kHz)	-126 dBm
Maximum detection time	1 s

These proposed requirements have been derived from [Ofcom2009] and serve as basis of system specifications for PMSE detection in PoC #1.

3.1.3 Building Blocks

As aforementioned, two distinct elements can be distinguished in the PoC #1, the scene emulator and the system of sensors. Their characteristics can be explained as follows in the next sections.

3.1.3.1 Primary Radio Scene Emulator building block

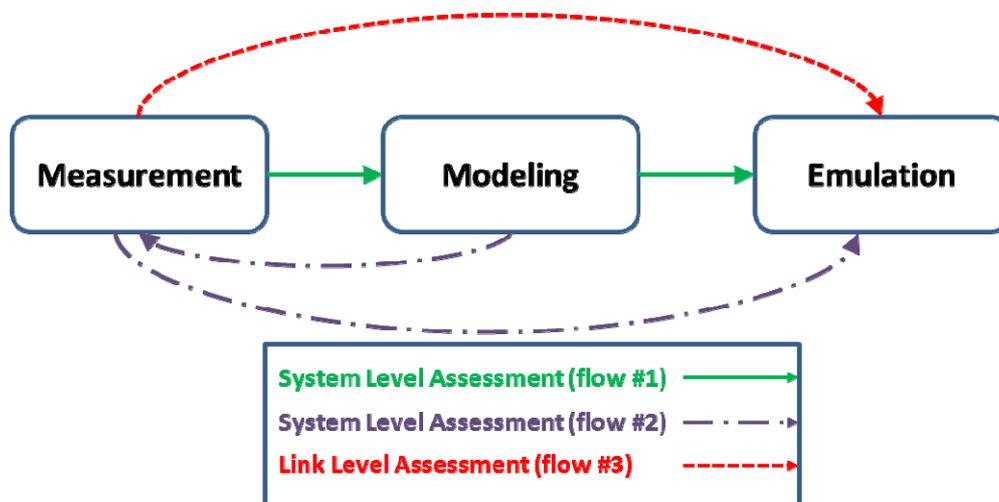


Figure 3-3: Primary radio scene based on Measurement, Modelling and Emulation approach

The principle behind the primary engine emulator is based on the following three pillars: Measurement, Modelling and Emulation (MME) of the radio environment as shown in Figure 3-3. In general, the radio frequency (RF) scene is first measured over a range of frequencies, time instants and locations. The data collected can then be turned into a mathematical model which can further be emulated in a controlled environment either in software or in hardware. It should be noted that besides this sequence (flow #1) it is possible that models are built from the scratch and then confirmed or fine-tuned through measurements, before finally being emulated (flow #2). Finally it is also possible that the modelling block is completely by-passed (flow #3). The last sequence will be called the deterministic case, where the measurement is immediately followed by emulation of the measured signals.

The timescale and target of flows #1 and #2 are different from the one from flow #3. In the first two cases, a system level evaluation is targeted and the aim is to evaluate the capacity of CR systems or the macro spectrum occupancy pattern. In particular, this methodology should assist the designers in evaluating the potential of CR system in various bands and locations. This activity will require measurements over multiple periods and may involve days or weeks. In the last case (flow #3), a link-level evaluation is targeted. Typically short radio scenes are captured and then directly replayed in the laboratory in order to evaluate, for example, the CR sensing algorithms. The timescale in this case can be considered to be in the order of fraction of seconds. The MME integrated approach brings the real-world environment to the lab, and aims to offer to the various CR stakeholders fully trustable results.

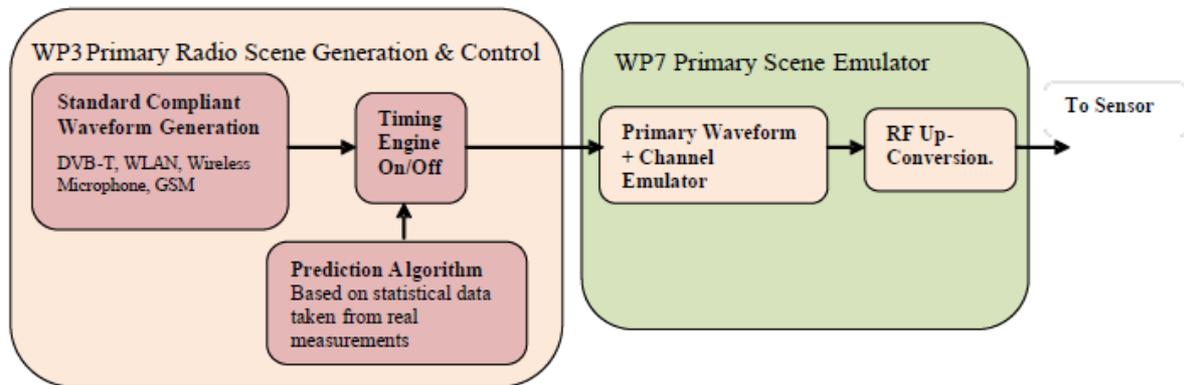


Figure 3-4: Detailed block diagram of the primary radio scene emulator

The detailed block diagram of the primary radio scene emulator is shown in Figure 3-4. Here the *primary radio scene generation and control* block involves the selection and creation of standard compliant waveforms for the selected bandwidth. There can be more than one type of waveform within the selected bandwidth. Each waveform will be independently turned on and off based on the decision taken by the predictive algorithm or as required by the user. The prediction algorithm results will be based on statistical modelling scheme that is derived from the measured data. The final predictive algorithm may be based on one or more distribution models that also consider various urban/rural, peak/off-peak scenarios. It should be noted that the primary radio scene generation and control block will be purely based on software while the emulator will be a hardware instrument such as PXB or MXG platform. The detail regarding the software is further elaborated in the demonstration section.

The *primary scene emulator instrument* will typically take the on/off switched version of various waveforms as input from the *primary radio scene generation and control* block. Finally the waveforms are up-converted to a RF frequency and then fed to one or more sensors in the cognitive test set-up.

3.1.3.2 Sensor building block

3.1.3.2.1 Frequency Domain PMSE detection

This sensing block considers an implementation of the frequency domain sensing block. The FFT implementation will be shared with the multicarrier FFT used at the receiver. Either a specific instantiation of the same FFT as developed in the demodulation or a shared instantiation is possible. Therefore the same building blocks as for the flexible transceiver will be considered. As the proposed multicarrier modulation envisages 15 kHz carrier bandwidth separation, it is suggested to develop the detector that accumulates energy over a span of 15 carriers (or $15 \cdot 15$ kHz) 225 kHz and to overlap the window of detection by an overlapping ratio of 50%. This is to increase the probability of non-detection since the central frequency of the PMSE to detect is not known *a priori*.

A functional implementation diagram of the sensor block is given in Figure 3-5 and will be implemented on the hardware platform specifically developed for QoS MOS to demonstrate the flexible transceiver of the cognitive radio.

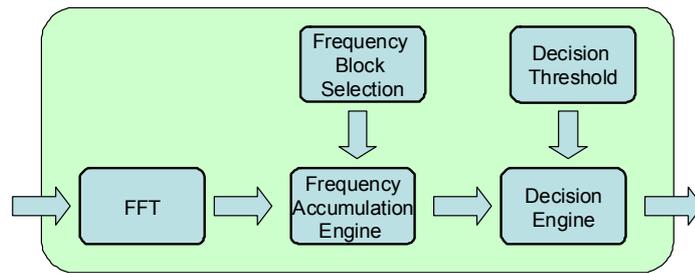


Figure 3-5: Functional architecture of frequency domain PMSE detection

The signal at the input of the FFT may be a complete 8MHz digitized TV Channel or a multiple of TV channels. At the output of the FFT, blocks of 15 carriers are accumulated together over an accumulation window. Every accumulation window the signal is compared against a decision threshold and a list of detected PMSE carriers is output.

Table 3: PMSE Sensing Engine Interface

Interface	Remark
Central_frequency	Central frequency of signal at the input of the sensing module (This interface parameter is assumed to be controlled externally to the sensing engine).
Accumulation_Counter	Number of FFT the sensing signal is accumulated for before a sensing decision is made by the decision engine. The duration of one FFT execution is expected to be of the order of 66 μ s. The following accumulation levels are considered: 256, 512, 1024, 2048, 4096, 8192, 16384. This corresponds to accumulations between 10 ms and 1 s.
Decision_Threshold	The decision threshold is a threshold of energy over which the detected signal is considered as potential incumbent.
PMSE_Detection_result	The PMSE detection result outputs a list of possible carriers that may contain some PMSE usage. Depending on the implementation of the decision engine (hardware on the FPGA or software on the ARM) the practical interface may slightly differ.

3.1.3.2.2 Sensor block

The energy sensor makes a hard decision on the presence of Incumbent User (IU) signal based on the input signal power. If the IU input signal power is above a given threshold (for a given number of samples), the sensor outputs a ‘1’ indicating the presence of IU. Otherwise, it will output ‘0’. The block diagram of the sensor is depicted in the next Figure 3-6.

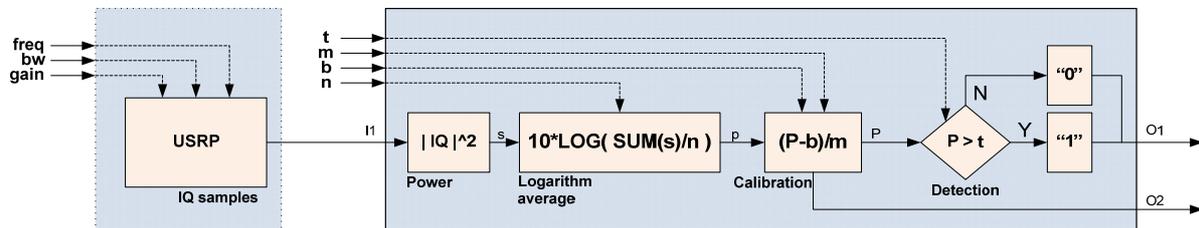


Figure 3-6: Sensor block algorithm

The RF and baseband processing are implemented, respectively, with the Ettus RFX2400 and Ettus USRP1 hardware (USRP in the figure). The parameters for this first block are the central frequency, the bandwidth and the gain. The detection algorithm was implemented in a PC with “GNU Radio-

companion” software. The parameters for this second block are the threshold, t , the number of samples, n , and calibration related constants b and m .

The detailed characterization of the sensor is made in section 3.3.3.1, where both the hardware and the implemented algorithm are described.

The energy sensor offers a friendly interface that allows the user to configure the different parameters involved in the process, as can be seen in Figure 3-7.

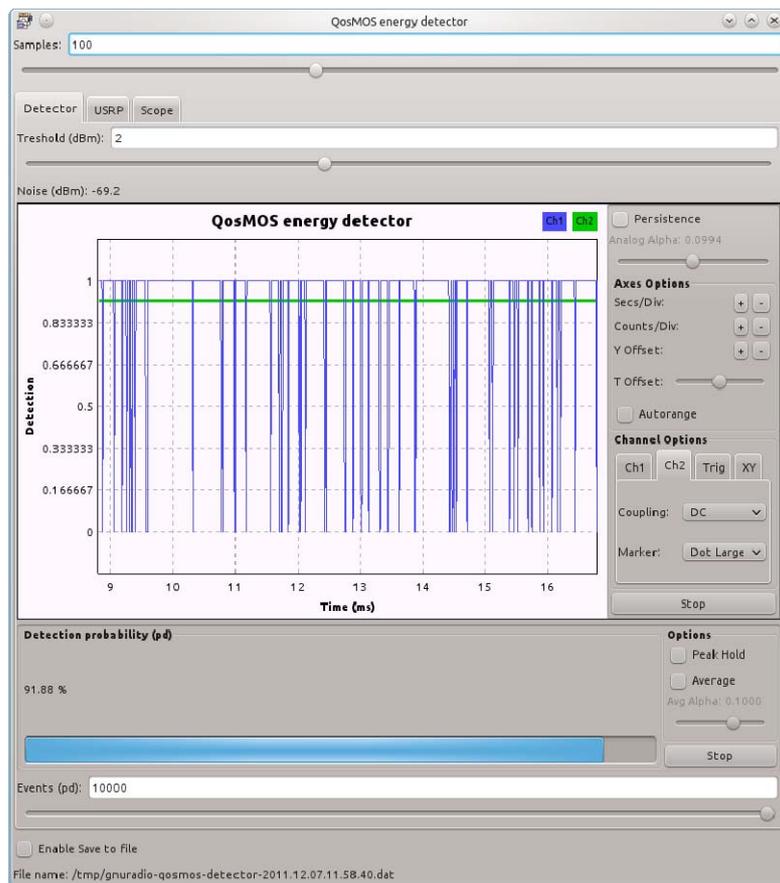


Figure 3-7: Sensor block application

In addition, using a Remote Procedure Call (RPC) software architecture for inter-block communication would allow easy integration of blocks coming from different partners, even if these blocks are written in different languages. Thus the sensor block will respond with sensing data when queried or prompted by another block.

3.1.4 Interaction among blocks

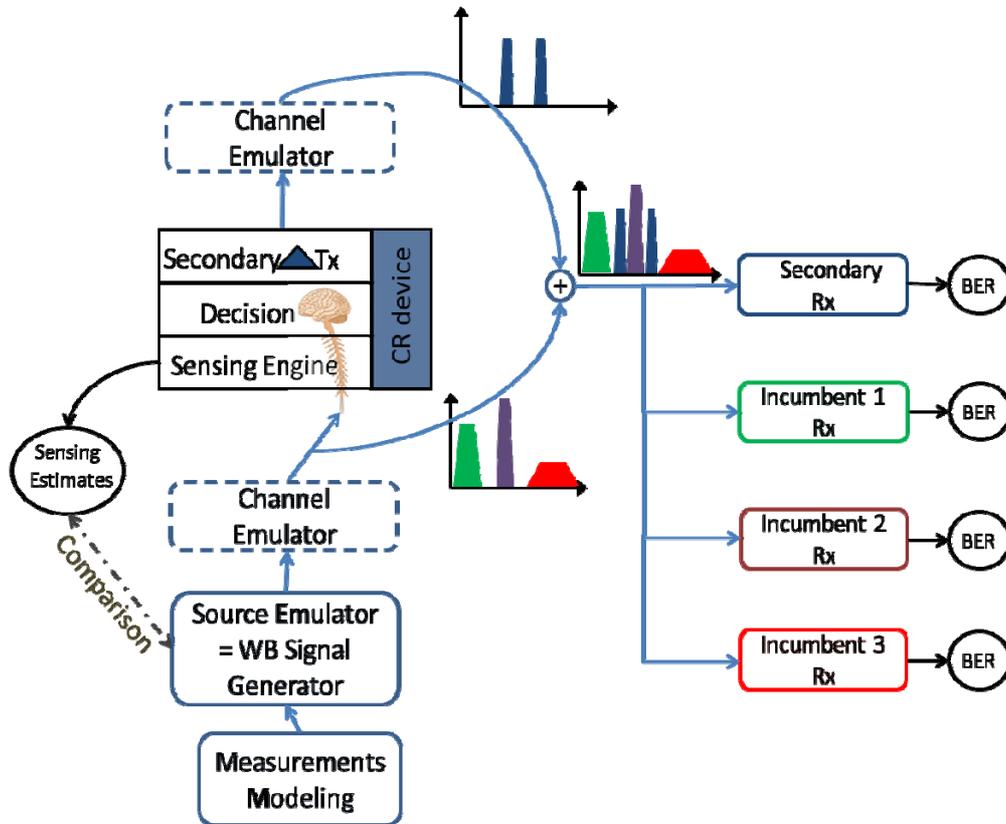


Figure 3-8: High level view of the demonstrator

Figure 3-8 shows the high level view of the primary scene emulator interfacing with the sensors. Here the emulator consists of a wideband (WB) signal generator that stimulates the sensing engine of a CR device with a set of waveforms derived from the measurement-modelling (MM) stages of the MME approach. As discussed in the introductory section, the emulation involves two cases with different time scales: deterministic and model-based.

In the first *deterministic* case, the modelling block is skipped and the recorded sequences obtained from the measurement campaign are directly replayed on the emulator without any changes. The incumbent usage pattern (on/off) is emulated without the need for any channel emulation. This emulation scenario serves the link-level performance evaluation and in particular the sensing engine performance study.

In the second *model-based* case, both statistical and database approaches are considered. Here the incumbent usage pattern emulation is combined with the channel emulation in order to accurately reproduce the actual RF scene. This emulation scenario serves the system level performance evaluation.

The Figure 3-8 shows that in the test-bed the sensing estimates of the CR device can be compared with the source in order to evaluate the performance of the sensing engine. Metrics like the probabilities of detection, false alarm or the detection speed can be evaluated in this manner. On the other hand, the CR device can also make decisions about the available opportunities based on the sensing engine outputs. In this case the transmitter of the CR device (secondary) can start transmitting on the available spectrum holes. The output of the secondary transmitter is then added to the stimulus signal and later fed to CR device receiver as well as the incumbent systems receiver. Through BER

measurements (as an example), both the quality of the secondary transmission and its impact on the incumbent systems can be evaluated. The emulator should have the following three properties:

- **Controllable**: the user should be able to precisely control the emulation scenario;
- **Repeatable**: the user should be able to repeat any desired sequence of events in the emulation scenario;
- **Representative**: the emulated RF scene should represent as well as possible the real environment that the CR system will experience. This is guaranteed through the MME vertical approach.

Besides the above desirable properties, the emulator should also provide a deep enough memory for the deterministic case emulation whereas a wideband system is typically required for both the deterministic as well as the model-based cases.

3.1.5 Novelties demonstrated

Thanks to the proposed setup a wide range of tests can be addressed. Among others, the following ones can be listed:

- Frequency accuracy of the sensing.
- Sensing latency.
- Time response to change in the environment.
- Probability of non-detection of an IU.
- Probability of false alarm.

This PoC will allow making an empirical comparison between different detection approaches as used by the sensors.

3.1.6 Integration Plan

Currently, there is an ongoing work in terms of specifications and the interface. Thus, the details of the common hardware platform related to the primary scene emulator are well known. Currently the primary scene emulator and the sensing blocks are being developed independently. The process of integration of different blocks is expected to begin from the spring of 2012.

In an integrated demonstration an important consideration will be to have a tighter interface with partners related to sensors and the primary scene emulator. This is needed so that there is a harmonious assembly of different isolated developments, in order to shape together a valid test. The interface requirements will be further developed with the partners in the forthcoming year.

3.2 Proof of Concept #2: Flexible transceiver

3.2.1 Motivation

Out of band emission requirements are difficult to meet using traditional OFDM techniques and alternative multicarrier modulations have been proposed, including .Frame Buffer Memory Controller (FBMC). FBMC has been proven by simulation to meet out-of-band requirement. The motivation of this PoC is to validate the out-of-band performance of FBMC in a complete radio system, where RF impairments are accounted for.

3.2.2 Requirements

The out-of-band leakage is much beyond the 55 dB and 65 dB emitted signal. However simulation does not include any of the analog-to-digital and RF impairments. The effect of finite precision registers, the linearity of the analog transmitter and particularly the RF amplifier but also the phase noise generated by the frequency synthesizers are possible sources of impairments that may cause the level of out-of-band rejection to be much lower than expected. One fundamental aspect the demonstrator will provide is a means to benchmark and specify the impairment levels and their impact

on the spectral density of the emitted signal. It should be noted that most widely commercially used multicarrier signals have spectrum mask requirements that are 20 to 25 dB above the requirements set by the TVWS (i.e.: DVB-T, IEEE802.11g) and are therefore much more relaxed than the TVWS expected requirement.

A reminder of key parameters from the US and UK regulation bodies is reminded in the Table 4 here below.

Table 4: Key Parameters of US and UK regulation bodies for TVWS

Parameter	FCC [Fcc2009]	Ofcom [Ofcom2009]	Note
Sensing sensitivity for DTT	-114dBm	-120dBm	
Sensing sensitivity for wireless microphones	-114dBm	-126dBm	In 200kHz bandwidth
Power for FD in adjacent band	Not allowed	Not applicable	
Power for FD in non-adjacent band with geo-location capability	30dBm	Not applicable	FCC: 36dBm EIRP with a gain antenna
Power for PPD in adjacent band	16dBm	4dBm	Gain antenna not allowed
Power for PPD in non-adjacent band with geo-location capability	20dBm	17dBm	Gain antenna not allowed
Power for PPD in non-adjacent band without geo-location capability	17dBm		
Out-of-band performance	<55dB	<-46dBm	Relative to in-band power in the case of the FCC
In-service monitoring period	60s	1s	
Evacuation time	2s	Not specified	

A second aspect motivating PoC#2 is on the consequence of the modulation robustness. The large constraint put on the spectrum mask, has lead to the choice of FBMC as a possible candidate. However, few real life transmissions of FBMC have been experimented in comparison to OFDM. PoC #2 is an opportunity to validate the performance of an implemented FBMC transceiver.

The following steps have been identified for the PoC. Since the transmitter spectrum mask is particularly difficult to meet, a first step will consist on demonstrating the performance of the FBMC transmitter in terms of spectrum mask and agility.

Step 1:

- 1a: TX demonstration of single channel spectrum occupancy – visualization of the Power Spectral Density (PSD) on a spectrum analyser, analysis of adjacent band leakage, comparison with simulation results, FBMC/OFDM spectral performance comparison
- 1b: TX demo of multiple channels with spectrum pooling - visualization of the PSD on a spectrum analyser, comparison with simulation results in order to check spectrum pooling viability

Step 2:

- TX / RX communication: RX = single channel capability (e.g. using RF TV tuner) – demonstration of FDMA schemes with FBMC

3.2.3 Building Blocks

3.2.3.1 Baseband Board

Both PoC#1 and PoC#2 are going to be implemented on QoS MOS boards specifically designed and built during the course of the project. The main modules considered in the development are a baseband board and an RF board. The main components of the baseband board are the following:

- 1 FPGA Xilinx XC7K325T-1FFG676C (Kintex7 Family)
- 326080 Logic cells / 840 DSP (25·18 multiplier) / 445 Blocks RAM 36 Kb: The component will be used to implement most baseband functionalities including signal processing of the transmitter and the receiver.
- 1 ARM microcontroller DM3730CBP100 (cortex A-8 at 1 GHz + DSP TMS320C64x): The microcontroller will allow the implementation of a software for the PHY for improved flexibility and the implementation of a software MAC, to interface lower layers with upper layers.
- 1 package on package memory module MT29C4G48MAZAPAKQ-5 IT = 4 Gbits Nand Flash + 2 Gbits LPDDR SDRAM: the memory module is build on top of the ARM microcontroller.
- 1 TPS65950 integrated power management (DC/DC converters, battery charger, USB OTG interface): the power management interface will allow “wire-free” demonstrations, important for mobility demonstration. Autonomy of the demonstration is expected to be at least larger than the hour at full power consumption.
- 2 dual ADC AD9643 14 bits / 250 MHz, the ADC using a differential interface allow for receive intermediate frequency up to 400 MHz.
- 1 quad DAC AD9148 16 bits / 1 GHz: interpolation is performed inside the digital-to-analog converter and allow for a good compromise between input interface throughput requirements and output sampling frequency.
- 1 clock generator AD9516-0: The clock generator allow distribution of as clean as possible analog clocks to the mixed signal modules of the board (analog-to-digital conversion and digital-to-analog conversion)
- 1 microSD card (compact flash)
- External interfaces have been also added to interface to the RF boards and to digital emulators:
 - 2 Samtec QSE-020 connectors for RF board plug-in
 - 2 Mictor Connectors (38 pins) towards Agilent channel emulator
- Other interfaces are added for communications to an external host
 - 1 USB interface High-speed OTG
 - 1 Ethernet interface 10/100 Mbps
 - 1 RS232 interface
 - 1 WLAN 802.11 Bluetooth interface using a TiWi-R2 module
- A set of interface may be used for media interface content
 - 1 Samtec SFMC-117 connector for interface to a LeopardBoard (camera)

- o 1 HDMI connector towards HDMI / DVI-D cable (screen) using a graphics controller

The proposed baseband circuit board is available at the Figure 3-9 here below.

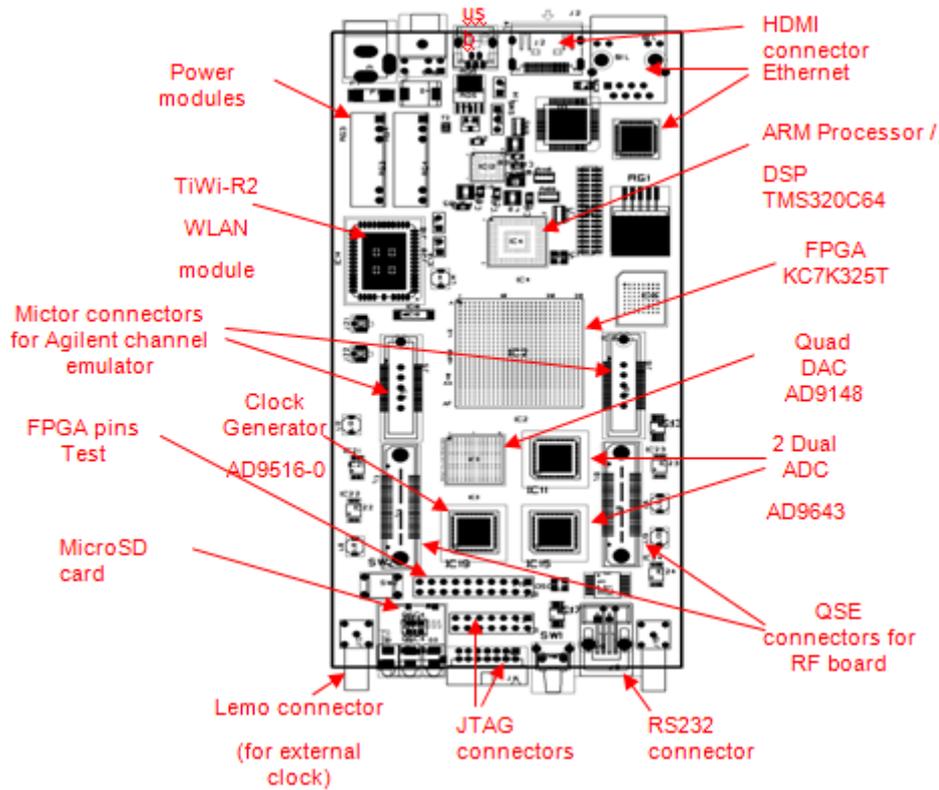


Figure 3-9: Baseband printed circuit layout

The objective of the hardware developed for QoS MOS is to fit in a case of the same size range as a Smartphone: it should be able to hand held the case of the demonstrator. The form aspect and dimensions of the proposed hardware is described in Figure 3-10.

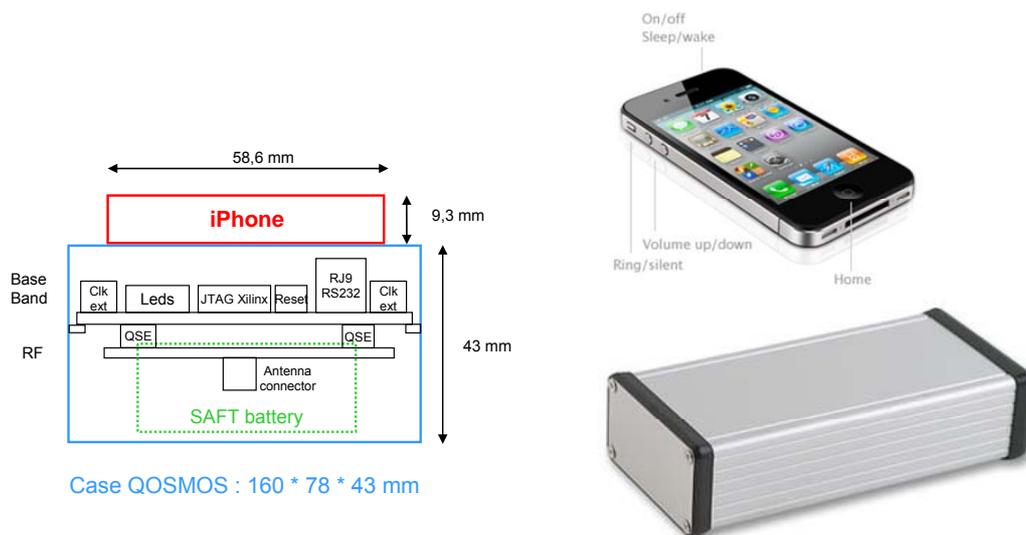


Figure 3-10: Form factor of the developed baseband transceiver and comparison with a Smartphone (iPhone)

Expected power consumption of the different elements populating the board has been evaluated. The results are presented in Table 5 below.

Table 5: Derivation of Power consumption

Component	Quantity	Supply Voltage					Power (Watt)
		3,6V	3,3V	1,8V	1,1V	1V	
ARM/DSP DM3730	1			0,025	0,3		0,375
Xilinx FPGA XC7K325T	1		0,05	1		3	5.0
Flash/SDRAM MT29C4G48	1			0,013			Negligible
Xilinx Flash PROM XCF128X	1			0,000025			Negligible
WLAN TiWi-R2	1	0,01		0,01			0,054
DAC AD9148 1GHz quad 16 bits	1		0,1	0,2			0,69
ADC AD9643-250 dual 14bits	2			0,3			1,1
Clock generator AD9516-0	1		0,4				1,3
UART SN65C3221	1		0,0003				Negligible
RF board	1	0,3					1,1
Ethernet LAN9220	1		0,1				0,33
Power Management TPS65921B1	0	0,2					0
graphics controller interface TFP410	1		0,2				0,66
26MHz / 10MHz oscillators	2		0,015				0,099
TOTAL CURRENT (A)		0,31	0,88	1,8	0,3	3	
TOTAL POWER (Watt)		1,1	2,9	3,3	0,33	3	10,7

The total expected power for the board is of the order of 10 W. When supplied with a Li-ion battery of 3.75 V and 6.8 Ah, the board should be autonomous for more than a couple of hours without battery recharge.

Physical interfaces have particularly been defined between baseband and radio boards through 2 QSE-20 connectors. This interface is particularly essential for the demonstrations as it includes:

- 2 TX dual differential lines (I+/I- and Q+/Q-)
- 2 Rx dual differential lines (I+/I- and Q+/Q-)
- 2 analog links for RSSI from RF receiver (3.3 V max)
- 1 analog link for external clock to or from RF board (bi directional)
- Digital links: 28 LVDS CMOS lines are available to program the RF board
- Power links: 8 power lines on both QSE connectors (4 pins of each QSE) provide either 3.7 V from battery supply or 5 V when the case is powered by an external DC supply.

A schematic of the designed interface is given here in Figure 3-11 for reference.

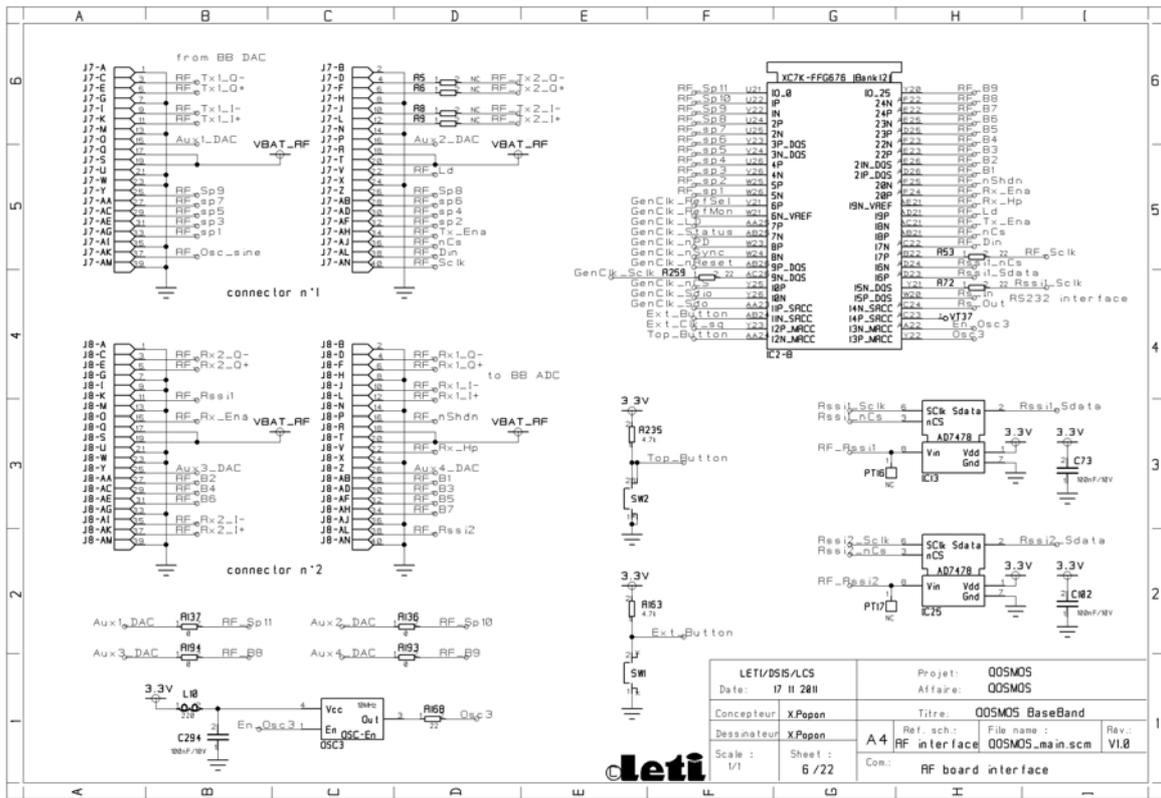


Figure 3-11: Baseband board schematic of QSE connectors.

Preliminary implementation evaluation of the baseband transmitter, carried out in WP4, has been used to validate the requirements of the chosen FPGA. An FBMC transmitter has been implemented using the architecture proposed in Figure 3-12.

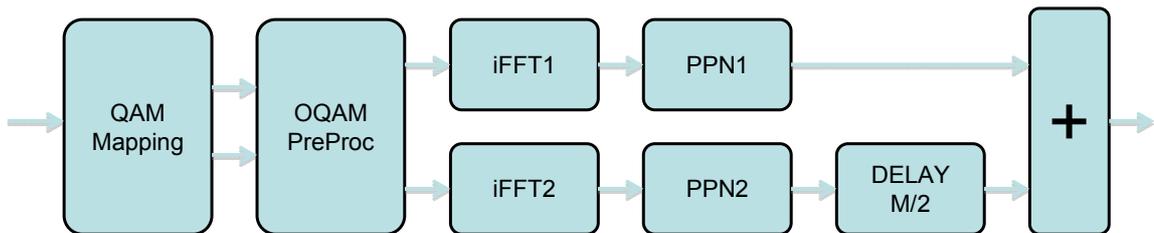


Figure 3-12: Implementation of the proposed baseband transmitter.

This implementation has then been synthesized and mapped to the Kintex7 used in the baseband board.

Using a 1024-point FFT as planned in the first scenario aforementioned the following results have been found (see Table 6).

Table 6: Resource usage of the baseband transmitter

FPGA Implementation	LUT	DSP48E1	RAM Block
IFFT (1024 points)	1066	6	12
PPN (Polyphase filters)	156	16	3
Total	2444	44	30
Total Available	50950	840	890
Ratio	4.8%	5.2%	3.4%

Similarly, the implementation of the proposed receiver is provided in Figure 3-13.

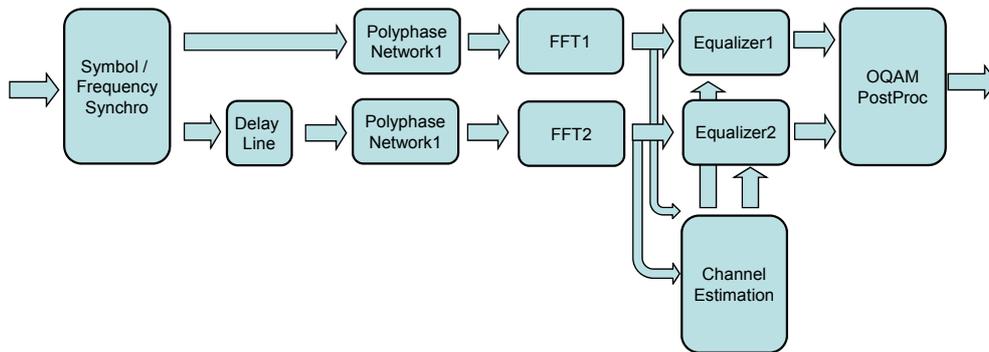


Figure 3-13: Implementation of the proposed baseband receiver.

This led to the conclusion that sufficient resources should be available for both RX and TX.

3.2.3.2 Transmitter Front-End

The block diagram of the transmitter front-end is shown in Figure 3-14. It is based on a super-heterodyne architecture. The bandwidth of this broadband transmitter is defined by the IF SAW (Intermediate Frequency Surface Acoustic Wave) filter which offers a nominal pass band of 40 MHz. The IF SAW filter has a centre frequency at 280 MHz. The transmitter front-end uses two external interfaces. One interface (pin connector QTE) is to connect the transmitter with the baseband board and the other one (SMA connector) with the antenna.

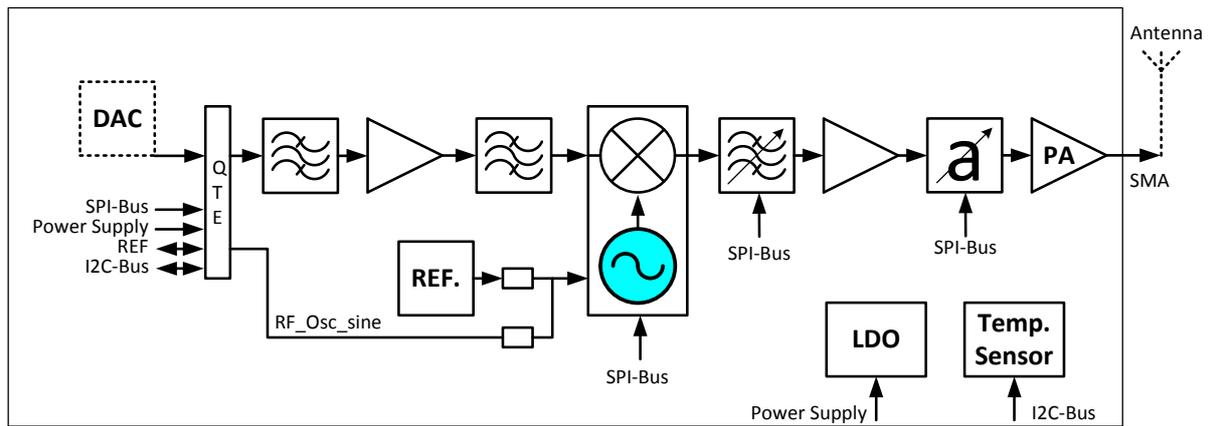


Figure 3-14: Block diagram of the transmitter front-end

The main components of the transmitter are:

- 1 power amplifier (PA) (RFPA0133)
- 1 tuneable band pass filter, digitally programmable
- 2 IF SAW filter (TFS280G)
- 1 digital step Attenuator (DSA PE43702)
- 1 RF synthesizer/VCO with integrated RF mixer (RFFC2072)
- 1 temperature compensated crystal oscillator (TCXO) for reference frequency (VT-803)
- 1 low-dropout linear voltage regulator (LDO REG104GA-A)
- 1 temperature sensor (MAX6625)
- 2 broadband amplifiers (SGC4263Z)
- 4 pin connector (2 QTE-20pin and 2 QSE-20pin)
- 1 SMA connector for RF output

3.2.3.3 Receiver Front-End

The block diagram of the receiver front-end is shown in Figure 3-15. It based also on a super-heterodyne architecture. The bandwidth of the receiver is the same as the transmitter bandwidth because of the use of the same IF SAW filter. The receiver has also two external interfaces to connect with the baseband board and the antenna.

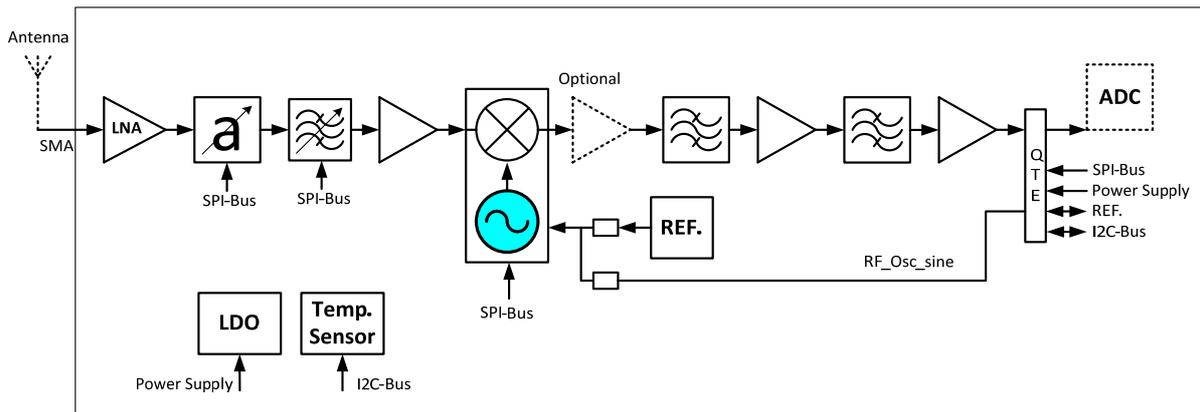


Figure 3-15: Block diagram of the receiver front-end

The main components of the receiver are:

- 1 low-noise amplifier (LNA)
- 1 tuneable band pass filter, digitally programmable
- 2 IF SAW filters (TFS280G)
- 1 digital step attenuator (DSA PE43702))
- 1 RF synthesizer/VCO with integrated RF mixer (RFFC2072)
- 1 temperature compensated crystal oscillator (TCXO) for reference frequency (VT-803)
- 1 low-dropout linear voltage regulator (LDO REG104GA-A)
- 1 temperature sensor (MAX6625)
- 4 broadband amplifiers (SGC4263Z)
- 4 pin connector (2 QTE-20pin and 2 QSE-20pin)
- 1 SMA connector for RF input

3.2.4 Interaction among blocks

The interface in PoC#2 between the baseband board and the RF front-end board are shown in Figure 3-18. All interfaces are connected over two board-to-board pin connectors type QSE/QTE.

For analogue links there are: 2 Tx dual differential links
 2 Rx dual differential links
 2 analogue links for RSSI value from RF board
 1 analogue link for reference clock from RF board with 25 MHz

For digital links there are: 28 lines LVCMOS 3V3

For power supply there are: 8 lines on both QSE connectors (4 pins of each connector)

3.2.5 Novelties demonstrated

With PoC #2, the performance of FBMC in terms of adjacent channel leakage ratio (ACLR) will be assessed and compared with the requirements from TVWS regulation. It has been shown in WP4 that FBMC outperforms OFDM on ACLR. More precisely, it was shown in WP4 that the implementation complexity of additional filtering required on top of OFDM to meet ACLR requirement is very significant. On the other hand, FBMC intrinsically provides filtering ability and does not need

additional filtering. In WP4, the ACLR performance of FBMC was assessed through floating point simulation at baseband level only. With PoC #2, the aim is to check how a real implementation of an FBMC TX impacts the ACLR performance. The key differences versus WP4 simulation are the use of limited dynamic baseband signal representation and the impact of the DAC and analog/RF TX chain. In WP8, ACLR was identified as a major roadblock for OFDM in IEEE P1900.7 standardisation [P1900.7]. PoC #2 may be a key step in this standardisation process, if PoC #2 experimentation quantifies the expected behaviour of the FBMC modulation scheme.

The second step of PoC #2 aims at establishing a point to point communication using FBMC with RF equipment in the UHF bands. This experiment will either be carried out on cable or over the air in a shielded anechoic chamber to meet regulatory constraints. This second step aims at showing that performance of FBMC is similar (if not better) than the one of OFDM. This would prove that link quality was not sacrificed to ACLR performance.

3.2.6 Integration Plan

This section shows the concept of the demonstrator to test the flexible transceiver and part of the transceiver blocks that were developed in WP4. It divides into four parts. Sec. 3.2.6.1 shows the demonstrator of the transmitter module. The demonstrator of the receiver module is described in Sec. 3.2.6.2. Finally, Sec. 3.2.6.3 presents the demonstrator of the transceiver as a whole. Eventually, the spectrum-aggregation demonstrator setup is discussed.

3.2.6.1 Transmitter Module Demonstration

The setup for the transmitter module demonstration is shown in Figure 3-16. The main components of the setup are:

1. Transmitter module (baseband board and RF front-end board)
2. Spectrum analyser to visualize the RF signal
3. Attenuator to reduce the output power of the transmitter

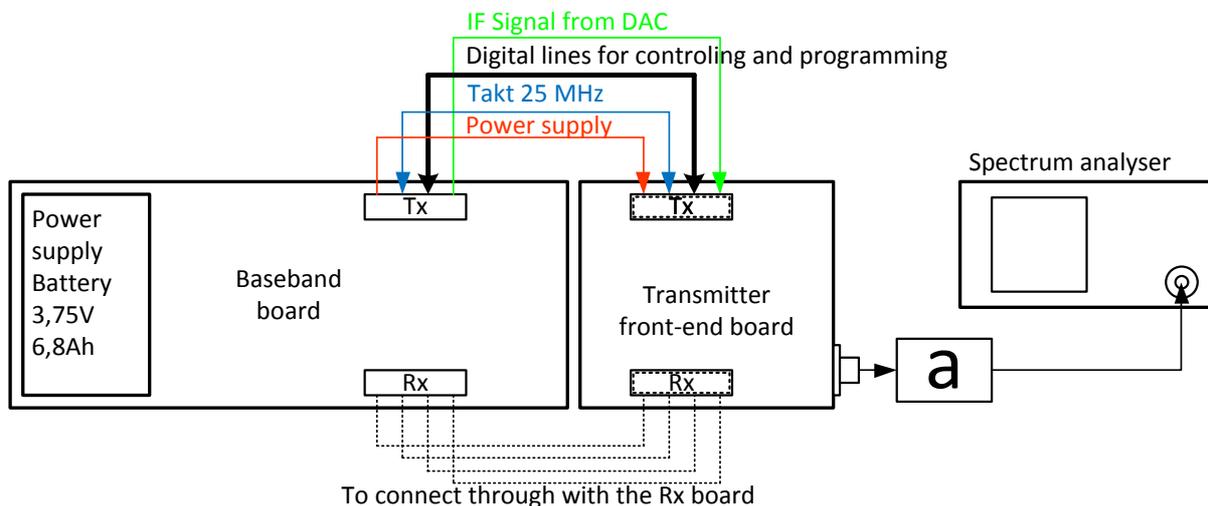


Figure 3-16: Transmitter demonstration setup

The characterization of the transmitter includes investigations on:

- The delay caused by the switching between distinct bands
- The signal quality at the transmitter output

3.2.6.2 Receiver Module Demonstration

The setup for the demonstration of the receiver module is shown in Figure 3-17. The main components of the setup are:

1. Receiver module (baseband board and RF receiver front-end board)
2. Signal generator

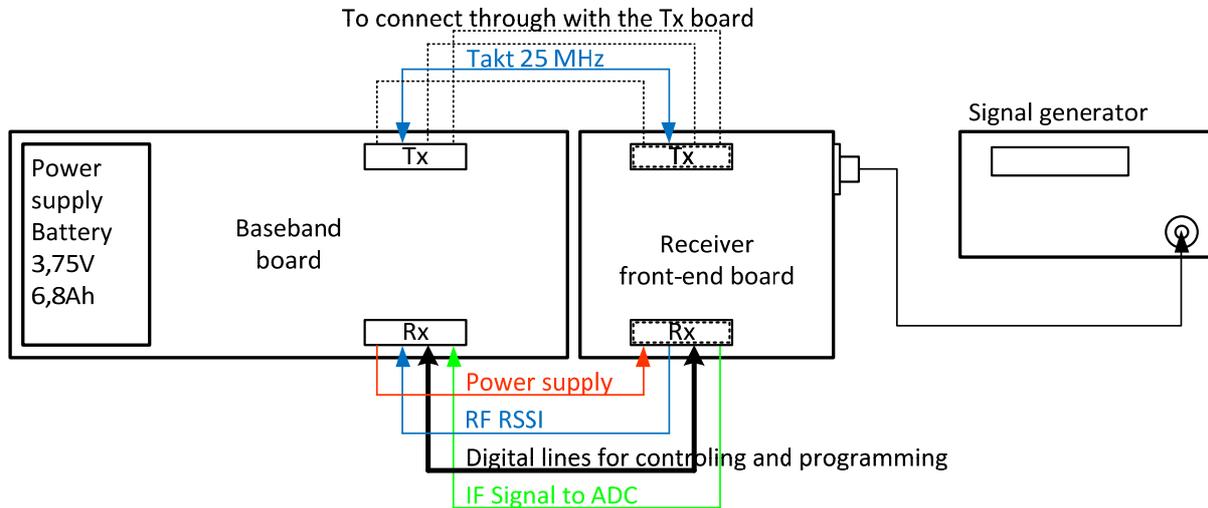


Figure 3-17: Receiver demonstration setup

The objectives of the demonstration of the flexible receiver are as follows:

- Receiver sensitivity
- Time required for changing between distinct bands
- Signal group delay

3.2.6.3 Flexible Transceiver Module Demonstration

The setup for the flexible transceiver demonstration is shown in Figure 3-18. The transceiver module can be characterised in terms of its communication and sensing performance. The main components of this setup are:

1. Transmitter module
2. Receiver module
3. Antenna for wireless connection
4. RF cable for direct connection

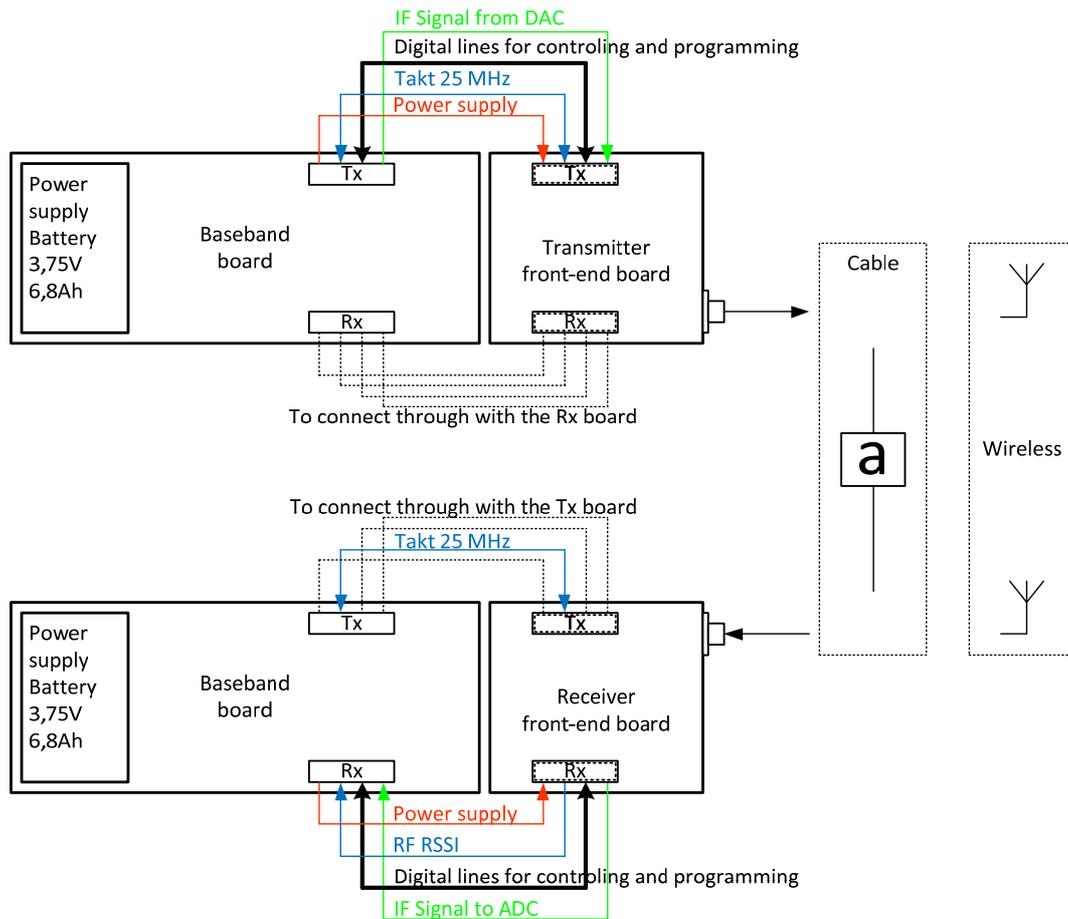


Figure 3-18: Transceiver demonstration setup

3.2.6.4 Spectrum Aggregation Demonstration

The setup for the spectrum aggregation demonstration is shown in Figure 3-19. The main components of this setup are:

1. Two receiver modules
2. Antenna for wireless connection
3. RF cable for direct connection

By means of this setup a communication link can be established simultaneously exploiting two frequency channels. The channels can be arbitrarily located within the whole frequency region covered by the front-end. Two frequency-agile signal branches are therefore implemented.

The architecture allows also for establishing a communication link using one signal branch while the other branch is used for spectrum sensing, i.e., both can be carried out simultaneously.

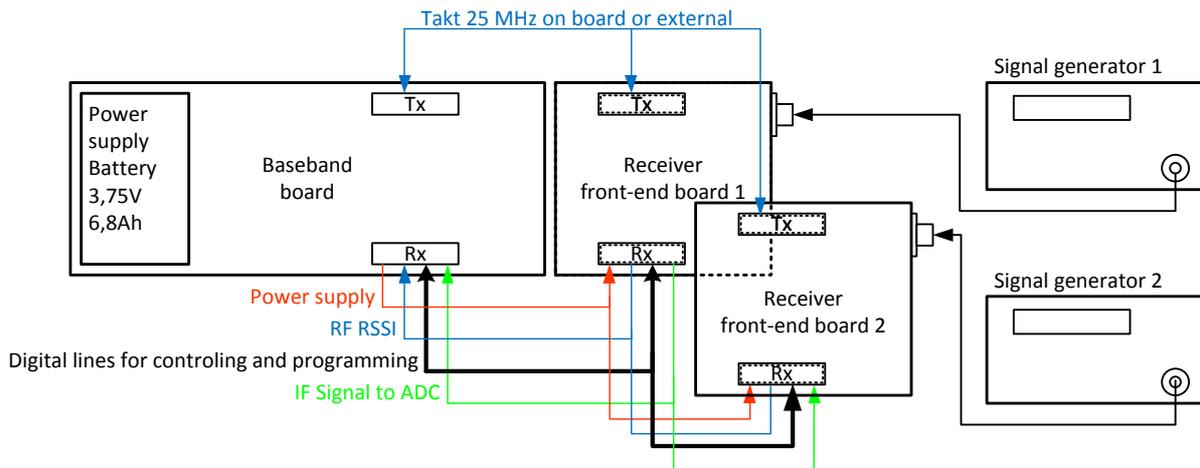


Figure 3-19: Setup for spectrum aggregation demonstration

3.3 Proof of Concept #3: Distributed/Collaborative sensing

3.3.1 Motivation

This PoC aims at demonstrating the benefit of the distributed sensing algorithms proposed and developed within WP3. In order to do so, a sensing scenario has been designed, including hardware and software sensors and a data fusion unit.

The challenge in spectrum sensing is the ability of detecting IUs that are located beyond the single OU interference range but can still be disturbed by the OU network, in a scenario where the propagation environment adds additional uncertainties, like deep channel fades or shadowing, that de-correlate the IU received signal power from the distance between the involved elements (the hidden node problem).

High sensitivity requirements on the single OU sensor device are assumed to tackle the challenges of sensing. To alleviate these requirements while still maintaining a high detection probability, cooperative/distributed sensing schemes can be adopted. There, multiple sensing devices work together to achieve a high level of confidence in the detection of IU.

Building on the work developed in WP3 where novel collaborative/distributed sensing algorithms are being investigated and evaluated via computer simulations, the aim of this demonstration is to proof the worthiness of the developed algorithms in scenarios as close to reality as possible.

The scenario of collaborative/distributed sensing is generically depicted in Figure 3-20.

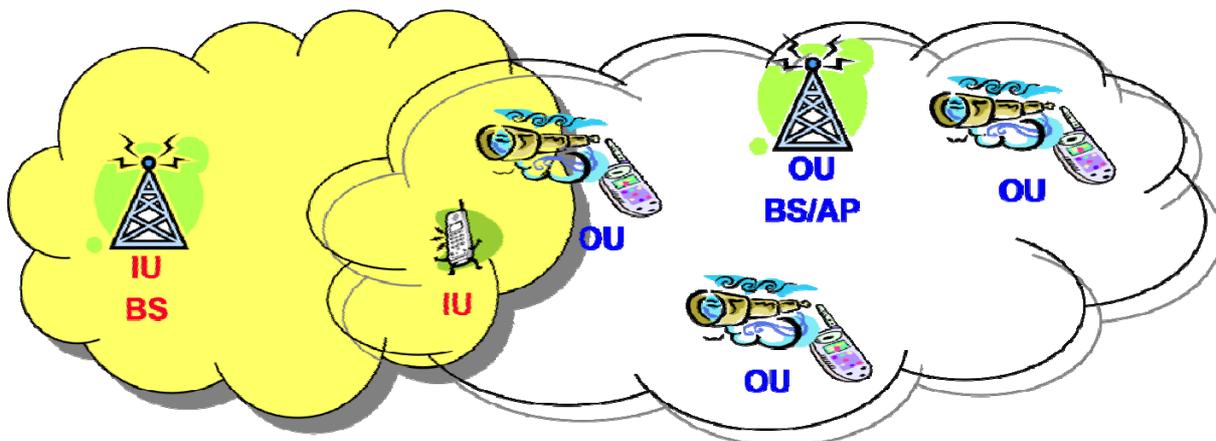


Figure 3-20: Collaborative/distributed sensing scenario

All in all, the PoC will prove the benefit of the distributed sensing algorithms developed under the scope of WP3 when using a mesh of sensor nodes.

3.3.2 Requirements

The requirements for this PoC are:

- The individual hardware sensors should mimic the sensing behaviour of the hardware to be used by opportunistic applications.
- The performance of hardware sensors must be fully characterized.
- The software sensors should mimic the hardware sensors by modelling their behaviour.
- The sensors communicate the local decision to the data fusion unit using an available communication interface.
- The PoC will prove the benefit of the distributed sensing algorithms developed under the scope of WP3 when using a homogeneous mesh of sensor nodes.

3.3.3 Building Blocks

Up to four distinct building blocks participate in this PoC test. First, the hardware sensor, in charge of performing an RF sensing and applying a local decision algorithm, as well as sending the final decision to the fusion unit.

Then, the software sensor, which scope includes mimicking HW sensor behaviour to achieve a large number of sensing nodes, generating local decisions on the presence of signals using the same algorithm as the HW sensor, and also sending the decision to the fusion unit.

This Fusion Unit itself shall receive local decisions from both the HW and SW sensors and process them to generate a global decision on the presence of signals.

And finally, a Scene Emulator is needed in order to carry out the development of a deterministic based primary engine.

The collaborative/distributed sensing PoC under development emulates a network of OU devices with sensing capabilities geographically scattered. The set-up consists of (see Figure 3-21):

- A mesh of sensing devices (OU)
- A data fusion unit (OU BS or AP)
- IU signal emulator

To simulate a mesh of sensing devices, two types of devices will be used: hardware and emulated. The hardware sensing devices will be implemented using a PC running GNU Radio Software-Defined Radio platform connected to a baseband processing board Universal Software Radio Peripheral (USRP1 or USRP2) equipped with either an Ettus RFX2400 daughterboard or an Ettus WBX Transceiver daughterboard. The emulated sensing devices will be implemented in a high level programming language. The model/behaviour of the emulated sensing devices will be extracted from the analysis of the hardware sensing devices. Its number is only limited by the number and processing power of the used PC's.

The data fusion unit emulates the decision block present on the BS/AP or a master OU (depending on the considered scenario [D2.1]) and is responsible for the generation of the decision on the presence of an IU. This unit gathers the sensing data (raw or processed) from the sensing devices. The sensing data can be processed locally at the sensing devices to generate a local decision, hard or soft, depending on the considered collaborative sensing algorithm. The data fusion unit is implemented in a PC with the required communication interfaces that connect it to all sensing devices. The distributed/collaborative sensing algorithms will be implemented in a high level programming language. The fusion unit is

responsible for the coarse synchronization of the sensing to replicate a real scenario where the OUs are geographically scattered, possibly not in transmission mode and are not required to be fully synchronized to an existing network clock to participate in a collaborative/distributed sensing architecture. The event of sensing can be simply triggered by the arrival of a predefined signalling message.

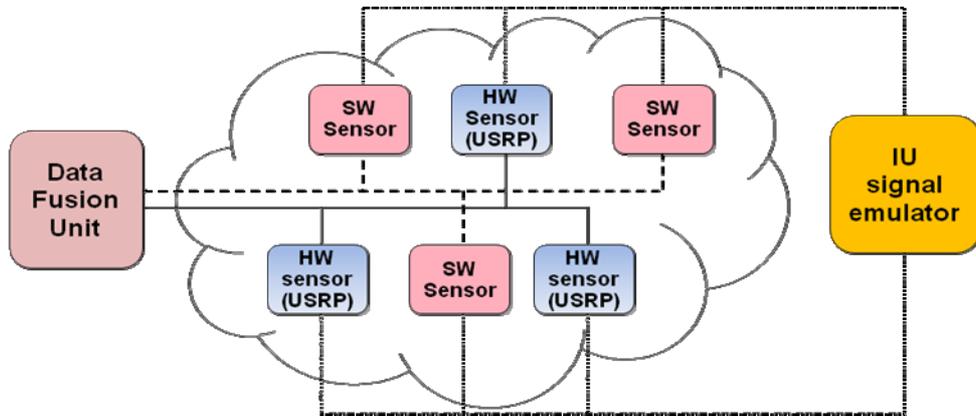


Figure 3-21: Architecture of distributed sensing

The IU signal emulator generates the signal that each sensing device should receive according to the IU service to be detected and the considered channel model. This proof of concept will focus on the detection of DVB-T signals. The IU signal emulator will be implemented by a PC-controlled waveform generator and an RF transmitter.

The sensors are implemented with a PC running GNU Radio and a combination of hardware present in Figure 3-22, resulting in the sensors that can be viewed in Table 7.

Table 7: Used sensors

USRP1+RFX2400	USRP2+RFX2400	USRP1+WBX	USRP2+WBX
---------------	---------------	-----------	-----------

The hardware used for sensing in this PoC will be the USRP and/or USRP2. These can be fitted with either the RFX2400 daughterboard, which is a transceiver from 2.3 GHz up to 2.9 GHz, or the WBX daughterboard, which is a transceiver from 50 MHz up to 2.2 GHz.

The USRP and USRP2 devices can interface with software defined radio environments through a USB 2.0 and Gigabit Ethernet connection respectively. The SDR environments available include GNU Radio, LabVIEW and MATLAB/Simulink.

The USRP2 is designed as an upgrade from USRP, having a larger FPGA and faster ADCs and DACs. However, the relative performances of the devices, for use as sensors, are comparable.

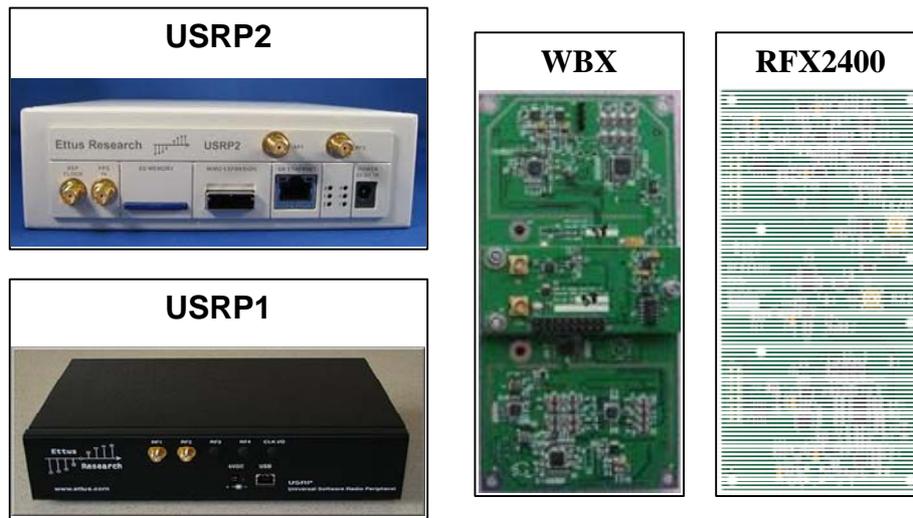


Figure 3-22: Sensors' hardware

3.3.3.1 Algorithm of the energy sensor

In this chapter, the algorithm implemented in the individual energy sensors is described. The sensor procedure can be divided into the following components, as seen in Figure 3-23.

- Power calibration
- Noise estimation and stabilization
- Probability of false alarm and detection

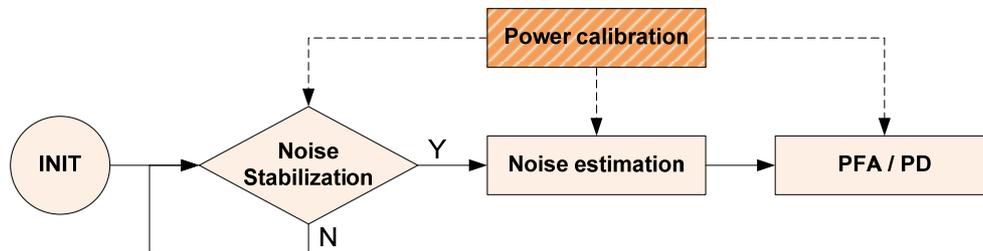


Figure 3-23: Sensor procedure

3.3.3.1.1 Power calibration

The signal arriving to the sensor is processed by the RF and BB block to generate the complex baseband samples that arrive at GNU Radio. Since the amplitude levels of the samples taken may vary between different RF and BB hardware, there is a need to calibrate the sensor for different setups used.

This calibration ensures that the power values measured by the sensor are the actual values that are present at the sensor input, the Figure 3-24 show the different blocks in the first stage of the energy sensor.

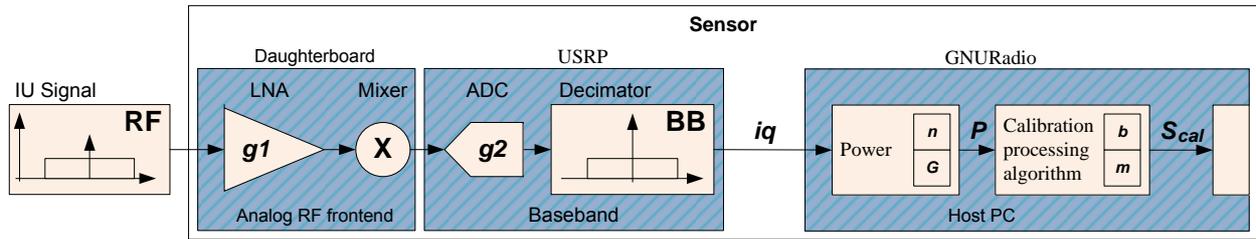


Figure 3-24: Power calibration architecture

The algorithm of the energy sensor consists in a first phase in a sensor RX power calibration procedure. This step is made in GNU Radio and consists in a linear relationship between the input signal power and power measured by the sensor hardware.

The input of the GNU Radio, iq , can be expressed as

$$iq = g_1 \cdot g_2 \cdot (iq_{IU} + iq_n), \quad (1)$$

where $g = g_1 \cdot g_2$ is the sensor gain (RF and BB), iq_{IU} represents the complex IU input signal and iq_n is the noise. The power of the IU input signal is

$$S_{IU} = E\{|iq_{IU}|^2\} \quad (2)$$

The input to the calibration processing algorithm in GNU Radio block is the raw measurements of signal power, P

$$P(iq) = 10 \log_{10} \frac{\sum_n |iq|^2}{n} - G = 10 \log_{10} \frac{\sum_n |iq_{IU} + iq_n|^2}{n} \quad (3)$$

where n is the number of samples and $G = 10 \log_{10}(g_1 \cdot g_2)$ the sensor gain (RF and baseband) is subtracted to remove the effect of the gain of the previous stages.

The output of the calibration process is the calibrated signal power, $S_{cal}(IU)$

$$S_{cal}(IU) = \frac{P-b}{m} \quad (4)$$

$S_{cal}(IU) = \frac{P-b}{m}$ where b is the calibration offset and m is the calibration gain (the values of b and m are obtained in the calibration process of the sensor).

Since the signals S_{IU} and N are uncorrelated,

$$E\{|S_{IU} + N|^2\} = E\{|S_{IU}|^2\} + E\{|N|^2\} \quad (5)$$

the output of this block can be expressed as

$$S_{cal}(IU) \cong S_{IU} + N \quad (6)$$

where N is the noise.

3.3.3.1.2 Noise estimation and stabilization

The second procedure of the sensor consists in repeatedly measuring the noise level until its value has stabilized (to a certain threshold) and after that get a more accurate estimate of the noise floor. The procedure is depicted in Figure 3-25.

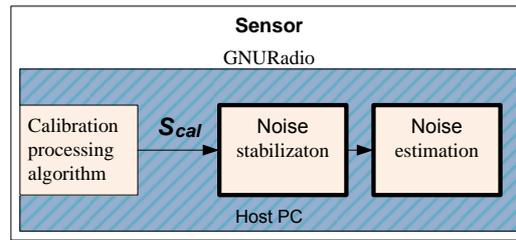


Figure 3-25: Noise estimation and stabilization architecture

During the various tests carried out, the noise level variation over time was noticed. This variation is significant at the beginning of operation of the system as seen in Figure 3-26 for one of the hardware sensors (USRP1+RFX 2400 daughterboard). The blue line shows the values of the noise level estimates (each estimate used 2^{20} samples). The light cyan line at top shows the maximum (and initial) value of the estimated noise level. The light red line at bottom is the average of all estimates. As can be seen, it takes a considerable number of samples for the system noise level to stabilize.

For the sensing results not to be affected by this noise level fluctuation, this noise stabilization procedure is required. The noise stabilization process must somehow detect when the noise level is stable to afterwards proceed to the next and crucial step of measuring the noise power.

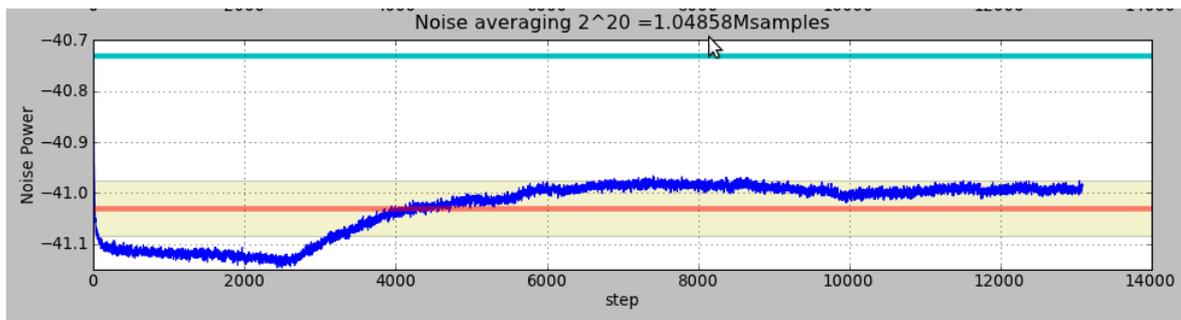


Figure 3-26: Evolution of the noise power

The noise stabilization process consists in gathering a certain number of samples and generating a noise level estimate, by making a weighted average of the gathered samples with the previous ones. Figure 3-27 illustrates how this process is done.

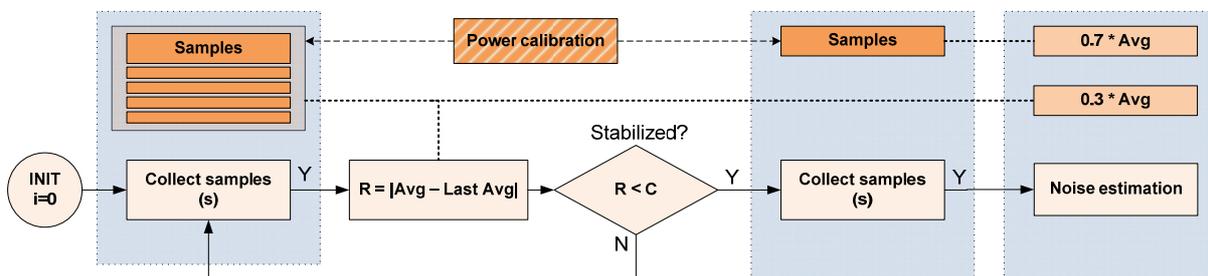


Figure 3-27: Noise estimation algorithm

The system is stable when the average noise level stops moving, *i.e.* $R \cong 0$. This is not a realistic condition and the adopted one is $R < C$, where C is the value for considering that the system is stable. During the noise stabilization the averaging is done using all captured samples. The update is made after s samples,

$$\begin{cases} \alpha = \frac{\sum_t S_{cal}}{t} \\ t = t + s \end{cases} \quad (7)$$

where t is total number of samples, s is the number of collected samples ($s \gg 1$) and α is the average of all captured samples.

When the system is stable, $R \ll C$, the noise power estimation is

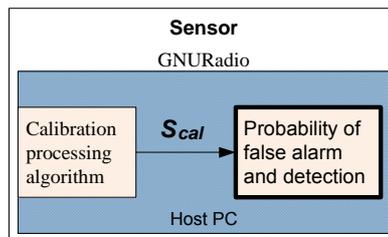
$$\begin{cases} N_g = 0.3 * \alpha + 0.7 * n \\ n = \frac{\sum_s S_{cal}}{s} \end{cases} \quad (8)$$

where N_g is the noise power estimation and n is the average noise power when the system is stable.

The estimated noise power value will be used as a reference for all the tests, especially to define the detection threshold levels. When emulating the IU signal, this noise power estimate is also important to define the signal level inputted to the sensor.

3.3.3.1.3 Probability of false alarm and detection

This block will perform the characterization of the individual sensors made the probability of false



alarm and detection of the several sensing devices. The procedure can be viewed in Figure 3-28.

Figure 3-28: Probability of false alarm and detection architecture

Samples S_{cal} coming in this block are the average of n samples of the signal power measured at the input S_{IU} plus internal noise. Detection occurs when S_{cal} is above the defined threshold. The probability is the ratio between the number of detections and the total number of events (checked samples S_{cal}).

This test is done for a range of thresholds, t_i , and samples, n_i , previously defined. The range of thresholds, t_i , is defined relatively to the estimated noise level N_g .

$$\begin{cases} t_i = \{t_0, t_1, \dots, t_n\} + N_g \\ n_i = \{n_0, n_1, \dots, n_n\} \end{cases} \quad (9)$$

where t_n is the relative threshold (to N_g) and , t_i is the corresponding absolute threshold level. n_i belongs to a defined sample lengths set.

The result of the test is the probability, $p(t_i, n_i)$. If an IU signal is present at the input, this is the detection probability, otherwise is the false alarm probability.

$$p(t_i, n_i) = \frac{d}{e} \quad (10)$$

where d is the number of detections and e is the total number of performed detection tests. The following Figure 3-29 shows the algorithm to find the probability.

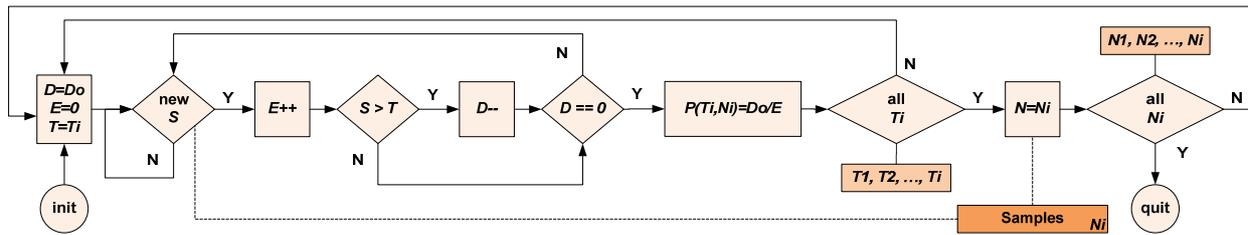


Figure 3-29: Probability of false alarm and detection algorithm

3.3.4 Interaction among blocks

The interfaces used by the block to share the information are:

- Data fusion sends sensing configuration parameters to sensors over Ethernet or Wi-Fi interface.
- Central frequency, number of samples, sample interval, sample rate, BW, gain and threshold/Pfa/Pd.
- Individual sensor configures sensing according to received parameters from data fusion.
- Individual sensor performs local sensing.
- Individual sensor performs local hard or soft decision.
- Individual sensor sends decision to data fusion over Ethernet or Wi-Fi interface.
- Data fusion makes final decision on the presence of IU with information collected from the different sensors.

3.3.5 Novelties demonstrated

The setup built in this PoC will allow the testing of several distributed sensing scenarios and algorithms, with emphasis on the analysis of the performance of distributed sensing with homogeneous and heterogeneous sensor nodes.

This PoC will show the benefit of the distributed sensing algorithms developed under the scope of WP3 when using a homogeneous mesh of sensor nodes and will study the impact of having a heterogeneous mesh of sensor nodes in the performance of the distributed sensing algorithms.

3.3.6 Integration Plan

Different activities have been considered with the intention of assuring a correct interaction among all the modules and thus developing a valid test. These diverse activities are as follow.

3.3.6.1 Hardware characterization

This activity aims at setting the power value of the noise floor and establishing a calibrated range of neighbouring power values where the sensing tests will be performed to determine the probability of false alarm and probability of detection. To achieve the lowest possible noise floor, the sensor gain is the set to its maximum value.

3.3.6.1.1 Calibration setup

The calibration setup is depicted in Figure 3-30.

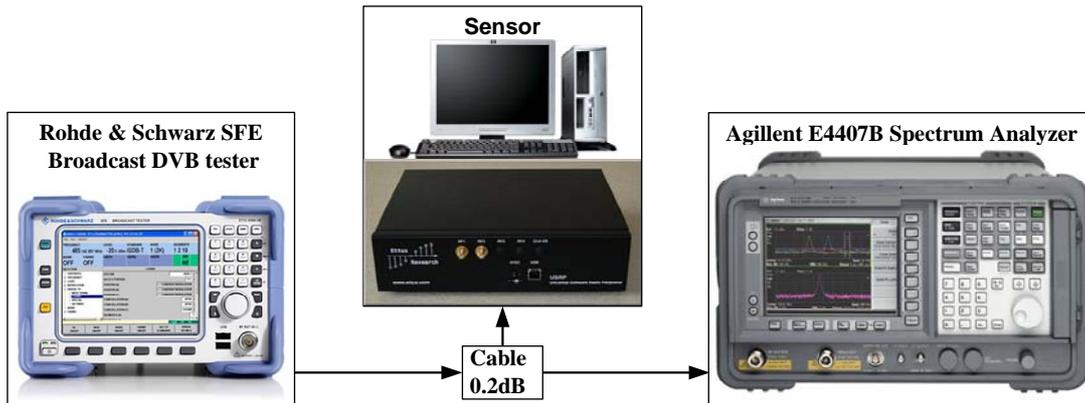


Figure 3-30: Calibration setup

The incumbent user signal was generated using a Rohde & Schwarz SFE Broadcast DVB emitter.

To calibrate the transmitted power, an Agilent E4407B Spectrum Analyzer was used. The transmitted power was measured using the channel power measure of this device.

3.3.6.1.2 Measurements

This process consists of an initial raw measure of the noise floor and the building of a table with the received power, S_{IU} , and raw measured power, S_{meas} with $b = 0$ and $m = 1$.

$$SN_{meas}(IU) = \begin{cases} S_{cal}(IU) = \frac{P - b}{m} = P \\ m = 1, b = 0 \end{cases} \quad (11)$$

The raw measure, SN_{meas} , is acquired with $b = 0$ and $m = 1$

$$SN_{meas}(IU) = 10 + \log_{10} \frac{\sum_n |iq_{IU} + iq_n|^2}{n} \quad (12)$$

The initial raw measure of the noise floor, N_{0meas} , was performed with the sensor RF input terminated with a ground connector, $S_{IU} = 0$, and the value measured by the GNU RADIO processing blocks.

$$N_{0meas} = 10 + \log_{10} \frac{\sum_n |iq_n|^2}{n} \quad (13)$$

The building of the table was done by inputting an IU signal in the range of the initial raw noise floor and measuring the values coming out of GNU RADIO processing blocks, SN_{meas} .

After acquiring the measured power values, the noise power is removed from the raw measured signal and the signal power can be expressed as:

$$S_{meas} = 10 * \log_{10} \left(10^{\frac{SN_{meas}}{10}} - 10^{\frac{N_{0meas}}{10}} \right) \quad (14)$$

Finally a linear approximation of the curve of the signal power in the region of operation where the tests will be performed, that is, in the neighbourhood of noise floor is obtained. This approach is done using the minimum mean square error and gives the values of m and b used in calibration processing algorithm.

The received IU signal power can be expressed as

$$S_{IU} = m * S_{meas} + b \quad (15)$$

where b is the calibration offset and m is the calibration gain.

The noise floor of the sensor can be expressed as

$$N_0 = \frac{N_{\text{sensor}} - b}{m} \tag{16}$$

and the sensor calibrated output signal power is:

$$S_{\text{cal}}(IU) = \frac{P - b}{m} \cong 10 \times \log_{10}(S_{IU} + N_0) \tag{17}$$

3.3.6.1.3 Hardware assessment

The sensors' assessment intends to characterize and determine a linear working area close to the noise floor. This assessment will provide the values of m and b that make the sensor's response close to linear.

The parameters used in calibration tests and the results are as follows (see Table 8):

Table 8: Relevant sensors calibration parameters

IU Signal	Sensor	Results
B_{IU} = bandwidth F_{IU} = frequency	B_{sensor} = bandwidth F_{sensor} = frequency G_{sensor} = gain	b = calibration offset m = calibration gain N_0 = noise floor

USRP1 + RFX2400 Sensor

The relevant test parameters and results are shown in Table 9.

Table 9: Calibration USRP1 + RFX2400

Parameters		Results
IU Signal	Sensor	
$B_{IU} = 6.656 \text{ MHz}$ $F_{IU} = 2,432 \text{ GHz}$	$B_{\text{sensor}} = 8 \text{ MHz}$ $F_{\text{sensor}} = 2,432 \text{ GHz}$ $G_{\text{sensor}} = 90 \text{ dB}$	$\left\{ \begin{array}{l} b = -46,322 \\ m = 0,99281 \\ N_0 = -68,893 \text{ dBm} \end{array} \right.$

The results of measurements can be seen in Figure 3-31.

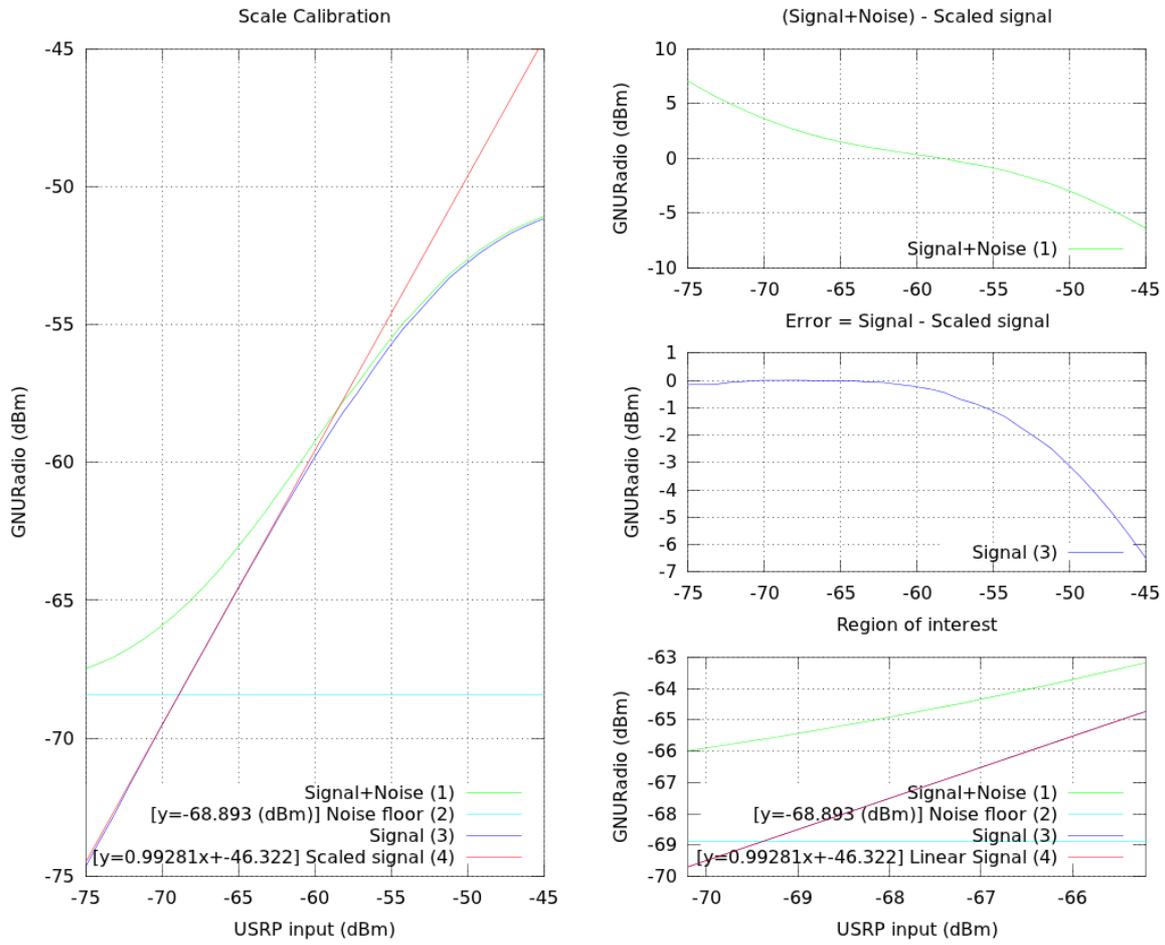


Figure 3-31: Calibration USRP1 + RFX2400

USRP2 + RFX2400 Sensor

The relevant test parameters and results are shown in Table 10.

Table 10: Calibration USRP2 + RFX2400

Parameters		Results
IU Signal	Sensor	
$B_{IU} = 6.656 \text{ MHz}$ $F_{IU} = 2.45 \text{ GHz}$	$B_{sensor} = \frac{25}{3} \text{ MHz}$ $F_{sensor} = 2.45 \text{ GHz}$ $G_{sensor} = 69.902 \text{ dB}$	$b = -38.91$ $m = 1.0194$ $N_0 = -70.608 \text{ dBm}$

The results of measurements can be seen in Figure 3-32.

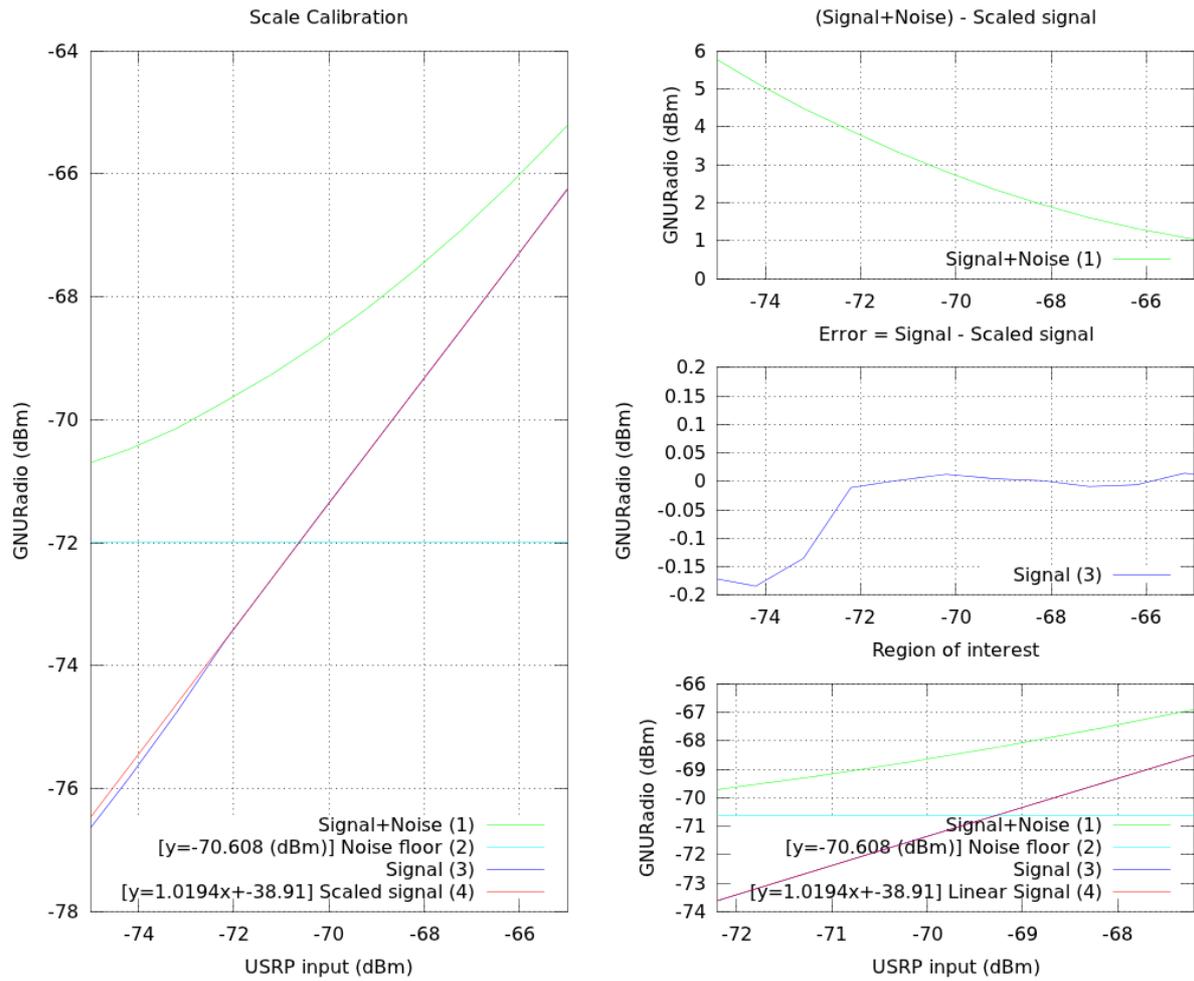


Figure 3-32: Calibration USRP2 + RFX2400

USRP1 + WBX Sensor

The relevant test parameters and results are shown in Table 11.

Table 11: Calibration USRP1 + WBX

Parameters		Results
IU Signal	Sensor	
$B_{IU} = 6.656 \text{ MHz}$ $F_{IU} = 800 \text{ MHz}$	$B_{sensor} = 8 \text{ MHz}$ $F_{sensor} = 800 \text{ MHz}$ $G_{sensor} = 51.5 \text{ dB}$	$\left\{ \begin{array}{l} b = -86,842 \\ m = 1,0047 \\ N_0 = -33,989 \text{ dBm} \end{array} \right.$

The results of measurements can be seen in Figure 3-33.

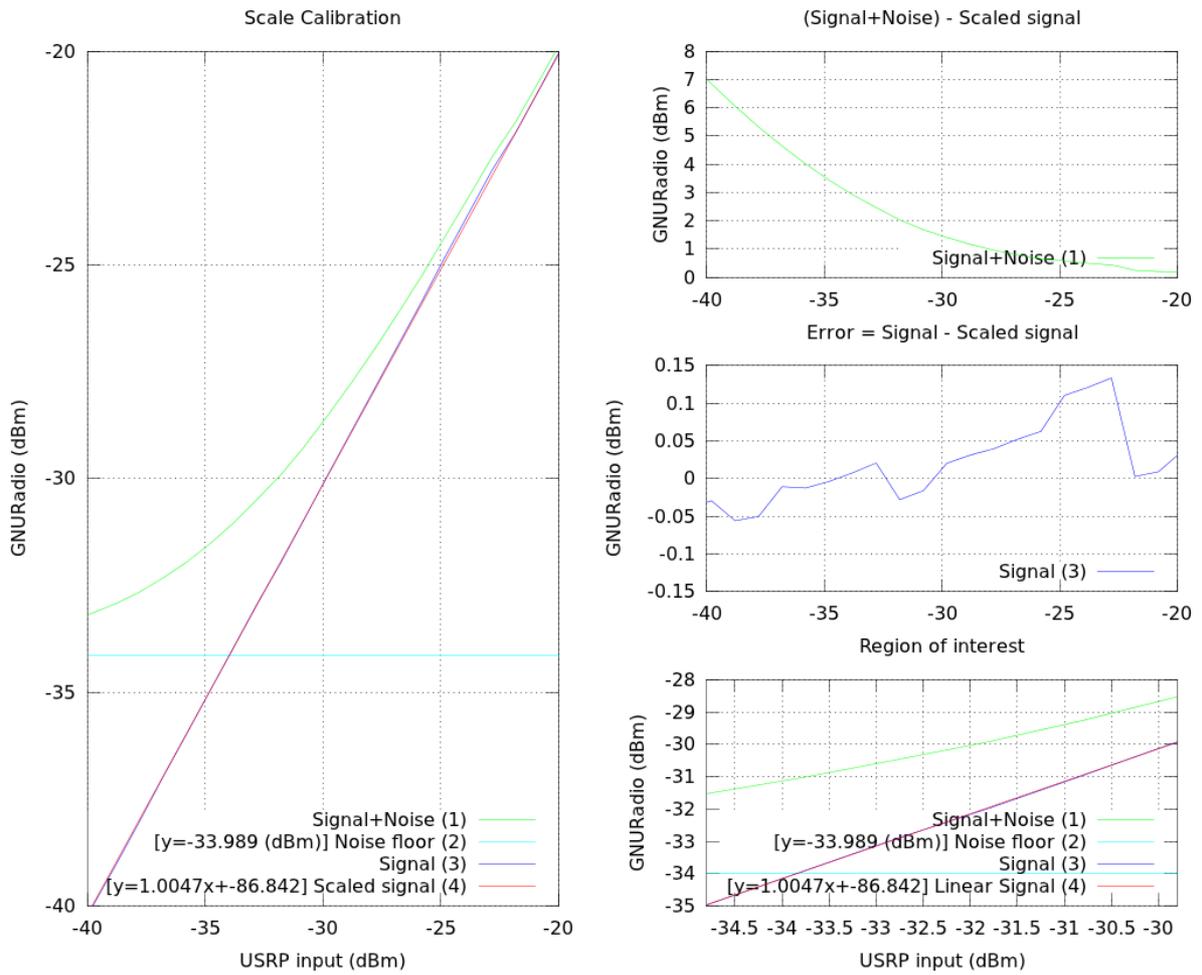


Figure 3-33: Calibration USRP1 + WBX

USRP2 + WBX Sensor

The relevant test parameters and results are shown in Table 12.

Table 12: Calibration USRP2 + WBX

Parameters		Results
IU Signal	Sensor	$\left\{ \begin{array}{l} b = -84,089 \\ m = 1,0346 \\ N_0 = -32,945 \text{ dBm} \end{array} \right.$
$B_{IU} = 6.656 \text{ MHz}$ $F_{IU} = 800 \text{ MHz}$	$B_{\text{sensor}} = \frac{25}{3} \text{ MHz}$ $F_{\text{sensor}} = 800 \text{ MHz}$ $G_{\text{sensor}} = 31.5 \text{ dB}$	

The results of measurements can be seen in Figure 3-34.

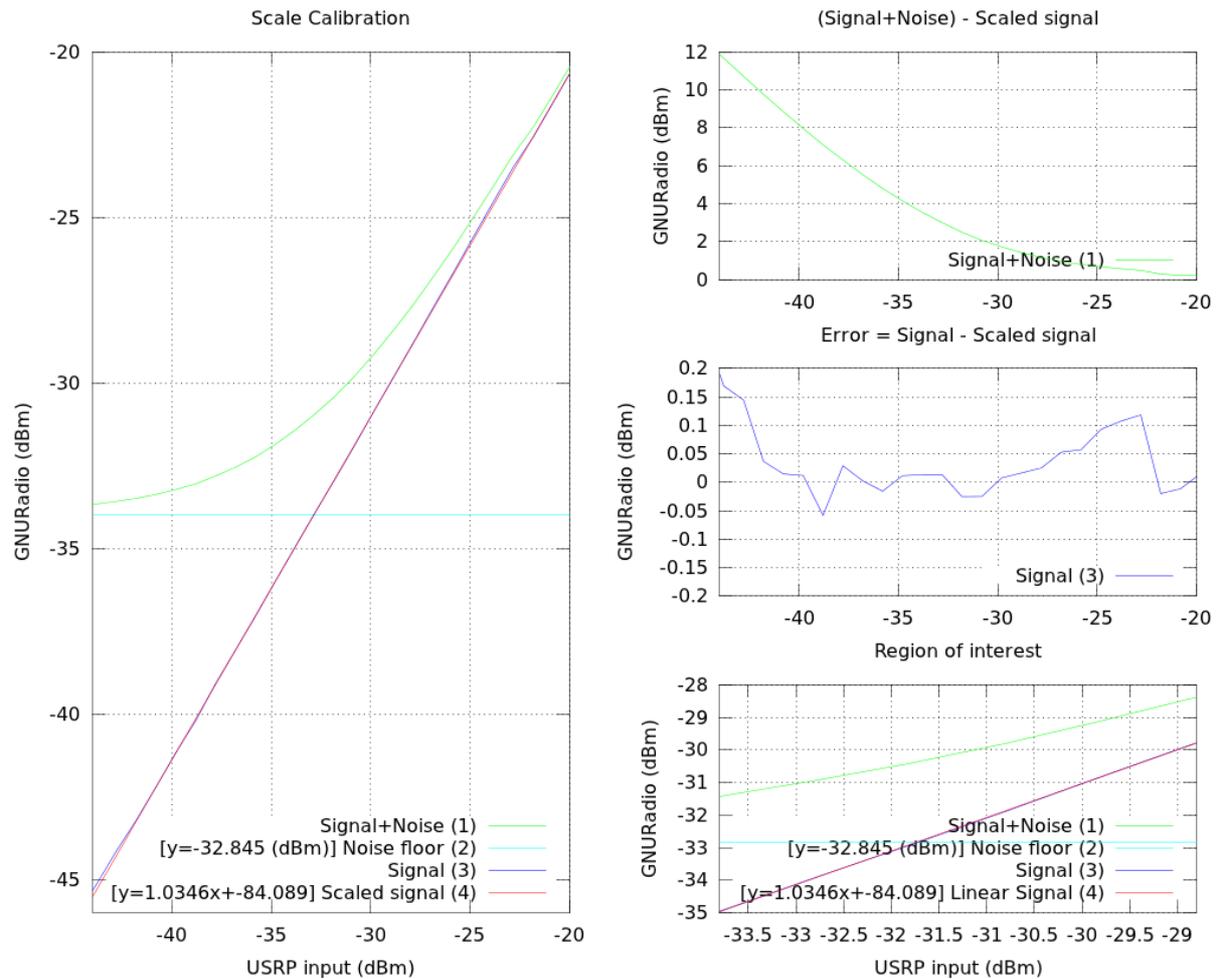


Figure 3-34: Calibration USRP2 + WBX

3.3.6.2 Energy sensors

In this PoC, four different hardware sensors, as previously seen in section 3.3.6.1.3, are implemented to assess the performance of the distributed sensing. The individual hardware performance was presented in the previous section. In this step the energy algorithm presented in section 3.3.3.1 has been implemented in the several hardware versions and assessed its performance. To assess the performance of the sensors the probability of false alarm and the probability of detection have been used.

The results of the performance assessment are presented in sections 4.3.1 through 4.3.4.

3.3.6.3 Initial distributed sensing

This setup is under development and consists in connecting several sensors locally to the fusion unit and generating a distributed decision on the presence of IU based on a simple logic OR of the individual sensors decision.

3.3.6.4 Evolved hardware sensor

The interaction with WP3 will lead to the definition of the radio context acquisition scenario.

The evolved hardware sensor will implement the local component of the radio context acquisition scenario.

The development of these sensors has not yet started.

3.3.6.5 Distributed Radio Context Acquisition

This is the final step in this PoC. An evolved version of the data fusion unit will implement the central component of the distributed radio context acquisition, coordinating the sensing performed by geographically scattered sensors, gathering its local decisions and generating the final decision on the presence of IU. The algorithms to be implemented are at time of writing under development in WP3, and therefore the derived results will be presented in following reports.

3.4 Proof of Concept #4: Integrated platform

3.4.1 Motivation

The integrated QoS MOS Proof of Concept can be seen as a long term labour where certain steps have to be made before building the complete solution. Thus, as a first step, a validation of certain CR concepts developed for link and upper layers has to be carried out. Among them, aspects as spectrum management, decision making and Adaptation Layer functionalities can be found.

The main goal is to illustrate a scenario that provides some relevance to QoS MOS, integrating some of the developments achieved in the previous PoCs and showcasing to some extent a real cognitive system. Specifically, the targeted scenario will involve a TVWS environment, where a cellular legacy system and a TVWS opportunistic system are combined.

The Cognitive Manager for Resource Management (CM-RM) is made of several functionalities targeting access control, resource allocation, mobility control, resource use, and environment cognition. As part of this prototype, some of the CM-RM functionalities will be demonstrated as well as the interaction of these CM-RM functionalities with the Cognitive Manager for Spectrum Management (CM-SM) functionalities. Namely, the CM-RM functions which will be demonstrated with this prototype are those related to the access control, which can be split into two functions: the admission control and the eviction control.

Besides, the CM-SM is a distributed entity mainly implemented throughout the core network, potentially including agents located at the base stations (BSs) and user equipments (UEs). For demonstrator purposes two distinct instances of the CM-SM will be considered, one collocated to the base station and one in the network representing the completeness of CM-SM entities that can be reached through an operator's core network. The main purpose of the base station instance of the CM-SM is interfacing with a collocated CM-RM entity. Thus, the demonstration will verify cognitive spectrum manager concepts by validating:

- The communication between a CM-RM and CM-SM instance.
- The communication between two CM-SM instances.
- The general interaction of a CM-SM with a distributed portfolio repository.

Some of the procedures likely to be tested will include:

- Creation, modification, deployment and revocation of a spectrum portfolio.
- Dedicated modification of a portfolio regarding back-up/reserve channel handling requirements.

Within the framework of the development of the reference model of QoS MOS architecture, it has been identified the need to offer an Adaptation Layer entity to cope with the following functionalities:

- Being able to abstract different technology-dependent functional blocks from the Resource (CM-RM) and Spectrum (CM-SM) Management entities. This gives to the QoS MOS framework the possibility to support multi-RAT interfaces offering a unified interface to these entities.

- Acting as a data dispatcher, the AL not only offers a way to abstract different physical interfaces, but it also will allow the communication between remote entities. All these actions are carried out while keeping the same unique interface for both local and over the network communications.

Therefore, on one hand it will be interesting to check the concept of the AL in a test bed, as an independent entity or functional block. Then, it should be integrated as part of the CM-RM and CM-SM proof-of-concept and it shall be a fundamental part in remote communications between CM-RMs and CM-SMs.

After this first “milestone” is validated, an integrated architecture will be created attempting to bring together the components from all other categories in order to showcase a live cognitive radio system. The main components involved are the primary scene emulator, local and distributed sensors with the associated data fusion unit, the upper layer CM-SM and CM-RM and the AL unit, and finally one or more secondary transceiver units. The “distributed smart entity” defined and simulated in WP5 will be part of this combined demo and its different software functionalities (networking mechanisms and algorithms) will also be tested.

Thus, the final demonstration will consist of different units and entities, roughly illustrated in Figure 3-35, where an opportunistic UE does handovers between TVWS bands, and/or between TVWS and licensed cellular system, demonstrating along the way a lot of capabilities of the QoS MOS system and showing up their relevancy. The demonstration will be composed of:

- A primary scene emulator to generate primary users signals.
- A Cellular network, deployed with two base stations:
 - Cell 1 using the flexible transceiver, operating in TVWS band.
 - Cell 2 (Femtocell) operating in licensed band.
- A Cognitive user equipment composed of a Smartphone and additional physical layer provided by the flexible transceiver for white space operation.

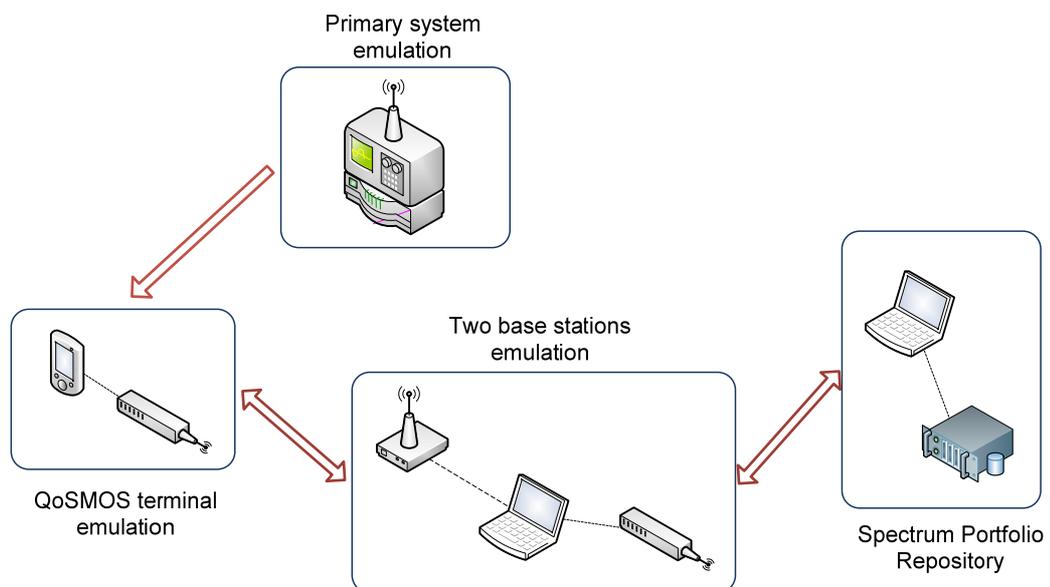


Figure 3-35: PoC #4 architecture overview

In the course of the execution of this PoC, various entities and functionalities coming from distinct work packages will be showcased, as the emulation of incumbent activity (WP2), the development of

a detection framework which includes sensing and/or geolocation capabilities (WP3), the employment of a flexible PHY, that can be visualized on a spectrum analyzer (WP4), the exhibition of certain CM-RM functionalities and Message Sequence Charts (MSCs) (WP2/WP5) and the execution of some activities regarding portfolio monitoring and CM-SM duties (WP6).

Through this demonstration, the main principles which will be demonstrated are the incumbent user protection thanks to eviction decisions. Indeed, the trigger for the eviction will be either an update of the spectrum portfolio coming from the CM-SM or the detection of incumbent users by the sensing engine embedded in the cognitive user equipment. This portfolio update or the sensing report will show that an incumbent user has appeared in the operating band, forcing the BS to reduce its bandwidth and manage the eviction of users. Two eviction decisions will be shown:

- The first case (Case 1 in Figure 3-36) will consist in instructing the UE to handover to another TV channel
- The second case (Case 2 in Figure 3-36) will consist in instructing the MT to handover to another RAT (licensed band). This happens when there is not enough spectrum to fulfil all the needs of the users and when no other white space is available.

The scenario for demonstrating is shown in the following Figure 3-36.

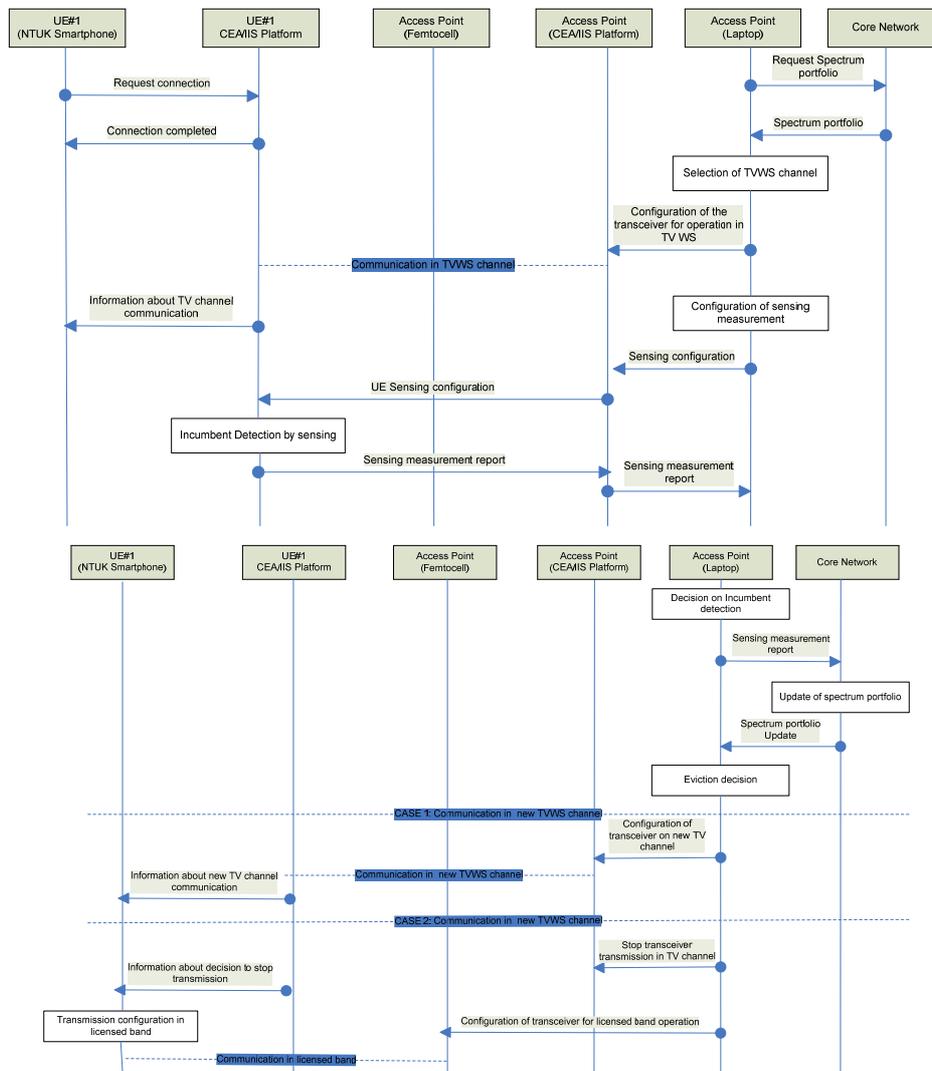


Figure 3-36: Scenario for demonstration in PoC #4

3.4.2 Requirements

The special condition of these PoC, where an integrated demonstration is expected, requires the tight collaboration among partners and the harmonious assembly of many of their isolated developments, in order to shape together a valid test.

Thus, a quite concrete and detailed definition of interfaces is mandatory, since the different blocks involved must be able to communicate through them. In addition, it is highly recommended to provide a common hardware platform that makes possible the mutual interaction of the diverse components.

In order to make the common hardware platform consistent, a first set of requirements have been detailed:

- UE (Flexible transceiver + Smartphone) related requirements
 - UE shall have the capability of spectrum sensing measurements to detect the incumbent system in operational TV channels.
 - UE shall send sensing report to Access Point.
 - UE may display operational channel and sensing result.
 - UE may initiate application service.
- Access Point (Femtocell + Flexible transceiver + Laptop) related requirements
 - Access point shall send query of spectrum portfolio providing access point location.
 - Access point shall select TV channel based on spectrum portfolio information.
 - Access point shall analyze the sensing measurement reports from deployed UEs and shall decide about primary detection.
 - Access point shall take eviction decisions based on sensing decision.
 - Access point may display operational channel (TVWS or licensed) and sensing result.
- Core Network related requirements
 - Core network shall provide the spectrum portfolios to provide accurate TV channel availability.
- Spectrum Database related requirements
 - Spectrum Database shall maintain the TV spectrum information.
- Incumbent system
 - Incumbent system shall generate PMSE (FM and QPSK) and DVB-T signals.
 - Incumbent system shall display incumbent signals.

3.4.3 Building Blocks

Several QoS MOS architecture blocks are involved in the development of this integrated PoC. The mission of PoC #4 consists in acquiring and integrating the results obtained in the three previous PoCs with some new and specific developments, giving form to a complete and valid test setup able to provide an overall view of the work carried out within QoS MOS project. The Figure 3-37 below depicts QoS MOS architecture blocks which are involved in this integrated PoC.

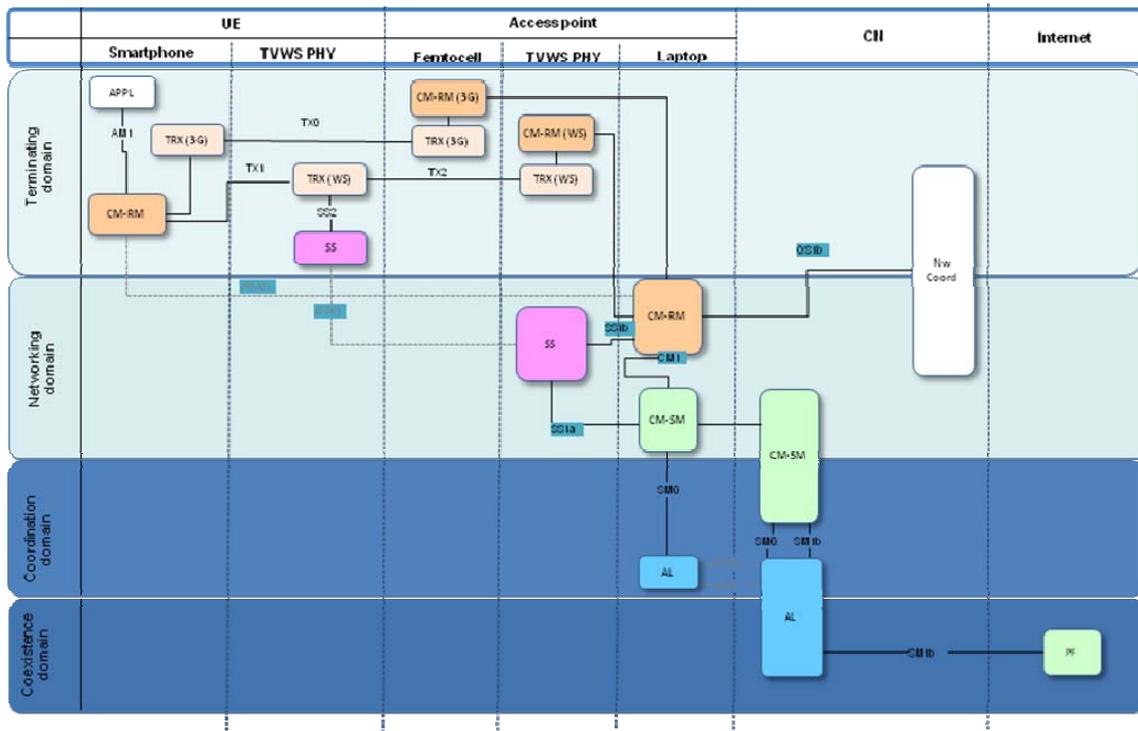


Figure 3-37: PoC#4 architecture

There are various blocks that compose the CM-RM. Specifically, the CM-RM AC (Access Control), CM-RM RA (Resource Allocation), CM-RM NC (Networking Cognition) and CM-RM RS (Resource Control Support), will be implemented in order to demonstrate admission and eviction control functionalities. These internal blocks are fully described in Deliverable 5.2 [D5.2].

The following Figure 3-38 proposes a mapping of the eviction and admission control functionalities onto the QoS MOS CM-RM internal architecture. However, only a selected set of them will be chosen and implemented in this PoC

On the other hand, it will be necessary to develop a valid Adaptation Layer implementation, in charge of dispatching messages received from the different QoS MOS entities it is connected to. This data will be converted to a common format and delivered in each case to the proper entities.

Given the special characteristics of this PoC, it has been decided to distribute the building blocks it comprises into four different sections, taking into consideration the diverse architecture points the integrated test involves.

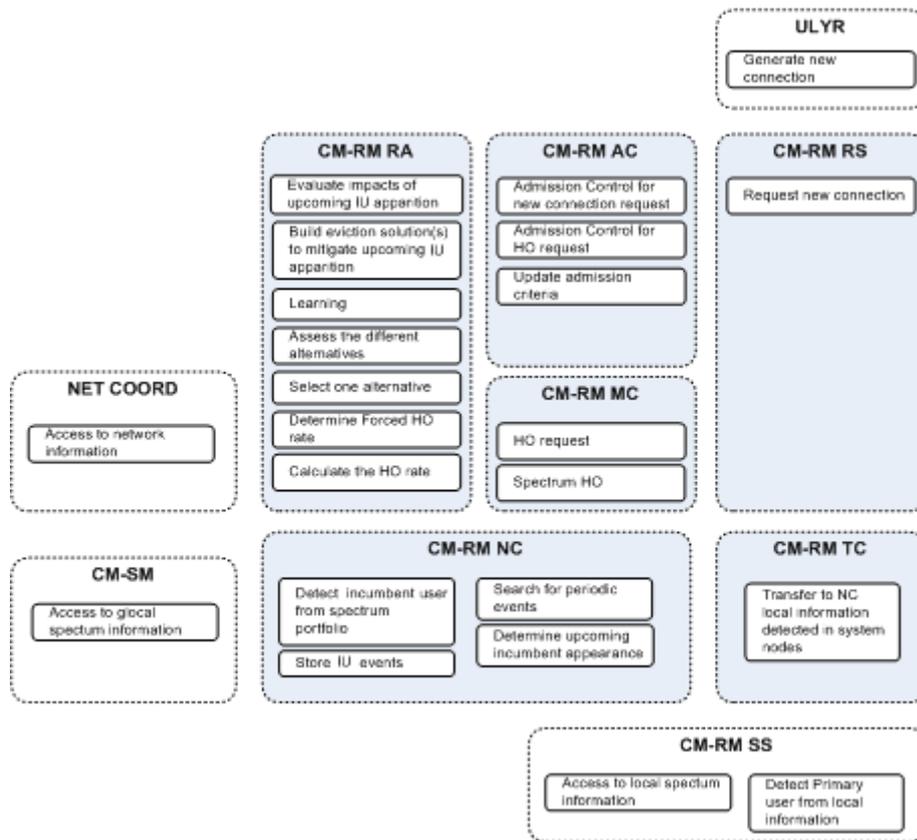


Figure 3-38: Cognitive admission control in QoS MOS context

3.4.3.1 User equipment

3.4.3.1.1 Application/CM-RM

CM-RM at the terminating domain will include the following functionalities:

- The command of transceiver configuration through resource exploitation (RE). In current context of the integrated PoC, it will configure the flexible transceiver depending on the context (TV channel operation, Switch off command)
- The command of operating sensing measurements. In terms of integrated PoC. More investigations are required to determine if sensing configuration will be dynamic in the PoC.

3.4.3.1.2 Flexible transceiver

The flexible transceiver emulation will be achieved by compound equipment made of a Smartphone and a QoS MOS transceiver board as illustrated in Figure 3-37. The QoS MOS transceiver is the same as the one developed for PoC #2 and will operate in the TVWS, while the Smartphone operates in legacy bands with a legacy air interface. Therefore, one key aspect of the QoS MOS board in PoC #4 is its interfacing ability. Because of the early design of the QoS MOS board, it was decided to adopt multiple options for future integration. These options are as follows:

- 1 USB interface High-speed OTG
- 1 Ethernet interface 10/100 Mbps
- 1 RS232 interface
- 1 WLAN 802.11 Bluetooth interface using a TiWi-R2 module

Besides the physical interface to connect the QoS MOS board with the host, the QoS MOS board also includes an ARM controller (Cortex A-8 + TMS320C64x) on which the software interfacing the PoC #2 PHY with the host will be implemented. This SW will be a simplified ‘MAC’ that will convey the packets to/from the host onto the QoS MOS PoC #2 air interface. To this end, the ARM controller interfaces the PHY FPGA through data FIFOs and control signals (including interrupts). The interfaces of the QoS MOS board that will be used in PoC #4 are detailed in the block diagram.

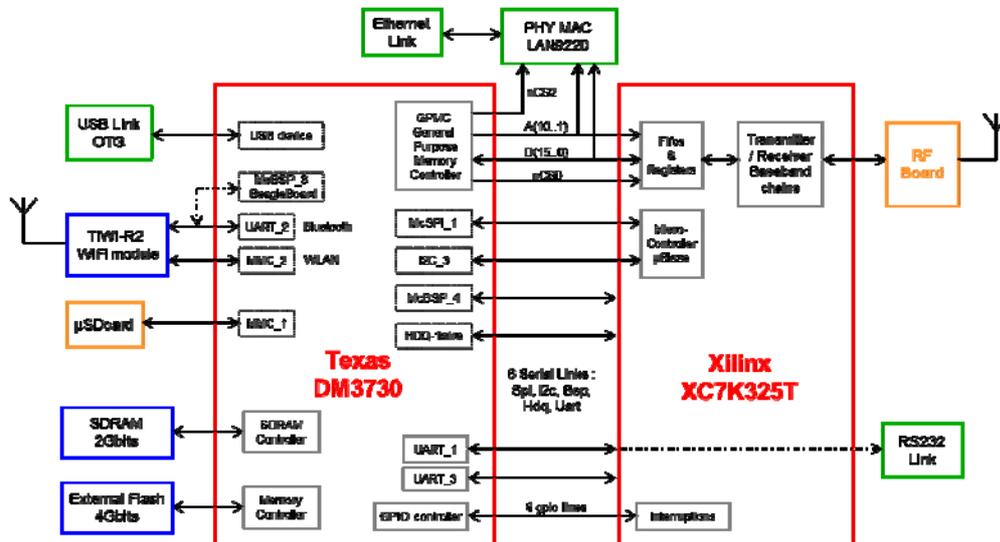


Figure 3-39: QoS MOS board ARM and Xilinx interfaces

3.4.3.2 Access Points

3.4.3.2.1 Flexible transceiver

The access point architecture is very similar to the one of the user equipment (see 3.4.3.1.2), except that the smart phone is replaced by an off-the-shelf ‘access point’.

The flexible transceiver to be used within PoC#4 includes the baseband board (cf. Sec. 3.2.3.1) and at least one RF receiver (cf. Sec. 3.2.3.2) and one RF transmitter (Sec. 3.2.3.3). It may be furthermore equipped with either one additional RF transmitter or one additional RF receiver.

Having two RF transmitters available allows providing data to two different users, possibly operating within different frequency channels. In this case, the users have to share a single back channel.

With two RF receivers, on the other hand, two different users can independently communicate with the access point via different back channels. The access may operate in a broadcast mode in this case, where at least two users share one frequency band for reception. It is also possible to establish a communication link between the access point and a user terminal while the access point can monitor the spectrum activity at the same time.

3.4.3.2.2 CM-RM (RA)

Upon primary user apparition, opportunistic system has to take protection measures to ensure it does not harm the primary user’s operation. Forcing UEs to handoff to other free TV channels or the licensed cells has been identified as a key measure for protecting primary users while maintaining connections to the network. This contributes to limit QoS degradation of served connections and to guarantee service continuity and to control Connection Dropping Rate.

This CM-RM (RA) entity has to gather the context information relative to the spectrum usage, but also to the status of the system (encompasses both eNodeBs and UEs). Associated to this event, eviction measures are considered, by identifying their impacts on the system in term of QoS. Then, the considered alternatives are assessed in order to select the most appropriate solution.

3.4.3.2.2.1 Incumbent Detection characteristic

There are two ways to identify the apparition of an incumbent:

- From SS entity in eNB that analyses the sensing measurements results from the deployed nodes,
- From CM-SM entity, which allocate a new portfolio excluding the channel where radio resources are pre-empted by the incumbent.

Once it has received the spectrum portfolio, CM-RM configures sensing measurements on both operating and reserve channels by requesting in-band and out-band sensing measurement to SS entities localized in the access point. The notification is then transferred to the local nodes through the SS0 interface, and potentially adapted for collaborative or cooperative sensing. Measurements are then done in the different connected user equipments and the results are returned to SS entity in the access point, where the analysis is performed. The analysis results are sent afterwards to CM-RM.

It is essential that SS informs CM-RM about the incumbent characteristics in order to enable the impact evaluation made by CM-RM (RA) entity. A possible set of parameters, under discussion, is the one shown in the following Table 13:

Table 13: Preliminary set of parameters CM-RM

Channel ID	uint32	dimensionless
Sensing periodicity	uint32	us
Sensing Duration	uint32	us
Sensing Results Delivery Time	uint32	us
Cell ID	uint32	dimensionless
Sensing type	uint8	WHITE_SPACE_SENS, INTERFERENCE_MON
Target PFA		%
Decision		
Spectrum sensing decisions	bool/uint8	EXIST, NON_EXIST
Probability of channel occupancy	uint8	%
Center Frequency	uint32	MHz
Bandwidth	uint8	MHz
Received power	int16	0.1 dBm
RM/SM Connection		
Multiple Sensor Information / Number of Sensors		
Sensor location absolute (elev)	int32	m
Sensor location absolute (lat)	int32	10-6 °
Sensor location absolute (long)	int32	10-6 °
Sensor location relative (elev)	int32	m
Sensor location relative (lat)	int32	10-6 °
Sensor location relative (long)	int32	10-6 °

From this set of information, it is important that SS determines:

- The coverage of the incumbent.
- Its operating frequency (central frequency + bandwidth).
- An incumbent ID may be useful if several incumbents are present in the measured channel.

3.4.3.2.2.2 Network system status

To determine the impacts of the incumbent upon the system, the network shall have a complete knowledge of the status of both deployed eNodeBs and UEs.

The required information is listed in the following Table 14:

Table 14: Context information from eNB and UE

eNodeB	UE
Radio resources capability	Connection Status
Guard band	Localisation
Cell load	Measurements on operating channel
Connection dropping rate (CDR)	Measurements on reserve channel
Connection blocking rate (CBR)	Measurements on neighbour cells (inter-RAT, intra-RAT)
Reserve channel status	Measurements on neighbour system (Wi-Fi ...)
Sensing measurements results (i.e. incumbent apparition / disappearance).	Sensing measurements
Operator policies (authorised CBR, CDR ...)	

Some of this information is currently supervised by existing deployed networks and in this case by the access point and the UEs. It has to be considered in the definition of the interface between these components and the decision-making of CM-RM RA entity.

3.4.3.2.3 Adaptation Layer

The Adaptation Layer in the AP appears as an element in charge of enabling the exchange of information between blocks in the AP and others located in the Core Network. The main action that the AL will perform is to provide the location of the different entities and the information they are sharing with the other blocks in QoS MOS architecture. The use that each block does of the information shared is not a task of the AL.

Furthermore, in some cases, it is possible to establish the communication link between two blocks through the AL. In this case, the AL will provide the needed underlying infrastructure, enabling the message transfer. How this process is done has been already presented in the description of Adaptation Layer architecture in D2.3 [D2.3]. Basically, the AL_END at one side will encapsulate data from each entity into an internal format that is de-capsulated at the destination AL_END, providing a secure and unaltered communication link. It is important to note that the AL will neither analyze nor process the information at application level. The AL only needs the destination address in order to transfer the data.

3.4.3.3 Core Network

3.4.3.3.1 CM-SM

The PoC counts with a baseline implementation of the CM-SM. The underlying cognitive engine as well as the rule set will be encapsulated into a dedicated virtual appliance based on the VMware workstation (version 7 or later) [VM11]. The software image delivered will be configured to run on all platforms that support this VMware Player version 7. As outlined in [D7.1], the cognitive spectrum manager is a distributed entity mainly implemented throughout the core network, potentially including agents located at the base stations and user equipments. For the sake of simplicity the foreseen PoC implementation will consist of not more than 2 instances, one associated with the CM-RM implementation and one associated with the Spectrum Portfolio Repository. This is considered sufficient to demonstrate the interaction of the three main entities responsible for QoS MOS cognitive spectrum management. This configuration already has been outlined in [D7.1] and is repeated here for the sake of completeness (see Figure 3-40).

A virtual machine encapsulates the Cognitive Engine (CE), some management processes required to start-up internal processes (Entity Management), functions for lifecycle management of the cognitive processes (Function Management), and functions for association and communication with entities situated outside the virtual machine. The latter is a dedicated task of the Communication Services (see Figure 3-41). External entities that communicate via the communication services are other CM-SM instances, cognitive functions (CF) and generic functions (F) that do not rely on cognition at all. Three implementation specific interface classes are specified for this purpose:

- The CE-CE interface is instantiated between cognitive engines such as those associated with other CM-SM or CM-RM entities. It enables exchange of rules, policies, context or obligations (i.e. a dedicated rule used to implement actions) for example.
- The CE-F interface is instantiated between cognitive engines and functions that do not employ cognitive capacities. It is a control interface mainly setting operational parameters and requesting the status of a function or result of an action. It may be used for context exchange (i.e. may be used to instantiate an IEEE Std 1900.6-2011 CE-S interface).
- The CE-CF interface is instantiated between cognitive engines and functions that employ dedicated cognitive capacities. It complements the CE-F interface by enabling the exchange of policies for example.

Please note that these interfaces do not map directly to the CM-SM internal interfaces as specified by [D6.3] since the PoC specific CM-SM implementation implies a number of co-location demands not considered for the logical entities and logical interfaces of the CM-SM reference model. Practical implementations of cognitive engines, cognitive functions or non-cognitive functions may demand for realizing more than one of the above interfaces at the same time, in particular if partial implementations of the fully cognitive functionality are targeted to relax requirements for a demonstration of the PoC.

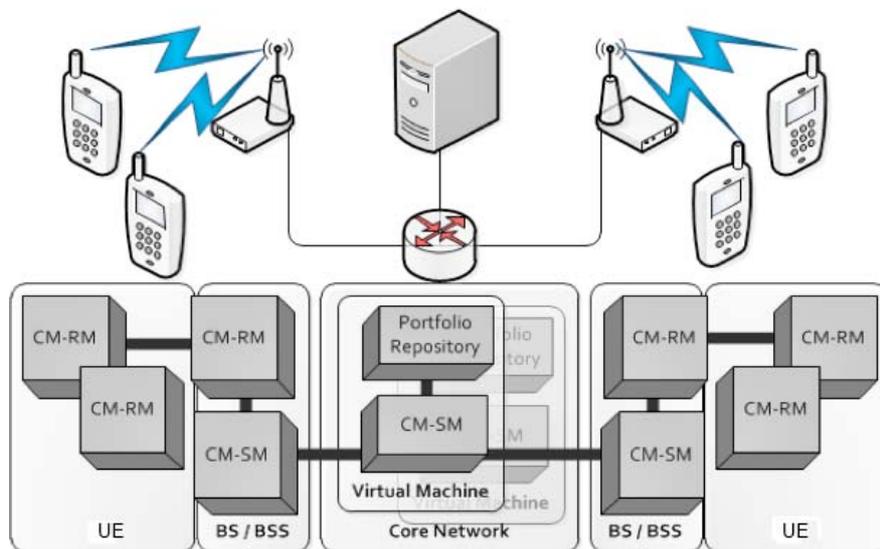


Figure 3-40: General deployment schemes of CM-SM entities (see [D7.1] for further details)

For the time being, it is assumed that a CM-RM is implemented as a cognitive engine demanding for a realization of the CE-CE interface and of the CE-F interface. Depending on the maturity of the CM-RM implementation of the PoC considered, it might be feasible to consider the CE-CF interface only.

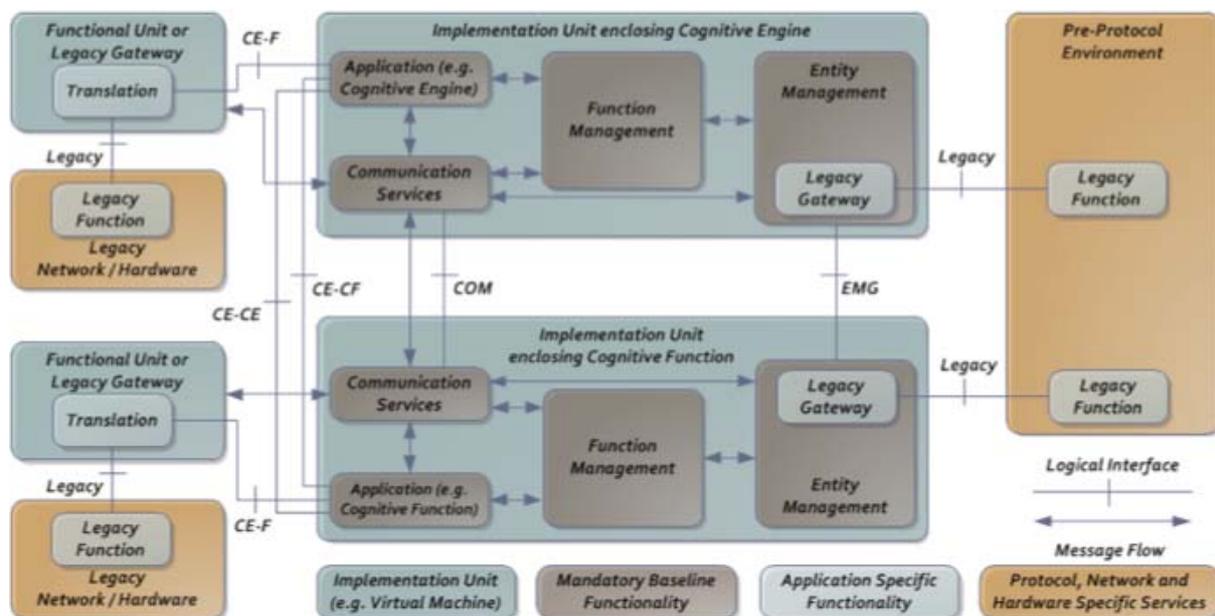


Figure 3-41: High-level logical entities for a CM-SM implementation

The interface between spectrum portfolio repository and CM-SM preferably is a CE-F interface, since it is not foreseen at the moment that this entity (i.e. a TVWS database for this PoC) provides cognitive functionality on its own.

The remaining interfaces as shown in Figure 3-41 refer to the interface between distributed entities of the communication services (COM) and the entity management functions (EMG). Functionality provided by these interfaces is considered of minor relevance to the PoC. A pre-protocol environment is considered to cover the demand for service announcement and detection in a distributed environment of several QoS MOS entities. This might become handy in case dynamic configuration is needed.

Entities external to the cognitive engines are mainly gateway or translation functions (e.g. proxies) required to interface with functions or entities provided by other QoS MOS partners or with the Adaptation Layer (AL).

For example, the Spectrum portfolio repository is accessed via an http and xml-based web service as outlined by subsequent sections. The Functional Unit or Legacy Gateway of Figure 3-41 hence has to act as a gateway translating 'set parameter' and 'get parameter' requests exchanged via the CE-F interface into the proper calls to the web service. Reported results may need to be pre-processed in return by the gateway to match the parameter response expected by the CE.

External entities in need of communicating with a CM-SM instance need to implement the interface to the communication services. Herein, it is called Service Access Point (SAP). The Function Management and the Communication Services handle the instantiation of a SAP whenever a peer-to-peer connection between service user and service provider (e.g. CEs or function and CE) is needed. For the PoC considered, required SAPs need to be preconfigured avoiding an implementation of the COM interface, which provides the 'connect' primitives required for that.

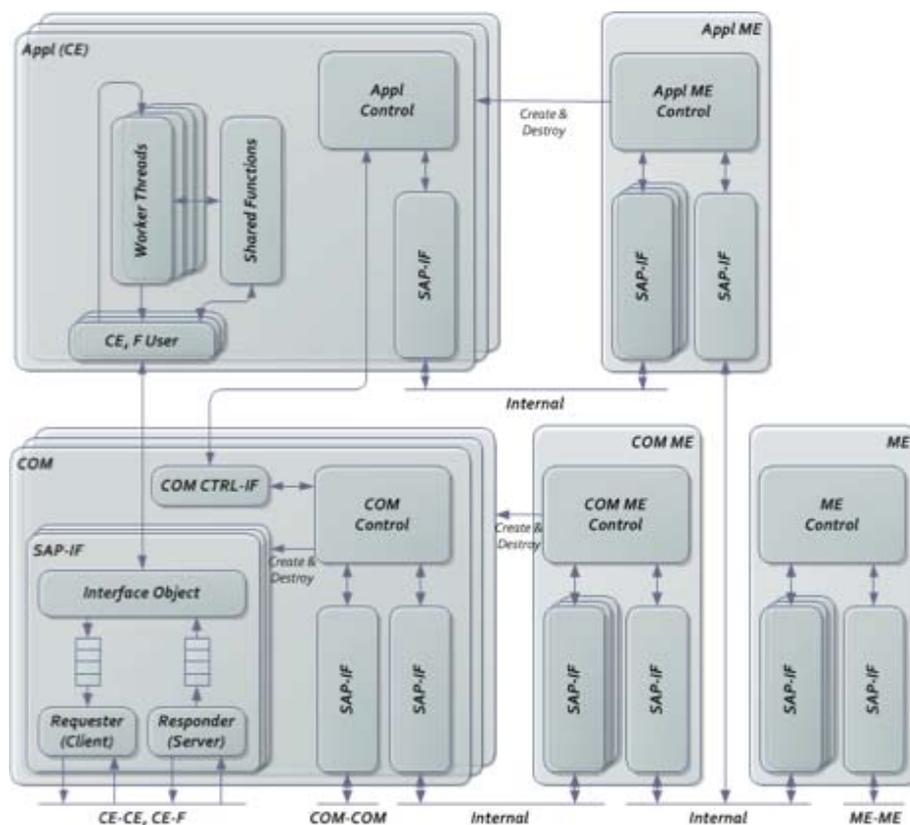


Figure 3-42: Utilization of SAPs (SAP objects) in a CE as considered by Figure 3-41

Some initial decisions on the implementation of a SAP have been taken as outlined by Figure 3-43. For the implementation a SAP object is considered the access interface between a vendor-specific implementation and the common protocol interface to be used across different providers of realizations of CM-RM, CM-SM or spectrum portfolio repository, for example. As depicted by Figure 3-42, the SAP is commonly used to realize protocol exchange between arbitrary entities.

- The **SAP interface** realizes the API provided to an implementation of an entity (e.g. to a cognitive engine, CE). It is vendor-specific and no assumptions are made on implementation method (e.g. the programming language used).
- The **SAP implementation** is also vendor-specific but usually implements the protocol engine that must be conformant to a protocol specification.
- **The CORBA-based interface [CORBA]** ensures that implementations of distinct providers of an implementation are able to establish protocol exchange. The use of CORBA/IIOP is a pragmatic decision. The concept is not bound to this decision and other methods are available (e.g. an ASN.1 based message exchange, which is also widely used), but have to be agreed across providers of implementations.

The following distinct steps should be taken to create a SAP object.

1. A protocol specification needs to be prepared for connecting local and remote SAP interface based on the service primitives defined earlier. The OSI approach and format of IEEE 802 has been followed here by specifying for each service the primitives 'request', 'response', 'indication' and 'confirmation'. A number of basic primitives already have been specified mainly to address requirements set by CM-SM-to-CM-SM communication as well as some generic primitives towards control functions that do not provide local (cognitive) control complementing the CM-SM targets.

2. The specification of protocol messages and protocol parameters is to be derived from the protocol specification generated in step 1. Clearly, a one-by-one mapping of primitives to protocol messages cannot be expected. This in fact demands for developing the protocol engine in parallel, based on the agreed MSCs. One or more IDL files are the outcome of this step
3. By availability of the IDL files from step 2, the CORBA-based interface, which has to be realized across all of the instances of Figure 3-41 for the PoC, can be generated automatically by the IDL compiler for the desired target programming language. The “C++” language has been utilized here.
4. For an implementation of the protocol engines realizing the message sequences as agreed, implementers are required to generate – manually, and by herein assuming a “C++” implementation – code files. In general the following files will be required:
 - a. The SAP interface API (“C” header file), as required by the SAP user (e.g. the cognitive engine).
 - b. The protocol message parameter types (“C” header file), as agreed upon during the protocol specification and obtained via step 2.
 - c. The protocol engine implementation (“C” file), as required by the agreed MSCs and designed during step 1 and step 2.
 - d. The implementation of the CORBA-based interface as generated by step 3, and their server-side and client-side stub implementations in accordance with step 2.

The design methodology described above is designed to ensure protocol-level interoperability across multiple partners providing software entities with a minimum effort. It does not address interoperability on the functional and application level. This is usually an issue to agree upon between collaborating partners working jointly on a specific topic, such as optimization of a spectrum portfolio.

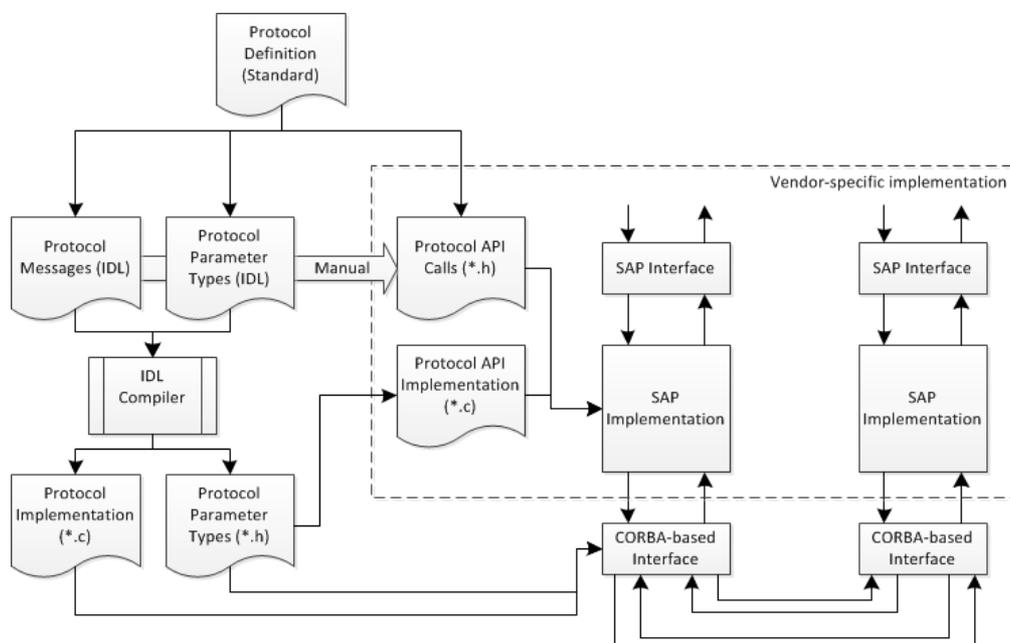


Figure 3-43: Development flow of the interface SAP implementation

The internal structure of the CM-SM cognitive engine is situated on top of a SAP interface (see Figure 3-42) and is considered a non-disclosed proprietary work in progress that will be equipped with some

decision-making rules especially designed for the purpose of the PoC under consideration. The high-level architecture is given by Figure 3-44.

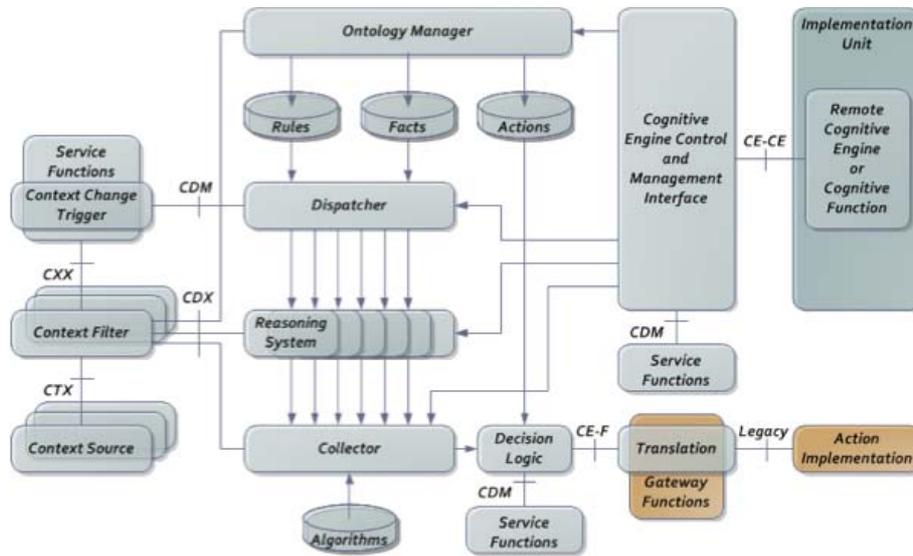


Figure 3-44: Top-level diagram of the implementation of a cognitive engine

Regarding the PoC objectives as given in section 3.4.1, the CM-SM implementation is foreseen to support at least the following services:

- The communication between a CM-RM and a CM-SM instance for the purpose of deploying and revoking a spectrum portfolio.
- The communication between two CM-SM instances for the purpose exchanging spectrum portfolios.
- The communication between a CM-SM and a spectrum portfolio repository for the purpose of obtaining an initial spectrum portfolio and associated policies.

In addition this implementation of a CM-SM aims to provide a service to modify and optimize a spectrum portfolio upon request of a CM-RM utilizing its reasoning and decision-making capacities, which may involve revocation, optimization and re-deployment of an already deployed portfolio, and portfolio modification upon request of another CM-SM instance communicating with an (alternative) spectrum portfolio repository.

3.4.3.3.2 Spectrum Portfolio Repository

A real-time TVWS database code, which now includes European transmitters and terrain (for Great Britain, Germany, and Portugal), will be included into the test-bed. The server is currently accessed through an XML-RPC interface [XML-RPC] (similar to SOAP). The client can be in python [XRPC-PY] (see example below), or any other language with an XML-RPC library. Internally, XML is used; but this is hidden from the programmer (at both ends) by a software layer. XML-RPC can work over HTTPS, thus achieving good levels of security if this is required.

```
import xmlrpcclib
tvwsdb=xmlrpcclib.Server('https://193.113.58.233:8008')
print tvwsdb.occupancy_lists_at_lonlat(-0.5704751,51.23631)
```

It has been suggested to design the demo to make it easy to work with multiple TVWS databases (including unknown future ones). This could be done by adding an adaptation (or translation) layer in the GUI, through which all spectrum requests are routed. This layer would then translate to the correct

protocol for the database server currently being used. Later the test bed might also support SQL or other protocols in this layer (such as the forthcoming PAWS standard). This is probably easier than redesigning the existing database servers. Alternatively, the translation could be done in another machine on the network; in other words, a kind of virtual server is being used.

To handle dynamic updates (PMSE etc.), it would be optimum adding a server translation layer as below. In the Figure 3-45 below the first diagram shows the existing architecture; the second diagram shows this working unaltered, but with another server layer to handle dynamic updates.

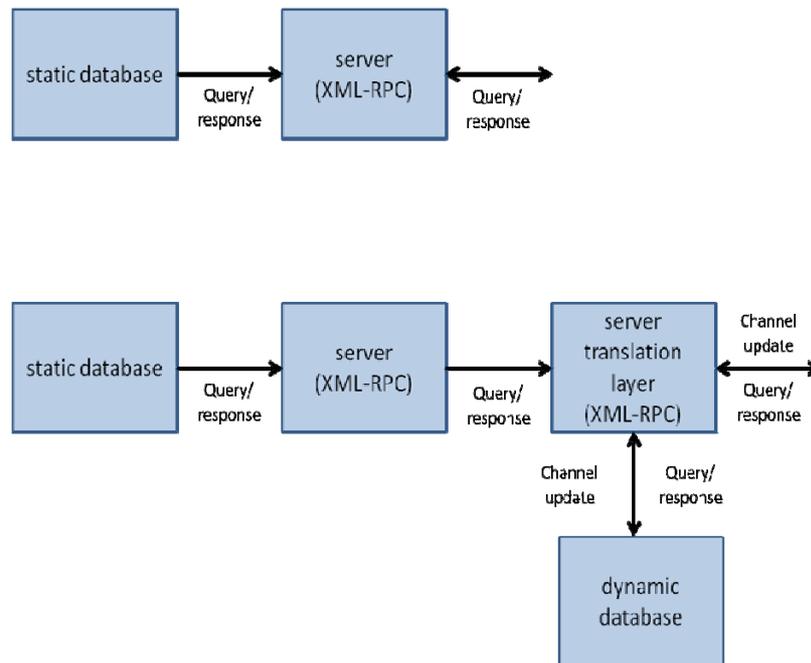


Figure 3-45: Architecture with/without server translation layer

3.4.3.3.3 Adaptation Layer

3.4.3.3.3.1 AL Internal Activities

There are some internal activities taking place in the Adaptation Layer during the PoC #4 test. These internal activities help in the communication among QoSMOS entities, through the AL, in the mentioned Proof of Concept. The most important actions which are being developed inside the AL are related to entity registration and deregistration, information update process and event subscription..

The entity registration process starts when a QoSMOS entity wants to connect to the Adaptation Layer. All entities that want to connect to the AL have to establish a connection with an AL_END first. Once the connection between the QoSMOS entity and the AL_END has been established, the QoSMOS entity has to register in the AL_CORE through its AL_END. The AL_END is in charge of changing the QoSMOS entity registration message to AL internal message format in order to be understood by the AL_CORE, which is in charge of accomplishing the registration process. This registration process consists in generating the response for the received message and saving in the data base the information of the QoSMOS entity which is registering. The type of information stored in the data base is shown in D2.3 [D2.3]. Once the data of the QoSMOS entity has been saved, the AL_CORE will generate the response for the QoSMOS entity in order to inform that the process has been accomplished correctly.

On the other hand, the entity deregistration process starts when a QoSMOS entity wants to disconnect from the AL. As well as in the previous process, the QoSMOS entity which wants to start a deregistration process sends a message to its own AL_END, in charge of sending this message to the

AL_CORE. When the AL_CORE receives the deregistration message, it has to generate a response, with the aim of confirming the QoSMOS entity which wants to deregister from the AL that the deregistration process can be done correctly. Once the AL_CORE sends the deregistration response message, it has to inform the rest of QoSMOS entities, which share information with the recently deregistered QoSMOS entity, about its recently deregistration. These way, these QoSMOS entities are warned about not to share information with this deregistered entity. The deregistration process concludes when the AL_CORE deletes from the data base all the information related to the recently deregistered QoS MOS block.

The information update process is fundamentally realized with the registration and deregistration process of a QoSMOS entity. The process is started by the AL_CORE each time a QoSMOS entity accomplishes a registration or deregistration process. When the process starts, the AL_CORE has to search in the data base the QoS MOS entities which can be interested in the information which provides the recently registered QoS MOS entity. The entities which have the same type of data that the recently registered QoS MOS entity are receiving this information update packets in order to inform about the information that can be shared between them. The AL_CORE has also to inform the recently registered entity about the registered entities that have its data type and can provide some useful information to it. So, the recently registered entity receives information update messages containing data of the possible QoS MOS entities which can share information with it.

Finally, event subscription takes place when a QoS MOS block makes the registration process, and it is automatically subscribed to a group of possible events that are being produced in the AL. Each block is subscribed to the events which are related to its type of data, due to the fact that the event messages are only being sent to the QoS MOS entities which have the same data type than the one which generated the event in the first place.

3.4.3.3.2 AL interaction with other entities

During the execution of the Integrated PoC the AL will act as a mean of communicating certain QoS MOS entities, dispatching the messages sent from one to another. Thus, it is necessary to communicate with them all through different interfaces.

On one hand, in order to count with updated portfolio information two distinct interfaces will be fitted out. The one in charge of interacting with CM-SM is based on a CORBA IDL standard, while the one dedicated to contact the Common Portfolio Repository works on a XML-RPC protocol.

This same protocol as well is the one selected and employed to facilitate the communication between the AL and the CM-RM.

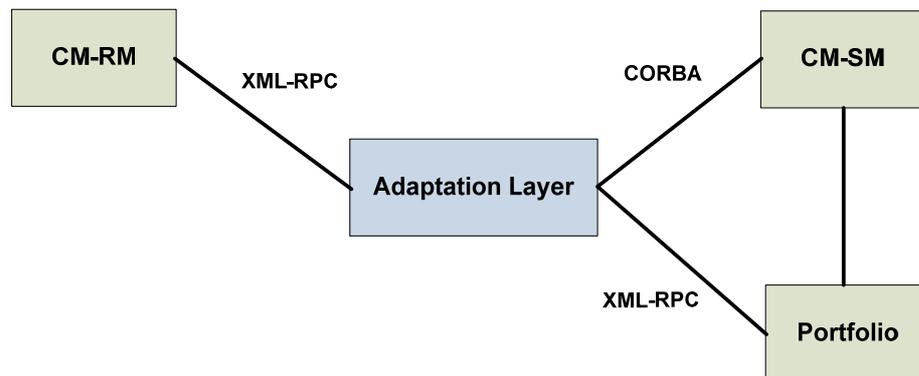


Figure 3-46: AL interactions

In order to explain how previous operation tests are used in the PoC, an MSC has been developed, where the process flow during the AL interactions with other entities is depicted. There the process that certain QoS MOS entities are following to interact with the Adaptation Layer in the PoC #4 is explained. The QoS MOS entities which are registering in the AL are the CM-SM, the CM-RM and the

Common Portfolio Repository. Figure 3-47 depicts the MSC where the information exchange followed by the different QoSMOS blocks is shown.

Firstly, the Common Portfolio Repository is sending a registration request to the Adaptation Layer. The AL receives the registration request and stores the registering information of the Common Portfolio Repository. Once the information is stored, the AL sends a registration response to confirm that the registration process is correctly done.

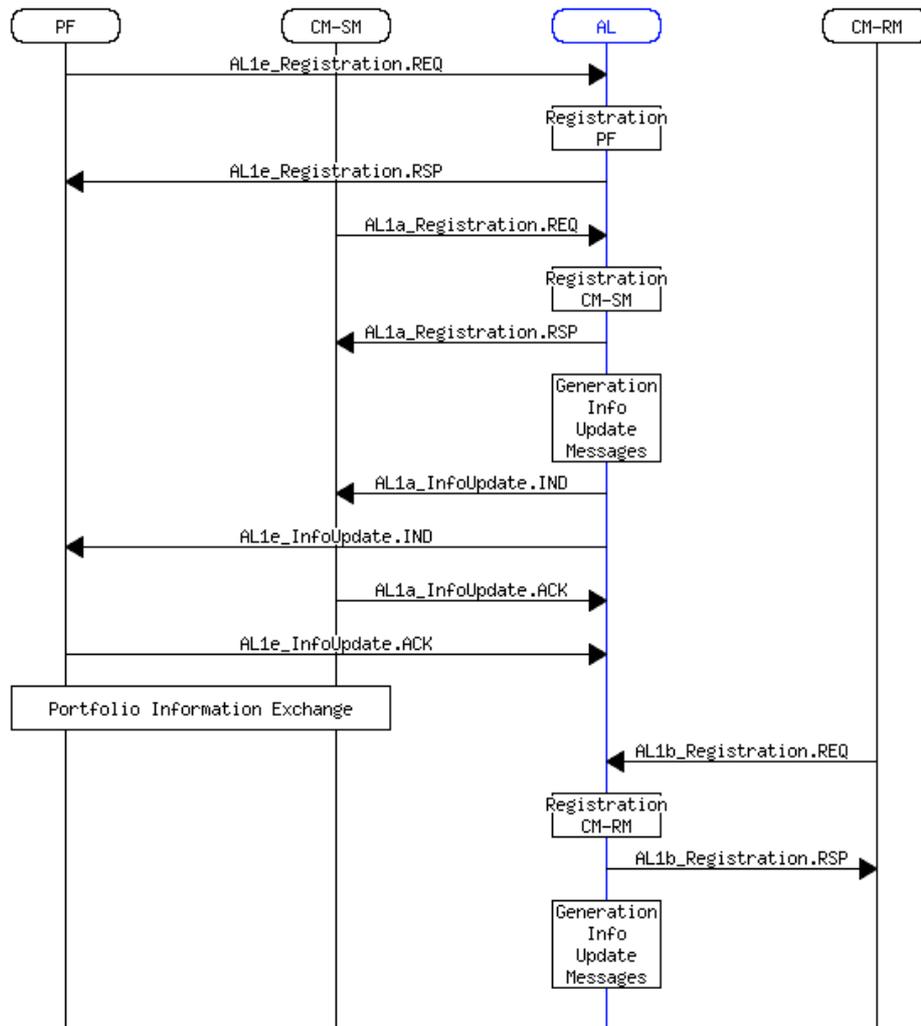


Figure 3-47: MSC of interactions between CM-SM, CM-RM and PF through the AL

Then, the CM-SM sends a registration request to the AL in order to make its registration. The AL, as in Common Portfolio Repository case, saves the registering information of the CM-SM in the data base and generates the response to the CM-SM in order to notify that the registration process is done correctly.

When these two entities are registered, the AL sends the information update messages to notify both entities about the existence of each other. Both entities answer with an information update response message and, in this way; they confirm that the information was correctly delivered (this process is deeply explained in [D2.3]). Once they know how to contact between them, they can proceed with the interaction, exchanging information in the way that is set by these two entities. At this point, the AL will only notify about the changes in the topology that affects the functions and behaviour of them. Otherwise, they will be contacted only for assuring the status.

The CM-RM block also can use the AL as mean for sharing and requesting information from other elements in the architecture, in this case the CM-SM. In order to do so, it is necessary that CM-RM performs the registration process in the same way that the previous two blocks have done. After confirming the registration, the CM-RM and the CM-SM will receive a message notifying about the presence and capabilities of each other.

When the information update process is finished, the CM-RM is able to request any parameter specified in the interaction between the blocks needed for the regular actions performed in the CM-RM, and also the other way around, being the CM-SM the one requesting information from the CM-RM.

3.4.3.4 Incumbent System

3.4.3.4.1 Primary Scene Emulator

The role of the primary radio scene in PoC #4 will not be much different from its role in PoC #1. The primary radio scene engine will essentially feed the sensors, in order to test the accuracy of sensors in both time and frequency dimensions. The radio scene will function either as a deterministic machine where the on/off pattern of the individual carriers within the composite signals are determined completely by the user, or the radio scene machine can function based on modeling approach where the on/off pattern of the carriers are determined by statistical data based on field measurements taken.

3.4.4 Interaction among blocks

As mentioned above, there are four major blocks in the PoC #4: a User Equipment, an Access Point and a Core Network, as well as an Incumbent System; all of them interacting during the execution of the proposed test.

The PoC can be divided into two important steps. In the first part, the test begins with the registration of the UE in the flexible transceiver in the User Equipment block. This registration is accomplished by Bluetooth technology. Simultaneously, in the Core Network the Spectrum Portfolio Repository and the CM-SM are connecting through the AL. The CM-SM asks for the Spectrum Portfolio information. When the CM-RM in the Access Point does its registration in the system through the AL, it asks to the CM-SM in the Core Network for the Spectrum Portfolio Repository information, in order to select a TVWS channel to operate.

When the TVWS channel is selected in the Access Point, the CM-RM has to configure the flexible transceiver of the Access Point to communicate with the flexible transceiver in the User Equipment. When this flexible transceiver of the User Equipment receives the transmission signal of the Access Point, it is in charge of configuring the TVWS channel used in the UE. Once established the communication, the CM-RM is responsible of configuring the Spectrum Sensing of the Access Point and the UE, in order than both can detect the possible appearance of an Incumbent User.

Later, in the second stage, the behaviour of the system when an incumbent appears is evaluated. The User Equipment block detects the incumbent signal through its flexible transceiver, and informs the Access Point. The Access Point (CM-RM) informs about the sensing measurement report to the Core Network (CM-SM). There, the CM-SM updates the Spectrum Portfolio information asking to the Spectrum Portfolio Repository through the AL. When the CM-SM has the Spectrum Portfolio information, it sends the information to the CM-RM in the Access Point. The CM-RM is in charge of fulfilling the solution to this situation.

Now, two possible solutions can be accomplished. The first possible solution is the configuration of the transceiver of the Access point in a new TVWS channel, in order to continue the communication with the User Equipment. The flexible transceiver of the User Equipment block receives the transmission signal of the Access Point and detects the change of TVWS informing to the UE. The second possible solution is the communication between the User Equipment and the Access Point through the licensed band. In this case, the Access Point informs the transceiver of the User

Equipment to stop the communication in TVWS band and change to the licensed band. The transceiver informs the UE about the changes and this starts the communication with the Access Point by the licensed band.

This way, every block in the test bed communicates and collaborates with the rest of building blocks, getting a joint functioning and carrying out the task they are intended to.

3.4.5 Novelties demonstrated

Taking advantage of the special characteristics of this integrated PoC, there are several and quite innovative functionalities that will be shown through its development and performance. The first one would be the access to the information present in the Core Network, using distinct access methods to do so. In addition, it is worth noticing the use that will be done of this data (e.g. channel selection).

Furthermore, the PoC will address transceiver configuration issues, as well as sensing measurements establishment, and in a later stage it will involve the detection of an incumbent signal arriving into the system. This IU signal will be transmitted to the AP, thus it will reach the Core Network, causing a Portfolio update.

All these operations lead to an eviction decision that results in a new channel selection, ending in an UE and AP reconfiguration.

3.4.6 Integration Plan

The complexity of this PoC, which involves the integration of quite different building blocks and the demonstration of several functionalities, invites to configure a modular and scaled integration plan, establishing different milestones in the development process. After completing each one of them, the validity of the system will be checked and thus the next stage in the evolution of the PoC will take place.

The different components are being developed independently and their first integration is expected to begin from early 2012, leading to an initial joint demonstration in late winter-early spring, which will showcase a selected set of functionalities.

Afterwards, the next steps in the full block integration will be made in order to achieve the proposed live cognitive radio system demonstration, with all the novelties hinted in Section 3.4.5.

4 Conclusions & Further Work

After the initial work shown in [D7.1], this report has provided a more detailed high level description of the diverse platform architectures and the four PoC demonstrations that will finally be carried out. The demonstrations within the first three categories mainly focus on testing and validation of the CR concepts in the lower physical (PHY) layer, while the fourth category validates the CR concepts for link and upper layers and attempts to integrate some of the selected demonstrations from the first four categories in order to showcase a live cognitive radio system.

The deliverable also provides the description of some of the different hardware and software components (API, applications) that are expected to be brought by different partners. These hardware/software components may be utilized or required by one or more partners in order to conduct their respective demonstrations.

This deliverable has brought the different components and sub-systems from various partners into well-defined PoC categories. Last PoC is a challenging task and its success will depend on the proper interaction between its different building blocks. The outcome of the activity in these test setups will be reflected on following deliverables and in the development of a real demo.

The correct design and performance of these proofs of concepts will guarantee the demonstration of several key concepts developed in QoS MOS framework. In the case of PoC #1 *Primary scene and sensing engine*, its development will allow making an empirical comparison between different detection approaches as used by sensors.

Further, PoC #2 *Flexible Transceiver* focuses on demonstrating spectrum polling capabilities using different modulation schemes, the spectrum aggregation capability and the simultaneous spectrum sensing and communication within TVWS.

Meanwhile, PoC #3 *Distributed/Collaborative sensing* shows the worthiness of the distributed sensing algorithms developed in the QoS MOS project using a homogeneous mesh of sensor nodes and studying the impact of having a heterogeneous mesh of sensor nodes in the performance of the distributed sensing algorithms.

Finally, PoC #4 *Integrated platform* will provide a full set of functionalities demonstrating the concepts introduced by QoS MOS: the interaction between both cognitive managers, transceiver configuration issues, as well as sensing measurements establishment, and in a later stage it will involve the detection of an incumbent signal arriving into the system. This IU signal will be transmitted to the AP, thus it will reach the Core Network, causing a Portfolio update.

In terms of future work, the first tests are currently under development and evaluation, according all these tests to the architectures proposed in this document, and their first results will be available in the next deliverables.

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