Quality Of Service and MObility driven cognitive radio Systems

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QoSMOS

D7.5

Analysis of demonstration results and conclusions

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Abstract:

Deliverable D7.5 is the final report on the QoSMOS Proof of Concepts, where a detailed analysis of the results obtained is offered, along with a quantification of improvements and enhancements brought about by the project. This way, recommendations to QoSMOS system architecture are delivered.

Keyword list:

Proof of concept, demo, cognitive radio, scenario, system architecture, analysis, improvements, recommendations.

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Abbreviations

3G	Third Generation
ACLR	Adjacent Channel Leakage Ratio
ADC	Analog-to-Digital Converter
AL	Adaptation Layer
AP	Access Point
BBG	BaseBand signal Generation
BW	BandWidth
CEA	Commissariat à l’Énergie Atomique
CM-RM	Cognitive Manager for Resource Management
CM-SM	Cognitive Manager for Spectrum Management
CORBA	Common Object Request Broker Architecture
CP	Cyclic Prefix
CR	Cognitive Radio
DB	DataBase
DFU	Data Fusion Unit
DTV	Digital TV
DVB	Digital Video Broadcasting
DVB-T/H	Digital Video Broadcasting-Terrestrial/Handheld
EDGE	Enhanced Data rates for GSM Evolution
FAP	Femto Access Point
FBMC	Filter Bank Multi Carrier
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FMT	Frequency Mask Triggering
FOKUS	Fraunhofer-Institut für Öffene Kommunikationssysteme
FPGA	Field Programming Gate Array
GFDM	Generalized Frequency Division. Multiplexing

GNU	GNU’s Not Unix
GSM	Global System for Mobile Communications
GUI	Graphic User Interface
HSDPA	High-Speed Downlink Packet Access
HTML	HyperText Markup Language
HW	HardWare
IA-PFT	Interference Avoidance transmission by Partitioned Frequency- and Time- domain processing
IE	Information Element
IF	Intermediate Frequency
IIS	Institut für Integrierte Schaltungen
IT	Instituto de Telecomunicaçoes
IU	Incumbent User
LTE	Long Term Evolution
ME	Master Entity
MIMO	Multiple-Input Multiple-Output
MME	Measurement, Modelling, and Emulation
MSC	Message Sequence Chart
NTUK	NEC Technologies UK
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OU	Opportunistic User
PC	Personal Computer
PD	Probability of Detection
PFA	Probability of False Alarm
PMD	Probability of Miss Detection
PoC	Proof of Concept
POI	Probability Of Intercept
PSE	Primary Scene Emulator

QoS	Quality of Service
QoSMOS	Quality of Service and Mobility driven cognitive radio Systems
RAT	Radio Access Technology
RC	Resource Control
RF	Radio Frequency
ROC	Receiver Operating Characteristic
RPC	Remote Procedure Call
RTSA	Real-Time Spectrum Analysis
RTSP	Real Time Streaming Protocol
RU	Resource Unit
SaaS	Software as a Service
SDR	Software Defined Radio
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
SS-CTRL	Spectrum Sensing – Control
SS-MGT	Spectrum Sensing – Management
SW	SoftWare
TCP	Transmission Control Protocol
TDD	Time-Division Duplexing
TLV	Type-Length-Value
TVCH	TV Channel
TVWS	TeleVision White Space
UDP	User Datagram Protocol
UE	User Equipment
UHF	Ultra High Frequency
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral
VSA	Vector Signal Analysis

W-CDMA	Wideband Code Division Multiple Access
WP	Work Package
XML	eXtensive Markup Language

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1 Executive Summary

The main objective of this deliverable is to provide a thorough analysis of the diverse results obtained through the execution of the different proof of concepts (PoCs) carried out within the scope of Work Package (WP) 7.

As stated in previous deliverables [D7.1][D7.2][D7,3], the definitive number of PoCs is four setups, covering aspects discussed and treated in the rest of technical work packages, this way having some kind of real-world assessment and validation of the theoretical concepts tackled within them. Thus, an updated and detailed description of these tests, thoroughly picked to demonstrate some of the system characteristics and main functionalities, is considered necessary and given. In addition, the depiction of the building blocks that the model comprises is offered as well.

The first PoC, designed to evaluate the achievements of WP3, is built around the sensing engine, focusing in showcasing the radio environment modelled there. In essence, it comprises the primary radio scene engine, emulated by the primary radio scene engine and in charge of creating incumbent user (IU) waveforms, which feeds the sensors developed in WP3 to test their accuracy in time and frequency domains. In addition, the waveforms present channel fading effects and the emulation involves effect of Doppler spread to simulate a mobile environment and represent a more accurate test for the sensors, which in turn operate with high dynamic range in order to be capable of detecting weak signals.

Meanwhile, the second setup has the flexible transceiver as central point, following the developments of WP4, where QoSMOS has validated Filter Bank Multi Carrier (FBMC) as a flexible and low interference radio technology for TVWS. This flexibility can be achieved employing a flexible physical (PHY) layer which can adapt its spectrum profile to allowed and/or available spectral resource. In this context, Orthogonal Frequency Division Multiplex (OFDM) was the initial choice for the PHY in Cognitive Radio (CR), mainly to its high spectrum efficiency and the fact it is deployed in broadcast applications. Anyway, it presents a notable adjacent leakage power and that’s where FBMC enters. Keeping the flexibility of multi-carrier modulation, it is possible to control the frequency response of each carrier by introducing a filter bank centered on every active carrier and based on the same prototype response. This prototype filter can be selected to minimize (null) adjacent channel interference, and the work in this PoC has involved developing a real hardware solution working upon these premises, creating a TVWS flexible radio digitally tunable over TV band, on a 40 MHz frequency window, and including a digital FBMC filtering to contribute to the spectrum pooling for channel selection in the desired window.

For its part, the third proof of concept is also related to the work developed in WP3, this time introducing a collaborative spectrum sensing demo thus proving the usefulness of the collaborative/distributed sensing algorithms developed there in scenarios close to real-life conditions. Detecting IUs located beyond the single opportunistic user (OU) interference range but can be disturbed by this OU network is the main challenge in spectrum sensing, in addition to propagation issues like fading or shadowing that derive in the hidden node problem. Cooperative/distributed sensing schemes are adopted in order to somehow alleviate the traditional tough requirements imposed in this field, therefore the deployment of multiple sensing devices working together to achieve a high level of confidence in the IU detection.

Finally, the fourth setup shapes an integrated PoC which covers several concepts of the overall system. This way, diverse aspects of the cognitive resource and spectrum managers are covered, while at the same time some themes developed within WP5 and WP6 are incorporated into the scenario. In addition, certain advances discovered in the rest of test setups which comprises this WP are incorporated to demonstrate a true cognitive radio system. This way, QoSMOS entities related to the Core Network, the Access Point and the User Equipment will be involved, depicting a scenario where an OU wants to stream some video application over TVWS and the appearance of different incumbent and/or opportunistic users forces the change of the operating TVWS channel or even carry out an action to switch back and continue the transmission on a legacy channel.

Finally, based on the results obtained conducting these experiments, WP7 is able to provide a list of recommendations to the QoSMOS system and deliver a series of use cases which could take advantage of the work done. Thereby, the investigations carried out in QoSMOS and translated into proof of concept setups would find the path to implement real-world solutions.

This document is organized as follows: Section 2 gives an overall introduction, presenting the WP participants, delimiting the context of this deliverable and giving a first look to the objectives and architecture of the QoSMOS proof of concepts. Sections 3 to 6 are devoted to explain in detail the respective demonstration tests that have been carried out to evaluate every concept, as well as the results obtained with each one of them, while an assessment of their portability to QoSMOS system architecture is offered and some hints of their potential for further work given. Finally, Section 7 consists in a compilation of concluding remarks derived from the tasks performed in this WP and the envisioned way forward.

2 Introduction

The main goal of this deliverable is to provide a thorough analysis of the diverse results obtained through the execution of the four PoCs the WP7 is divided into, leading to certain conclusions which can be converted into recommendations for the QoSMOS system and a series of use cases which could take advantage of the work done, quantifying the improvements and enhancements brought about by the QoSMOS project.

2.1 Work Package participants

A wide representation of QoSMOS consortium partners comprises the WP7 unit, this group is composed of 7 out of the 15 total partners, depicted in Figure 2-1. Each one of them has had a different role in the tasks to carry out within the proof of concepts.

Figure 2-1: QoSMOS partners involved in WP7

BT, leader of the consortium, has contributed to the definition of testing scenarios and specification of threshold parameters for sensing algorithms in selected cases involving networks of cognitive devices. Furthermore, BT works towards the integration of the collaborative sensing algorithms developed in WP3 and also in the development of a geolocated dynamic TVWS database.

CEA has brought a hardware platform used as platform for sensing/transceiver mapping and mapping into it functionalities coming from QoSMOS WP3 and WP4 foreground.

IT has helped in the definition of the specifications of the collaborative sensing algorithms and its integration with other modules developed for the demonstrations. In addition, IT has worked looking for the integration of the collaborative sensing algorithms defined in WP3 into the WP7 PoCs.

NTUK brings its knowledge of system architecture given its involvement in WP2 and contributes in the definition of the integrated scenario, as well as provides algorithms to the QoSMOS prototyping environment in order to demonstrate end-to-end QoS management.

Agilent brings, into this WP, the scene emulator developed within the scope of WP3. Hence the cognitive designs developed can face in the demonstration setups close-to-reality conditions while offering reproducibility and controllability. In addition, Agilent contributes its expertise and testing tool to evaluate diverse QoSMOS cognitive aspects, namely the influence of the opportunistic user on the incumbent user (IU). In the context of analysis, Agilent provides a real-time spectrum analysis solution and has developed a frequency mask triggering feature for the detection of signals in defined regions of interest.

Fraunhofer IIS uses its SDR platform to implement and integrate the radio frequency (RF) parts developed in WP4 into the demonstrator. On the other hand, Fraunhofer FOKUS contributes to the integrated platform specification, test and validation with a clear focus on identifying the requirements regarding the preparation of spectrum manager software components and implementing tools to visually represent the changes happening in the scenario.

Finally, TST acts as WP7 leader and contributes to the definition of the PoCs, being actively involved in the integrated platform. There TST's Adaptation Layer (AL) is present, having been depicted as part of the system architecture in WP2 and further developed and tested in WP5.

2.2 Context of this deliverable

WP7 is closely linked with all the rest of QoSMOS work packages as illustrated by Figure 2-2 below. Relevant scenarios and system architectures have been derived from WP1 and WP2 respectively. The sensing engine and the flexible transceiver developed in WP3 and WP4 have been essential blocks of the WP7 platforms.

In addition, the management of the spectrum, QoS and mobility, coming from WP5 and WP6, are part of the integrated demonstration, which consists in a software/hardware implementation of selected schemes.

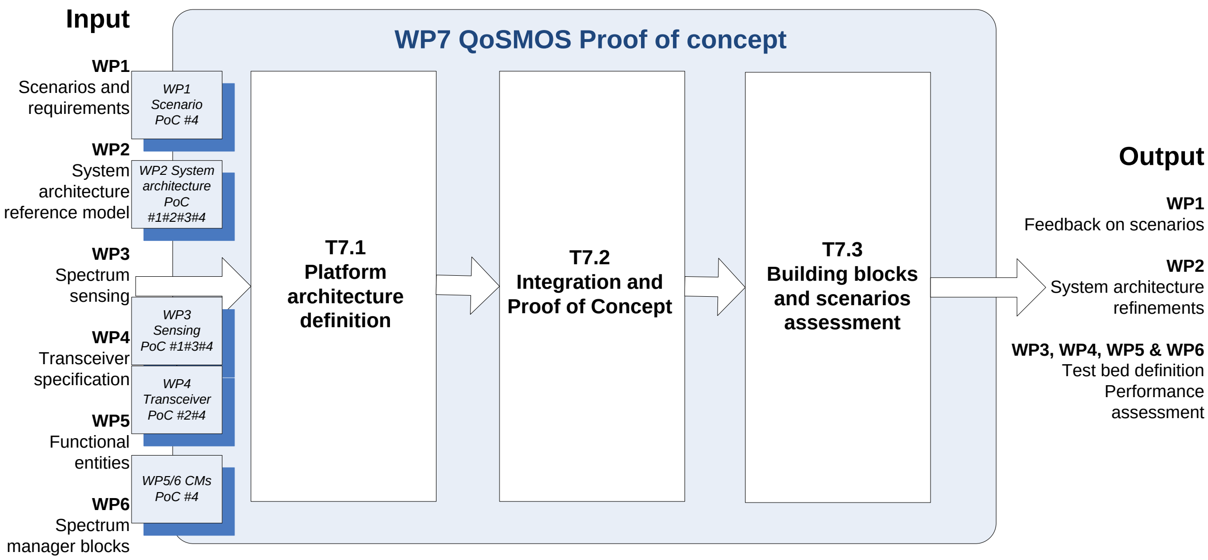


Figure 2-2: Work Package 7 interactions with other work packages

These links shown in the picture are bi-directional, since the platforms definition conducted in WP7 is related with the actual hardware implementation of the different sub-systems, done in the rest of WPs.

2.3 Proof of Concepts

A variety of reasons led the consortium to pick the definitive four PoC set. Regarding PoC#1, to perform an analysis related to the evaluation of diverse detection schemes and their performance when used by the sensors. It also represents a critical role within the integrated platform.

Meanwhile, PoC#2 aims to validate the out-of-band performance of Filter Bank Multi Carrier (FBMC) in a complete radio system, where RF impairments are accounted for.

PoC#3 has been chosen in order to prove the worthiness of the developed distributed sensing algorithms in scenarios as close to reality as possible.

Finally, the integrated platform in PoC#4 illustrates a scenario that provides relevance to QoSMOS, integrating developments achieved in the previous PoCs and showcasing to some extent a real cognitive system.

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

3.1 Description of demonstrator

Primary scene and sensing engine proof of concept demo was defined in [D7.1]. It aims at showcasing the radio environment modelled in WP3. In this PoC, the primary radio scene engine will feed the sensors developed within WP3 in order to test the accuracy of sensors in both time and frequency dimensions. The radio environment that is emulated by the primary radio scene engine consists of incumbent user waveforms modelled over wide frequency band. The channel fading effects are also added on the waveforms before the faded signals are finally delivered to the sensors. The channel emulation also involves the Doppler spread effect in order to evaluate the performance of the sensing engine in a mobile environment. The sensors operate in high dynamic range to be able to detect very weak signals.

The key elements of this PoC, i.e. scene emulator and sensors, play a critical role in the distributed sensing PoC#3 and the overall integrated PoC#4. This fact resulted in a high level of requirements on the development and validation process. Special attention was paid to the robustness and compatibility of the elements to make sure that this PoC functions as expected before it can be included in more sophisticated or complicated scenarios as the ones represented by these aforementioned PoCs #3 and #4. Furthermore, this test setup will provide important analysis baseline related to the study of different detection schemes and their performances as used by the sensors.

In addition, within the scope of this PoC an experimental wideband Real-Time Spectrum Analysis (RTSA) test setup with Frequency Mask Triggering (FMT) capability has also been realized. It has been applied to a number of test scenarios for Cognitive Radio (CR) spectrum monitoring. The main contribution over the state-of-the-art RTSA is that a platform and a digital architecture combining a significantly wide real-time analysis bandwidth with FMT capability have been performed.

3.1.1 Components of the demonstrator

The PoC#1 test bed is composed of these main entities:

- Primary scene emulator (PSE) – PSE is required to generate the IU signal that particular detection devices should receive according to the defined IU service and the channel model considered.
- Sensors – Hardware sensor is in charge of listening to Radio Frequency (RF) signals and making a sensing decision based on a local decision algorithm.
- Spectrum analysis – Experimental setup for performing wideband real-time spectrum analysis with FMT.

The analogue interface between these high-level entities is in the RF wave domain. In practice it is realized by means of standard RF coaxial cables (BNC- and/or SNA-type). A block scheme of the sensing test bed is given in Figure 3-1. The functionality of the particular blocks is explained in the following sections.

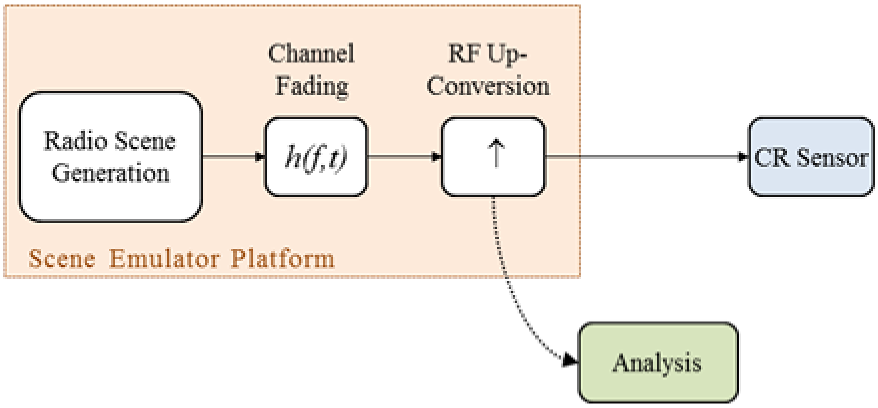


Figure 3-1: Block diagram of the PoC#1

3.1.1.1 Primary scene emulator

The scene emulator concept is an advanced test platform for the evaluation of wireless systems that enables the reproduction of radio environment in laboratory conditions. The advantage over testing in the field is the full controllability and reproducibility of real-world test scenarios.

This platform is especially well suited for the testing of cognitive radio sensing devices. It offers the capability to generate standards compliant waveforms, which is useful for feature-based CR sensing algorithms, for instance, combined with a wide operating bandwidth. In order to provide a realistic radio environment that the tested device might experience in real conditions, the scene emulation features also channel emulation block. Here, the generated waveforms are subjected to channel fading and Doppler spread effect.

The scene emulator concept is an integral part of the *Measurement, Modelling, and Emulation (MME) Approach* proposed in [Tandur12]. This three-pillar approach addresses the evaluation of the performance of CR systems and how to ensure trustworthy results for the various CR stakeholders. To achieve this objective the authors highlight the controllability, repeatability, and representability of the test platform as the crucial components of the evaluation.

There are four main components, two software suites and two advanced hardware platforms, involved in the scene emulator test platform architecture:

- Signal Studio - Standards compliant baseband signal creator software.
- SystemVue - Electronic Design Automation software tool.
- [PXB] - Advanced multiple baseband signal generator and channel emulation platform.
- [MXG] (or [ESG]) – Baseband signal generator and RF up-converter platform.

3.1.1.1.1 Radio scene generation

Signal Studio and SystemVue serve within the scene emulator platform for the design of the radio scene. Signal Studio is a signal creation software suite that generates arbitrary waveforms compliant with various standards, such as Long-Term Evolution (LTE)/LTE-Advanced supporting both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), Digital Video, Worldwide Interoperability for Microwave Access (WiMAX), Global System for Mobile Communications (GSM), Enhanced Data rates for GSM Evolution (EDGE), and others.

The radio scene, in general, may involve in a particular RF band multiple signals from various wireless standards. The implied flexibility in terms of supported number of signals, carrier frequency locations, and the overall bandwidth over time is facilitated by the SystemVue software.

The signals that are to be multiplexed may have a different native sampling rate, for instance, GSM has a native data sampling rate of 270.833-kHz and LTE a multiple of 1.92 MHz, and the emulator should be able to accommodate all the carriers in the band of interest at a common sampling rate. SystemVue's signal combiner performs this combination and resampling of the different signals while keeping the additional computational complexity limited. The segment length is made equal by repeating the baseband contents of the signals that are generated for shorter duration. Moreover, SystemVue provides by means of its library models also the possibility to generate standards compliant waveforms.

The radio scene segment is downloaded to the baseband generator instrument's memory (PXB or MXG) and then played back in a loop or for a pre-defined number of times. In case there are multiple segments and an MXG is performing the baseband generation, external triggering can be used to sequentially advance over different stages of the radio scene (refer to Section 6.1.1.1 for further details on triggering).

3.1.1.1.2 Channel emulation

Agilent PXB baseband generator and channel emulator platform is an advanced testing equipment with inbuilt multiple signal generator and channel emulation capability (see Figure 3-2). It contains digital signal processing (DSP) blocks that can be defined by the firmware for baseband generation or fading, thus allowing for variable configuration such as 1x4 Single-user multiple-input and multiple-output (MIMO) or 4x2 Multi-user MIMO, for instance. The DSPs configurable for the purpose of Baseband Signal Generation are referred to as BBG cards.

Figure 3-2: Agilent PXB Baseband Generator and Channel Emulator

The faders can be applied independently to one or more arbitrary waveforms, either played back from the BBG cards or coming from an external source.

The output of the fader can then be summed up before finally sending the signal to the output. The summing operation makes possible the emulation of various MIMO scenarios.

Each BBG card has access to up to 2 GB hard disk memory for the playback of the arbitrary waveforms. The standard maximum supported playback bandwidth of the generated signal is 120 MHz.

The PXB test instrument provides the possibility to interface with up to 4 external devices through both the input and output digital card outlets given at the rear side of the instrument. These input/output cards can be directly accessed either by the DSPs meant for baseband signal generation or the DSPs meant for the purpose of channel emulation (faders).

As the test instrument provides the possibility to sum either the outputs of the BBG cards or the faders, thus it is possible to set up the instrument into various pre-configured setups. Typically, the BBG card of the PXB instrument plays back the standard compliant waveform that has been downloaded to the memory associated with the BBG card.

The channel emulation supports a broad selection of standardized models, e.g., Wideband Code Division Multiple Access (W-CDMA), High-Speed Downlink Packet Access (HSDPA), LTE, or others. The channel fading can be time and frequency selective in nature. The time varying channel fading is always emulated in real-time whereas the frequency selective channel fading can be static in nature.

Each fader card can emulate up to 6 multiple paths at 120 MHz bandwidth configuration and up to 24 paths at 40 MHz bandwidth configuration. The amplitude, delay and angle of arrival for individual paths can be independently configured. In addition the fader also provides the possibility to add white Gaussian noise on the arbitrary waveform.

For tests in licensed radio spectrum, the advantage of a channel emulator from a legal point of view is that it is not necessary to request temporal radio licenses. This fact simplifies the whole testing process quite significantly and also increases the flexibility of test scenarios.

3.1.1.1.3 RF up-conversion

Depending on the scene emulator configuration the platform architecture may involve one or more MXGs. Agilent’s MXG RF vector signal generator (see Figure 3-3a) is a sophisticated baseband signal generator and an RF up-converter instrument. However, the instrument can be used solely as an RF up-converter. The MXGs are connected to the PXB’s output interface, one per each transmitter chain, in order to up-convert the faded baseband signals to the RF and then finally feed the output to the tested sensors. All RF up-converters involved in the setup are perfectly synchronized with each other by means of a reference signal. An alternative instrument that has similar functionality as the MXG and can serve as a substitution is the ESG vector signal generator (see Figure 3-3b).

(a) (b)

Figure 3-3: Agilent (a) MXG and (b) ESG Vector Signal Generator

An overview of the particular processing steps involved in the primary scene emulator and the corresponding HW/SW platform responsible for the realization of that step is given in Table 3-1.

Table 3-1: Scene emulation steps and HW/SW platform providing corresponding functionality

Processing step / Required platform	Signal Studio	SystemVue	PXB	MXG (ESG)
1. Signal creation	✓	✓		
2. Signal combination and resampling		✓		
3. Baseband generation			✓	✓
4. Channel fading			✓	
5. RF up-conversion				✓
6. Advanced segment timing/triggering				✓

3.1.1.2 Sensors

The sensing node is built on top of the GNU Radio [GNURadio] and USRP hardware. The USRP (Universal Software Radio Peripheral) devices used in the current test bed are composed of Ettus [USRP] USRP1 and B100 motherboards and SBX, WBX and TVRX2 daughterboards that are responsible, respectively, for baseband and radio frequency processing. Other USRP devices can be easily adopted using the Universal Hardware Driver recently present in GNU Radio releases. The sensing node is in charge of performing the RF sensing and applying a local decision algorithm, as well as sending the final decision to the fusion unit.

3.1.1.2.1 Sensing node build blocks

The different tasks implemented by each sensing node can be grouped in four main building blocks as can be viewed in Figure 3-4 and are described below:

(a) Analogue RF Daughterboard

(b) Digital baseband motherboard

(c) QoSMOS sensing application

(d) QoSMOS control application

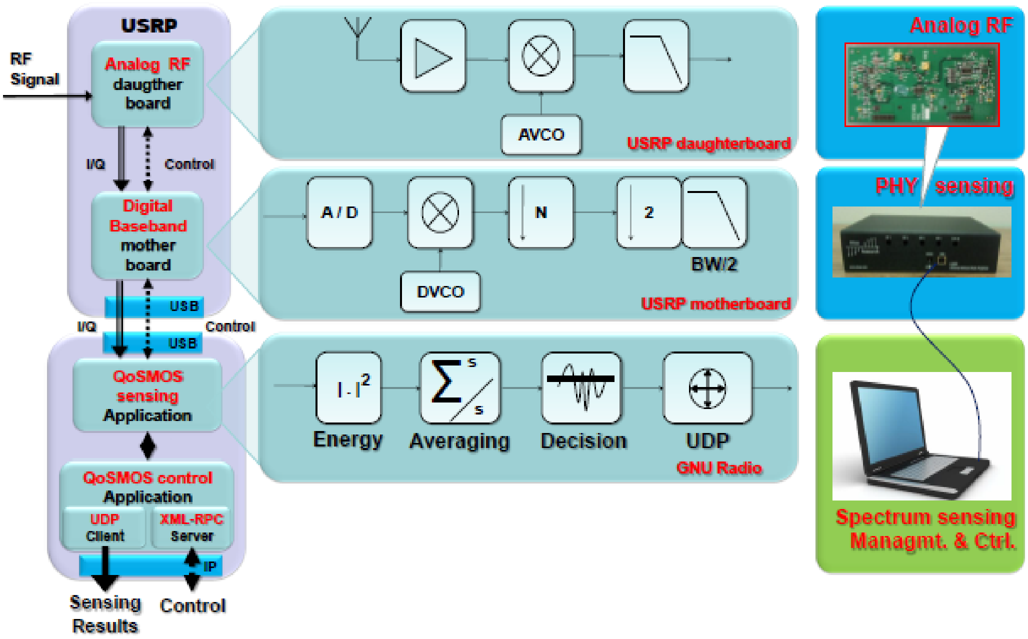


Figure 3-4: Sensing Node Architecture

(a) Analogue RF Daughterboard – The RF block resides inside the USRP hardware. All boards have a similar receiving path; a low noise amplifier followed by a complex mixer with its oscillator and a low pass filter. The boards receive the RF signal and output the analog baseband (or low intermediate frequency) IQ signal (phase and quadrature) with a bandwidth BW. The relevant parameters to control the daughterboards are:

→ Tuning frequency (F): the frequency range changes with the daughterboard used. In the current test bed the common frequency range is 400MHz to 860MHz;

→ Gain (G): the amplifier gain used on the sensors is the maximum supported by the daughterboard to maximize the SNR (Signal-to-Noise Ratio) at the output of block (i.e.: the input of analogue-to-digital converter, ADC);

(b) Digital baseband motherboard – This block resides inside USRP hardware and its main component is a baseband processing Field Programming Gate Array (FPGA). Two additional blocks that stand-out are the ADC and the host interface. The input ADC receives the analog IQ signal from the daughterboard. Once digitized, the signal is processed by the FPGA. The signal goes to a mixer that allows the fine tuning of the frequency. Then the signal is decimated in order to meet the bandwidth specifications of the host interface (Universal Serial Bus, USB, 2.0 in the described scenario). The relevant parameters to control the motherboard are:

→ Tuning intermediate frequency (IF): the digital mixer oscillator frequency (when the wanted RF frequency can't be tuned by the daughterboard RF oscillator, a fine adjustment is made in the digital mixer in order to centre the signal at the desired frequency);

→ Decimation (D): decimation value to be used in decimation filters to achieve the required host interface bandwidth;

(c) QoSMOS sensing application – This block resides in the host computer and it is here that the detection algorithm is implemented. The input of the block is the baseband IQ signal coming from the USRP hardware. This block outputs the local decisions that are encapsulated in UDP packets. The relevant control parameters of this block are:

→ Sensing time (S): period between sensing decisions;

→ Samples (N): number of samples used in detection;

→ Threshold (T): sets the detector decision threshold;

→ Network address (N): set the destination IP address and port for the UDP stream;

(d) QoSMOS control application – This block implements the CM-RM-RU (Resource Unit) present in the sensors. It receives the configuration, remotely via XML-RPC, and applies the parameters to the respective sensor blocks inside the SS-CTRL.

3.1.1.2.2 Sample calibration

The signal reaching the sensor is processed by RF and baseband blocks to generate the complex baseband samples that are received in GNU Radio. Since the amplitude levels of samples taken by the ADC are not referenced to the RF input (receiver path losses are not known), there is a need for a calibration procedure of the various sensors. This is crucial for the test bed performance. The diverse experiments carried out showed that similar hardware devices can have differences of over 1dB in the uncalibrated measured power. These differences, if not corrected, would severely impact the outcome of the trials, leading to erroneous results. This calibration ensures that the values measured by the sensor's ADC are properly scaled and accurately represent the signal at its input. The unit of interest for the implemented detection algorithm is the input signal power $P=E\{|i|^2\}$. This procedure should be executed before the algorithm evaluation runs to ensure that the impact of the calibration errors is minimized. Figure 3-5 shows the blocks that must be considered in the calibration procedure.

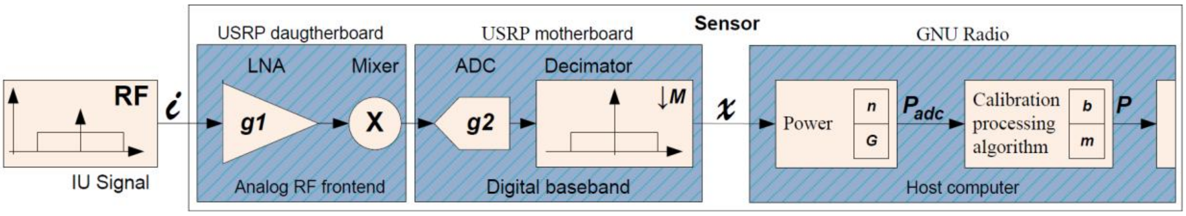


Figure 3-5: Sensing Node Calibration

The input of the GNU Radio is a complex signal $x = \sqrt{g}(i+n)$ where $g = g_1.g_2$ is the sensor gain (RF and baseband), *I* represents the complex IU input signal and *n* is the noise. The input of the power calibration algorithm is the uncalibrated power measured by the ADC and is expressed in (1), where *N* is the number of samples utilized to measure the power and $G = 10\log_{10} g$ is the sensor gain.

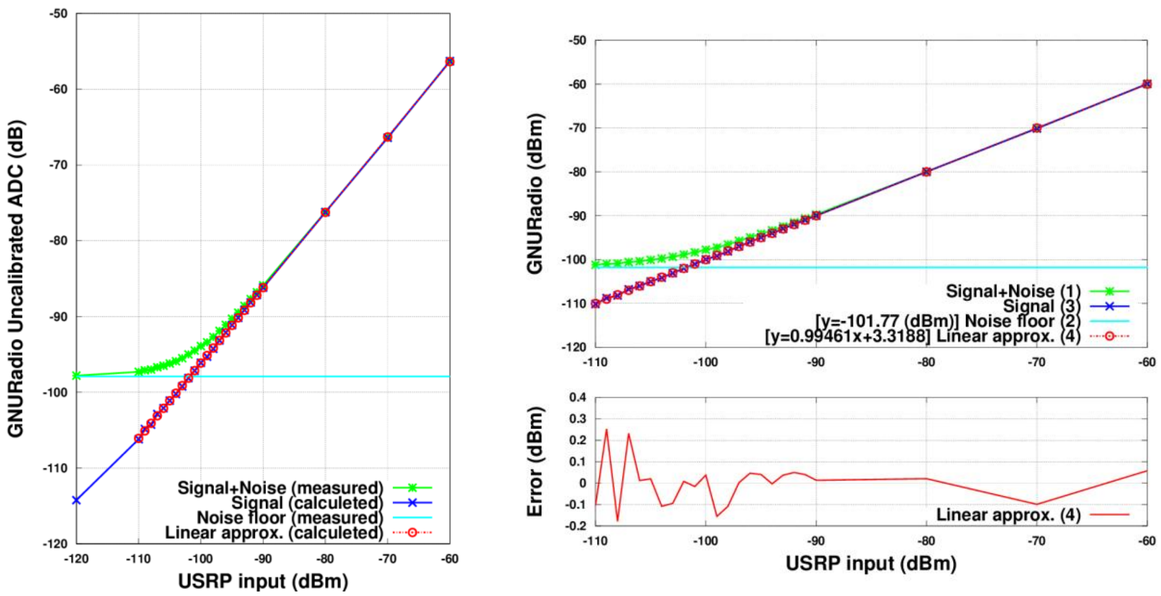
$$P_{adc}(x) = 10\log_{10}\frac{\sum_N |x|^2}{N} - G \quad (1)$$

The power of the signal measured by the ADC is $P_{adc}(x) = 10\log_{10}\sum_N |i+n|^2 / N$. The output of calibration block is the calibrated signal power of the input IU, as shown in (2).

$$P(x) = \frac{P_{adc}(x) - b}{m} \text{ (dBm)} \quad (2)$$

where *b* is the calibration offset and *m* is the calibration gain. The values of *b* and *m* are constants obtained in the calibration procedure.

To get the values of *m* and *b*, the sensor's input is feed with a calibrated signal with varying power levels. A table with pairs (input signal power, measured (signal+noise) power) is built. The noise floor of the sensor is also estimated, terminating the sensor's RF input with a 50Ω impedance. By subtracting the noise floor and using a mean square error algorithm, a linear approximation of the ratio input signal power to measured signal power is obtained, resulting in the wanted *m* and *b* values of (2). An example of the calibration process is showed in Figure 3-6. The uncalibrated laboratory measurements, Figure 3-6a, were done with *m = 1* and *b = 0* in (2), to find the calibration constants *m0* and *b0*, and noise floor. The linear approximation which provides *b0* and *m0* can be seen in red, Figure 3-6a. The calibrated results are present in Figure 3-6b with *m = m0* and *b = b0* in (2), applied to the same data set acquired previously. The top plot is the calibrated result and the bottom one is the error in the linear approximation.



(a) Uncalibrated laboratory measurements ($b = 0; m = 1$)

(b) Calibrated results ($b = b0; m = m0$)

Figure 3-6: Sample Calibration Example

In [D7.2] the initial calibration results were presented. In this deliverable, in Table 3-2, the final calibration results for the set of sensors used in the different tests are being presented. The individual calibrations performed for all the sensors are shown in the different figures below, from Figure 3-7 to Figure 3-13.

Table 3-2: Sensors specification and parameters

Sensor	Motherboard (Serial)	Daughterboard (Serial)	Rx port	Rx Gain (dB)	M	b	Noise Floor (dBm)
S1	B100 (E0R11Y9B1)	SBX (ECR15X3XS)	RX2	51	0.99461	3.3188	-101.77
S2	B100 (E1R11YAB1)	SBX (EAR15XDXS)	TXRX	51	0.99749	2.8172	-100.87
S3	B100 (E3R10ZFB1)	SBX (EAR15XBXS)	RX2	51	-0.96684	-1.9058	-97.322
S4	B100 (E5R11YCB1)	SBX (E1R11YBXS)	RX2	51	-0.99108	5.641	-101.55
S4	B100 (E5R11YCB1)	SBX (E1R11YBXS)	TXRX	51	-0.99387	4.5865	-101.01
S5	B100 (E0R11Y9B1)	WBX	RX2	51	-1.031	-47.269	-56.68
S6	B100 (E3R10ZFB1)	TVRX2 (E2R10ZERT)	RX2	0	-0.96908	42.668	-98.411
S7	USRP1 (45f1c6c0)	SBX (ECR15X3XS)	TXRX	51	-0.98112	-10.303	-98.251

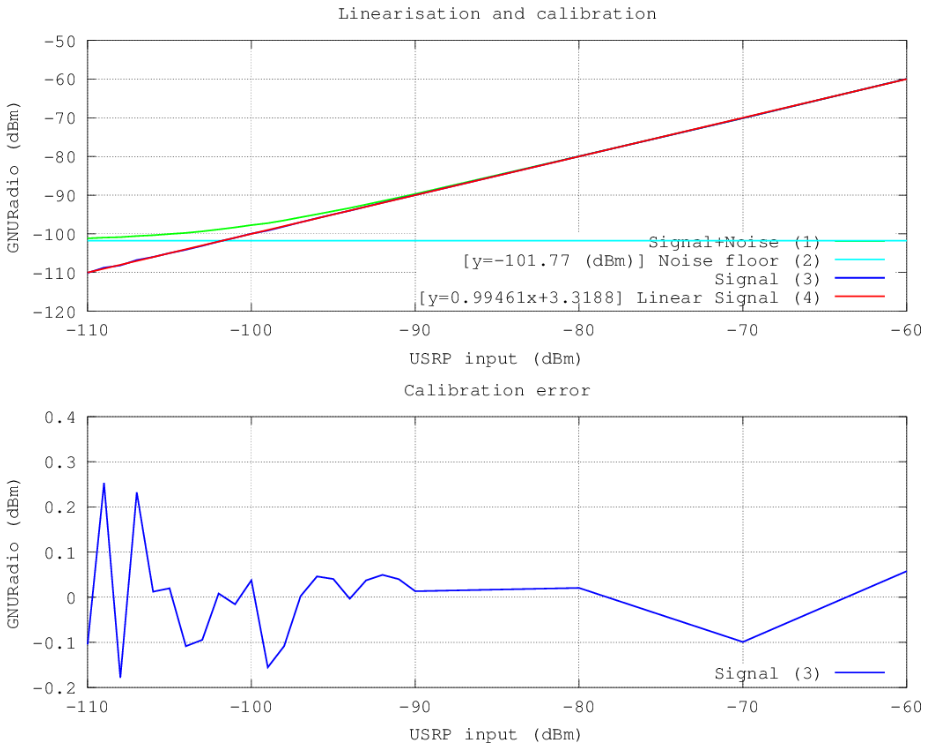


Figure 3-7: Sensor S1 calibration results

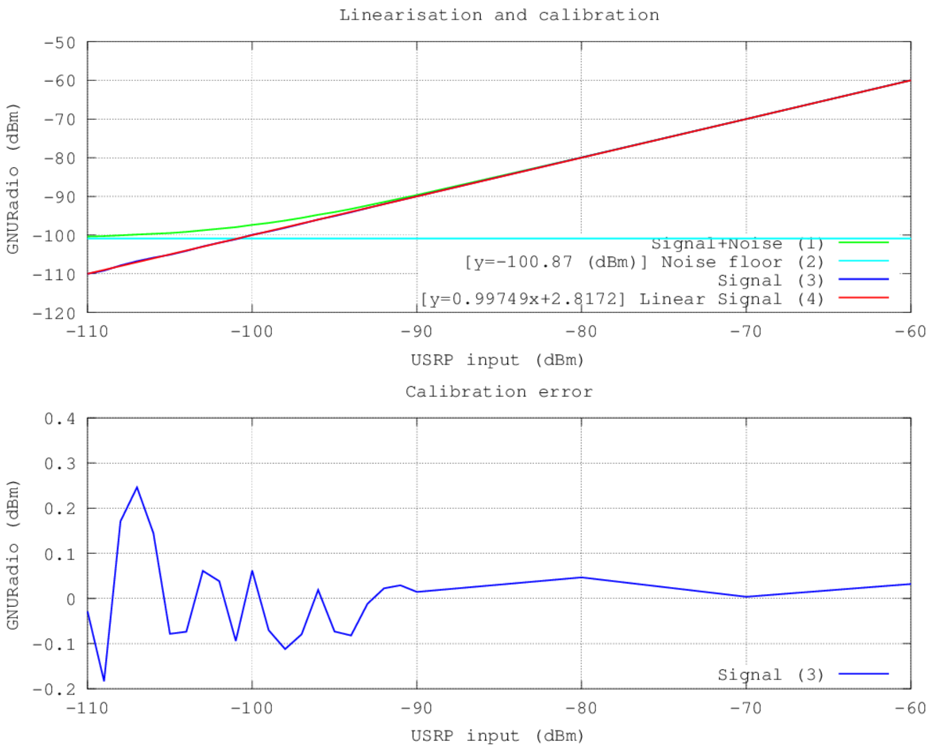


Figure 3-8: Sensor S2 calibration results

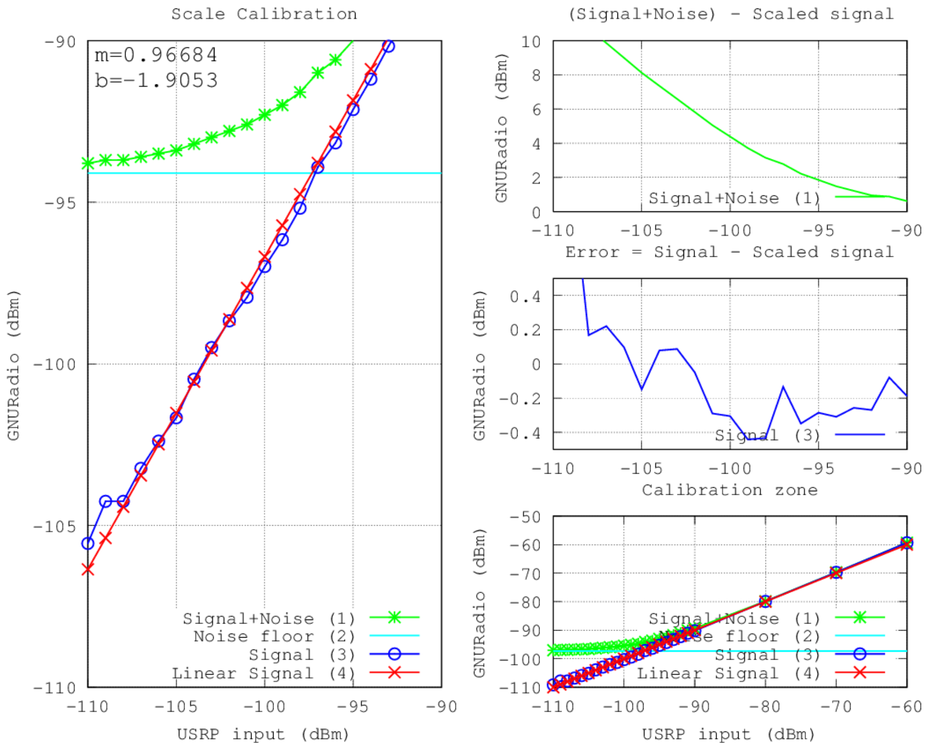


Figure 3-9: Sensor S3 calibration results

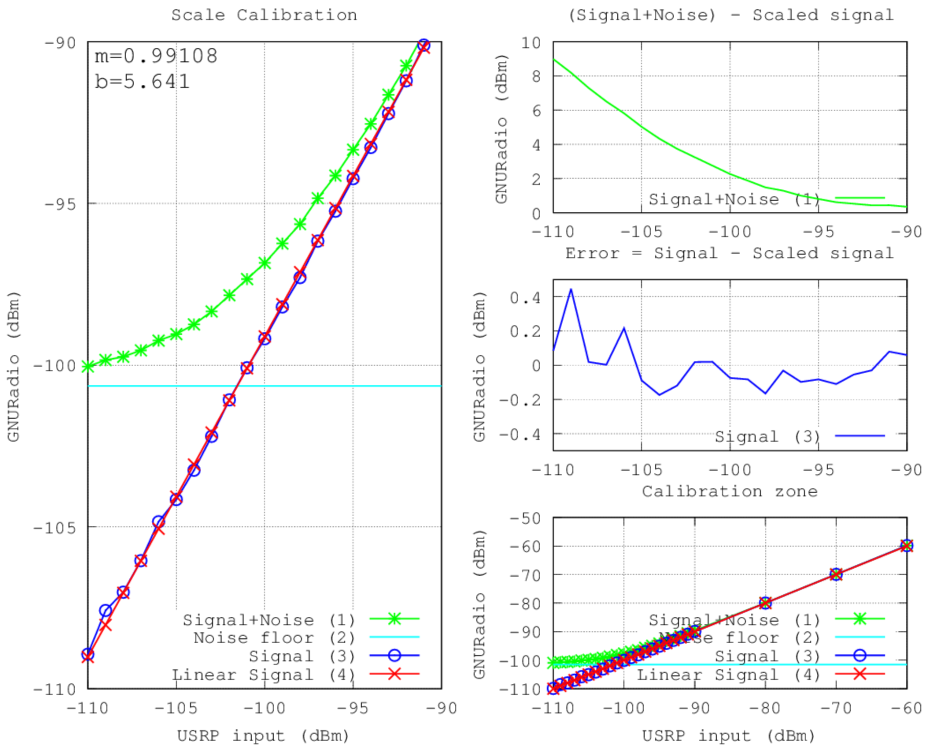


Figure 3-10: Sensor S4 calibration results

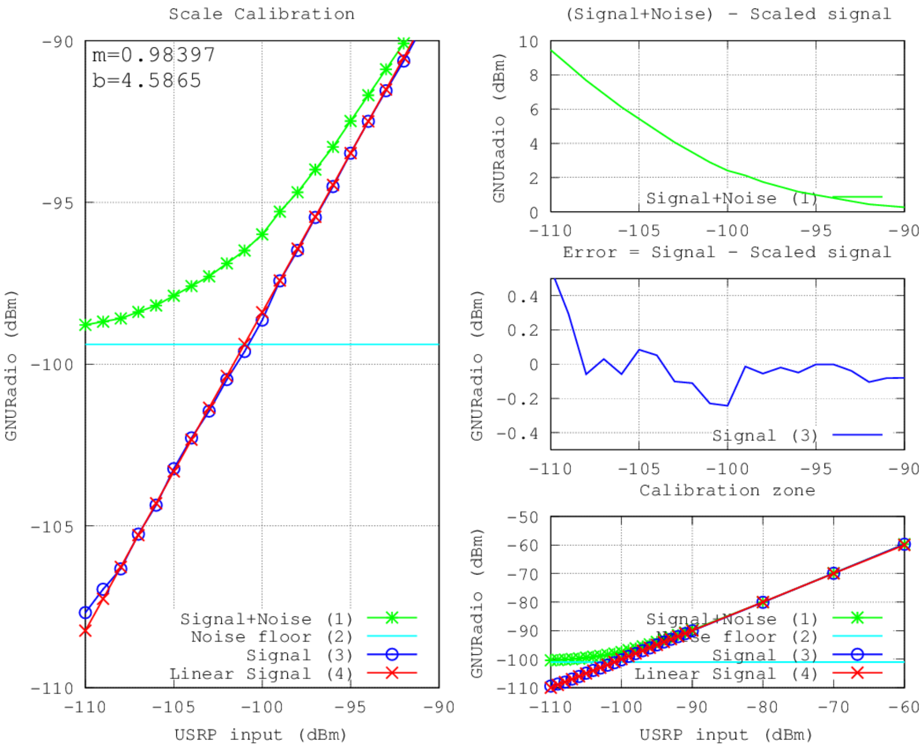


Figure 3-11: Sensor S4 calibration results

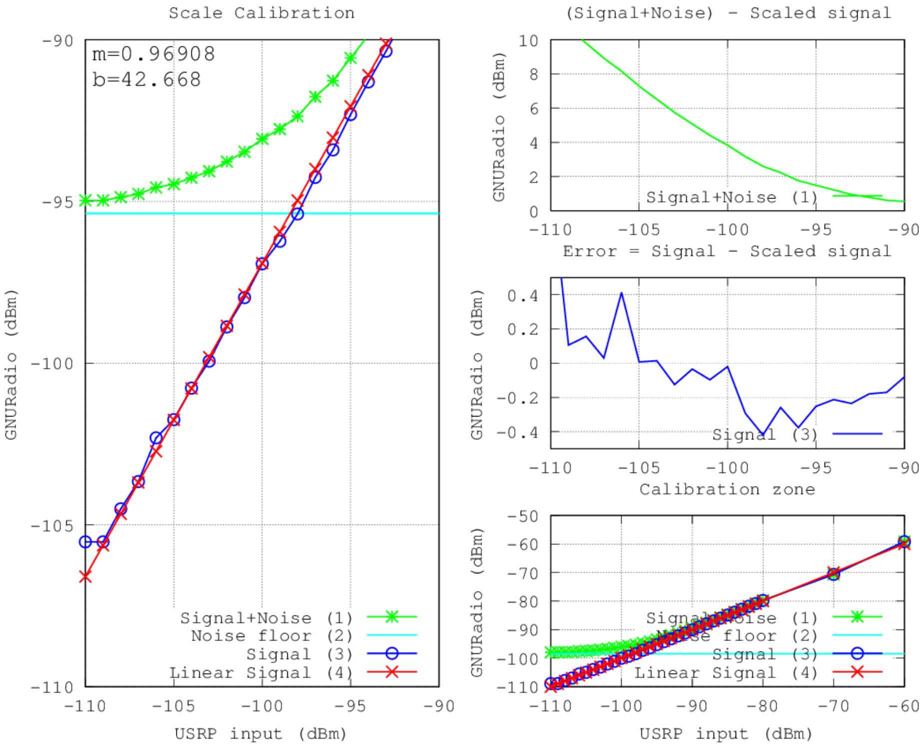


Figure 3-12: Sensor S6 calibration results

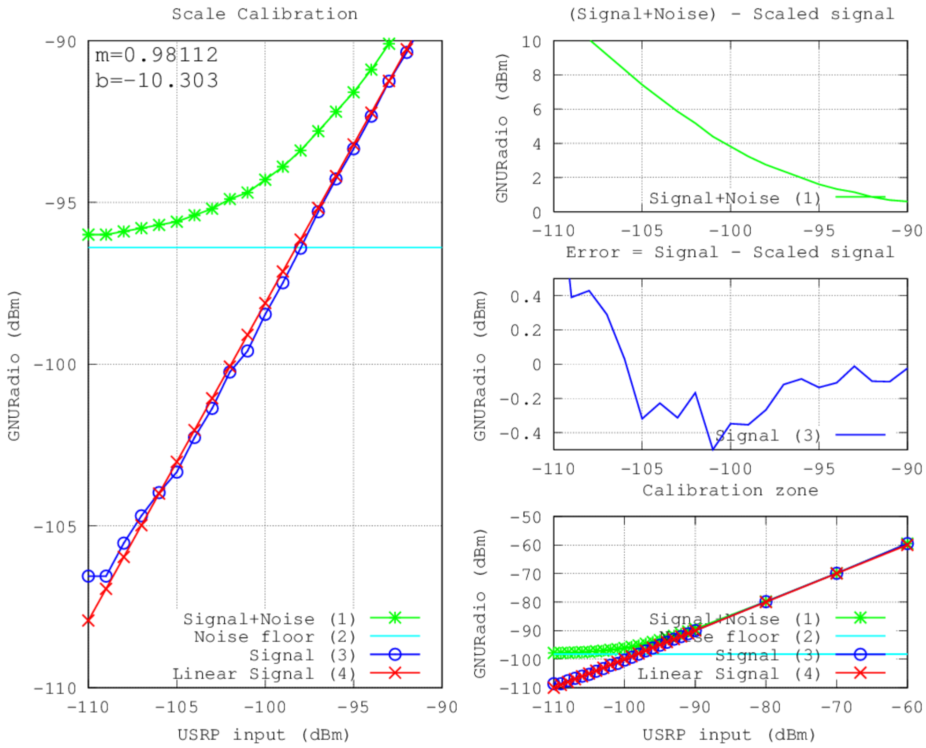


Figure 3-13: Sensor S7 calibration results

3.1.1.2.3 Local energy detection algorithm

The energy sensor makes the decision on the presence of the IU signal based on the energy of a predetermined number of samples, *N*, of the signal at its input. If the signal power *P* is greater than the decision threshold, *T*, the sensor indicates the presence of IU.

The implementation of the algorithm in the energy sensor is illustrated in Figure 3-14. The RF signal inputs in the USRP [1]. After processing, the IQ samples are passed to the host Personal Computer (PC) running the sensor application. The samples are squared [2], summed and passed to logarithmic scale [3], calibrated [4] and the decision made [5]: output '1' indicates the presence of IU and '0' its absence [6].

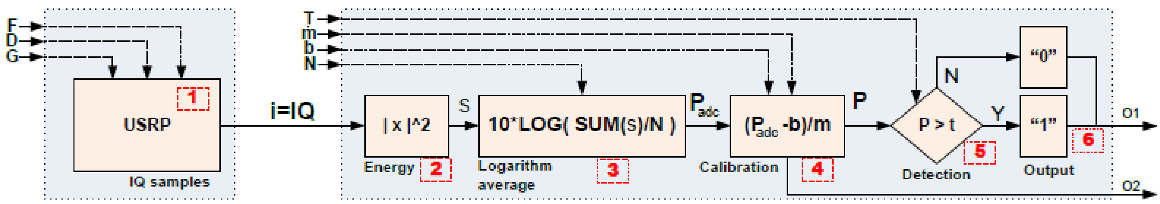


Figure 3-14: Local energy detection algorithm

3.1.1.3 Wideband Real-Time Spectrum Analysis with Frequency Mask Triggering

Real-Time Spectrum Analysis is a key tool for studying transient phenomena in the spectral domain. QoSMOS offers an RTSA solution with the Agilent PXA high-performance spectrum analyzer (see Figure 3-15) which is currently outperforming the competitive products. The key specifications are:

- Gap-free real-time spectrum generation at 293,000 FFT/s;
- Generation of multiple displays: density, real-time spectrum, spectrogram, power versus time;
- Real-time analysis bandwidth of 160 MHz;
- Frequency Mask Triggering (FMT): detect signals as short as 3.57 µs with 100% Probability of Intercept (POI);
- Spurious Free Dynamic Range (SFDR) of -75 dB over full analysis bandwidth;
- Integrated analysis software through VSA (Vector Signal Analysis) 89600 software suite.

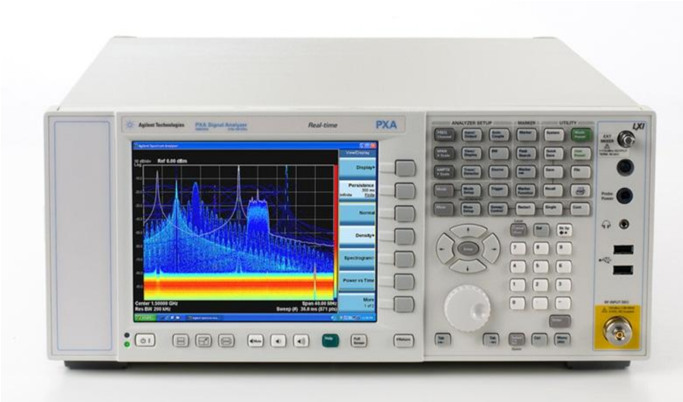


Figure 3-15: State-of-the-art Agilent PXA spectrum analyzer with RTSA

Gap-free operation means that real-time spectra are generated continuously, on consecutive blocks of samples. In this way, all events (including short transients) are processed and can be triggered on.

QoSMOS has focused on significantly increasing the real-time analysis bandwidth further to 250 MHz, in connection to FMT. This approach has two effects. First, it allows monitoring a significantly wider spectrum portion in real-time, and second, it allows for a shorter signal detection time (trigger response to transient event) for a given FFT size.

Figure 3-16 shows the RTSA development environment of the real-time spectrum analyzer baseband portion. It includes the digitizer, the DDR3 memory and FPGA resources. The FPGA is a Xilinx XC6VLX240T on an ML605 board. On the FPGA the following functions are implemented:

- Signal conditioning and reformatting;
- Down-conversion from intermediate frequency (IF) to baseband and filtering;
- FFT processing, generating a continuous real-time spectrum without gaps;
- log scale (dB) representation;
- Frequency Mask Triggering module;
- Interface to Ethernet link.

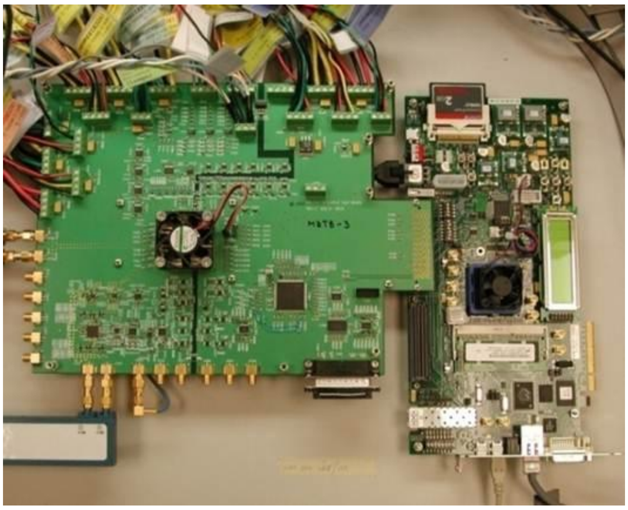


Figure 3-16: Development platform with digitizer board (left) and ML605 board (right)

The command interface and the graphical user interface (GUI) run on a PC interfacing with the development platform over an Ethernet link (see Figure 3-17). This Java-based software takes care of all initializations, parameter programming and FMT mask programming. Furthermore it displays the real-time spectrum, FMT frames and mask definitions.

The FMT module is capable of comparing the streaming real-time spectrum with two masks simultaneously. The FMT module generates a trigger signal when an FFT frame violates one or two FMT masks. Upon this trigger signal, a snapshot of the real-time FFT spectrum is taken and additional actions can be issued. The masks are fully programmable with the same frequency resolution as the FFT. This allows fine grain monitoring of a specific radio scene.

The dual mask feature enables some interesting applications:

- Testing the severity of a violation, by comparing the real-time spectrum with two masks which are distinguished by a magnitude offset and a frequency tolerance.
- Testing if the spectral components stay within specified power levels as a function of frequency.

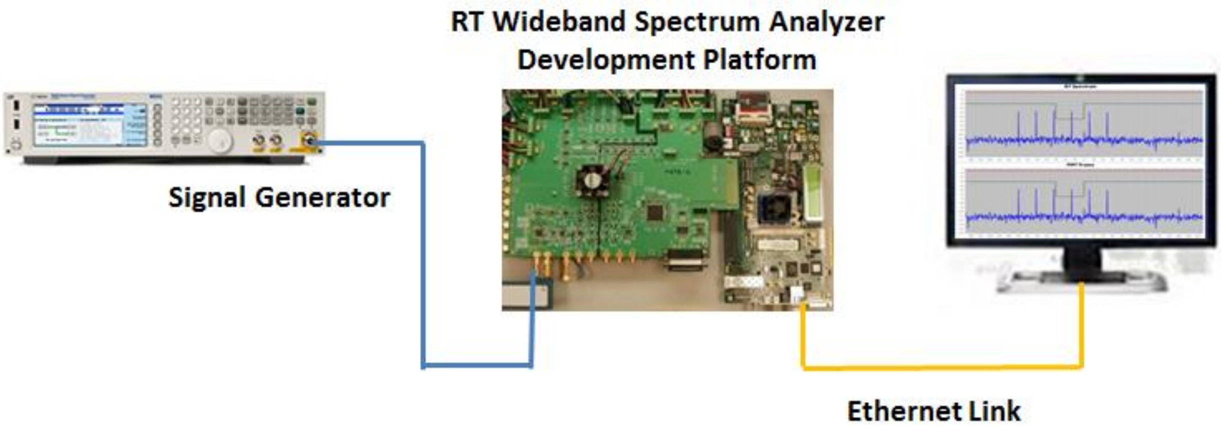


Figure 3-17: FMT Real-time spectrum analysis test setup

3.2 Validation process and results obtained

This section discusses the validation tests carried out and gives the results obtained. First, the multi-standard radio aspect of the primary scene emulator is validated with a set of three independently evolving signals. Then, the radio scene for the CR sensor tests is defined and the channel fading functionality is demonstrated. The following subsection reports on the results of the CR sensor performance evaluation for a set of different conditions. Finally, the results of the FMT real-time spectrum analysis in two test scenarios are presented.

3.2.1 PSE configuration and validation

The primary radio scene generation 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. For validation of this concept we consider a scene with three different incumbent waveforms:

- DVB-T/H signal (bandwidth 8 MHz) in the band centred at 0.8 GHz;
- GSM/EDGE signal (bandwidth 1.08 MHz) centred at 0.792 GHz;
- LTE FDD signal (bandwidth 5 MHz) centred at 0.808 GHz.

Exemplary evolution of such radio scene is given in Figure 3-18; the screenshots from spectral analyzer at corresponding scene segments verify the output of the scene emulator. Each waveform is independently turned on and off at predefined time instances. The process of emulating a scene can be also viewed as a sequence of quasi-stationary (from spectral point of view) waveform segments, with segments changing at time instances *t1-t8*.

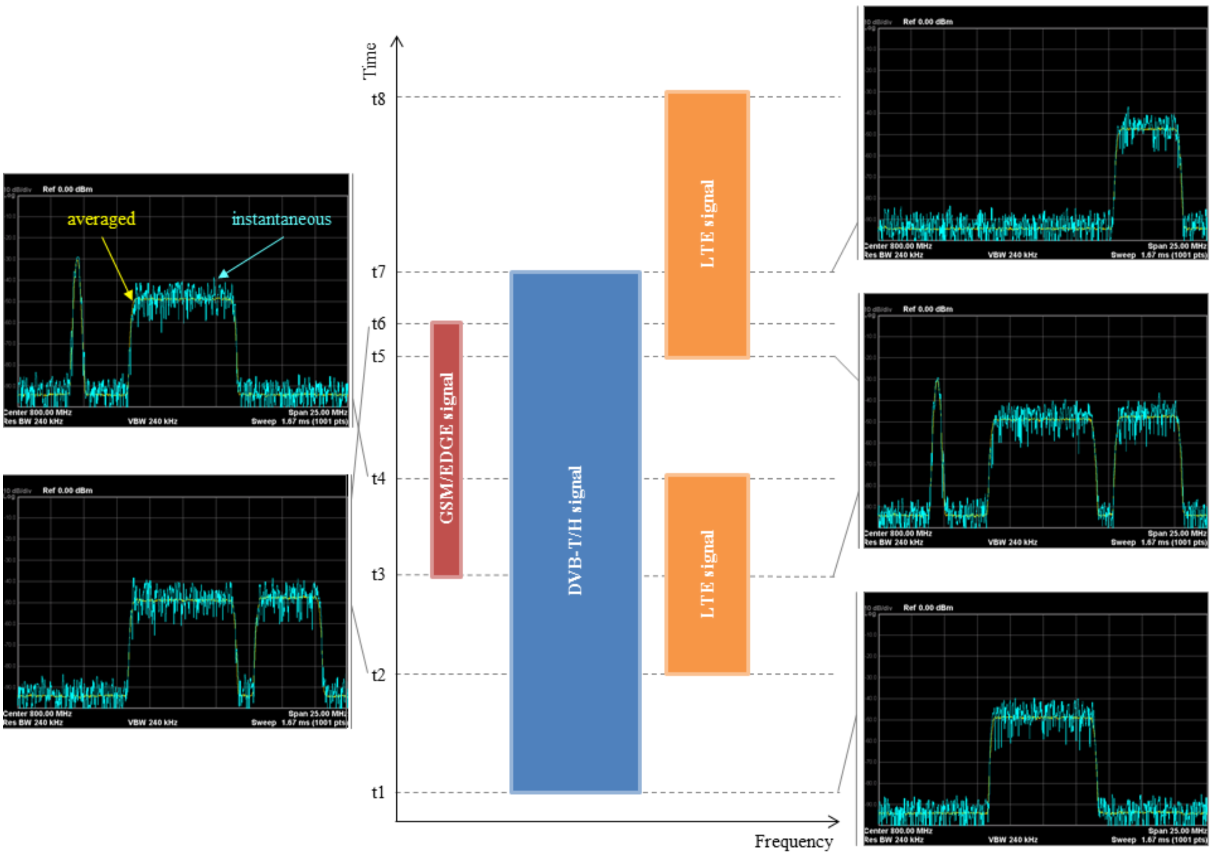
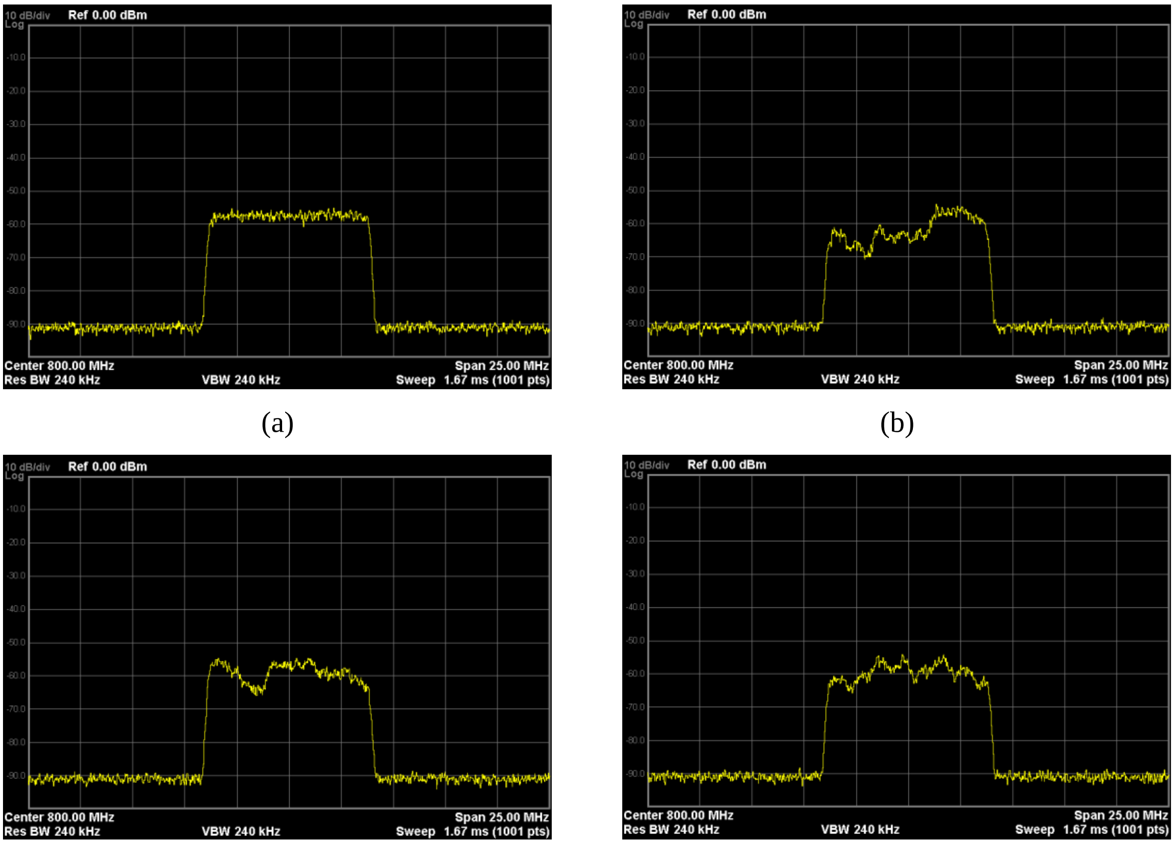


Figure 3-18: Evolution of an emulated radio scene with corresponding (instantaneous and averaged) spectrum

For the verification of the PSE-to-CR-sensor link an over-complicated scene is not necessary. In order to feed the sensors with an emulated signal a scene without the necessity of combining multiple signals is chosen. It consists of one superframe of an 8 MHz bandwidth Digital Video Broadcasting-Terrestrial/Handheld (DVB-T/H) signal in 8K mode and centred at 0.8 GHz carrier frequency. The duration of such DVB waveform segment is 0.30464 s. The guard interval is equal to¼4 of the T_u (useful symbol duration).

A 1x1 single-input single-output (SISO) configuration setup is used with the DVB-T-based radio scene being played back from one BBG card. Channel fading is applied to the DVB signal according to a vehicular channel model (for an increased fading effect)

The effects of channel fading on the signal spectrum are shown in Figure 3-19. For better visibility the spectrum is averaged over 15 samples.



(a) (b)

(c) (d)

Figure 3-19: Spectrum of an emulated 8 MHz DVB-T/H waveform (a) before and (b), (c), (d) after channel fading

3.2.2 RF sensing tests and results

3.2.2.1 Tests

The performance of the sensing tests was characterized using the probabilities of false alarm (PFA) and detection (PD). The tests were performed with and without fading channel, resulting in the metrics PFA, PD without channel ($\mathrm{PD}_{\overline{channel}}$) and PD with channel ($\mathrm{PD}_{\mathrm{channel}}$). The methodologies adapted to experimentally measure the metrics were the ones presented in Figure 3-20:

- PFA - measurements were performed terminating the sensor's input with 50 impedance.
- $\mathrm{PD}_{\overline{channel}}$ - measurements were performed feeding the sensor's input with the DVB signal generated by the scene emulator and setting the signal power to get a SNR of 0dB and 2dB.
- $\mathrm{PD}_{\mathrm{channel}}$ - test was performed the same way as the previous one ($\mathrm{PD}_{\overline{channel}}$) with the addition of an emulated LTE Extended Typical Urban Low Doppler channel [3GPP8] that affects the DVB signal received by the sensor's input.

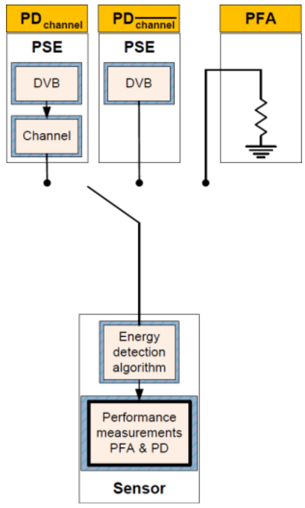


Figure 3-20: Experimentally methodologies

The tests were performed with the sensors shown in Table 3-2. It is important to stress that both the values of the decision threshold and SNR are dependant of the intrinsic characteristic (and highly relevant) of each of the sensors–- its noise floor, *nf*. All the sensors are tuned for 800MHz with a bandwidth of 8MHz. The different lines in each plot correspond to the decision thresholds, $T = nf_{sensor} + \{0,1,2\}\ (\mathrm{dB})$, used in the detection. Each line was built using the different number of samples, $N = \{10,20,30,40,50,60,70,80,90\}$.

3.2.2.2 Algorithm

The algorithm used is shown in Figure 3-21, the samples, S, entering the block [2] is the estimated energy of the input signal in dB computed with Ni samples. Detection occurs when these samples, S, are above the detection threshold defined by Ti, block [4]. The probability is calculated in block [7] and is the ratio of the total number of detections, D0 block [1], and the total number of events, E block [3], performed on all test (S samples examined). The total number of detections D0 is defined in variable D at the beginning of block [1], and this variable will be decremented in block [5] where samples S are above the threshold of detection, block [5]. When the block [6] checks the condition D = 0 means that D0 detections have been performed. The blocks [8], [9] and [10] serve to traverse the sets of numbers of samples, N, and decision thresholds, T, defined for testing.

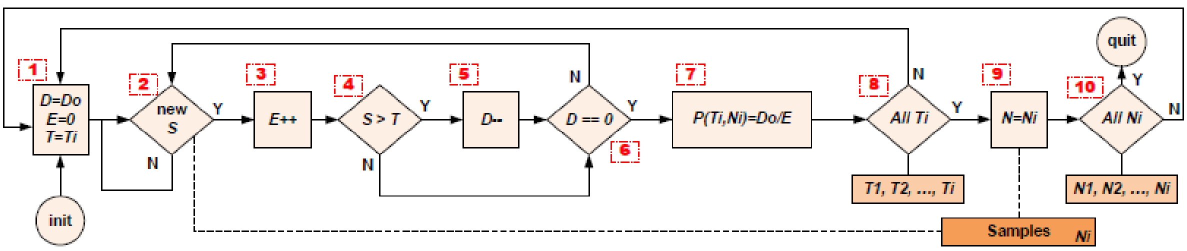


Figure 3-21: Experimentally methodologies

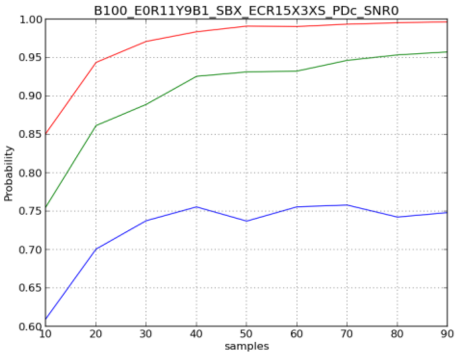
The test result is the matrix of probabilities, $P(n,t)$ (3), where *n* is the number of samples and *t* is the decision threshold:

$$P(n,t) = \begin{bmatrix} p_{n_0,t_0} & p_{n_0,t_1} & p_{n_0,t_2} & \cdots & p_{n_0,t_t} \\ p_{n_1,t_0} & p_{n_1,t_1} & p_{n_1,t_2} & \cdots & p_{n_1,t_t} \\ p_{n_2,t_0} & p_{n_2,t_1} & p_{n_2,t_2} & \cdots & p_{n_2,t_t} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{n_n,t_0} & p_{n_n,t_1} & p_{n_n,t_2} & \cdots & p_{n_n,t_t} \end{bmatrix} \quad (3)$$

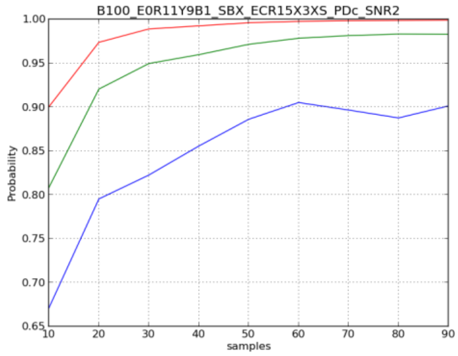
These matrices are displayed in graphical form for each test performed and the probabilities can be viewed based on the number of samples used for the various decision thresholds.

3.2.2.3 Results

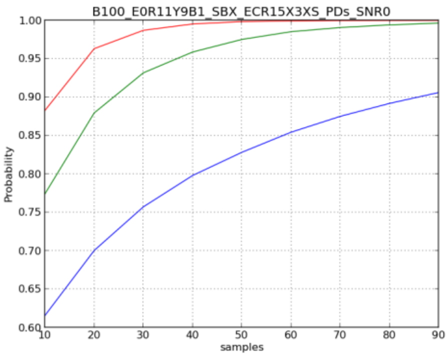
The graphs shown from Figure 3-22 to Figure 3-28 show the probability of false alarm and detection of the set of sensors utilized. No significant differences exist between the sensors because the SNR at the input of the various sensors is equal. The different lines refer to the decision thresholds used, T=0dB (red), T=1dB (green) and T=2dB (blue).



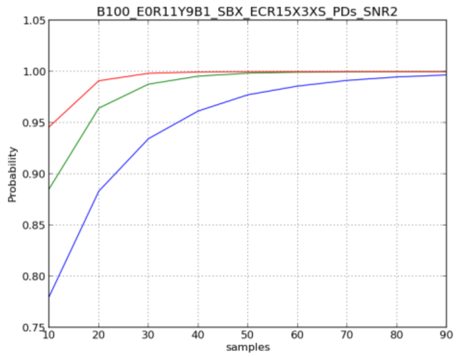
(a) PD(SNR=0dB, channel)



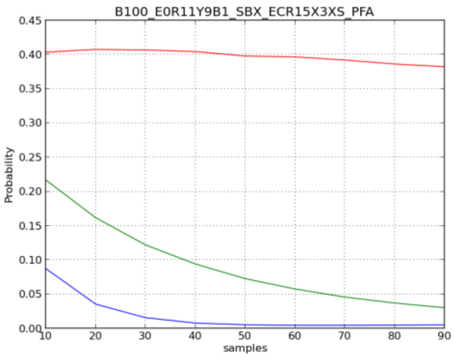
(b) PD(SNR=2dB, channel)



(c) PD(SNR=0dB, nochannel)

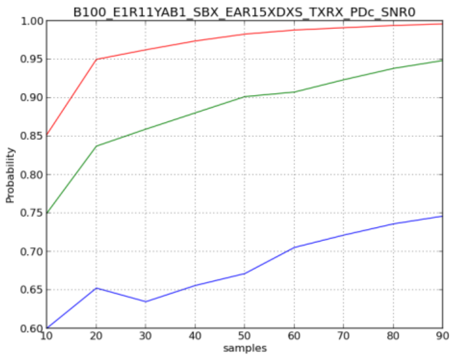


(d) PD(SNR=2dB, nochannel)

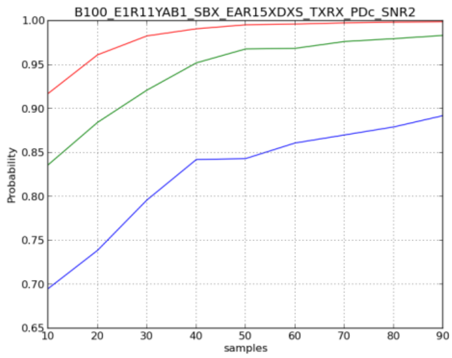


(e) PFA

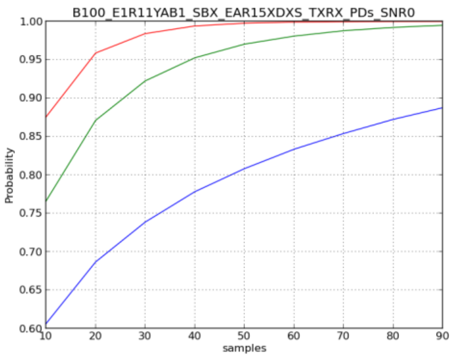
Figure 3-22: Detection and false alarm probability of sensor S1



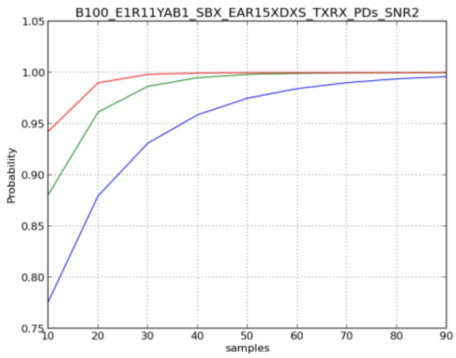
(a) PD(SNR=0dB, channel)



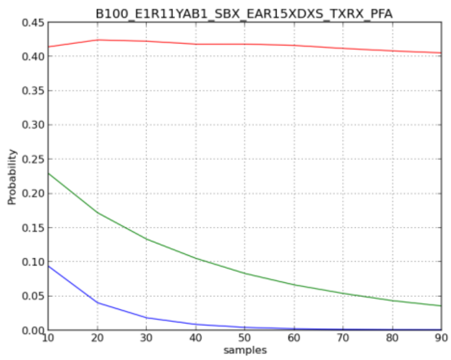
(b) PD(SNR=2dB, channel)



(c) PD(SNR=0dB, nochannel)

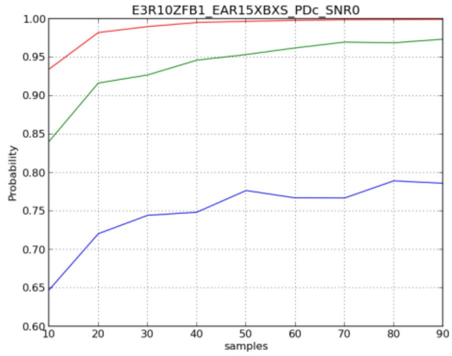


(d) PD(SNR=2dB, nochannel)

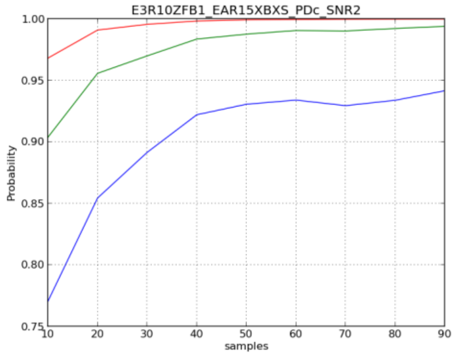


(e) PFA

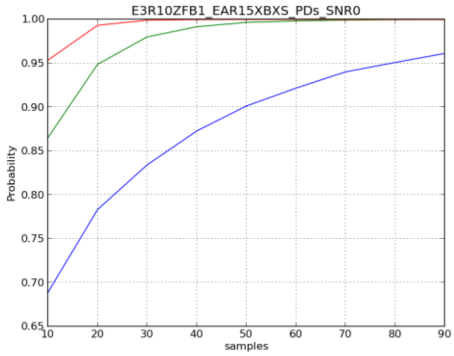
Figure 3-23: Detection and false alarm probability of sensor S2



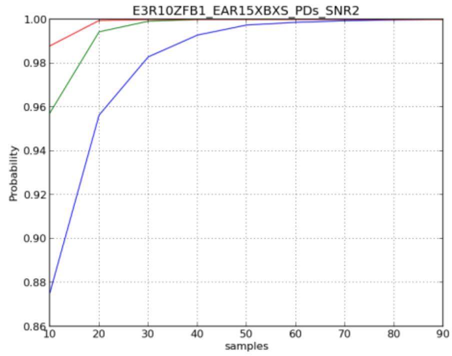
(a) PD(SNR=0dB, channel)



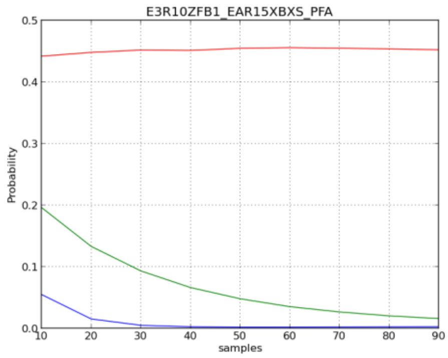
(b) PD(SNR=2dB, channel)



(c) PD(SNR=0dB, nochannel)

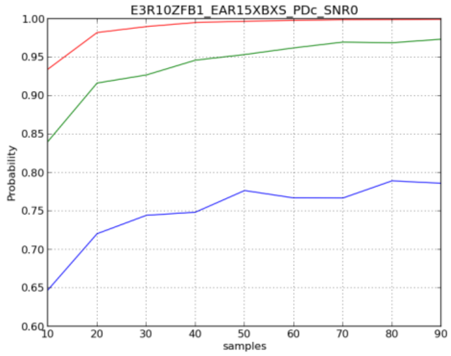


(d) PD(SNR=2dB, nochannel)

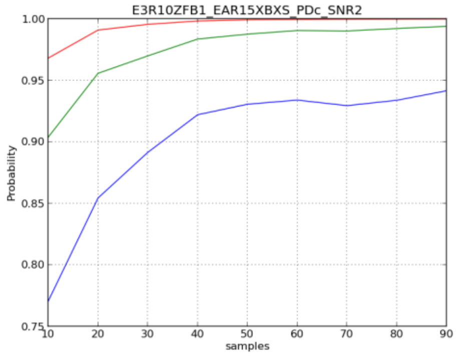


(e) PFA

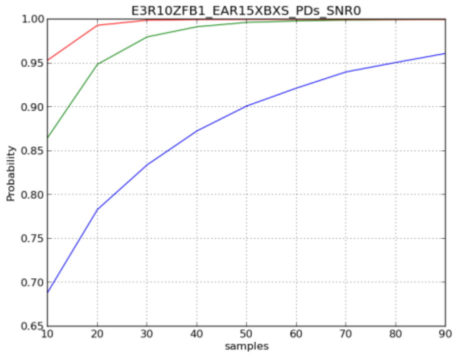
Figure 3-24: Detection and false alarm probability of sensor S3



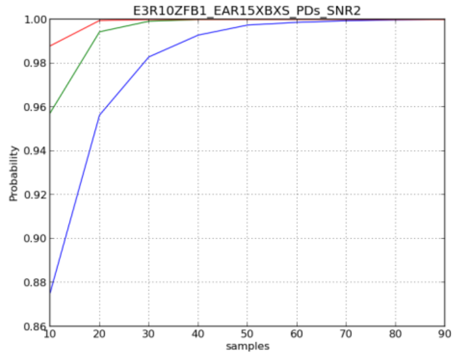
(a) PD(SNR=0dB, channel)



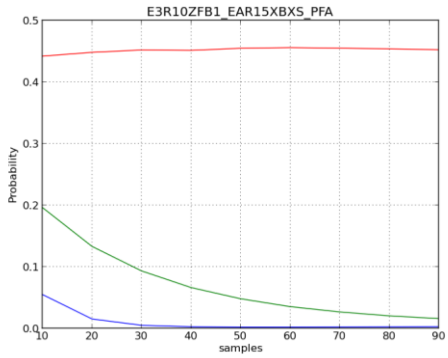
(b) PD(SNR=2dB, channel)



(c) PD(SNR=0dB, nochannel)

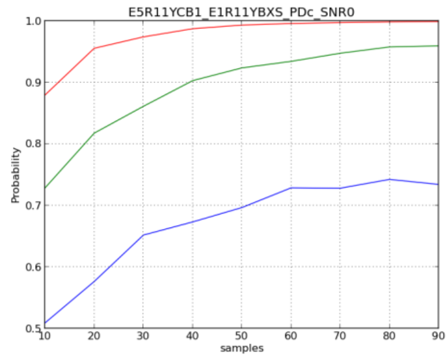


(d) PD(SNR=2dB, nochannel)

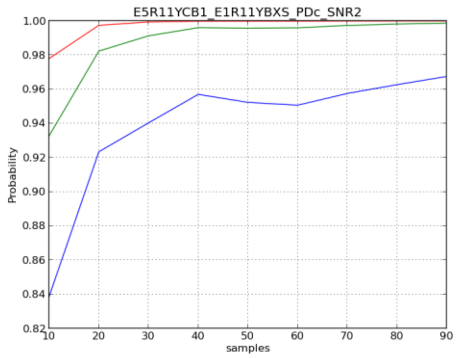


(e) PFA

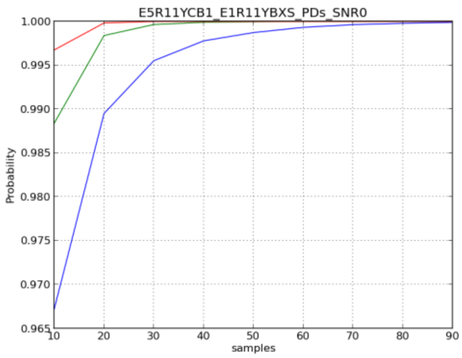
Figure 3-25: Detection and false alarm probability of sensor S4



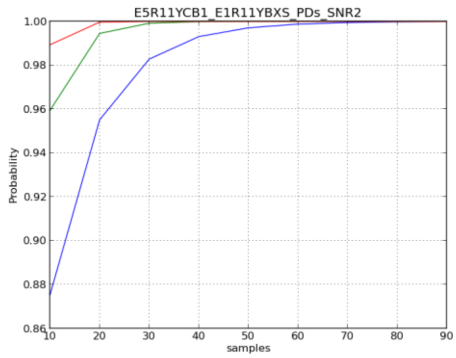
(a) PD(SNR=0dB, channel)



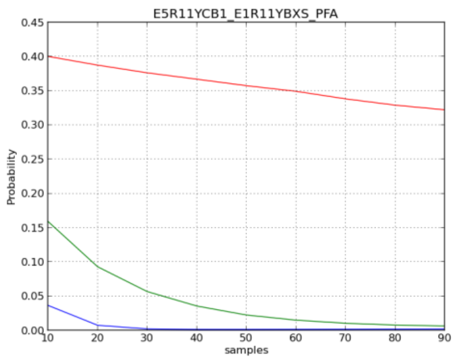
(b) PD(SNR=2dB, channel)



(c) PD(SNR=0dB, nochannel)

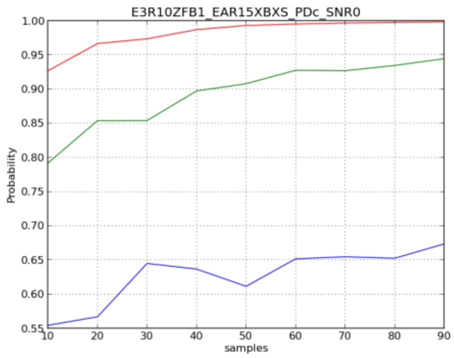


(d) PD(SNR=2dB, nochannel)

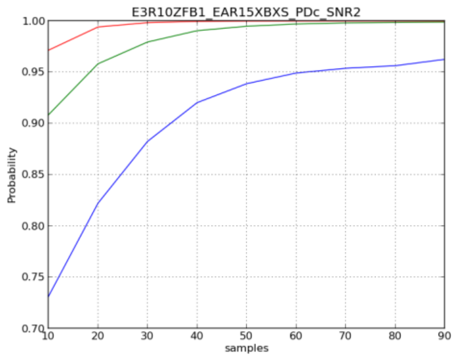


(e) PFA

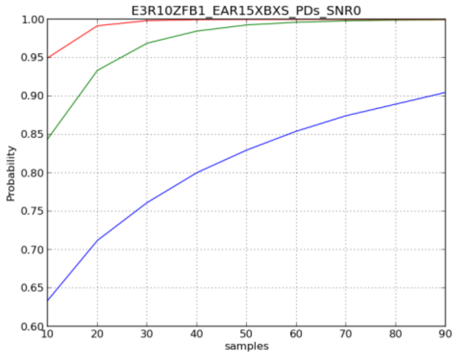
Figure 3-26: Detection and false alarm probability of sensor S5



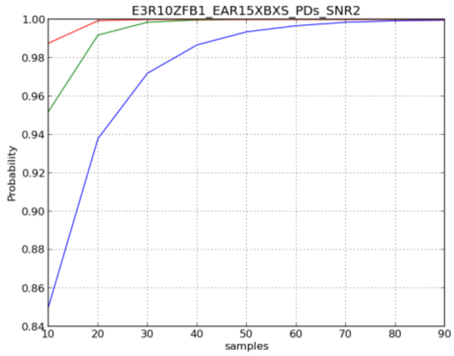
(a) PD(SNR=0dB, channel)



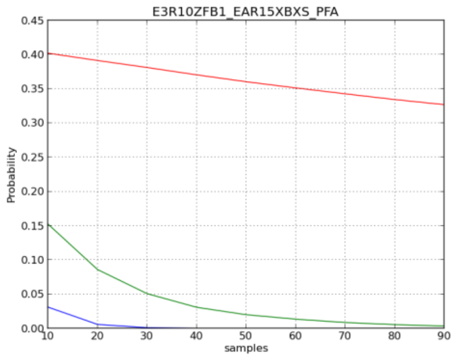
(b) PD(SNR=2dB, channel)



(c) PD(SNR=0dB, nochannel)

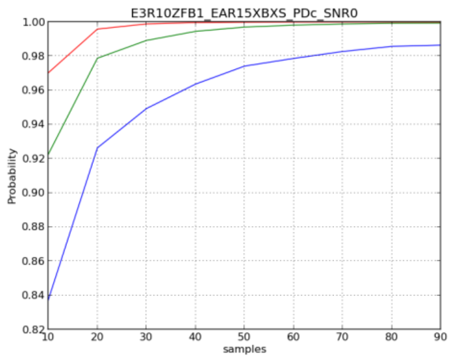


(d) PD(SNR=2dB, nochannel)

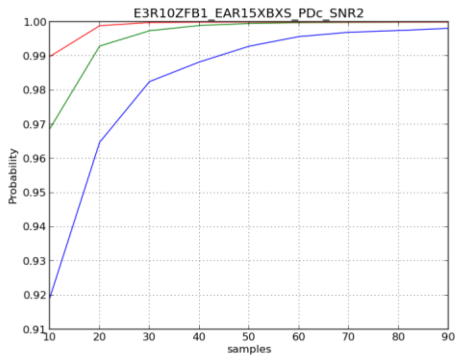


(e) PFA

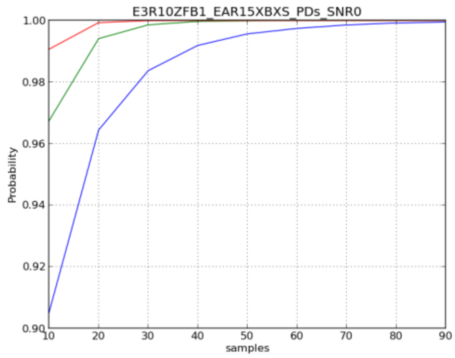
Figure 3-27: Detection and false alarm probability of sensor S6



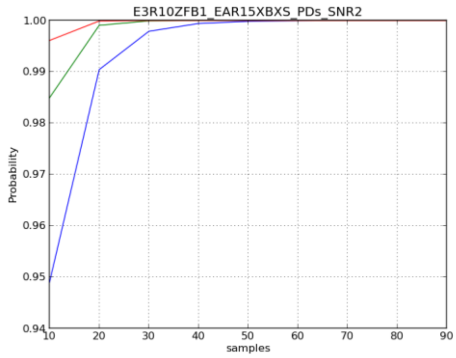
(a) PD(SNR=0dB, channel)



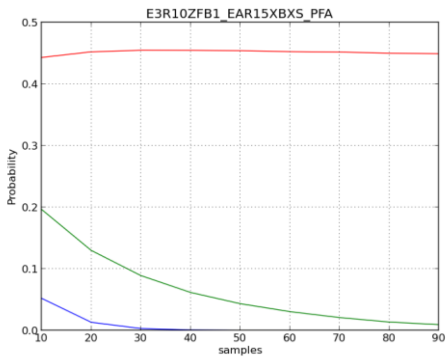
(b) PD(SNR=2dB, channel)



(c) PD(SNR=0dB, nochannel)



(d) PD(SNR=2dB, nochannel)



(e) PFA

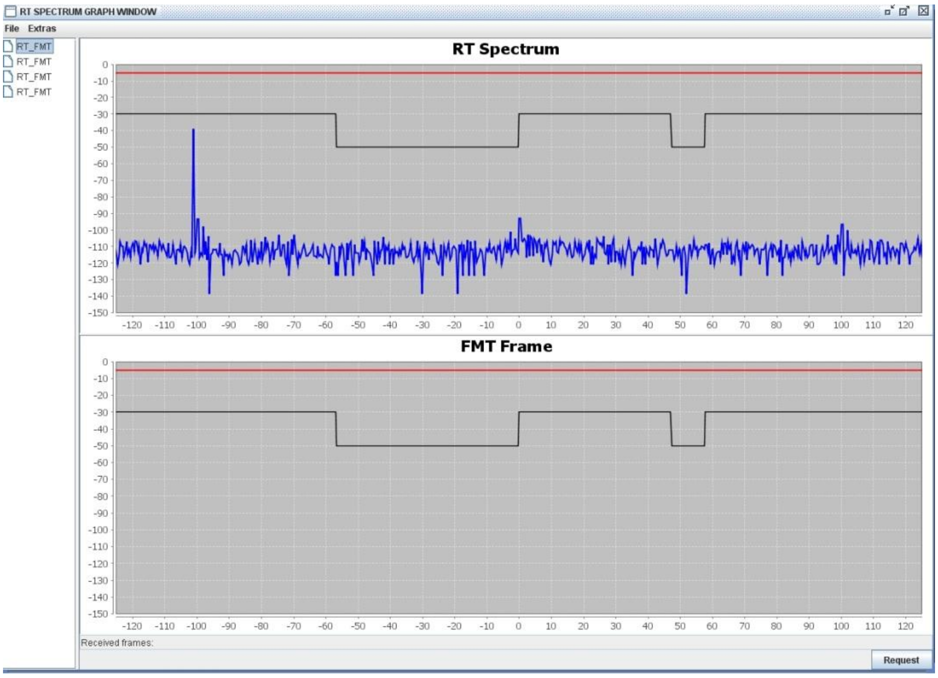
Figure 3-28: Detection and false alarm probability of sensor S7

3.2.3 FMT real-time spectrum analysis test results

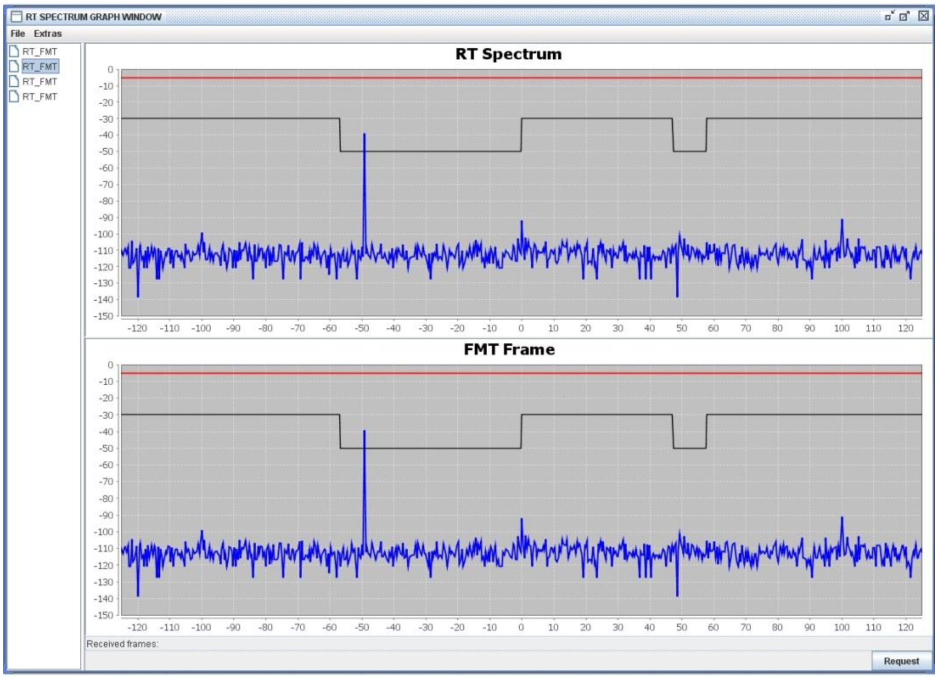
A number of tests related to Cognitive Radio scenarios have been set up. The purpose of these tests is to show that:

- A wideband spectrum of 250 MHz can be monitored in real-time without gaps.
- An arbitrary number of subbands to be monitored can be defined in bandwidth and threshold using FMT masks.
- Carriers entering these subbands and passing a threshold are triggered upon on a gap-free basis, i.e. not missing any event, and with a very fine time resolution.

Scenario 1: A spectrum mask is set defining a number of frequency bands which are forbidden. A sinusoidal carrier is sweeping through the wideband spectrum and is triggered upon entering the spectrum zone that is forbidden. The screenshot of the GUI with the sweeping carrier outside and inside the zone of interest is given in Figure 3-29 (a) and (b), respectively.



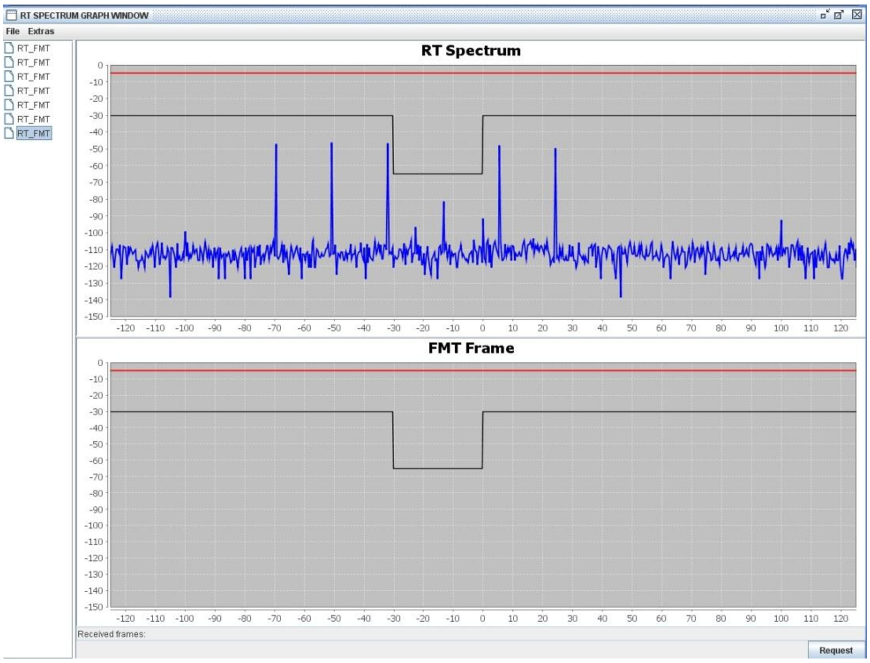
(a)



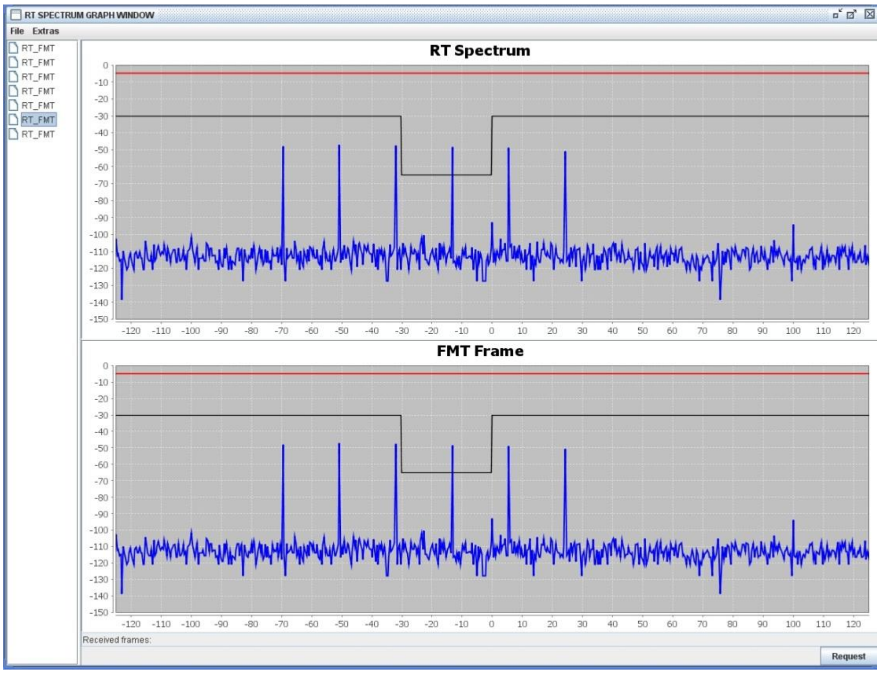
(b)

Figure 3-29: RTSA screenshots for scenario 1 (a) No mask violation (b) Mask violation resulting in FMT frame capture and display

Scenario 2: A wideband spectrum with a spectrum hole is generated with the signal analyzer. The frequency mask is positioned to monitor this spectrum hole. When a signal is appearing in the spectrum hole and a power threshold is being passed, the signal is triggered upon. The real-time spectrum sequence is then available for further analysis and/or actions associated to this event. Figure 3-30(a) and (b) show the situation when the amplitude of an RF tone is below and above the defined frequency mask threshold.



(a)



(b)

Figure 3-30: RTSA screenshot for scenario 2 (a) Carrier in spectrum hole below threshold (b) Mask violation in spectrum hole detected

3.3 Assessment of portability to QoSMOS system architecture

Thanks to the scene emulator and analyzer developed in the course of the QoSMOS project a realistic and flexible test solution for sensing-based CR is now available. Furthermore, the system spans an unprecedented 250 MHz frequency bandwidth which is covering the most of the possible CR system testing needs.

3.4 Potential for further work

Two major directions are considered for further work in the context of radio scene emulator and analysis, these are as follows:

- Increasing the operating bandwidth (i.e. beyond 250 MHz) both at the emulator and at the analysis side;
- Development of more advanced FMT capabilities such as the use of multi-level threshold masks and the introduction of time constraints for trigger threshold violation.

4 Proof of Concept #2: Flexible Transceiver

4.1 Description of demonstrator

PoC#2 proposes to demonstrate some of the Flexible Transceiver aspects developed in QoSMOS. One element of demonstration that has been considered proposes to demonstrate the usage of TVWS as an application of the algorithms and design developed in WP4, notably the implementation of a Filter Bank Multicarrier Transceiver (FBMC). This PoC focuses on measuring the out-of-band performance of FBMC in a complete radio system, where RF impairments are accounted for. This is performed without compromising the flexibility of the transceiver, notably its frequency agility. One element that has been considered is to measure performance of the newly developed FBMC and the interference it may generate to incumbent users and may be compared against results simulated in WP4. A comparison with OFDM (Orthogonal Frequency Division Multiplexing) performance is also performed. PoC#2 serves as a basis for PoC#4 to demonstrate the complete integrated scenario.

4.1.1 Components of the demonstrator

The PoC is based on the QoSMOS T-Flex board developed in WP7 and already presented in [D7.3]. The digital baseband board is composed of:

- 1 FPGA Xilinx XC7K325T-1FFG676C (Kintex7 Family)
- 1 ARM microcontroller DM3730CBP100 (cortex A-8 at 1GHz + DSP TMS320C64x)
- 2 dual ADC AD9643 14 bits / 250 MHz, the ADC using a differential interface allows for receiving intermediate frequency up to 400 MHz.
- 1 quad DAC AD9148 16 bits / 1 GHz: interpolation is performed inside the digital-to-analog converter and allows for a good compromise between input interface throughput requirements and output sampling frequency.

The digital board is interfaced to the RF TX and RX daughterboards in order to generate UHF (Ultra High Frequency) signal from 470MHz up to 860MHz in a flexible way. The ARM processor controls the digital board and the RF Boards and interfaces to an external PC via either a USB, an Ethernet or a Wi-Fi connection.

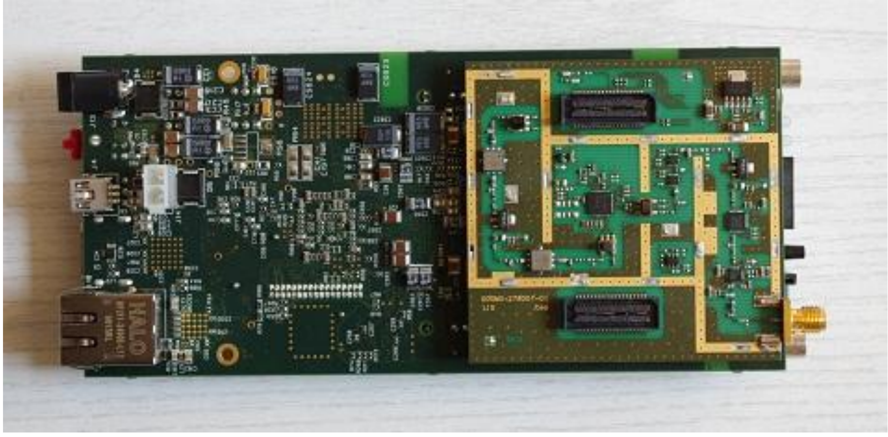


Figure 4-1: PoC#2 Main component – QoMOS T-Flex

A setup has been proposed to evaluate the performance of the implemented flexible transceiver designed in WP4.

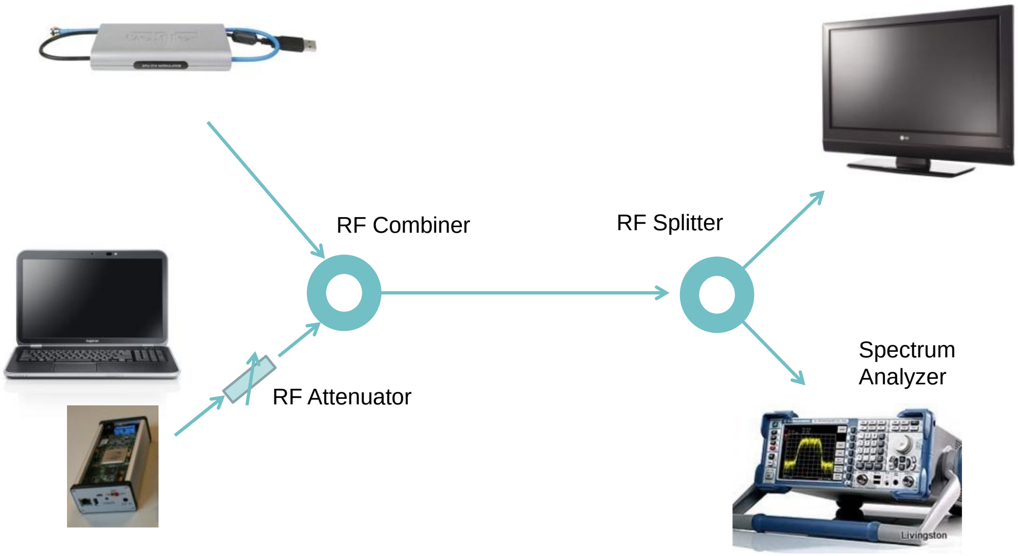


Figure 4-2: Proof of concept of Flexible Transmitter

Figure 4-2 describes the setup proposed in PoC#2 in order to demonstrate the capability of FBMC in terms of both transmitter flexibility and performance. A QoSMOS T-Flex transmitter is generating FBMC signal. The Transceiver is controlled by a Personal Computer. At the same time a DVB-T modulator is used to transmit a television service. DVB-T and FBMC transmitted signals are combined then divided to a Digital TV (DTV) receiver and a spectrum analyzer.

A graphical user interface (Figure 4-3) has been developed, interfacing the QoSMOS T-Flex transmitter. It allows changing dynamically the central frequency of the transmitted signal. Spectrum pooling, the ability to switch on or off part of the transmitted carriers, is also demonstrated with a resolution of 2MHz subband in 20MHz. FBMC or CP-OFDM (Cyclic Prefix-OFDM) may be chosen. This graphical interface is running on a PC and connected to the QoSMOS T-Flex using a Wi-Fi or USB link. Data and configuration of transmitted carrier are dynamically sent to the board.

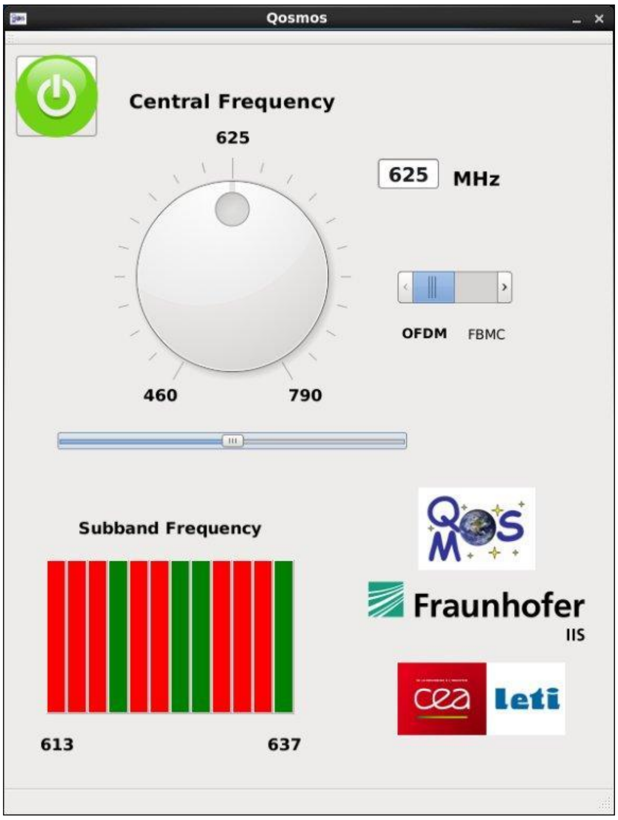


Figure 4-3: QoSMOS Transmitter Graphical Interface

This technology has been used to evaluate the performance of the transmitter and its impact on TV signal.

A spectrum representation of one of the proposed scenarios developed in PoC#2 is given in Figure 4-4. Possible interference generated by FBMC and OFDM generated signals may be measured and its impact on DTV may be estimated. An attenuator is placed at the output of the RF transmitter and set in order to be on the limit of the DVB-T receiver performance. This limit is sometimes called Quasi Error Free limit, when a DVB-T service is available in presence of adjacent signal. The results are presented in the next section.

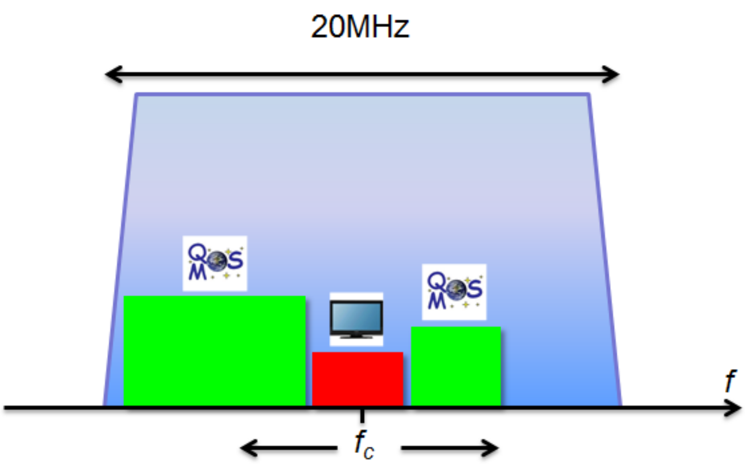


Figure 4-4: Proposed Test Scenario

4.2 Validation process and results obtained

4.2.1 Performance of FBMC ACLR

Simulation results performed in WP4 have demonstrated that FBMC is particularly well adapted to a flexible transmission of signal and provides, only with its internal filtering, a level of adjacent channel rejection ratio well within the 55 dB required by FCC (Federal Communications Commission) and Ofcom (Office of Communications) and specified in [D2.3].

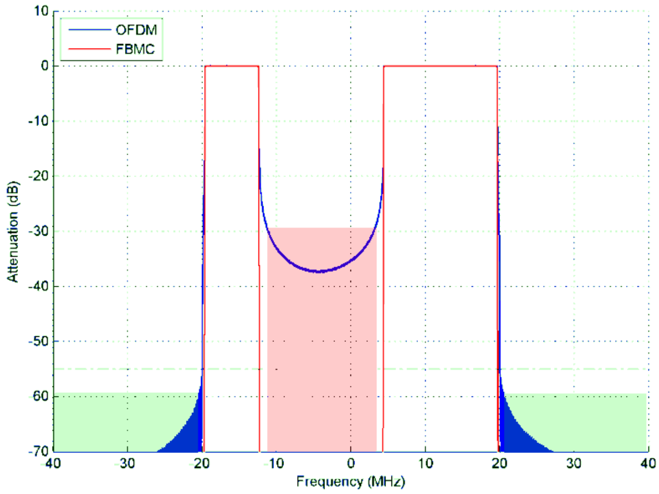


Figure 4-5: FBMC/OFDM Comparison – Simulation

The same type of measurement is realized with the QoSMOS T-Flex and displayed on a spectrum analyser.

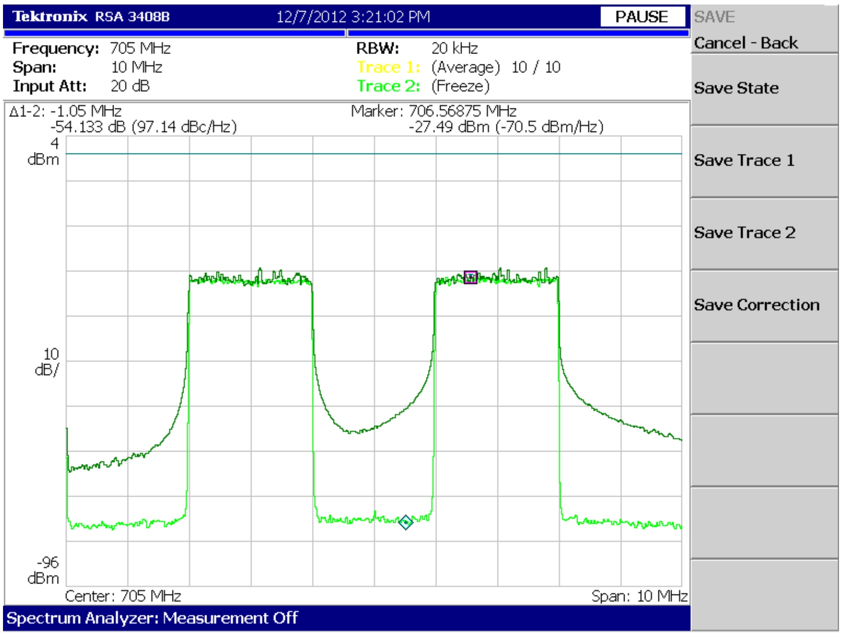


Figure 4-6: FBMC/OFDM Comparison – Measurement

A comparison with CP-OFDM is also performed to measure the impact on a DVB-T receiver of ACLR (Adjacent Channel Leakage Ratio) performance. When using direct adjacent channels on both sides of the DVB-T signal (64QAM 7/6), the OFDM signal should be attenuated by 7 dB in comparison to the FBMC signal in order to get a quasi-error free DVB-T service. The measurement has been performed with a very low cost USB DVB-T demodulator centred at 642MHz (Channel 42). The performed measurements are depicted in Figure 4-7 and Figure 4-8.

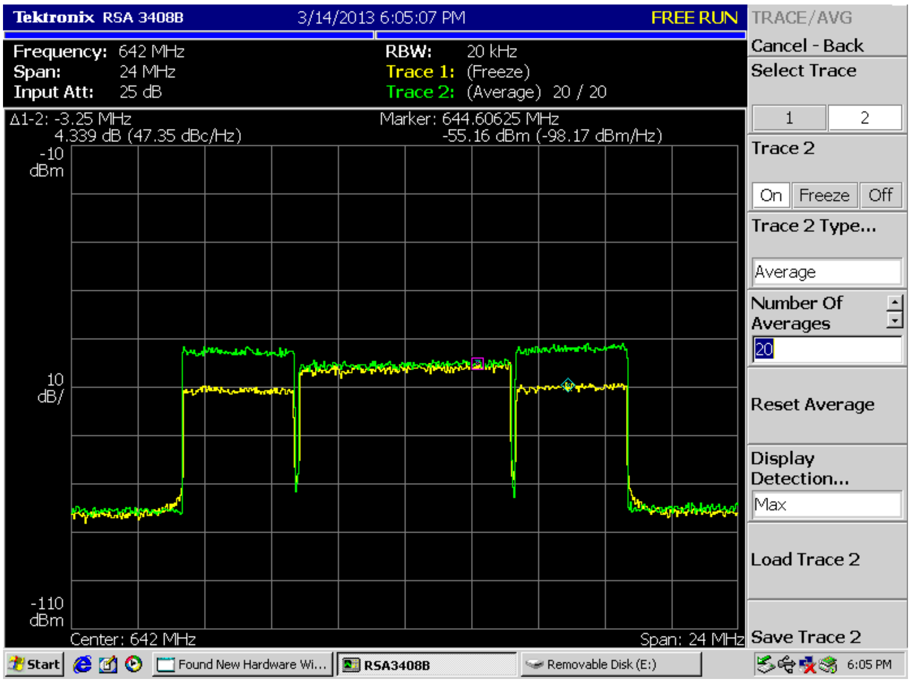


Figure 4-7: FBMC/OFDM in presence of DVB-T (central frequency DVB-T modulated signals) yellow (OFDM), dark green (FBMC) for quasi error free DVB-T demodulation

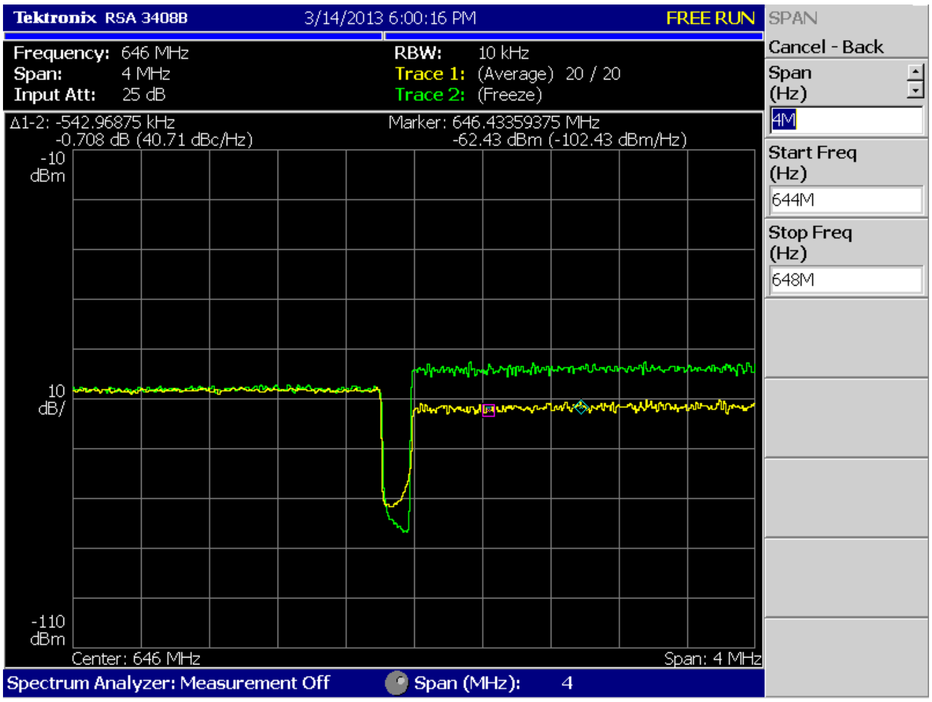


Figure 4-8: FBMC/OFDM in presence of DVB-T (central frequency DVB-T modulated signals) Spectrum on the Left is DVB-T, Spectrum on the right is TVWS Cognitive yellow (OFDM), dark green (FBMC) for quasi error free DVB-T demodulation (Zoomed at the transition)

4.3 Assessment of portability to QoSMOS system architecture

The transceiver developed within this PoC aims to demonstrate some concepts investigated in WP4. With this objective, a new physical layer architecture is developed as one of the main research investigation areas considered for the PoC demonstration, which is based on the FBMC air interface that was selected as the most promising solution for low ACLR performance in the aforementioned technical work package 4.

Regulation requires that ACLR of the TVWS transmitter must be at least 55 dB relative to the in band channel of the opportunistic user, which is a constraint around 10 dB above the recommendation for LTE. Therefore, it is a struggle to achieve that kind of performance with classical air interfaces, much more when the desire is to obtain frequency agility. The traditionally used OFDM techniques would imply employing hardware consuming filtering circuitry and, as demonstrated in WP4 analysis, would not be compatible with the aim of simultaneously addressing several discontinuous channels through spectrum pooling.

The development and application of FBMC within this PoC represents a step forward in this field, since its use allows offering the desired flexibility of high ACLR and spectrum pooling techniques.

4.4 Potential for further work

One of the main concerns that TVWS may face is on adjacent channel rejection. QoSMOS WP7 developed a demonstrator that proves that a flexible transceiver in the UHF bands is possible. FBMC waveforms are well adapted to the requirements set in this environment and first prototype implementations have confirmed the simulation potential of these newly rediscovered waveforms.

Improvement to the robustness of the data link notably for the case of fragmented spectrum and multi user usage should be envisaged, as has been demonstrated, since the TVWS environment (interleaved spectrum) is expected to be fragmented.

5 Proof of Concept #3: Distributed/Collaborative Sensing

5.1 Description of demonstrator

This PoC aims at demonstrating the benefit of the distributed sensing algorithms proposed and developed within WP3 in [D3.5]. In order to do so, a sensing scenario has been designed, including hardware 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 were investigated and evaluated via computer simulations, the aim of this demonstration is to prove the worthiness of the developed algorithms in scenarios as close to reality as possible.

The hardware sensor is in charge of performing an RF sensing and applying a local decision algorithm, as well as sending the final decision to the fusion unit. The data fusion unit is responsible for the generation of the decision on the presence of an IU. This unit gathers the sensing data from the sensing devices and generates the final decision. And finally, a Primary Scene Emulator is needed to generate the IU signal that each sensing device should receive according to the IU service to be detected and the considered channel model.

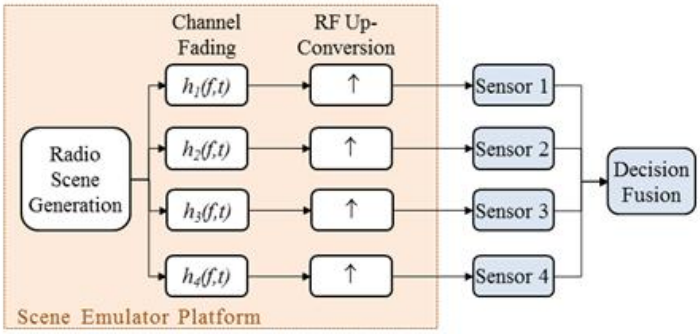
5.1.1 Components of the demonstrator

The PoC#3 is composed of three main entities:

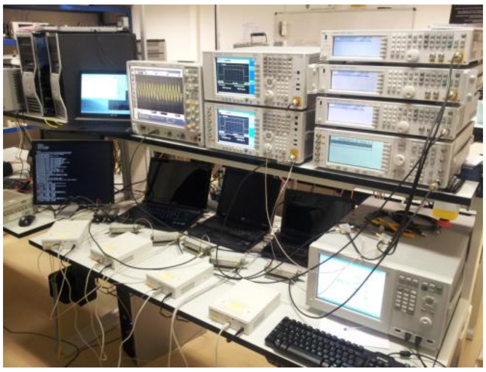
1. Primary scene emulator (PSE) - The emulator is required to generate the IU signal that each detection device should receive according to the IU service to be detected and the channel model considered;
2. Sensors - The hardware sensors (or CR) are in charge of listening to RF signals and sending the result of a locally implemented decision algorithm to the data fusion unit;
3. Data fusion unit (DFU) - DFU is responsible for collecting sensing data from various CR users in the network and generating the final decision on the presence of the IU.

The analog interface between the primary scene emulator and sensors entities is in the RF wave domain. In practice it is realized by means of standard RF coaxial cables (BNC- and/or SNA-type). Otherwise the interface between the sensors and data fusion utilize uses an Ethernet network. The entities are connected between themselves with standard UTP cables and with an Ethernet switch.

A block scheme and practical realization of the PoC#3 sensing test bed are given in Figure 5-1(a) and in Figure 5-1(b), respectively. The functionality of the particular blocks is explained in the following sections.



(a) Block diagram



(b) Implementation test bed

Figure 5-1: Block diagram of the PoC#3

5.1.1.1 Distributed sensing architecture

The distributed sensing architecture implemented in the test bed, with its main building blocks and relevant interfaces, is shown in Figure 5-2. The main blocks in the user equipment (terminal domain) are the Cognitive Manager - Resource Manager - Resource Unit (CM-RM-RU) and the Spectrum Sensing - Control (SS-CTRL). The main blocks in the central node (network domain: gateway/base station) are the Cognitive Manager - Resource Manager - Resource Control (CM-RM-RC) and the Spectrum Sensing - Management (SS-MGT). The functionalities of the main building blocks are as follows:

- CM-RM-RU: communicates with the central unit CM-RM-RC to set the local sensing configuration and apply it on the local sensing unit SS-CTRL.
- SS-CTRL: defines and apply the RF and baseband parameters where the algorithms are implemented for local sensing. It performs hardware sensing, packs and sends the result to the central unit SS-MGT.
- CM-RM-RC: coordinates the sensor network, defining the operating parameters of the sensing units (local and central).
- SS-MGT: receives the sensing information from local units, SS-CTRL, buffering the individual decisions. It implements the distributed sensing algorithm chosen to generate the final decision on the occupancy of the analyzed band.

The interfaces used for inter-block communication are the SS0, RM0 and SS1b. The purpose of these interfaces is:

- SS0: transport spectrum sensing (SS) data. Sensing measurements data is reported in this interface from local sensing units, SS-CTRL, to the central unit, SS-MGT.
- RM0: transport resource manager (RM) data. Sensing configuration is send on this interface from central unit, CM-RM-RC, to local sensing units, CM-RM-RU.
- SS1b: this interface is utilized to apply the spectrum sensing configuration on the respective sensing block SS.

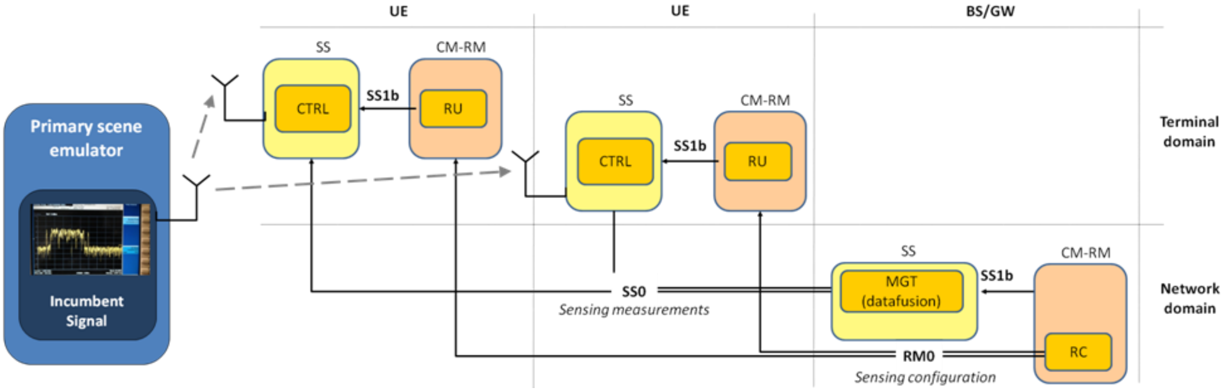


Figure 5-2: QoSMOS Distributed sensing architecture

5.1.1.2 Primary scene emulator

Primary scene emulator has already been covered within PoC#1, for a detailed description refer to Section 3.1.1.1.

5.1.1.3 Sensors

The sensors are described in PoC#1 chapter (Table 3-2) and in this test are remotely controlled over the network by the data fusion unit.

5.1.1.4 Data fusion unit

The DFU is the central network controller that receives the decisions of the various nodes and generates the final decision. The main blocks that can be identified in the data fusion unit are illustrated in Figure 5-3. The DFU contains one CM-RM-RC instance for each sensor and this instance is in charge of setting up the sensor configuration via XML-RPC over RM0 interface. The SS-SMGT is made up of a set of UDP server blocks and the QoSMOS Fusion Unit Application. The several UDP server blocks receive the local sensing decisions from their respective sensor (over the SS0 interface) and forward it to QoSMOS Fusion Unit Application, which generates the final decisions on the presence of IU.

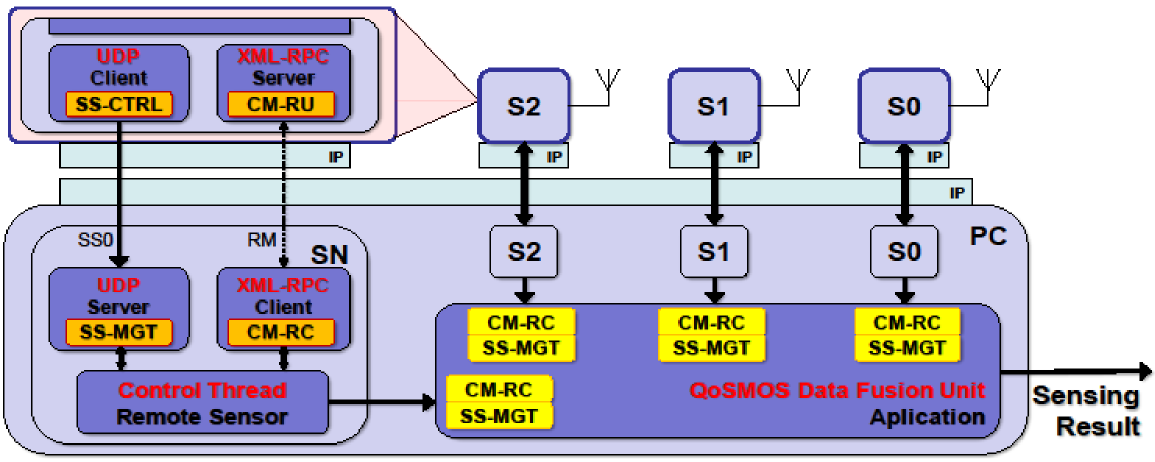


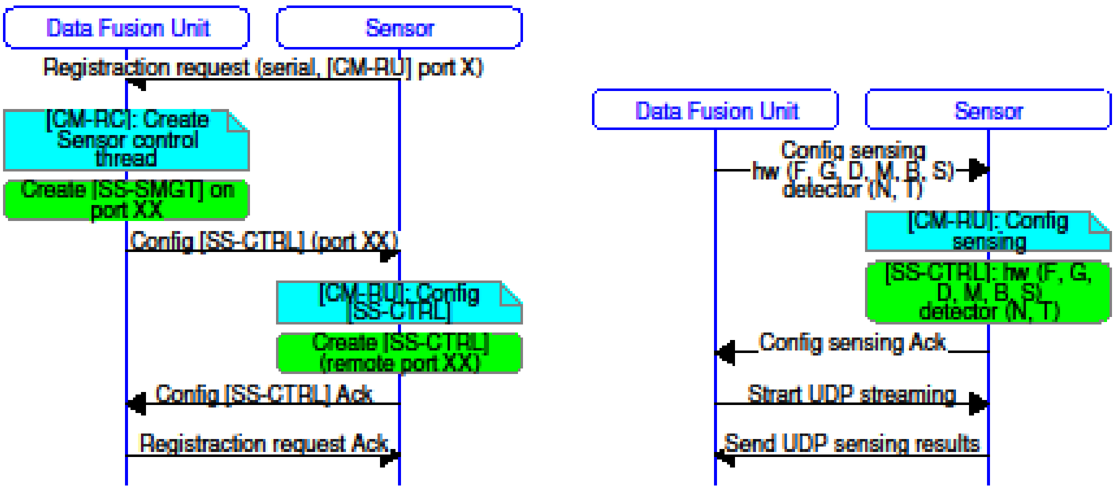
Figure 5-3: Distributed sensing implementation

5.1.1.4.1 Communication and control of remote sensing nodes

The most relevant message exchange that occurs between sensors and DFU is shown in Fig. 10. The registration and un-registration are the main control procedures that allow the configuration of each sensor.

- Registration - started by each sensor for the registration of its unique serial number. This information is later used for calibration and identification of the sensor. The sensor uses a DFU's XML-RPC server known port to be able to contact the CM-RM-RC block, that will later control the sensor, Figure 5-4(a).
- Un-registration - terminates the connection with the sensor, destroying the DFU's control and reception blocks (CM-RM-RC and SS-SMGT) associated with the serial number.

The CM-RM-RC initially configures the sensor (hardware and detector) sending its configuration. In turn, the remote sensor CM-RM-RU applies the configuration desired by the CM-RM-RC. After the successful configuration of the sensor, the CM-RM-RC orders the sensor to start the streaming of the sensing results (sent by sensor's SS-SCTRL to DFU's SS-SMGT), Figure 5-4(b).



(a) Registration (b) Start sensing

Figure 5-4: Message sequence chart between sensors and DFU

5.1.1.4.2 Synchronization of the central decisions

The decisions sent by sensors SS-CCTRL blocks are routed to a set of FIFO stacks as they are received by the SS-SMGT blocks of the respective sensors in DFU. The superior entity of the SS-SMGT block, which is common to all sensors, is in charge of consuming local decisions, which are in fifo stacks, synchronously and deliver to the decision algorithm to be made the final decision. The arrival moment of the decisions of different sensors has a variation that depending on network delays of UDP packets that is not possible to control. To synchronize the decisions that come from the sensors was used the methodology described in Figure 5-5.

The consumption of decisions is performed synchronously with the aid of a timer that consumes the data at a rate equal to the period of sensing {SLEEP *sp*}.

After waiting *sp* seconds, all FIFOs are checked in {READ SIZES}, to know the number of elements in each one. The numbers of elements in each of these are the decisions sent by the sensors (S1 and S2 in Figure 5-5). After this verification, the variables *smin*, *smax* and *d* are known (the number of elements in the smaller stack is *smin*, in the higher is *smax* and the difference between the maximum and minimum *d* = *smax* - *smin* serves to determine when the system no longer be synchronous).

The following procedure is to consume *smin* elements {GET(*smim*)} in all heaps that are delivered to the DFU decision algorithm {DFU decision}.

The threshold *dmax* is used to synchronize the system. This is the maximum difference allowed between the number of elements in smaller and larger stack. So the *dmax* is the only parameter provided by the user. When the difference *d* is higher than the threshold *dmax* {*d* > *dmax*} it's assumed that the system is not synchronized and all FIFO stacks are clean {CLEAR}.

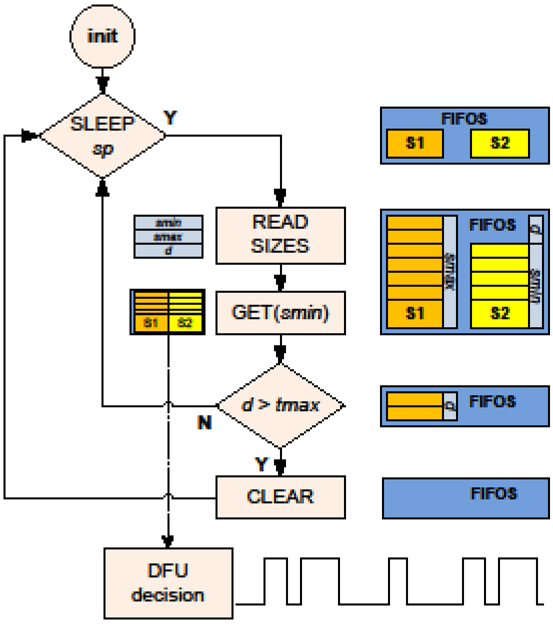


Figure 5-5: DFU Synchronization

5.1.1.4.3 Data fusion decision algorithm(s)

The combination process, also known as data fusion, is often implemented using the k-out-of-M rule [Varshney]. The ideal value of k depends on the type of channel that CR users are subject to. This means that if k of the M sensors decide '1' in the test hypothesis for the presence of primary, the output of the combining at the DFU will be '1'. The most used logic functions are the OR, AND and majority rules. What distinguishes these three rules is the used k value. The rule implemented in DFU was the 1-out-of-M (OR), has it been shown in [Ghasemi] that this rule has the best detection performance.

The other algorithm that is implemented in DFU is the selective reporting that is present in D3.5.

5.2 Validation process and results obtained

The performance of the distributed sensing test bed was characterized using the probabilities of false alarm (PFA) and miss detection (PMD), where PMD=1-PD (probability of detection). The tests were performed with and without fading channel, resulting in the metrics PFA, PD without channel ($PD_{\overline{channel}}$) and PD with channel ($PD_{channel}$). The adopted methodologies to experimentally measure the metrics were [Quaresma]:

→ PFA - measurements were performed terminating the sensor's input with 50Ω impedance.

→ $PD_{\overline{channel}}$ - measurements were performed feeding the channel sensor's input with the DVB signal generated by the scene emulator and setting the signal power to get a SNR of 0dB and 2dB.

→ PD_{channel} - test was performed the same way as the previous one ($PD_{\overline{channel}}$) with the addition of an emulated LTE Extended Typical Urban Low Doppler channel that affects the DVB signal received by the sensor's input.

The tests were performed with four sensors with the specifications shown in Table 3-1 (the values of *m*, *b* and *nf* were determined in the calibration process). It is important to stress that both the values of the decision threshold and SNR are dependent to the intrinsic characteristic and highly relevant to each of the sensors, which is its noise floor, *nf*. All the sensors are tuned for 800MHz with a bandwidth of 8MHz.

5.2.1 PSE configuration

The radio scene is basically the same as used in PoC#1. However, in this case a 1x4 single-input multiple-output (SIMO) configuration setup is used, with the DVB-T-based radio scene being played back from one BBG card. The radio scene does not require the combination of multiple signals, because it consists of a single superframe of an 8 MHz bandwidth DVB-T/H signal in 8K mode and centred at 0.8 GHz carrier frequency. The duration of the waveform is 0.30464 s. The applied channel model is equal for all four faders; a vehicular model is used for an increased fading effect on the DVB signal.

5.2.2 Tests performed

The test performed is the same as used in PoC#1 (3.2.2).

In the local tests of PoC#1 there is only one sensor and the result is the characterization of the performance of this same sensor in an isolated way, Figure 3-20. On the other hand the distributed tests characterize DFU performance, i.e. a set of sensor that works in a distributed way, Figure 5-6.

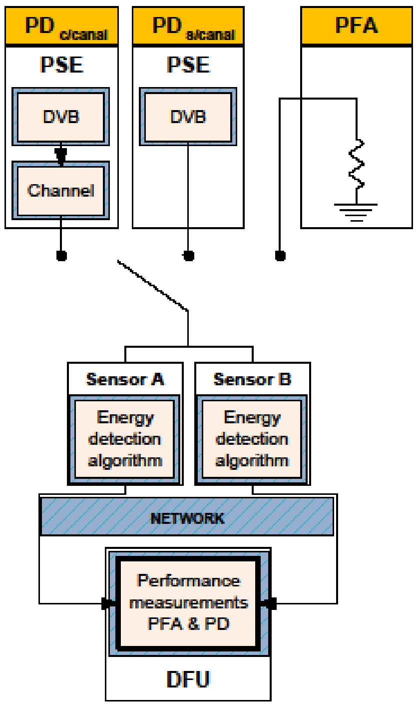


Figure 5-6: DFU setup tests

5.2.2.1 Algorithm

The algorithm used to obtain these metrics allows characterizing both the individual sensors as the distributed system. The algorithm (implementation) can be seen in Figure 3-20 (3.2.2.2). However, in the distributed system, one part of the algorithm is executed remotely by the sensor and the other locally by the DFU. The detection is done remotely by sensors and it is sent through the network to the DFU, which generates the final decision and executes the remaining algorithm of the probabilities measurement.

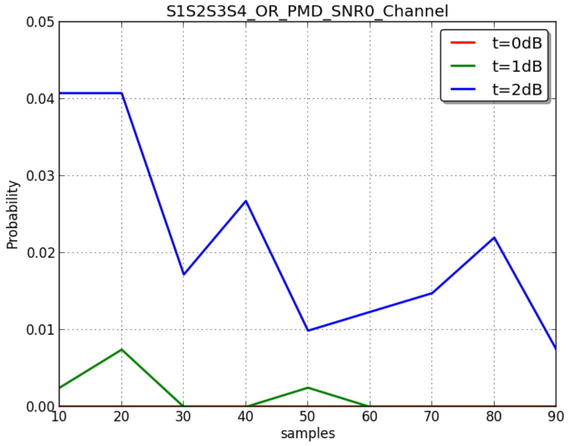
5.2.3 Results obtained

The Figure 5-7 to Figure 5-12 shows the receiver operating characteristic (ROC) of the data fusion unit. Two different groups of sensors have been tested and are presented below:

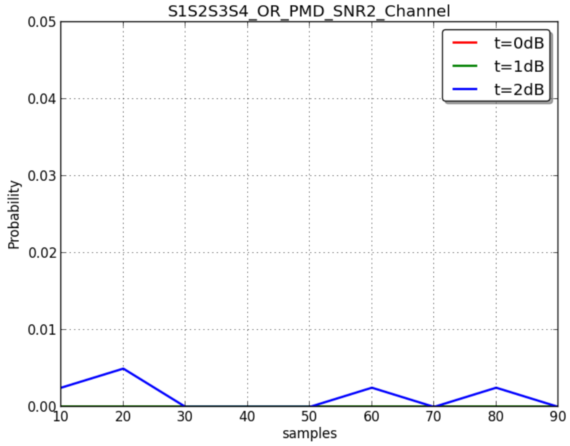
1. Homogeneous – this set is constituted by the sensors S1, S2, S3 and S4. All the sensors have the same hardware characteristics.
    - The Figure 5-7 shows the miss detection and false alarm probability of DFU with the k-out-1 rule.
    - The Figure 5-8 shows the miss detection and false alarm probability of DFU with selective reporting.
    - The Figure 5-9 shows the differences in probabilities between selective reporting and k-out-1.
2. Heterogeneous – this set is constituted by the sensors S4, S5, S6 and S7. All the sensors have different hardware characteristics.
    - The Figure 5-10 shows the miss detection and false alarm probability of DFU with k-out-1 rule.
    - The Figure 5-11 shows the miss detection and false alarm probability of DFU with selective reporting.
    - The Figure 5-12 shows the differences in probabilities between selective reporting and k-out-1.

The differences between the selective reporting and k-out-1 rule are insignificant and show that both obtain the same distributed sensing performance, as shown in Figure 5-9 and Figure 5-12.

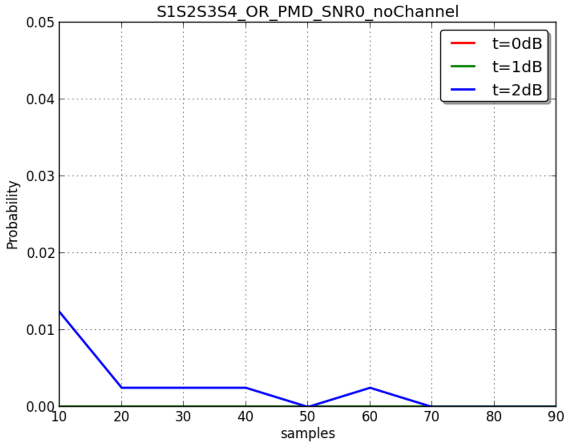
The differences in the results of the selective reporting algorithm between the homogeneous and heterogeneous group of sensors is very low, as depicted in Figure 5-13. The sensors have different noise floors but all of them have the same SNR at its input and that is the principal reason for the very low difference between them.



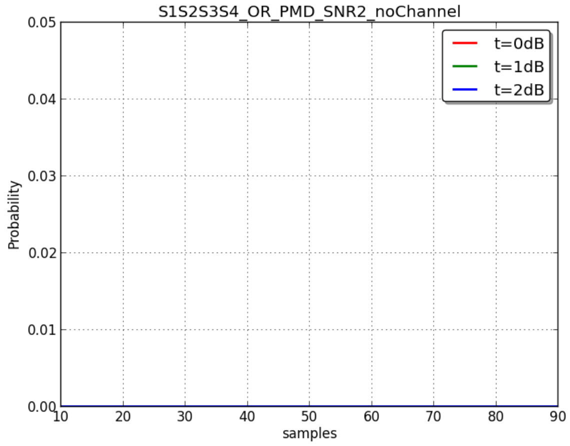
(a) PMD(SNR=0dB, channel)



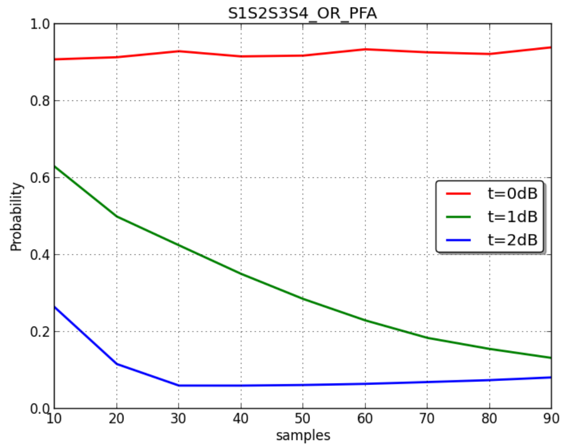
(b) PMD(SNR=2dB, channel)



(c) PMD(SNR=0dB, nochannel)

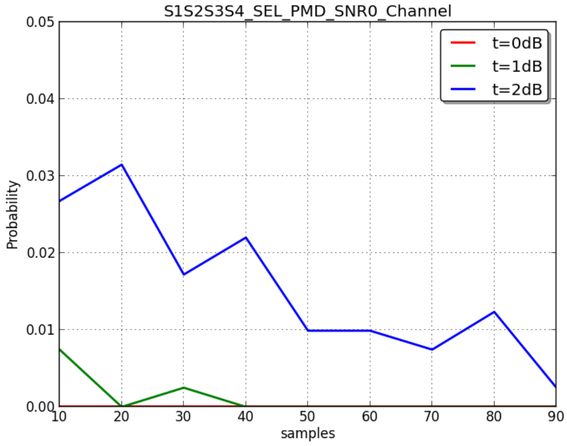


(d) PMD(SNR=2dB, nochannel)

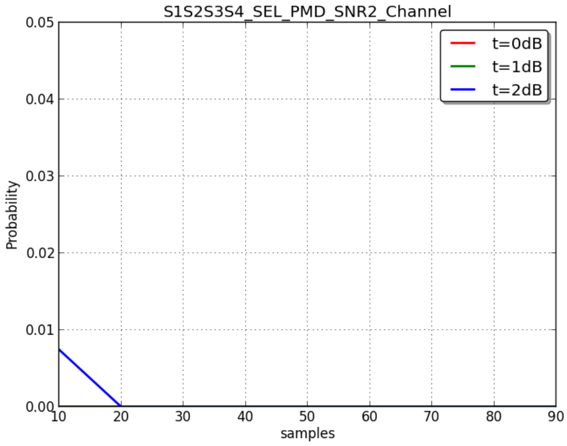


(e) PFA

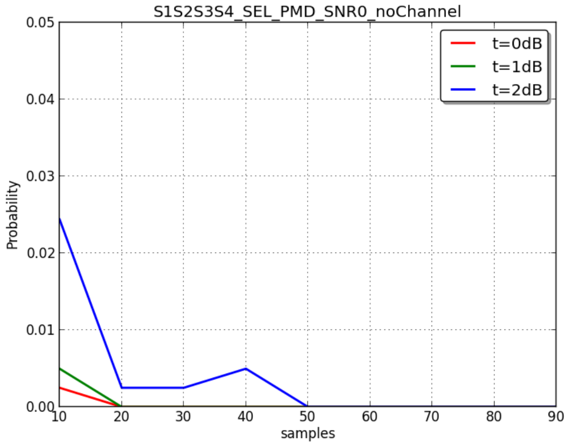
Figure 5-7: Miss detection and false alarm probability of DFU with k-out-1 rule (homogeneous set of sensors, S1, S2, S3 and S4)



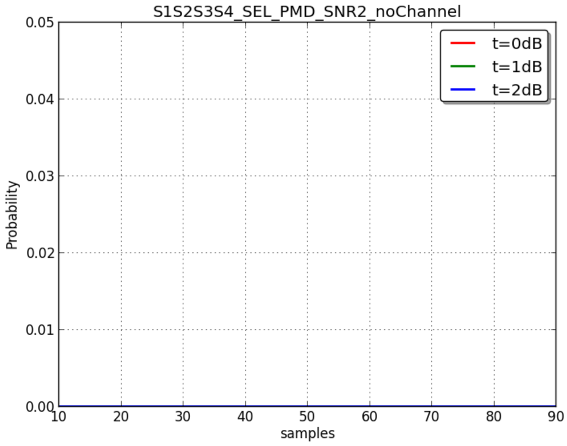
(a) PMD(SNR=0dB, channel)



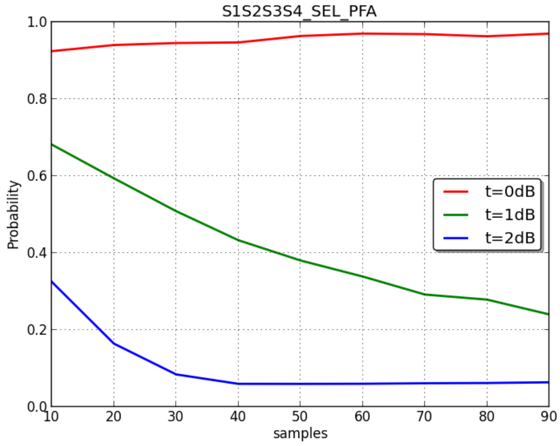
(b) PMD(SNR=2dB, channel)



(c) PMD(SNR=0dB, nochannel)

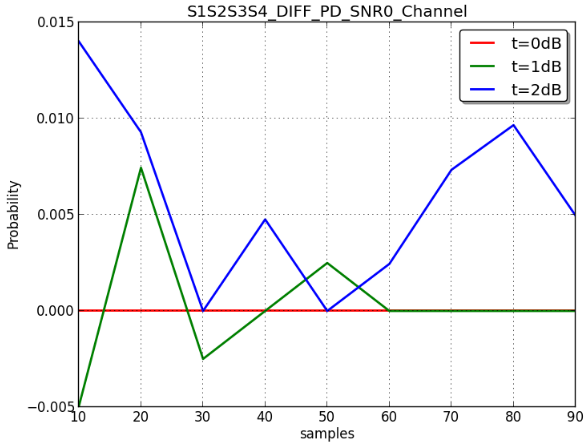


(d) PMD(SNR=2dB, nochannel)

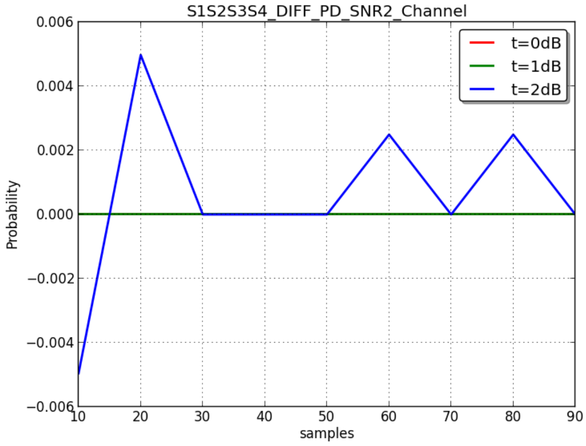


(e) PFA

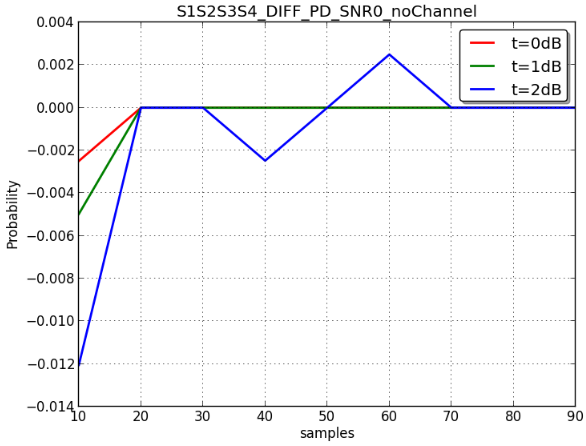
Figure 5-8: Miss detection and false alarm probability of DFU with selective reporting (homogeneous set of sensors, S1, S2, S3 and S4)



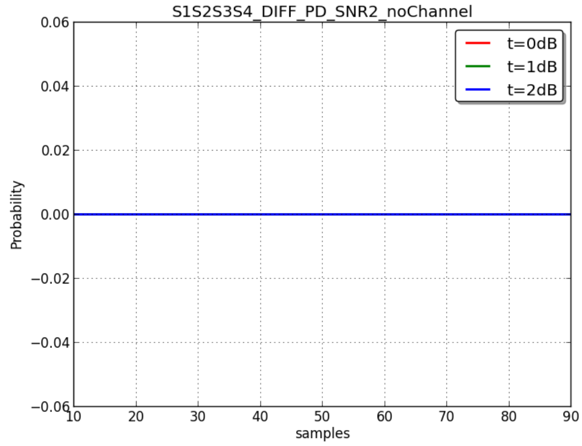
(a) PMD(SNR=0dB, channel)



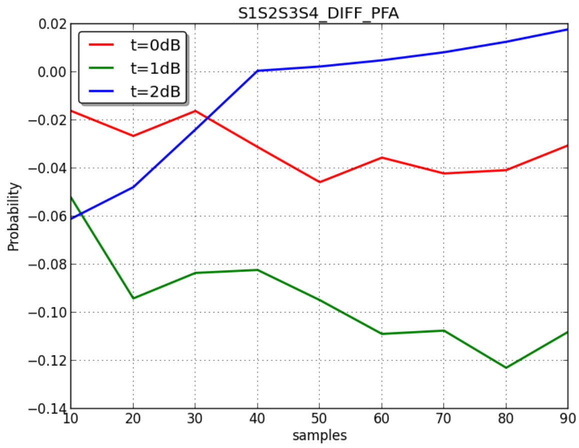
(b) PMD(SNR=2dB, channel)



(c) PMD(SNR=0dB, nochannel)

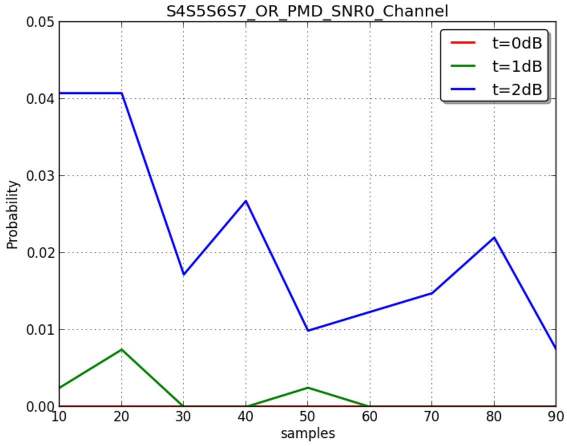


(d) PMD(SNR=2dB, nochannel)

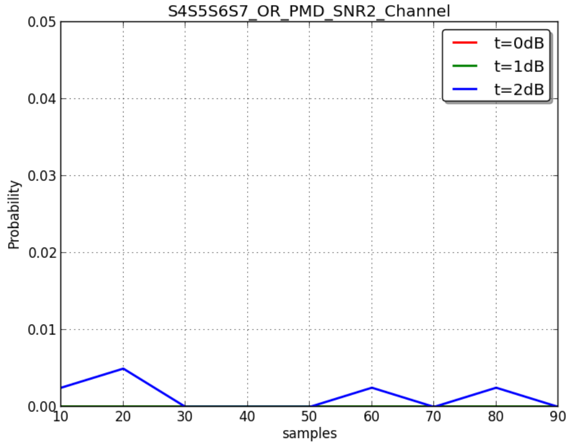


(e) PFA

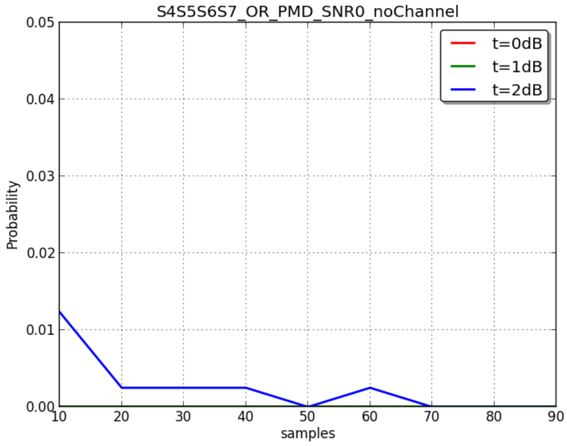
Figure 5-9: Differences in probabilities between selective reporting and k-out-1 (homogeneous set of sensors, S1, S2, S3 and S4)



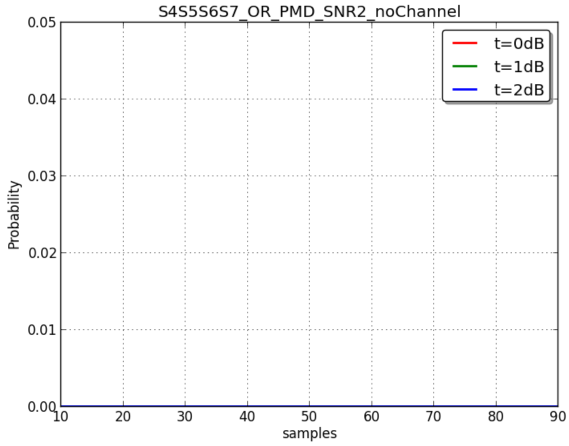
(a) PMD(SNR=0dB, channel)



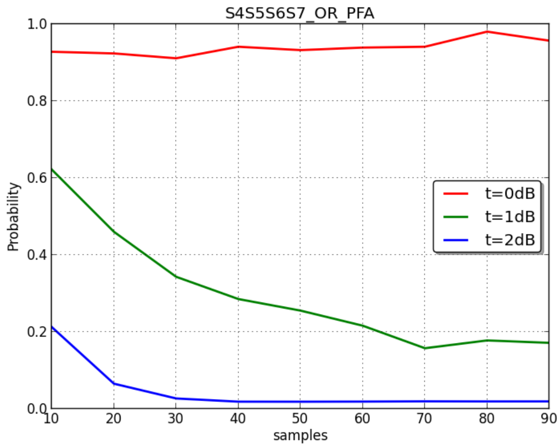
(b) PMD(SNR=2dB, channel)



(c) PMD(SNR=0dB, nochannel)

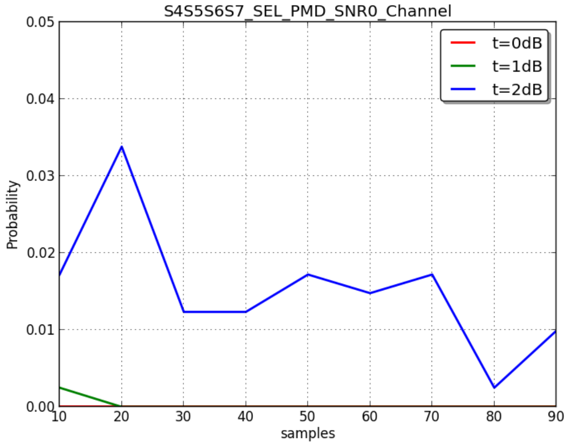


(d) PMD(SNR=2dB, nochannel)

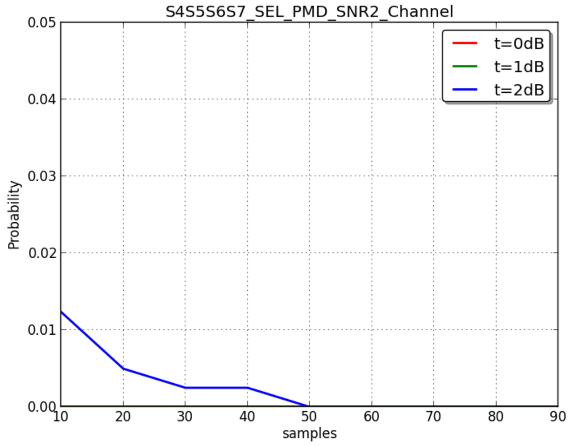


(e) PFA

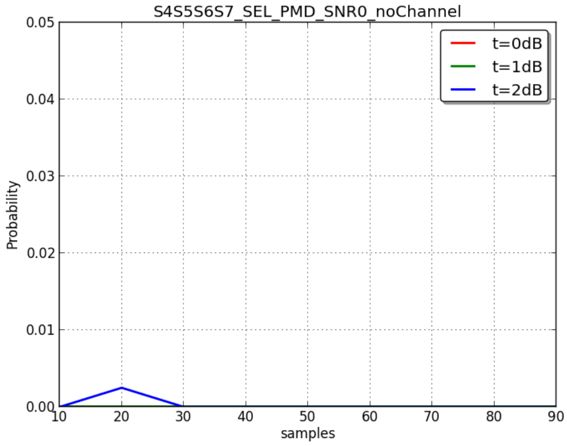
Figure 5-10: Miss detection and false alarm probability of DFU with k-out-1 rule (heterogeneous set of sensors, S4, S5, S6 and S7)



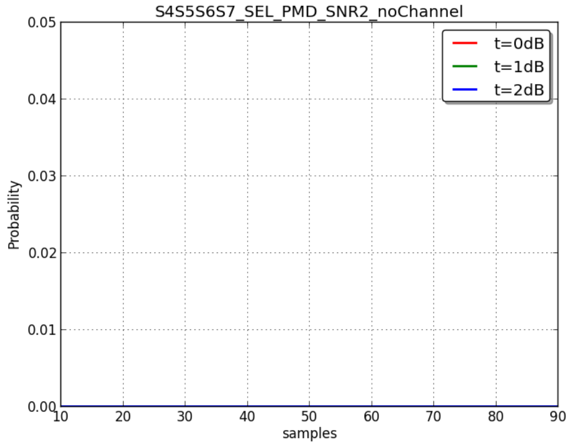
(a) PMD(SNR=0dB, channel)



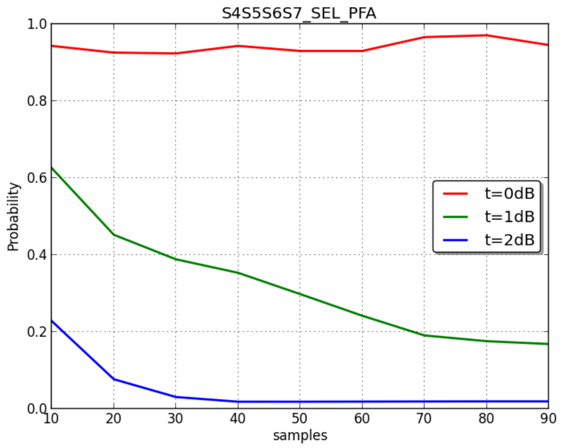
(b) PMD(SNR=2dB, channel)



(c) PMD(SNR=0dB, nochannel)

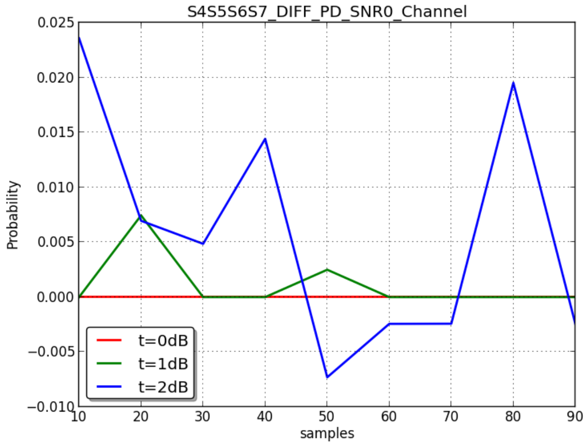


(d) PMD(SNR=2dB, nochannel)

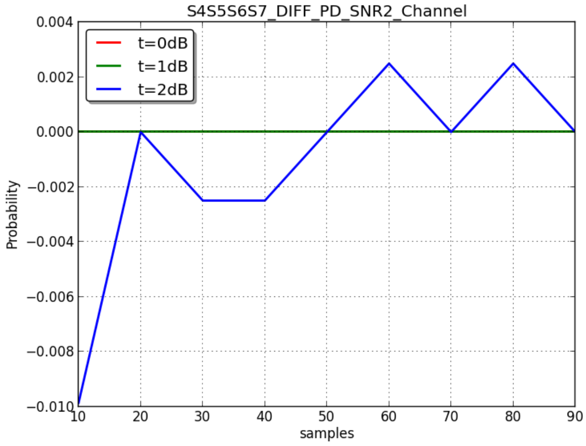


(e) PFA

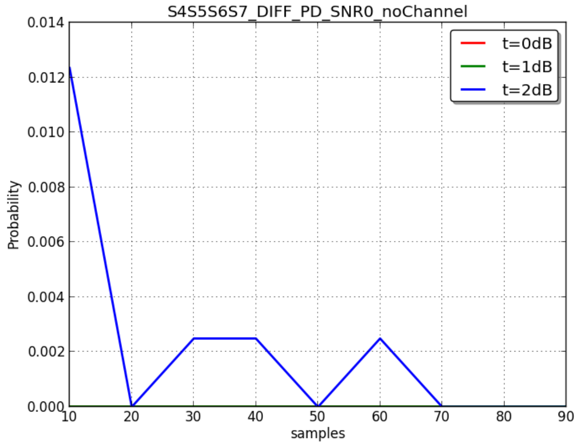
Figure 5-11: Miss detection and false alarm probability of DFU with selective reporting (heterogeneous set of sensors, S4, S5, S6 and S7)



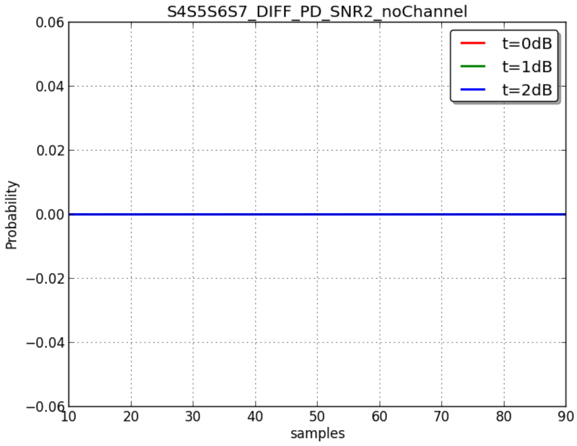
(a) PMD(SNR=0dB, channel)



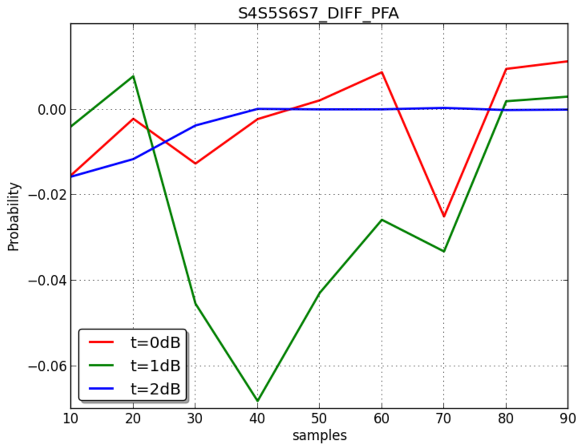
(b) PMD(SNR=2dB, channel)



(c) PMD(SNR=0dB, nochannel)

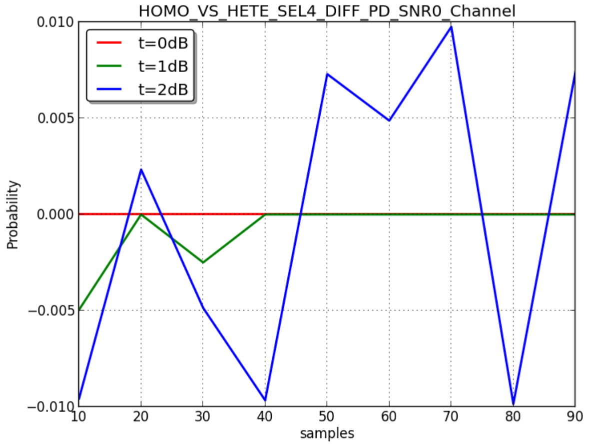


(d) PMD(SNR=2dB, nochannel)

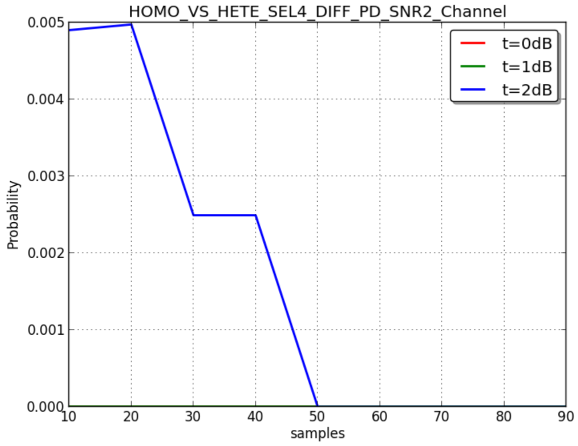


(e) PFA

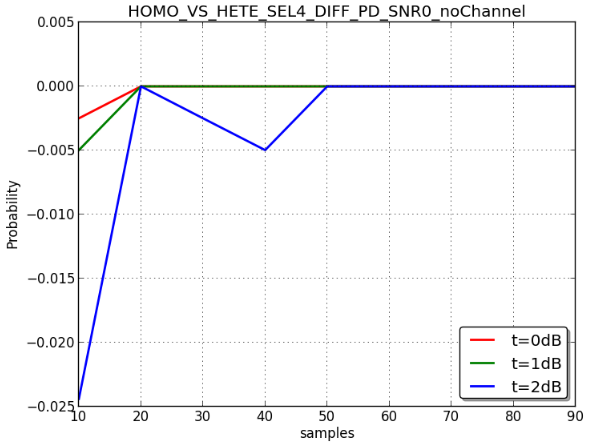
Figure 5-12: Differences in probabilities between selective reporting and k-out-1 (heterogeneous set of sensors, S4, S5, S6 and S7)



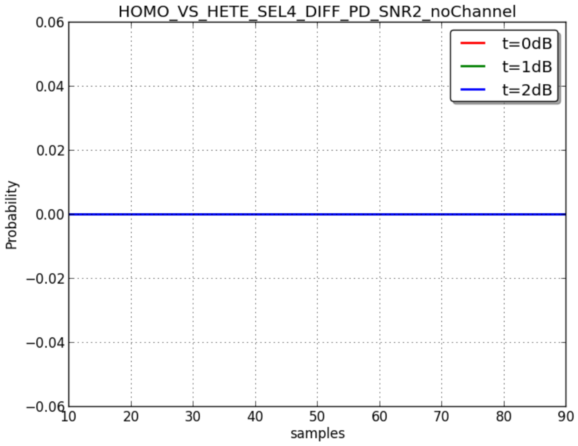
(a) PMD(SNR=0dB, channel)



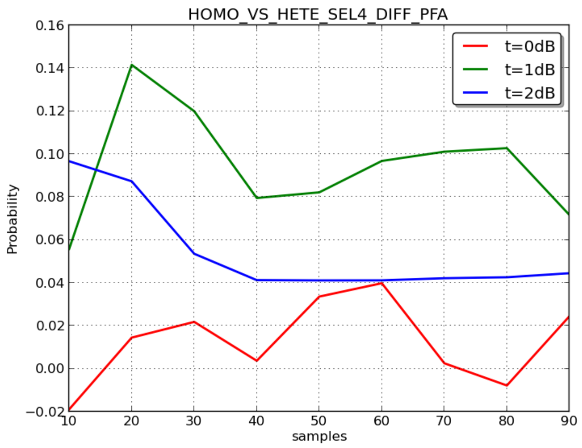
(b) PMD(SNR=2dB, channel)



(c) PMD(SNR=0dB, nochannel)



(d) PMD(SNR=2dB, nochannel)



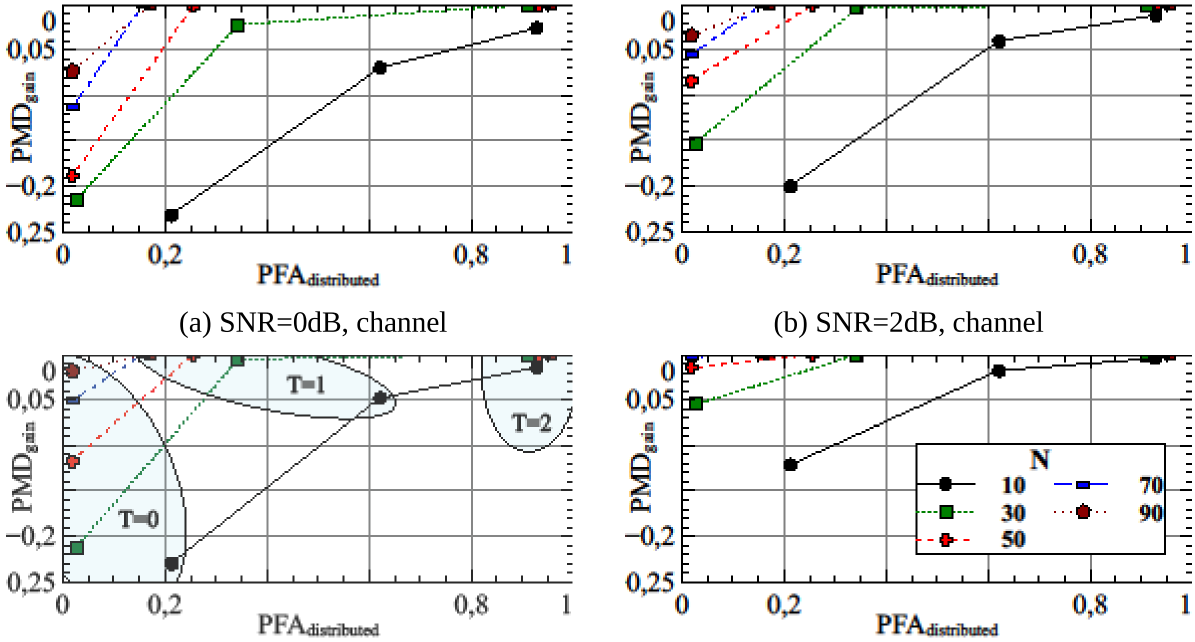
(e) PFA

Figure 5-13: Differences between homogeneous and heterogeneous sets of sensors (selective reporting)

5.2.3.1 Distributed sensing gain

The Figure 5-14 shows the gain of the distributed sensing system relative to one of the sensors, PMDgain = PMDdist – PMDsingle. The different lines are relative to the number of samples used in detection N = {10, 30, 50, 70, 90}, while the points that compose them represent the decision threshold used T = {0, 1, 2} (dB). The input power is SNR = 0 dB and SNR = 2 dB in setups with and without channel.

The PMD gains of the distributed setups in the most important operating region (higher PMD) are considerable, reaching 24% with four sensors, Figure 5-14(a). The maximum PMD gain is obtained for both distributed setups in the most demanding scenario (SNR = 0 dB, N = 10, T = 0 with channel). Increasing the number of samples used in detection, N, the gain of the distributed setup is less significant because the single sensor's PMD is close to zero, ROC1, and there is little room for improvement. The channel effect is visible comparing Figure 5-14(b) and Figure 5-14(d). The PMD is significantly higher when the channel is active and the distributed setups achieve its highest gains in this situation. The results are coherent with the theoretical performance reported in [9], showing that the distributed sensing significantly enhances the PMD gain in the most critical (higher) PMD region.



(a) SNR=0dB, channel

(b) SNR=2dB, channel

(c) SNR=0dB, nochannel

(d) SNR=2dB, nochannel

Figure 5-14: Heterogeneous distributed sensing gain

5.2.3.2 Selective reporting network load

The Figure 5-15 shows the network load when using the Selective reporting algorithm with a heterogeneous group of sensors. It has been experimentally verified that the behavior is identical to the homogeneous group. It is clearly visible that this algorithm uses half of the bandwidth during most of the time.

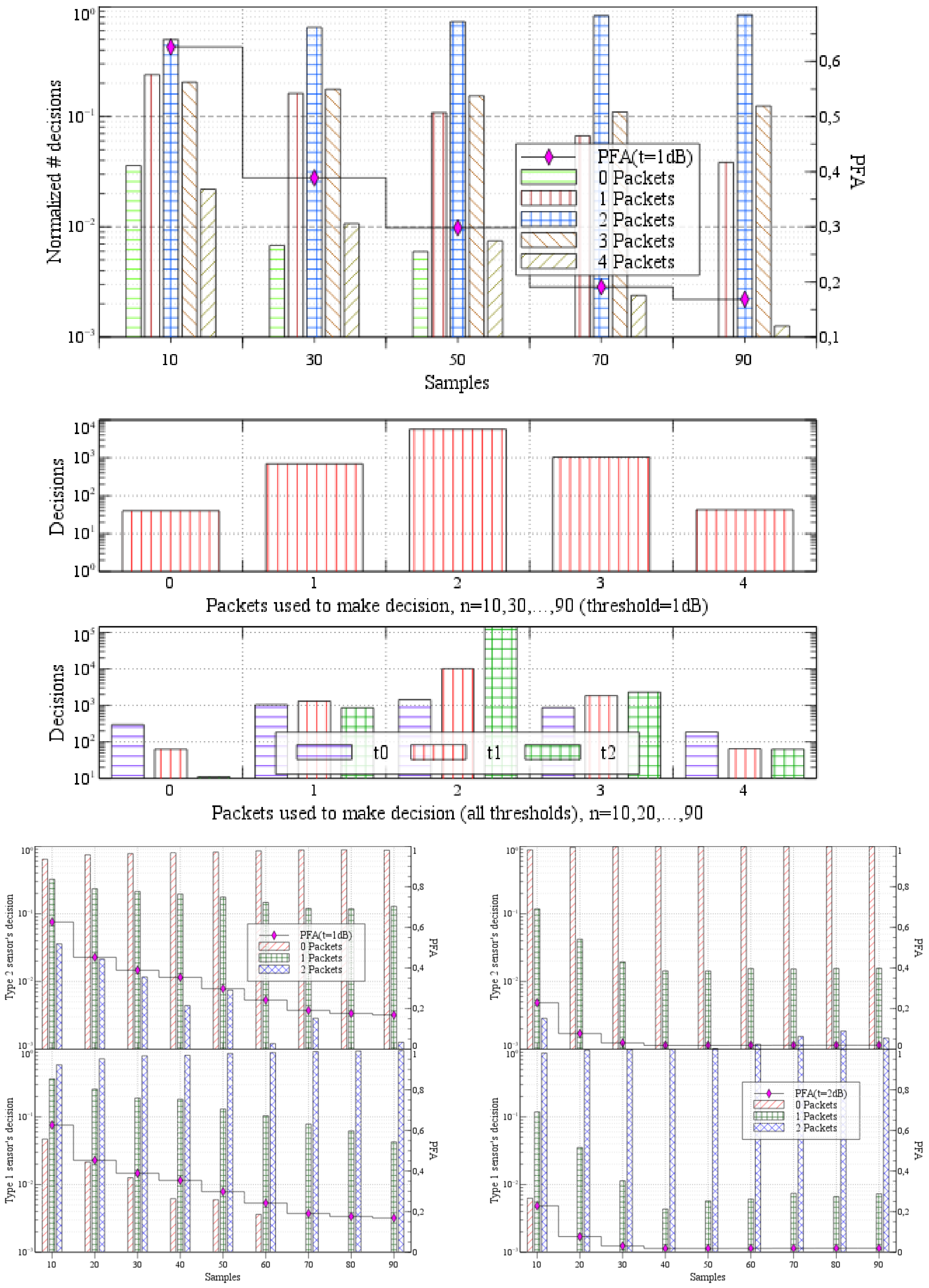


Figure 5-15: Selective reporting algorithm network load (heterogeneous set of sensors, S4, S5, S6 and S7)

5.3 Assessment of portability to QoSMOS system architecture

The portability of the QoSMOS system architecture is proved in the PoC#3 implementation. This PoC implements some blocks and interfaces of QoSMOS system architecture in different approaches and technologies. The SS and CM-RM blocks are built in GNURadio with C++ and Python. While the SS and SM interfaces are done in UDP raw streaming and Python-XML-RPC, respectively.

The test bed implemented is working in distributed sensing scenarios. The DFU performance was measured and its most relevant metrics are acquired (PFA, PD, and PMD), in a work tightly related and following the direction provided in WP2.

5.4 Potential for further work

Some improvements and new features can be added to the distributed sensing system currently in operation; the most relevant are the following:

- Porting code of GNURadio and QoSMOS for an embedded system like ARM, to enable more flexibility in embedded applications.
- Do the calibration (*m* and *b*) in the FPGA, eliminating unnecessary processing in the sensor by using the USRP to perform this operation.
- Porting the energy detector code to run on FPGA.
- Implement other local and distributed algorithms.
- Mark samples with temporal reference.
- Geo-reference sensors to improve the performance/reliability of the distributed sensing.
- Using a database to record a history of the frequencies occupancy.

6 Proof of Concept #4: Integrated Platform

6.1 Description of demonstrator

This integrated platform is designed to perform the validation of certain Cognitive Radio (CR) concepts developed for link and upper layers such as the spectrum management, the decision making algorithms and the Adaptation Layer functionalities

The proposed use case implies a sequence of interactions taking place between the QoSMOS system and some of its actors, involving a TVWS environment, where a cellular legacy system and a TVWS opportunistic system are combined.

Finally and after a serious period of analysis, a complete group of QoSMOS entities have been selected as they represent a reliable sample of the system architecture. They all are presented in the subsequent sections of this chapter, as well as the interactions taking place and the overall flow of the designed scenario.

6.1.1 Components of the demonstrator

The proposed scenario is composed of different entities, coming from the developments carried out within the rest of work packages, and has been previously hinted in [D7.3]. This rough version of the setup is depicted in Figure 6-1 below.

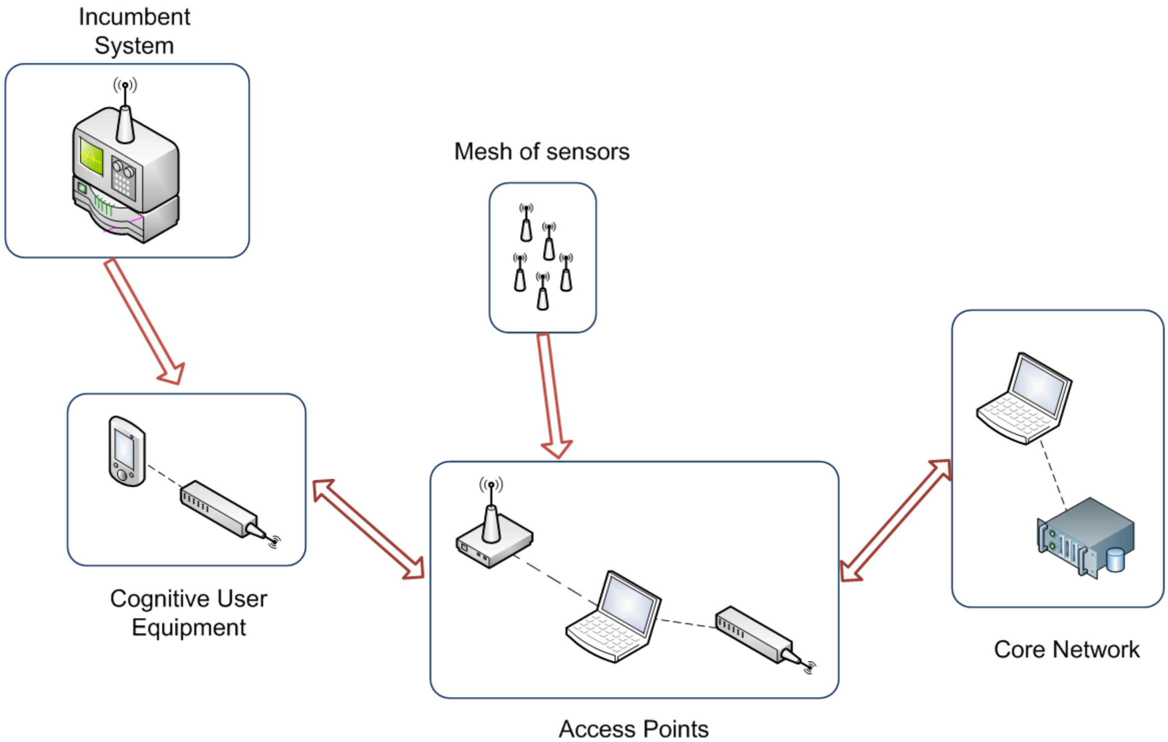


Figure 6-1: PoC#4 scenario

Thus, a Primary Scene Emulator (PSE) is used to generate opportunistic user signals. A spectrum portfolio repository is emulated in the so called Master Entity (ME) to provide access to the databases. This ME is the centralising point in the scenario, presenting features of the Adaptation Layer and of some other QoSMOS architecture entities not fully developed for this test bed.

A cellular network is deployed in order to work within two different environments. Cell 1 uses the flexible transceiver, operating in a TVWS band, while cell 2, in form of a femtocell, operates in a licensed band (3G).

In addition, a User Equipment (UE) with cognitive features is present, composed of a Smartphone and an additional feature for white space operation, provided by the flexible transceiver.

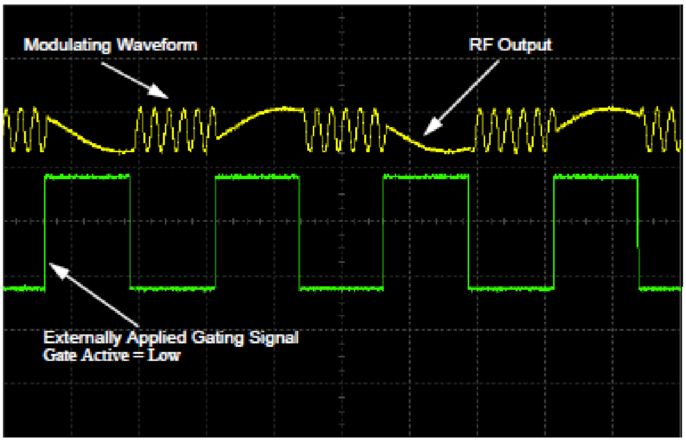
Finally, a mesh of sensors is present in order to carry out distributed sensing duties and get a proper frequency to work with based upon the results offered by the data fusion unit (DFU).

All this equipment is properly and broadly explained in the following subsections.

6.1.1.1 Scene Emulator with waveform triggering

Triggers control data transmission by controlling when the signal generator transmits the modulating signal. Trigger can be configured so that data transmission occurs once (Single mode), continuously (Continuous mode), or starts and stops repeatedly (Gated and Segment Advance modes). A trigger signal contains both positive and negative states; either of them can be used for triggering.

Segment advance mode plays a waveform segment in a sequence only if triggered. The trigger source controls segment–to–segment playing. A trigger received during the last segment loops play to the first segment in the sequence. Gated mode triggers the waveform at the first active triggering state, then repeatedly starts and stops playing the waveform in response to an externally applied gating signal. Figure 6-2 is an example display of both the output of the signal generator, and the external triggering signal. The figure shows the waveform modulating the output during the gate active periods (low in this example).



Source: Agilent N5161A/62A/81A/82 A/83A MXG Signal Generators User's Guide

Figure 6-2: Gated triggering example

It is possible to achieve the required scenario in several ways; first option would be to create a multiple segment sequence with different combinations of arbitrary signals and hopping over these segments based on the triggering signal. The advantage of this option is the necessity of only one MXG signal generator. The alternative is to employ multiple MXGs where each of the generators can be triggered independently. This choice offers a higher level of freedom and flexibility regarding the temporal evolution of the emulated radio scene. For this reason the latter option was picked as the preferred approach for the final integration of PoC#4.

Figure 6-3 shows the functional diagram of scene emulator with independent triggering signals controlling the gated start and stop of the emulation of different scene elements (i. e., waveforms).

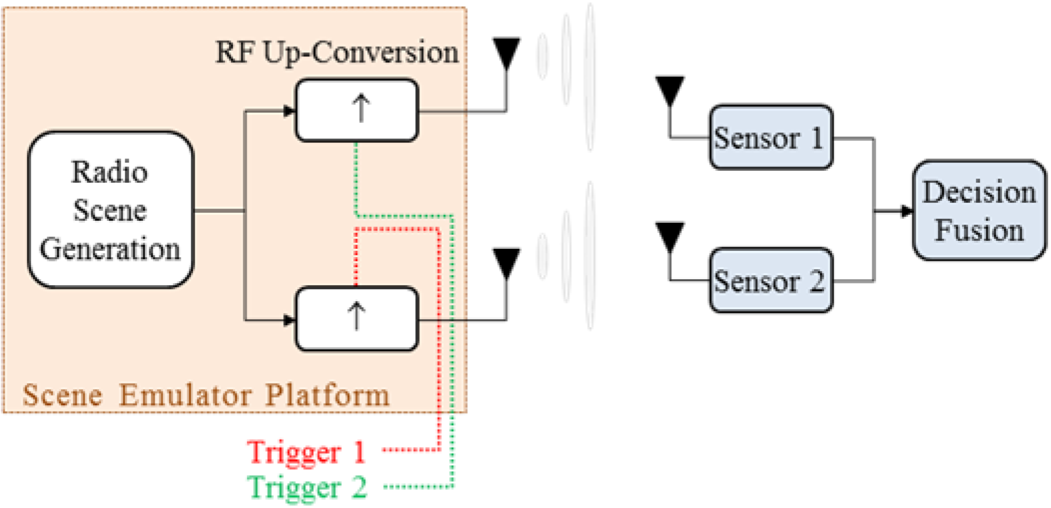
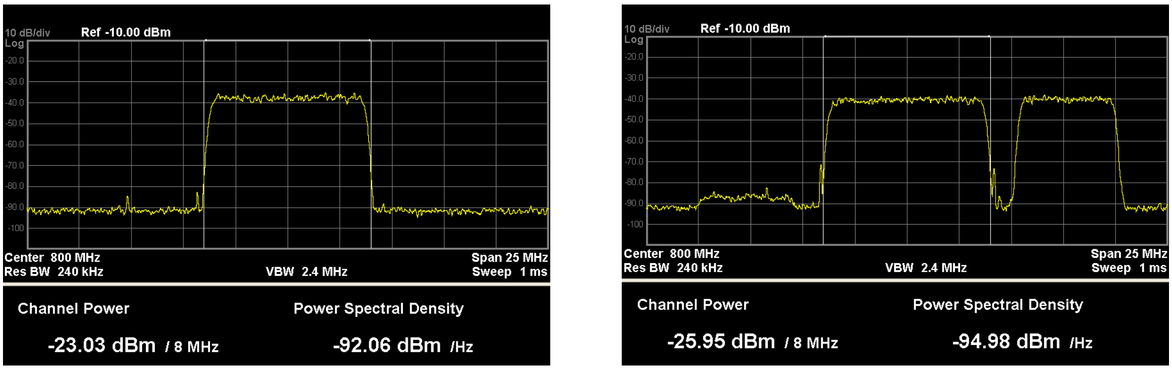


Figure 6-3: Primary scene emulation with triggers in the PoC#4

The evolution of the radio scene based on gated triggering is demonstrated in Figure 6-4. The analysis of the radio scene frequency spectrum shows how an LTE user pops up after having been triggered next to an already present incumbent DVB-T/H user in an adjacent RF band.



(a) (b)

Figure 6-4: Triggering functionality - Spectrum of (a) the Incumbent DVB-T/H user alone and (b) after LTE user popped up in the adjacent frequency band

6.1.1.2 Sensors and Data Fusion Unit

The DFU provides some functions that are used in POC4. These functions allow the ME setting the following configurations:

- Configure some parameters of sensing

  The relevant sensing parameters are the threshold and the number of samples utilized in the energy detection algorithms. Other important parameter is the TV channel where the sensors will perform the sensing and finally the DFU has an enable

  - Sensing samples - number of samples in energy detector.
  - Threshold – decision threshold in energy detector.
  - TV channel – change sensing channel frequency in energy detector.

- Making the interface with the PSE triggers

To send the trigger to the PSE intended by ME the DFU as an FPGA. This FPGA is controlled over the RS232 serial port and generate the signal to stimulating the input triggers in PSE.

- Trigger incumbent HW – enable PSE.
- Trigger1 to start Incumbent Tx – enable channel 1.
- Trigger2 to start Incumbent Tx – enable channel 2.

- Define the destination where to send sensing data

  The sensing data that come from the sensors is processed by de DFU to made final decision on the occupation of the channel. This data are sent over UDP packets to a remote host (in this case ME) for future processing and analyses.

  - Set the remote host IP and port – define the address of the destination host
  - Trigger distributed sensing On – enable the transmission of the UDP stream to the destination host.

All the other functionalities involved are explained in more detail in PoC#1 and PoC#3 sections.

6.1.1.3 Master Entity

The Master Entity has been created considering the different gaps that need to be filled for setting the whole PoC#4 scenario. It was originally conceived as the Adaptation Layer, but in order to advance towards a more realistic scenario, some parts of other entities have been also included.

The Master Entity follows the SaaS (Software as a Service) architecture, thus enabling the addition or modification of the behaviour of the small pieces that belong to it. This is really useful for adapting the modules to the particularities of the scenario where they are performing, thus optimizing the resources used in terms of memory.

In this scenario, the Master Entity is in charge of the following actions:

- Detect the QoSMOS entities connected. This functionality corresponds to the Adaptation Layer definition, extensively documented in [D2.3]. The Master Entity checks the status of the different elements that must participate in the scenario reporting this information to the graphical interface.
- Synchronize the execution of the PoC#4. The ME is in charge of controlling the different locks located in the code for launching all entities at the same time.
- Selection of the operating technology and channel. The ME emulates a Portfolio database where the information regarding channel status is stored. Furthermore, due to the processing of the changes produced in that database, it is able of alerting and triggering that the UE must change its configuration.
- Configuration of AP-UE connection. Tightly related with the previous functionality, the Master Entity has to send the different commands needed for reconfiguring both AP and UE. This is done sending control messages to the Transceivers and Access Control modules in both sides.
- Forward sensing reports from Data Fusion Unit to CM-SM instance. This functionality just enables filling the Portfolio for exploiting this information by third parties in a technology-agnostic manner.

The following picture (see Figure 6-5 below) shows how the different modules of the Master Entity are placed and their relationship with the other entities involved in the PoC#4 scenario.

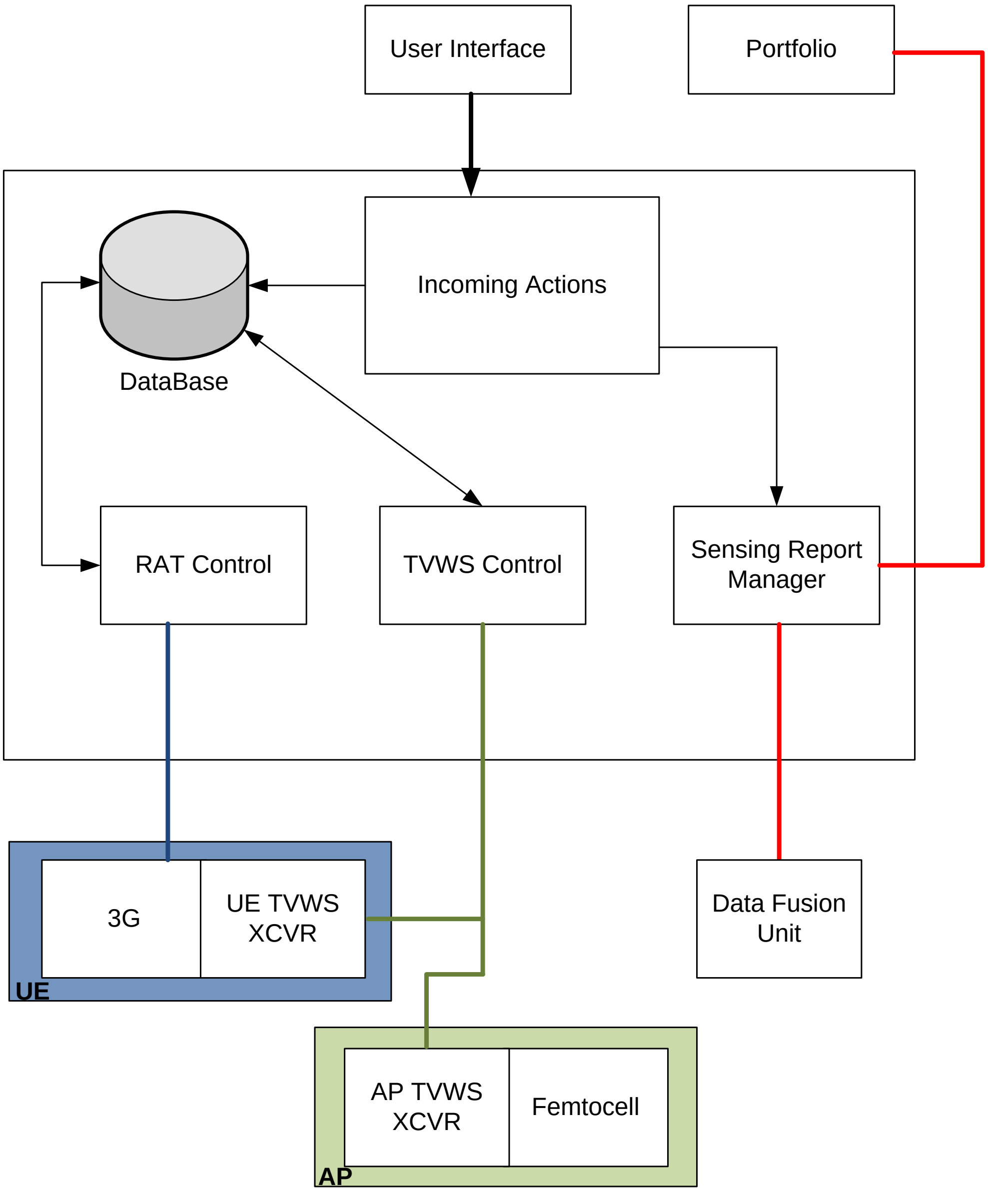


Figure 6-5 Master Entity relationships

Detection of modules in the scenario

The first activity performed by the Master Entity is the detection of the diverse entities participating in the QoSMOS system. The existence of these entities in the system is feasible due to the key role that the Master Entity is playing in the whole scenario. Since it is centralizing the management flow of the whole scenario, all entities send a message to the ME for requesting actions or confirming its presence (as depicted in Figure 6-6). This information is properly collected and stored, enabling the mapping of the whole connectivity track of the PoC#4.

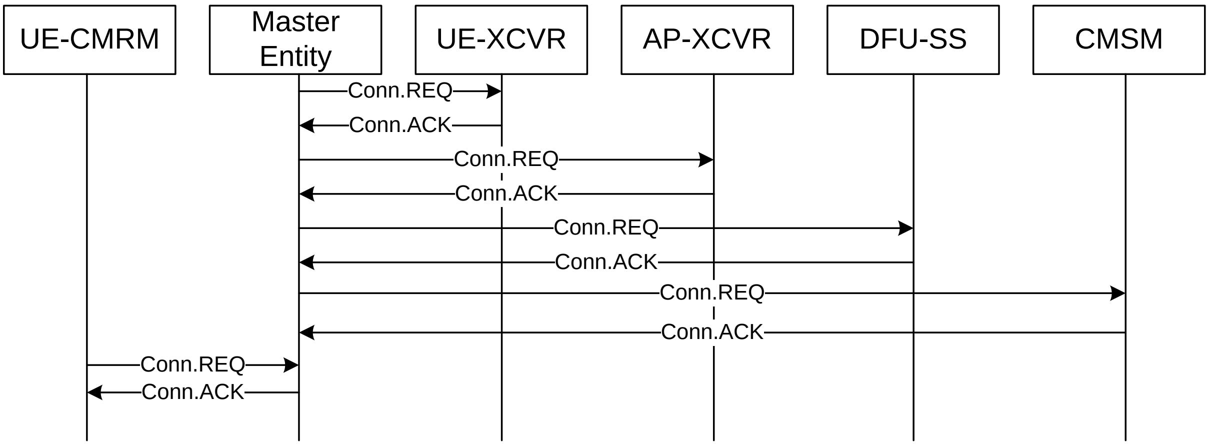


Figure 6-6 Notification of presence

Resource Selection Procedure

As it has been already stated, the Master Entity is in charge of selecting the best technology and the best channel for creating the wireless link that maximizes the QoS served to the User Equipment. The following Figure 6-7 represents the flow for this process of selecting the most appropriate channel. Once the resource request has been received by the ME, a process that consists in accessing the database for evaluating resources is triggered, selecting the best choice and informing both UE and TVWS boards about the new configuration.

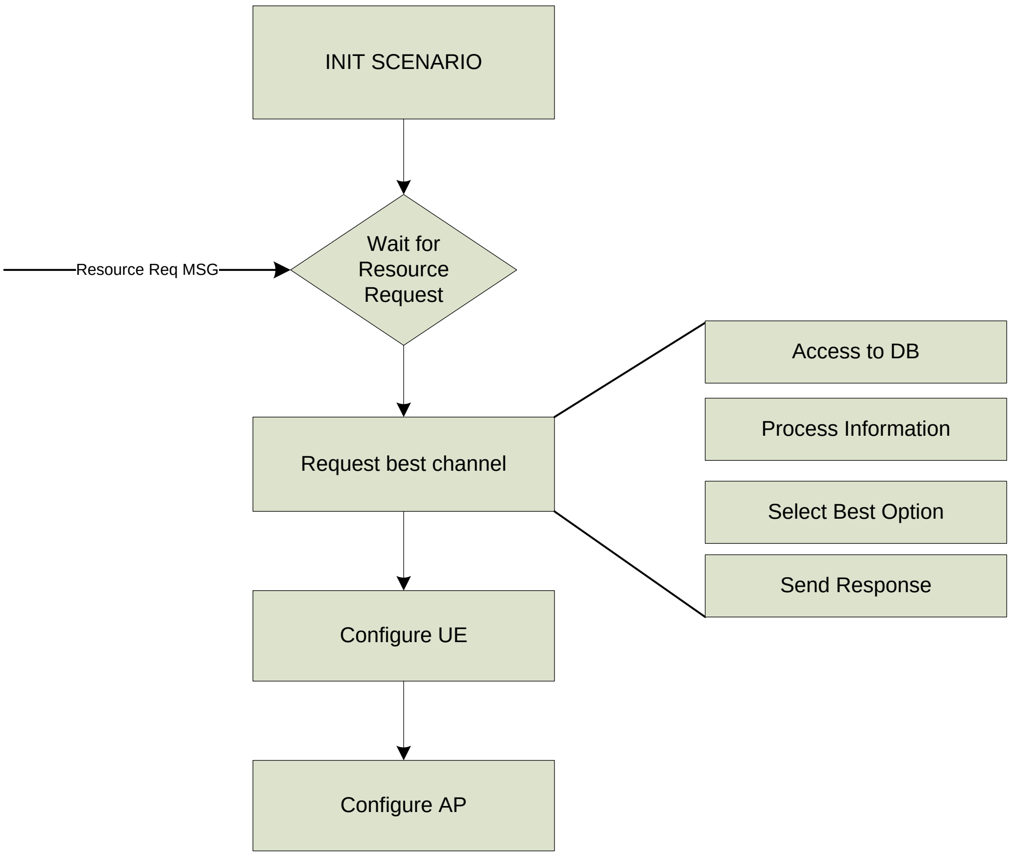


Figure 6-7 Resource Selection Procedure

Depending on the specific situations, the flow and messages sent are different. The first case occurs in the first connection, when the messages required are only those for configuring TVWS boards (see Figure 6-8). Note that it is mandatory to configure first the receiver and then the transmitter, in order to avoid potential problems.

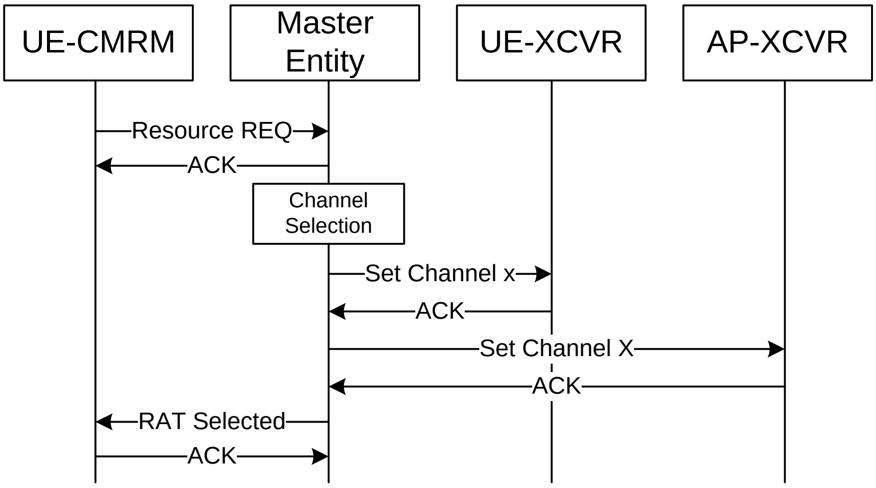


Figure 6-8 Configuring TVWS board

In the second scenario, the TVWS boards have to be reconfigured for operating in a different channel. In this case the UE access control module does not need to be informed about this change that only affects the physical channel where TVWS boards are working. Since the boards need to be stopped, the transmitter shall be stopped first, and then it will be receiver's turn. This process is depicted in Figure 6-9.

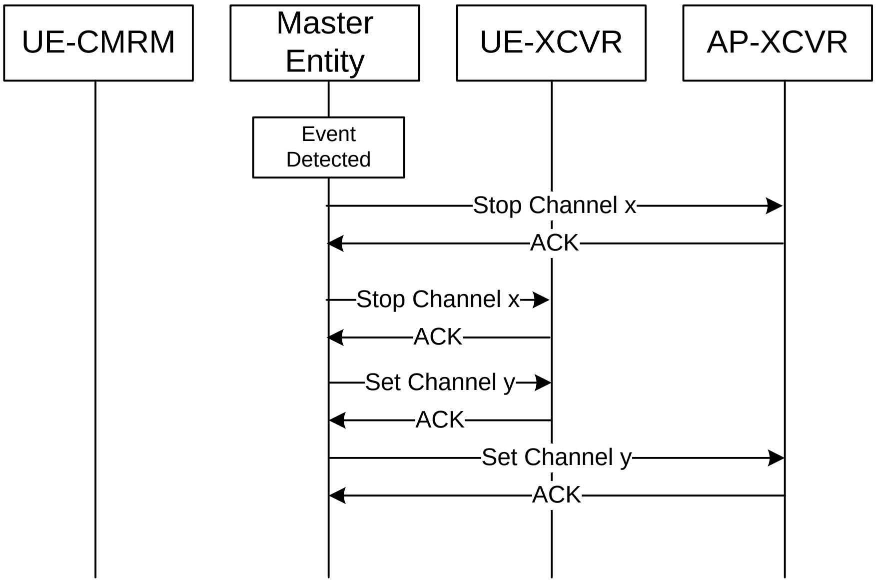


Figure 6-9 Reconfiguration of TVWS boards

In the last case evaluated in the proposed scenario, the communication is transferred from TVWS to 3G in a different band; this handover process requires to stop the communication on TVWS boards and configure the UE for working in 3G. The picture in Figure 6-10 below shows the message flow for performing this task.

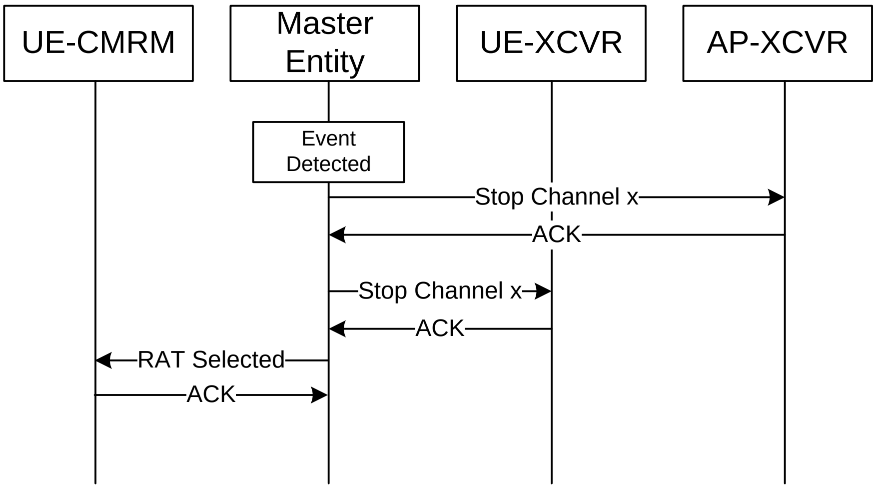


Figure 6-10 Handover from TVWS to 3G

Event Management

The Master Entity is in charge of handling different events that suppose changes in the overall PoC#4 configuration. These events can be triggered either by the user interface or by the entities in the scenario, due to the detection of lower QoS or by processing data base information. The events that are considered in this scenario are the following:

- Start Scenario. The User interface implements a button for launching the whole PoC. This request is sent to the Master Entity, which triggers different messages for activating all the entities involved in the PoC.
- Stop Scenario. In a similar way that in the start scenario case, the user interface counts with a button dedicated to warn all entities in the PoC to come back to the initial state. After pushing this button, the ME recomposes all the global parameters to the initial state and also sends messages to all the entities registered to restore their default configuration, thus returning to the initial state.
- Channel Selection. The Master Entity is in charge of selecting the best wireless technology and configuring the transceivers in both sides of the link. After receiving the alert warning some switch is needed, the ME will generate the necessary control messages for adapting the entities to the new functional conditions.

Interaction between Master Entity and Graphical Interface

The Master Entity, fulfilling its role as coordinator of the PoC, is in charge of interacting with the user interface. This communication is bidirectional: on the one hand, the interface provides commands that have to be mapped into changes in the scenario. On the other hand, the ME provides all the information that needs to be displayed in the interface. This process is depicted in Figure 6-11.

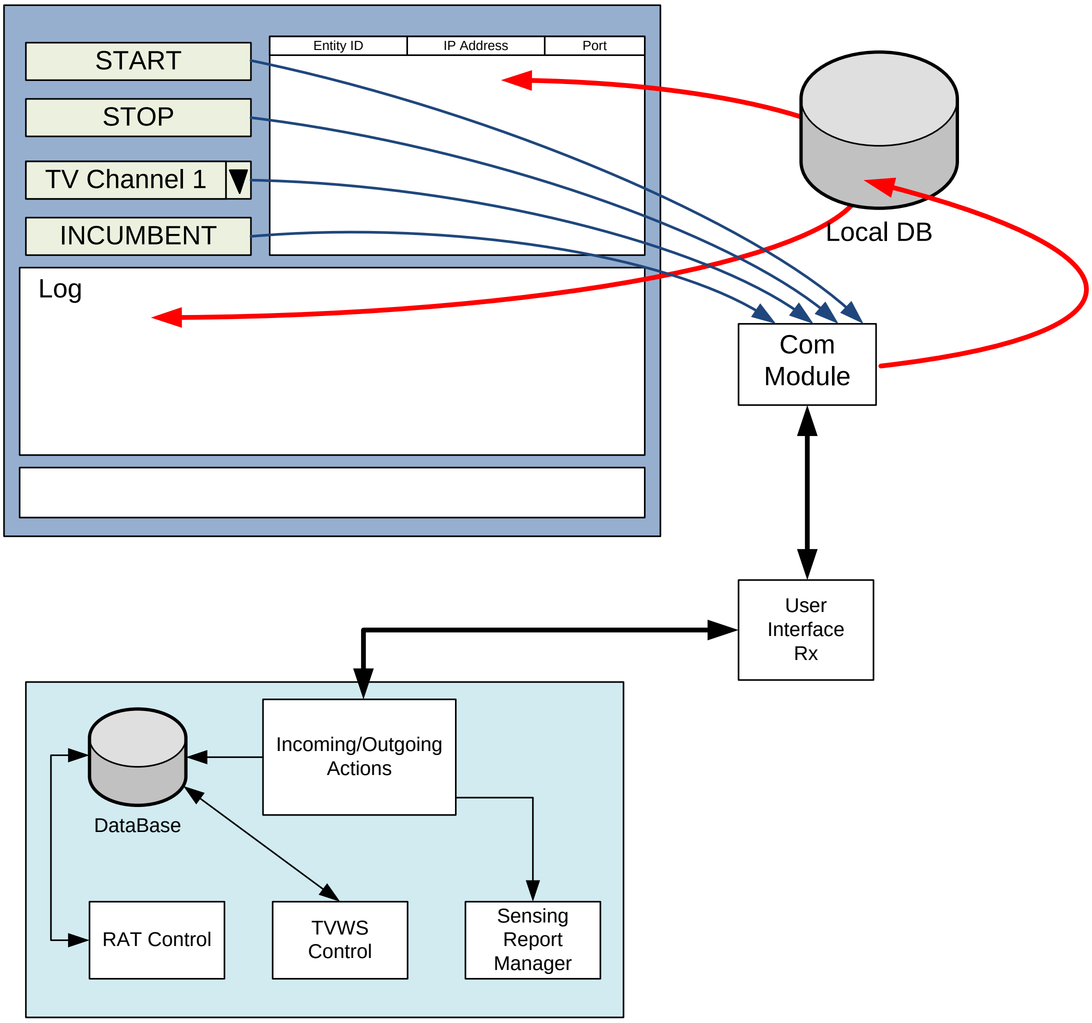


Figure 6-11 Interaction between Master Entity and User Iterface

In order to facilitate the integration of User Interface and Master Entity, two scripts have been created thus enabling the execution of the user interface remotely. These two scripts map the commands and messages locally in the databases. This simple process simplifies the execution of the ME in heterogeneous or variable environments without the need of modifying any parameter in it.

6.1.1.4 CM-SM instance

An instance of the CM-SM has been implemented and configured for the PoC#4 scenario, which enables to demonstrate the exchange of spectrum portfolios between entities as documented in detail by [D6.5][D6.6][D6.7] and to conduct initial interoperability and performance tests. The implementation provided consists of three entities, namely a CM-RM (a partial implementation focused on the communication protocols in fact), a CM-SM entity (managing spectrum requests originating from the CM-RM), and a CM-SM interfacing a TVWS database managing white space spectrum in terms of spectrum portfolios.

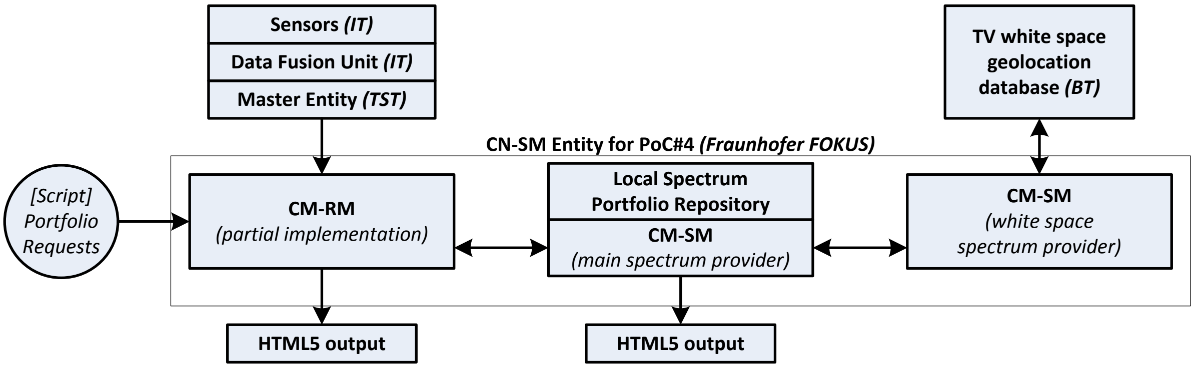
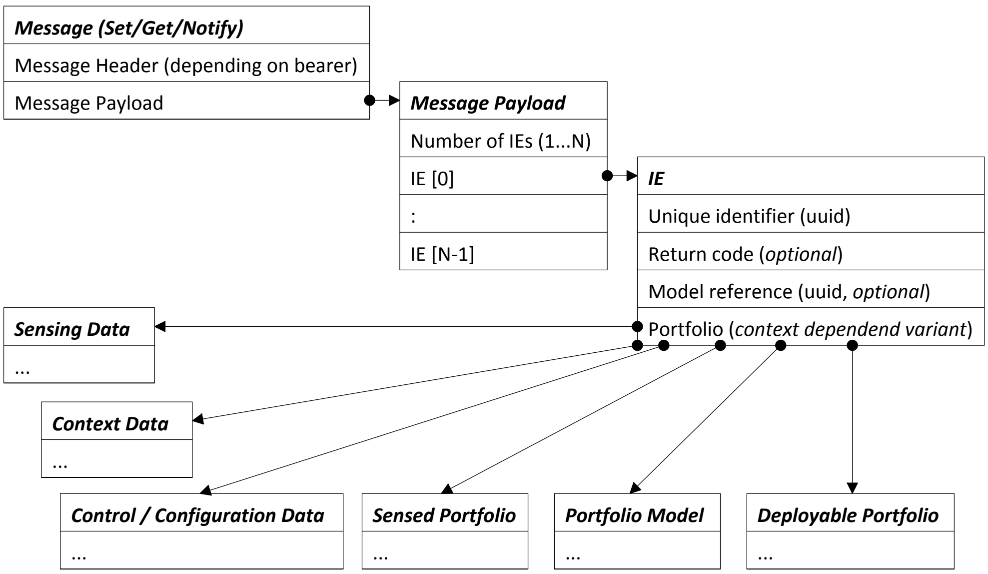


Figure 6-12: Configured CM-SM entity for the PoC#4 scenario

The spectrum portfolio is realized as the data structure outlined by Figure 6-13. Only mandatory information elements (IEs) have been implemented for PoC#4, namely the spectral constraints (i.e. a vector of frequency blocks and related spectral masks), spatial constraints (i.e. the geographical area where spectral constraints apply), and temporal constraints (i.e. a lease time). These parameters unambiguously define the usage rights for the portion of spectrum considered by the portfolio.

Portfolio communication between entities shown (cf. Figure 6-12) relies on binary encoded (Type-Length-Value, TLV) messages as shown in Figure 6-13. Message transport here has been implemented on top of CORBA. This choice allows performance estimates that avoid uncertainties due to complex message parsing. Nevertheless the underlying toolkit also supports XML based message formats and communication mechanisms other than CORBA.



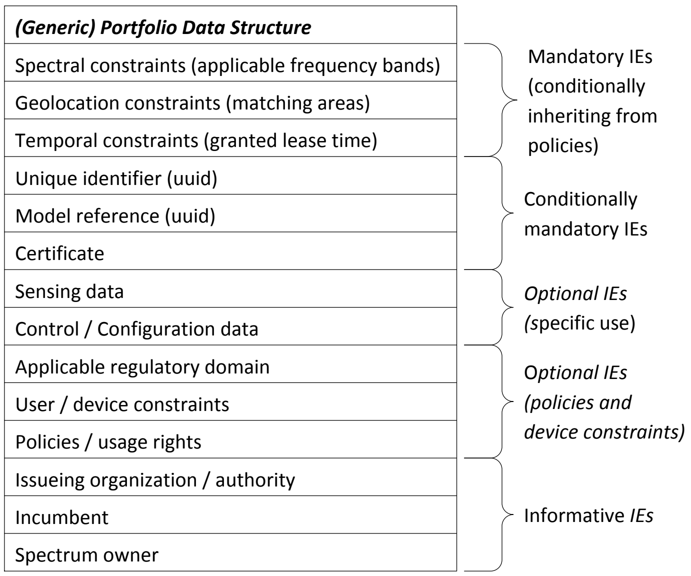


Figure 6-13: Top-level Spectrum Portfolio layout and message format for the PoC#4 scenario

For the PoC#4 scenario, the basic mechanisms for portfolio management have been implemented and tested, namely request, revoke, deploy, release, update and report using spectrum portfolios. Both satisfying requests from a local portfolio repository as well as forwarding portfolio requests in case the request could not be satisfied locally has been implemented (cf. Figure 6-14). In that, spectrum portfolio requests for multiple frequency bands can result in composing one or more portfolios into a single portfolio to combine licensed and shared spectrum provided from different CM.-SM entities, for example.

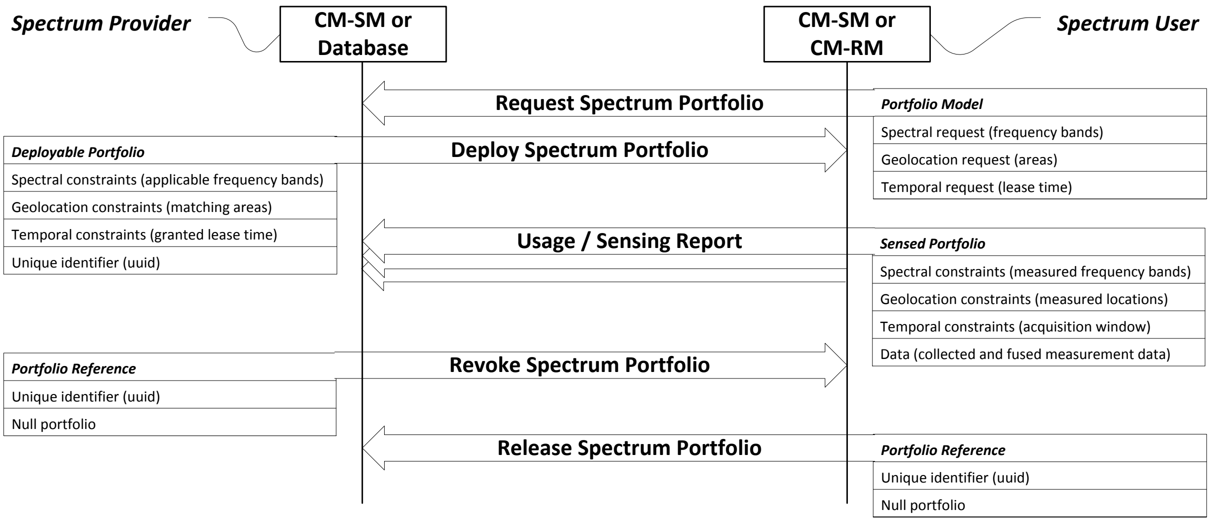


Figure 6-14: Spectrum Portfolio exchange implemented for the PoC#4 scenario

Although the CM-SM instance as described above was intended to integrate with the PoC#4, it also was designed to act self-contained while complementing and augmenting the PoC#4. For that reason a dedicated CM-RM entity was configured both to receive spectrum requests from the cognitive UE and access points as well as to simulate spectrum requests through a pre-configured script. In addition, the CM-RM entity can receive spectrum sensing information from both real-world spectrum sensors and simulated sensors. The CM-RM communicates with these entities through the master entity of Figure

6-16 that provides access through the Adaptation Layer. All information (i.e. spectrum requests and sensor reports) is conveyed back and forth in form of a spectrum portfolio as shown in Figure 6-13.

Optionally, the CM-RM provides a small web server allowing an HTML5 capable web browser to access and visualise the CM-RM entity state.

Besides the main CM-SM entity responsible for handling CM-RM requests and reports, a second CM-SM entity was configured to provide access to the Geolocation Database. Any requests regarding white space spectrum towards the main CM-SM entity are forwarded to this CM-SM, which in turn queries the database for an unused channel satisfying the spatial constraints provided. In contrast to the master entity querying the database in a similar way, the CM-SM converts the database response into a spectrum portfolio, caching the information for further use matching the temporal constraints provided.

6.1.1.5 AP and UE RF control boards

AP and UE flexible boards are both controlled by an embedded ARM Cortex A8 processor. A Linux operating system runs on the platform. These features have been used to integrate the flexible transceiver proposed in WP4 to proof of concept #4. One issue that has been raised was found in interfacing the flexible TVWS to an IP network. In order to solve that issue a light MAC interface has been developed in the embedded Linux in order to make the cognitive data link transparent to the user. This solution is depicted in Figure 6-15.

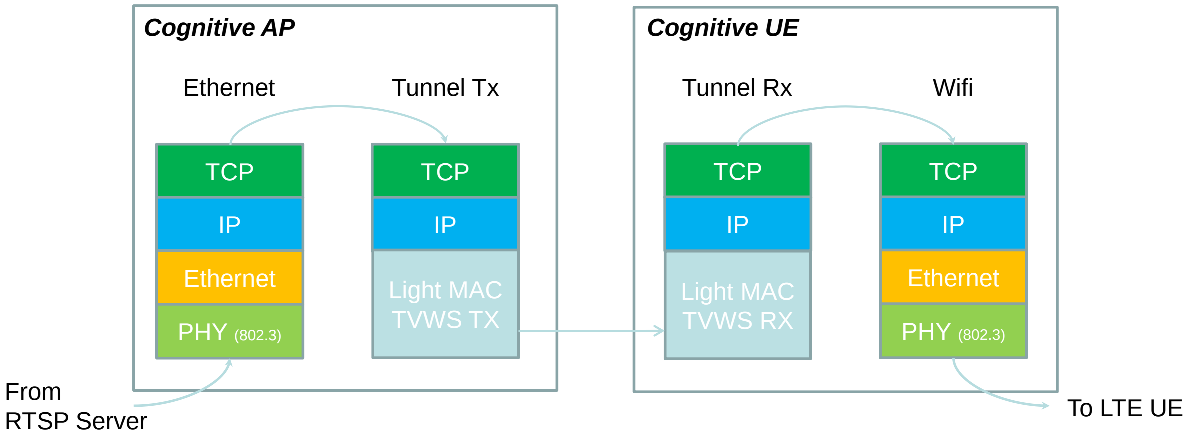


Figure 6-15: Interface of TVWS Cognitive Radio to other elements of PoC.

This interface has been performed by creating a tunnel inside both the cognitive access point (AP) and the cognitive user equipment (UE). The tunnel then interfaces to the specifically developed light MAC the flexible physical layer. The Light MAC allows for frequency channel selection and data transfer. It interfaces to the Master Entity to enable the link, disable the link and choose the TVWS channel where the link is performed. This set-up allows for complete transparent IP transmission independent from the application from through the QoSMOS flexible cognitive Radio transceiver.

6.1.1.6 User Equipment

The cognitive User Equipment is a NEC Smartphone working with an Android OS which will be the device trying to connect to the different TVWS channels and/or the legacy system.

The User Equipment will contact the Access Point section in the test setup. For accessing the legacy system, the user equipment will connect to NEC Femto Access Point (FAP) which is a ‘zero touch’ plug-and-play consumer device providing the 3G legacy network. The NEC Femto Access Point is installed and connects to the simulated operator’s core network over by using an Ethernet connection.

For accessing the TVWS channel, the User Equipment will connect through the transceiver through a wireless link, a Wi-Fi AP, thus being able to receive any data.

Due to IP stack priority policies of the cognitive user Equipment, a light cognitive Radio Access Technology (RAT) control engine has been developed to interact with both the 3G connection and the TVWS channel link. This RAT control engine has to perform the following functionalities:

- Detect the presence of the Master Entity which controls the cognitive User Equipment,
- Get the information about the selection of the operating technology. The User Equipment will receive an alert of the operating RAT and it will trigger the RAT control to change its configuration
- Configure the RAT to be able to play the video in RTSP video player of the User Equipment. The User Equipment has to ensure that RAT is available after each re-configuration and that the master entity is still accessible.

6.1.2 Depiction of the scenario

The aforementioned equipment is deployed according the QoSMOS architecture described in the technical work packages and presenting certain constraints due their condition as proof-of-concept versions. These special characteristics impose the creation of a quite detailed network to let them all interact with each other as expected and proceed with the desired tests using a couple of TVWS and a legacy channel.

In the end, the network created in this test setup is the one shown in Figure 6-16 below.

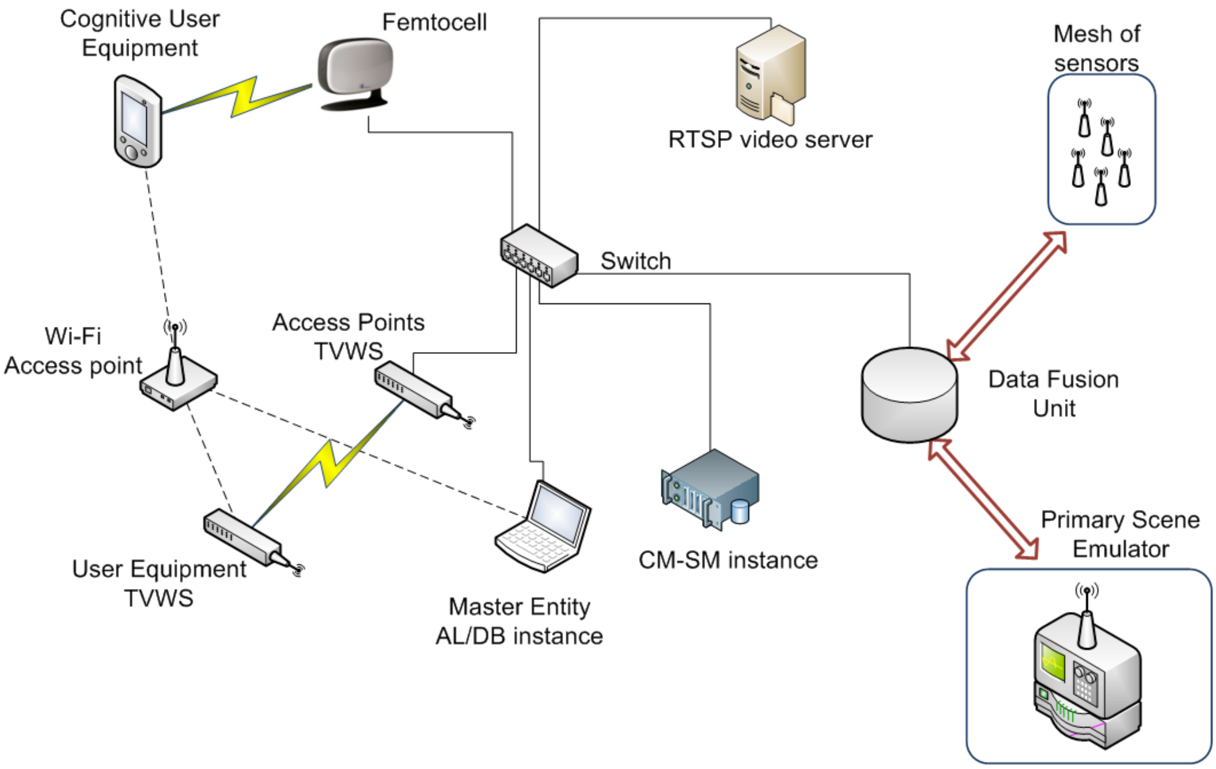


Figure 6-16: PoC#4 network description

As stated previously, the user equipment, represented by an Android cell phone, is going to play a video sent from a RTSP (Real Time Streaming Protocol) server (based on TCP (Transmission Control Protocol) for control duties and on UDP (User Datagram Protocol) for data) through different TV channels and, after an eviction process is executed, a 3G connection, being the conceptual flow of the test the one depicted in Figure 6-17.

In this simplified version of the test bed behaviour, it is clearly stated that the Opportunistic transmission that will be carried out begins using TV Channel 1. After a while, an Incumbent User is going to appear in that same TV channel, thus making it necessary to change to another one to continue the video streaming. The sensors inform that TV Channel 2 is not in use, so the transmission can be changed to that channel. Moments later, another Opportunistic User is going to make use of that same TV Channel 2, thus producing Quality of Service (QoS) decline which pushes the system to switch to a legacy channel in order to continue, and successfully end, the video streaming transmission.

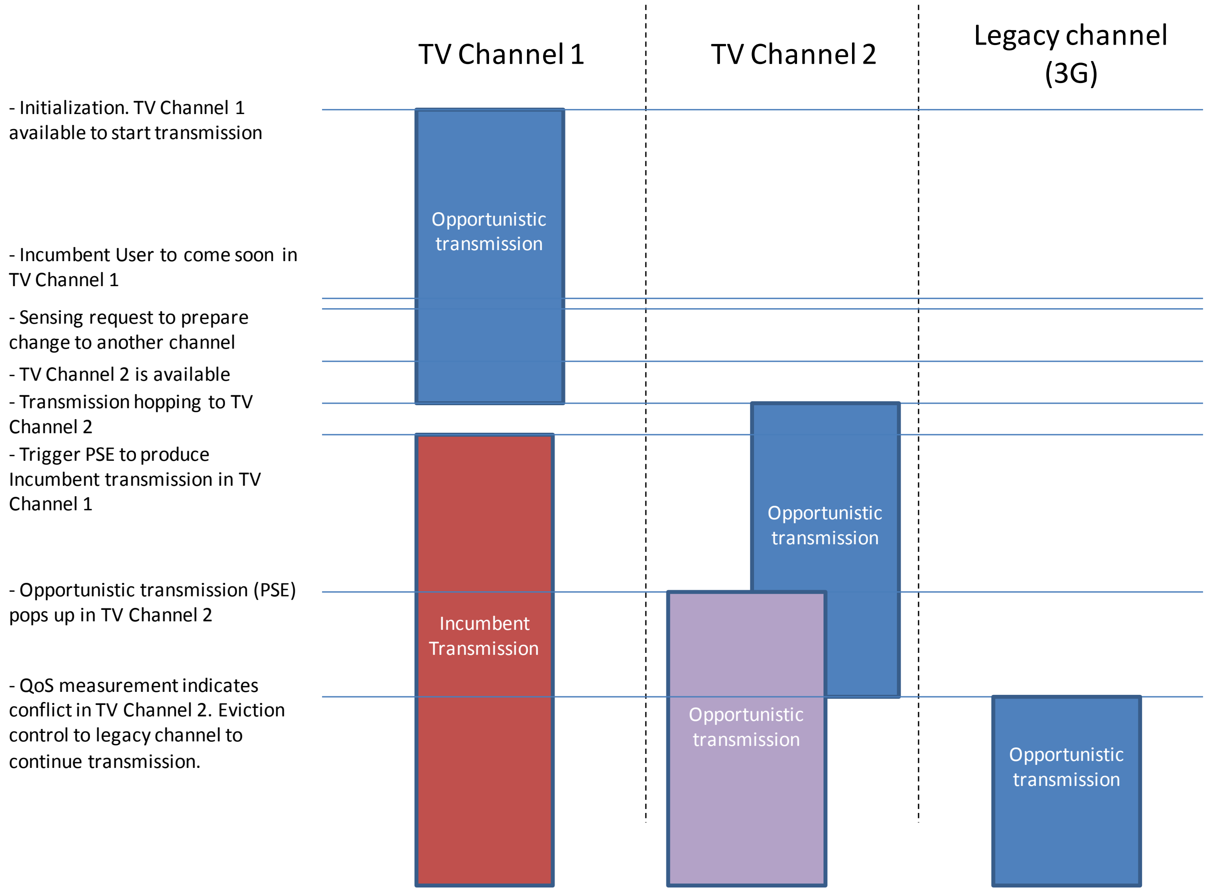


Figure 6-17: PoC#4 scenario flow

Taking into account this flow of the test, it is mandatory to properly specify the role of each one of the involved actors. First of all, the Master Entity gets in sync with all entities, for which the creation of TCP (Transmission Control Protocol) servers to communicate is carried out, along with an initial communication with the XML-RPC (eXtensive Markup Language – Remote Procedure Call) server established in the Data Fusion Unit specifying the destination for the sensing reports. The aforementioned TCP servers are created in the ME, to create a communication path with the UE, and in both AP and UE boards, to let the ME communicate with them.

It is important to note that during the whole process the user is capable of knowing the active entities, along with the events happening during the test, thanks to the a main GUI (Graphic User Interface) which shows it all on screen.

Once these communication paths are settled among the ME and the entities initially active in the scenario, the DFU, the AP and UE boards, and the UE itself, the ME requests the DFU to start sensing on TV channel 1 (TVCH1). This request is transformed into a trigger to the sensors, which immediately begin retrieving data from that TVCH1. The collected data is sent to and processed in the DFU, which sends the corresponding sensing reports to the ME. These reports on TVCH1 are forwarded to the CM-SM instance, which is provided with a GUI where the sensing reports are depicted.

It is time for the UE to launch the video application, and so requests the ME for resources. In turn, ME informs both AP and UE the communication can start on TVCH1. Thus, the video streaming using TVCH1 from RTSTP server to UE smartphone initiates.

After the resource selection process that informs the communication can be established in TVCH1, the ME immediately requests the DFU to configure itself to sense TVCH2, so it is time for the sensors to retrieve data from that TV channel. This data is once again sent and processed into the DFU, which sends the definitive sensing reports to the ME, and then they are forwarded to the CM-SM instance, in charge of presenting them in a graphic way in its GUI.

Then, the system is able to predict the incoming apparition of an Incumbent User in the TV channel currently in use. In this setup, the user can make use of a button present in the main GUI which triggers that IU apparition in TVCH1. Before the Incumbent transmission begins, the ME asks AP and UE to stop communicating using TVCH1, carries out a new resource selection process and warns AP and UE the video streaming can continue over TVCH2 instead. The moment this latter communication is started, the ME sends a trigger to the DFU which forwards it to the PSE informing it is time indeed to start the incumbent transmission. Thus, the PSE proceeds with the IU transmission in TVCH1 while the video streaming goes on in TVCH2.

After a while, the UE detects a QoS dropping in the video play due to the apparition of an Opportunistic User in the operating TV channel, and warns the ME about that issue. In the test setup scenario the GUI is provided with a selector to specify this QoS drop, which makes the ME to start the process of triggering the apparition of a new OU in TVCH2, and thus the ME needs to carry out a new resource selection process and inform the UE smartphone it is time to change transmission to a legacy channel, 3G in this particular case, since there are no more TV channels available. In addition, the ME asks both AP and UE boards to stop communication on TVCH2. Thus, UE smartphone continues video streaming from RTSP server using the 3G connection provided by the femtocell.

Any moment it is desired to stop the execution of the test, regardless of its current status,, the user can push a button on the main GUI to stop the scenario and make it return to the initial state, standby mode. This same event occurs the moment the video streaming finishes,

All these interactions give form to a Message Sequence Chart (MSC), presented in Figure 6-18, which helps to determine the steps followed in the test scenario.

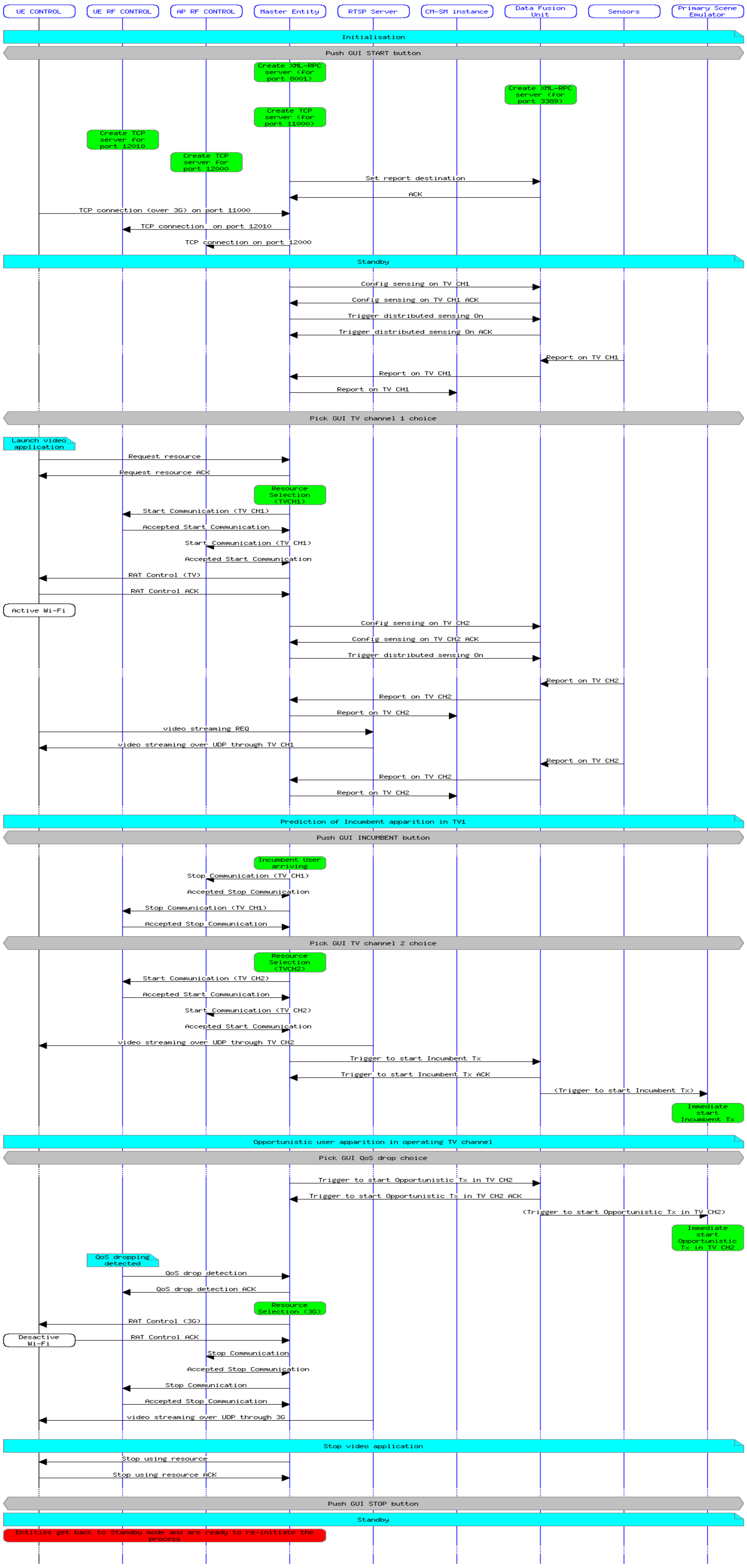


Figure 6-18: PoC#4 scenario message sequence chart

6.2 Validation process and results obtained

As PoC#4 is a get together of the other proofs-of-concept, it is not the easiest one to collect direct measures and results. That is the reason why the validation process carried out within this proof-of-concept, a simplified version of QoSMOS architecture, has consisted in a system level approach, trying to observe what happens in certain entities when one of them sends a message, how they all react. This way, the results could be exported to future more detailed scenarios, leaving the pure metrics to the individual PoCs (1-2-3).

6.2.1 Tests performed

In order to thoroughly test the modules involved in this integrated proof of concept, preliminary separated tests have been carried out. To this purpose, two major sub-scenarios have been designed, one of them focusing on the Core Network, while the other one puts its effort on the User Equipment and Access Point part, being the Master Entity the central point that brings them both together.

With regard to the Core Network, it was agreed to use two independent triggers (not only in time, but also physically) between the DFU and the PSE generating the IU and OU signals. Therefore, the resulting ability to trigger two independent radio scenes (and its combinations) providing increased flexibility and safety in this PoC.

Once this point had been settled, the main effort has consisted of verifying the proper delivery of sensing reports generated from the DFU to the ME, and how this entity forwards them to the CM-SM instance present in the scenario. Afterwards, some synchronisation issues need to be addressed for the CM-SM GUI to be able to correctly interpret this information and paint the correspondent sensing reports on screen, thus letting the user know the evolution of the frequency channel which is being used at any stage of the test, thanks to the ability of this portfolio manager to learn from its context and provide mobility support.

As for the sub-scenario involving the Access Point and User Equipment part of the test bed, due to the aforementioned technical limitations in the equipment a network solution has been designed and tested with the intention of achieving the goals of the proof-of-concept. Once developed and validated, the video transmission application has been successfully ran, the data flowing from the RTSP server to the user Smartphone.

Given the promising results obtained with that test, an additional one has been proposed. It consists in employing a HTTP server, integrated into the test scenario, and doing some web browsing using the UE Smartphone, accessing QoSMOS webpage. This trial has also been successful, and the user is capable of browsing the web using the UE smartphone, and although this HTTP transmission is much less resource demanding than video streaming it is useful to demonstrate the validity of the proposed solution.

6.2.2 Results obtained

In the Core Network sub-scenario, the communication via XML-RPC between ME and DFU has turned out to be the most proper choice for this kind of transmission, producing negligible delays in the transmission of the sensing reports, which implies a non important latency.

Regarding the Access Point and User Equipment sub-scenario, the validation of the network architecture of PoC#4 has been the focal point to be validated, as well as the ability to split and/or merge the duplex streams over different nodes has been solved and tested. This way, a video from the RTSP server has been streamed to the UE smartphone, where it has been played almost seamlessly independently of the communications channel in use, both TVWS and legacy one.

Once these two sub-scenarios have been joined together, the overall scenario presents a proper functioning, with all entities synchronizing properly at the beginning of the test and thus being able to communicate with each other throughout the different stages of it without experiencing any noticeable adverse effect in form of delays or package dropping.

6.3 Assessment of portability to QoSMOS system architecture

The execution of this test has served to demonstrate the validity of the system architecture proposed by QoSMOS project, involving an innovative approach within the cognitive radio field.

The two cognitive manager approach has been hinted and validated within this test bed, replying them through instances of their complete architecture, demonstrating that it is a valid way to go in implementing cognitive radio networks.

All in all, the main objective of the design presented in this PoC consists of developing a modular system through which portability and interoperability between components developed can be provided, even though they may all be using different programming languages.

In addition, the interfaces employed abstract the complex implementation of the setup and give consistency, thereby providing portability and supporting heterogeneity across different radio devices and operating platform.

6.4 Potential for further work

The promising results obtained with this setup pave the way and serve as a starting point to this task.

First of all, a complete development of the different entities that compose the QoSMOS system architecture should be carried out, since most of the ones present in PoC#4 are simplified versions of them. Thus, totally functional cognitive managers, for spectrum and resource management, could be developed and different algorithms, both the ones used in this PoC and new ones, deployed over them, handling tasks like the spectrum sensing, or the cognitive discovery and management of resources, along with adaptation duties.

Also, the inclusion of a real TVWS database interacting with the rest of equipment in the scenario should improve the overall system, since this database would manage much more information regarding channel availability thus giving a major freedom of operations and effectiveness to the scenario. The TVWS database with geo location capabilities developed within the project and presented in [D7.3] means a step in that direction.

Lastly, a more consistent approach to network security could certainly imply some benefits, assuring that nothing compromises the integrity of any of the entities that are part of the system while at the same time implies a correct exchange of information and data among them all.

Once these points are settled, mobility should be addressed in a more wide scope than the one presented by this test bed. This would imply deploying QoSMOS solution in a more realistic scenario, where users could indeed move all along the place, forcing the system to make the right decisions at all times.

7 Concluding remarks

Latest initiatives anticipate that cognitive radio technology will soon emerge from early stage laboratory trials to become an important platform for wireless communications, given the shortage of cleared spectrum. Thus the effort invested within this work package in the development of selected tests to evaluate the performance of the distinct elements of the architecture designed in the technical work packages of QoSMOS project.

Through the execution of these proof of concepts, the intention has been bringing some realism and ease in development of a cognitive radio network system, testing its diverse building blocks separately and ultimately putting them together to simulate a flexible cognitive radio solution, this way evaluating the proposed CR system architecture at various stages of its development.

Therefore, several sensing algorithms proposed for the radio context acquisition have been developed, and their performance compared and analyzed through diverse simulation tests. The platform demonstrators which have evolved around this topic have specifically aimed at integrating the primary scene emulator, which is emulating incumbent users, with the sensors, and the results provided processed by a data fusion unit which generates and offers the most proper decision on the presence of an IU, taking the sensing reports as its input.

On the other hand, CR for white spaces needs to assure incumbent protection and a dynamic spectrum usage, thus it is required to control the interference and using a flexible radio technology. Therefore it is clear that TVWS is a context where spectrum efficiency and incumbent protection cannot be guaranteed simultaneously by mainstream OFDM technology, QoSMOS has investigated alternatives to tackle these issues, with up to three approaches being investigated, namely Interference Avoidance transmission by Partitioned Frequency- and Time- domain processing (IA-PFT), Generalized Frequency Division Multiplexing (GFDM) and FBMC, being this last one thoroughly analyzed down to its actual implementation, thus demonstrating a high ACLR and flexible access to fragmented spectrum, providing promising results and leading to the this technology being currently under discussion in IEEE DYSPAN P1900.7.

Finally, the integrated scenario aims to provide relevance to QoSMOS efforts, integrating developments achieved in the previous PoCs and in the technical work packages, thus showcasing to some extent a real cognitive system. Through its development, certain CR concepts for link and upper layers have been thoroughly tested and successfully validated.

However, a considerable difference exists between counting with this efficient test bed validated and a real-life large-scale deployment of a CR network, able to optimize the spectrum use in a dynamic way. Thus, the desirable way forward would imply testing, evaluating and demonstrating the cognitive networking system proposed by QoSMOS at scale and in real-world deployment.

With the intention of presenting the work carried out within the project to a wide audience, with representatives of different sectors (vendors, stakeholders, regulators ...), the PoCs were demonstrated in the QoSMOS briefing event held in London on December 12th 2012. PoC#1 and PoC#3 were combined, where a channel emulator was connected to a bank of sensors and the output from the sensors were combined (data fusion) to increase detection reliability. The PoC#2 took the form of a hardware demonstration of FBMC generation. The PoC#4 was partially represented at this event by the integration of the adaptation layer with the spectrum manager. The demonstrations of the PoCs were repeated at the QoSMOS spectrum sharing event in Washington DC on 22nd March 2013.

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