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Lead beneficiary:	EURE
Participants:	Dominique Nussbaum (EURE), Renaud Pacalet (IT)
Reviewers	Konstantinos Chatzikokolakis (UoA), Alexander Jaschke (IIS)

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DISSEMINATION LEVEL		
PU	Public	**X**
PCA	Public with confidential annex	
CO	Confidential, only for members of the consortium (including Commission Services)	

EXECUTIVE SUMMARY

This is deliverable D6.4 of the FP7 ICT SACRA project. It describes the real time trial activities of the developed cognitive radio platform. As described in D6.1 and in D6.2, the intra-cell Spectrum Aggregation scenario allows the validation of most of the concepts developed in SACRA. The present document illustrates the demonstration and trials activities that have been conducted to prepare the implementation of the intra-cell Spectrum Aggregation scenario around the Eurecom building, in Sophia-Antipolis, France.

In Chapter 2, an overview of the demonstration is given. The overall demonstration comprises:

- The SACRA terminal (dual band, developed in the WP4 for RF modem), integrated in a host PC that is used for the protocol stack
- A TVWS (470-790 MHz) and 2.6 GHz LTE eNodeB: those logical entities are co-localized and are physically the same equipment.
- A Joint Radio Resource Management (JRRM) entity, which attributes the radio resources in both bands, UHF and 2.6 GHz. In Spectrum Aggregation (Use Case 1 that is actually demonstrated), it allows the combination of the 2 bands resources to increase the throughput.

The hardware parts of the eNodeB are discussed in Chapter 3. The eNodeB parts comprise:

- 2 antenna sub-systems, one for the 2.6 GHz band and one for the TVWS band. The 2.6 GHz antenna sub-system comprises 1 antenna, the TVWS antenna sub-system comprises 2 antennas
- The antenna subsystems are connected through RF cables to an RF equipment to be installed in the control room beneath the mast, namely the PA-LNA Subsystems. The aim of those elements are to amplify and filter the Signal of Interest both on the RX and TX side
- the PA-LNA Subsystems are connected to the RF/baseband Conversion box. The aim of this part is to convert the RF signal into base band signal.
- The RF/base Conversion box is connected to a distribution board (which aim is to put all the RF signals and controls into one single connector to ExpressMIMO) and to ExpressMIMO. ExpressMIMO is a FPGA-based board dedicated to Base Band processing. The protocol stack of the eNodeB is done in a host PC, connected though a PCIexpress interface.

The hardware parts of the UE are presented briefly in Chapter 4, since the detailed description of those parts was in the scope of WP4 deliverables. In Chapter 5, the soft modem is described as well as the protocol stack implementation. In order to implement full over-the-air communications between the eNodeBs and the SACRA terminal, we have reused the Open Air Interface (OAI) protocol stack (http://www.openairinterface.org/) developed by Eurecom.

Finally, the experiments that have been performed are discussed in Chapter 6. For those experiments, the overall setup comprises:

- an eNodeB located in the Eurecom building, with capabilities in TVWS band (TDD duplexing mode) and 2.6 GHz (FDD duplexing mode)
- a terminal that is put in a car.

CONTENTS

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

This document is the deliverable D6.4 of the SACRA project and describes the real time trial activities of the developed cognitive radio platform. As described in D6.1[1] and in D6.2[2], the intra-cell Spectrum Aggregation scenario allows to validate most of the concepts developed in SACRA. This document illustrates the demonstration and trials activities that have been conducted to prepare the implementation of the intra-cell Spectrum Aggregation scenario around the Eurecom building, in Sophia-Antipolis, France.

In Chapter 2, an overview of the demonstration is given. The hardware parts of the eNodeB and the UE are discussed in Chapter 3 and 4. In Chapter 5, the soft modem is described as well as the protocol stack implementation. Finally, the experiments that have been performed are discussed in Chapter 6.

1.2 DOCUMENT VERSIONS SHEET

Version	Date	Description, modifications, authors
0.1	04.12.2012	Initial document, Dominique Nussbaum
0.2	21.12.2012	Creation of Chapters, initial content
0.3	5.01.2013	Revision of all the Chapters
0.4	20.01.2013	Insertion of pictures, results
0.5	28.01.2013	Insertion of pictures, results
0.6	18.02.2013	Insertion of pictures, results
0.7	22.02.2013	Internal review
1.0	23.02.2013	Finalization

2 OVERVIEW OF THE DEMONSTRATION

As described in D6.1, the overall SACRA demonstration will aim at demonstrating a Spectrum Aggregation (SA) scenario. We have selected a Use Case with a cognitive access to the TVWS band and a classical cellular access to the licenced band (2.6 GHz). Moreover, we have defined in D6.2 the system specification. The demonstration setup is derived from the specification of the SACRA system. Therefore, as depicted in Figure 2-1, the overall demonstrator comprises:

- The SACRA terminal (dual band, developed in the WP4 for RF modem), integrated in a host PC that is used for the protocol stack
- A TVWS (470-790 MHz) and 2.6 GHz LTE eNodeB: those logical entities are co-localized and are physically the same equipment.
- A Joint Radio Resource Management (JRRM) entity, which attributes the radio resources in both bands, UHF and 2.6 GHz. In Spectrum Aggregation (Use Case 1 that is actually demonstrated), it allows the combination of the 2 bands resources to increase the throughput.

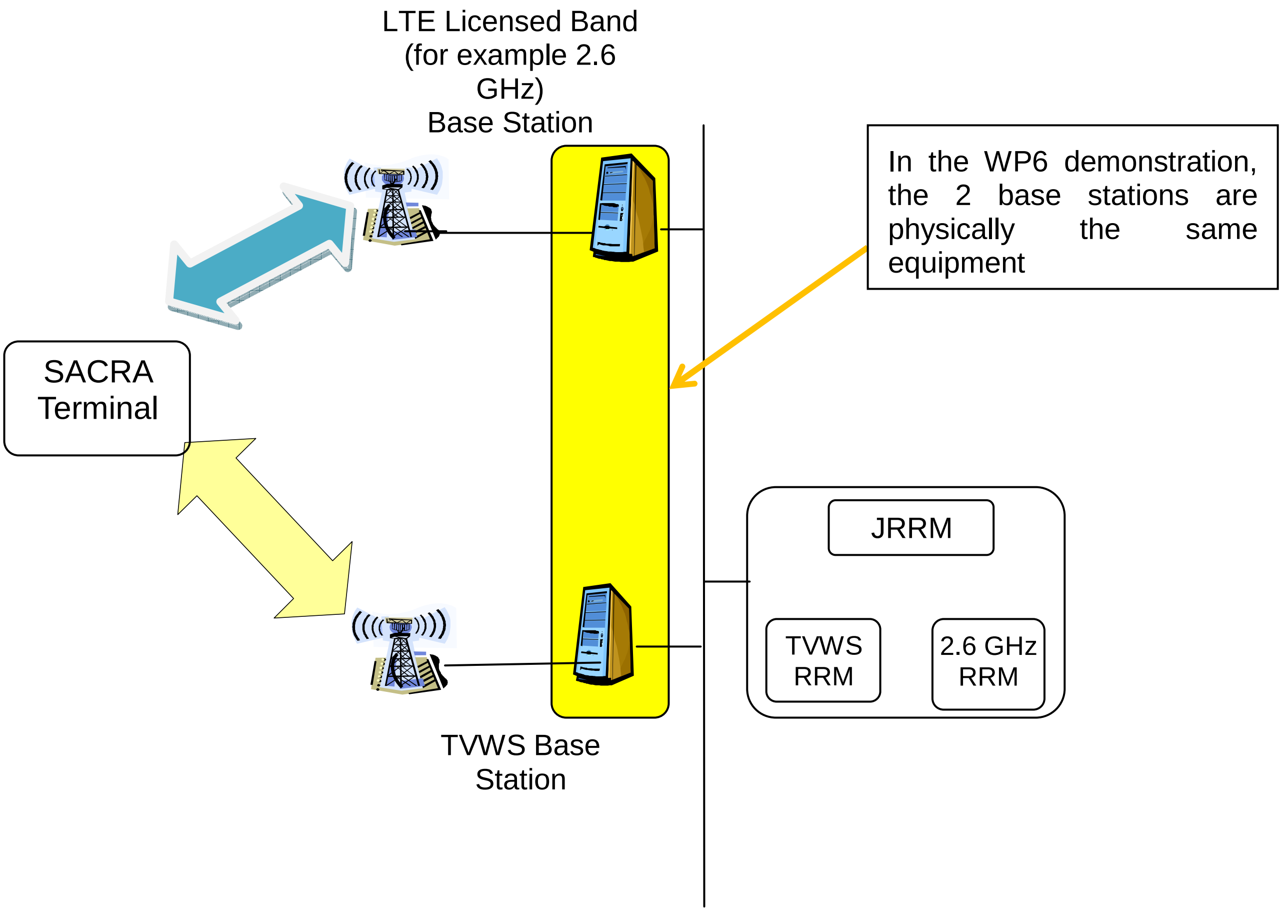

Figure 2-1: SACRA demonstration abstraction view

As stated in D6.1[1], the SA scenario that will be implemented can be divided into 5 steps:

- Step 1: the SACRA terminal is connected to LTE base station through the 2.6 GHz band. The SACRA system monitors the available/free channels in the TVWS band in the area (continuous sensing). Here we can simulate interference on some part of TVWS if necessary and hence sensing is able to detect which channels in the band are free and which are in use. Indeed, there is no guaranty that a primary user can enter in our coverage at a given time; we will therefore emulate a primary user thanks to a microphone. We will transmit in a specific channel, in order to validate the sensing algorithms.
- Step 2: Better QoS is required and the system sends a request to the TVWS base station asking for allocation of resources in TVWS.
- Step 3: The SACRA terminal gets a TVWS resource (the same it asked) from the TVWS base station. From now it is receiving one 2.6GHz carrier (from LTE base station) and one TVWS carrier (from TVWS base station). During this period, the sensing system monitors the band in order to ensure an efficient evacuation of the used band. The list of the available/free TVWS channels is also maintained.
- Step 4: A primary user (a microphone) appears on the TVWS carrier used by the SACRA terminal. The system detects the primary user (detection distributed between the TVWS base station and the UE). The information is sent to the JRRM.
- Step 5: The TVWS carrier of our SACRA terminal is changed from the initial carrier and from now it is receiving the same 2.6GHz carrier but a new TVWS carrier (selected from the JRRM).

The specifications of the SACRA system are derived from this scenario, and are mainly described in D6.1[1].

3 ENODEB PARTS

First of all, it shall be noticed that the 2 eNodeBs (the cellular eNodeB at 2.6 GHz and the cognitive eNodeB in the TVWS band) are co-localized, and are physically the same equipment.

The eNodeB parts comprise:

- 2 antenna sub-systems, one for the 2.6 GHz band and one for the TVWS band. The 2.6 GHz antenna sub-system comprises 1 antenna, the TVWS antenna sub-system comprises 2 antennas, as illustrated in Figure 3-1.
- The antenna subsystems are connected through RF cables to an RF equipment to be installed in the control room beneath the mast, namely the **PA-LNA Subsystems.** The aim of those elements is to amplify and filter the Signal of Interest both on the RX and TX side.
- The PA-LNA Subsystems are connected to the **RF/baseband Conversion** box. The aim of this part is to convert the RF signal into base band signal. The RF/baseband Conversion box is based on LIME LMS6002D evaluation boards [6]. LMS6002D is a fully integrated multi-band, multi-standard single-chip RF transceiver for 3GPP (WCDMA/HSPA and LTE), 3GPP2 (CDMA2000) and WiMAX applications.
- The RF/baseband Conversion box is connected to a distribution board (which aims to put all the RF signals and controls into one single connector to ExpressMIMO) and to **ExpressMIMO.** ExpressMIMO is a FPGA-based board dedicated to Base Band processing. The protocol stack of the eNodeB is done in a **host PC**, connected though a PCIexpress interface.

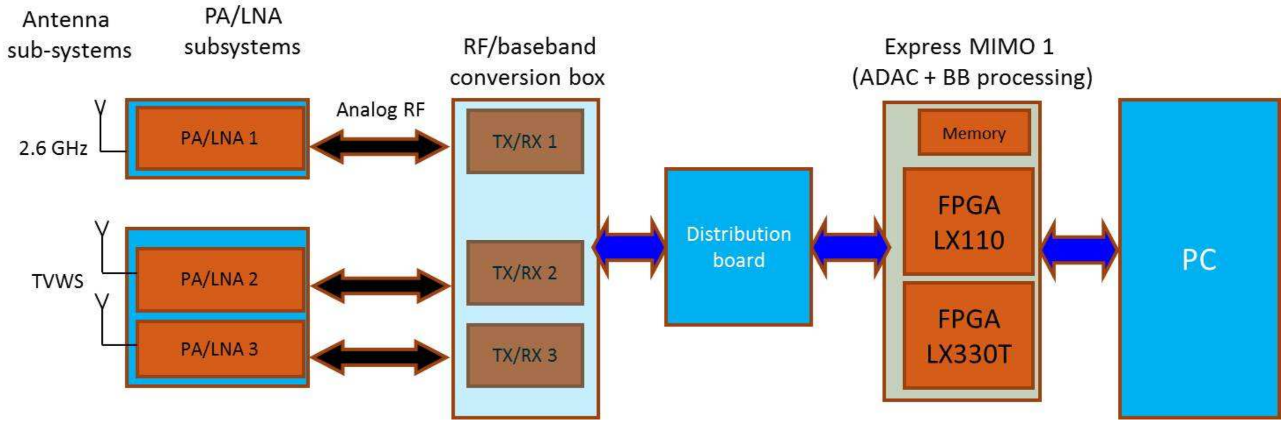

Figure 3-1: Block diagram of the eNodeB equipment

3.1 ANTENNA SUB-SYSTEMS

As mentioned in the previous section, the SACRA demonstrator has 2 antenna sub-systems, one for the 2.6 GHz band and one for the TVWS band. The 2.6 GHz antenna is an off-the-shelf antenna from HUBER+SUHNER (ref SPA 2500/85/17/0/DS). The TVWS antennas are the antennas provided by IT in the frame of the WP4 of SACRA (see D4.4 for the evaluation of the antenna). The antennas are put on a mast of the Eurecom building, as illustrated in Figure 3-2 and Figure 3-3.

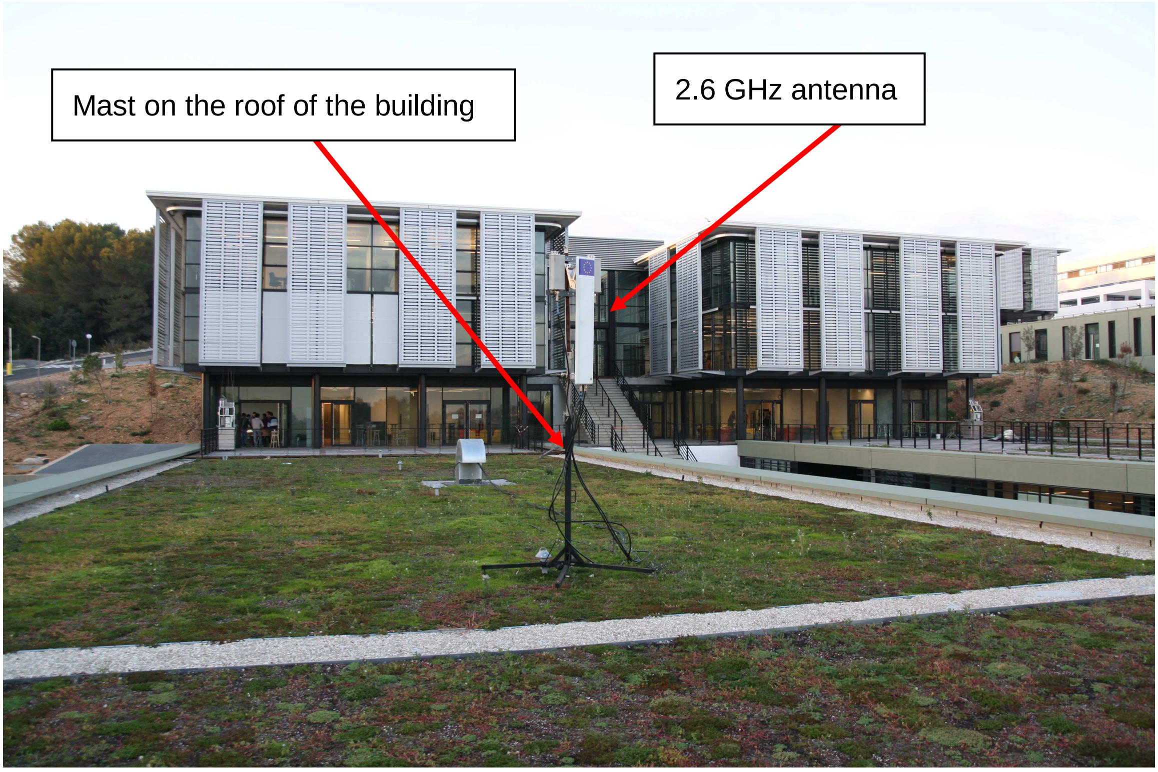

Figure 3-2: mast on the Eurecom building, front view

The antennas are connected to the PA/LNA subsystems through RF cables. Those cables are connected on the roof to the antennas, then go down to the lab in the building through a dedicated aperture.

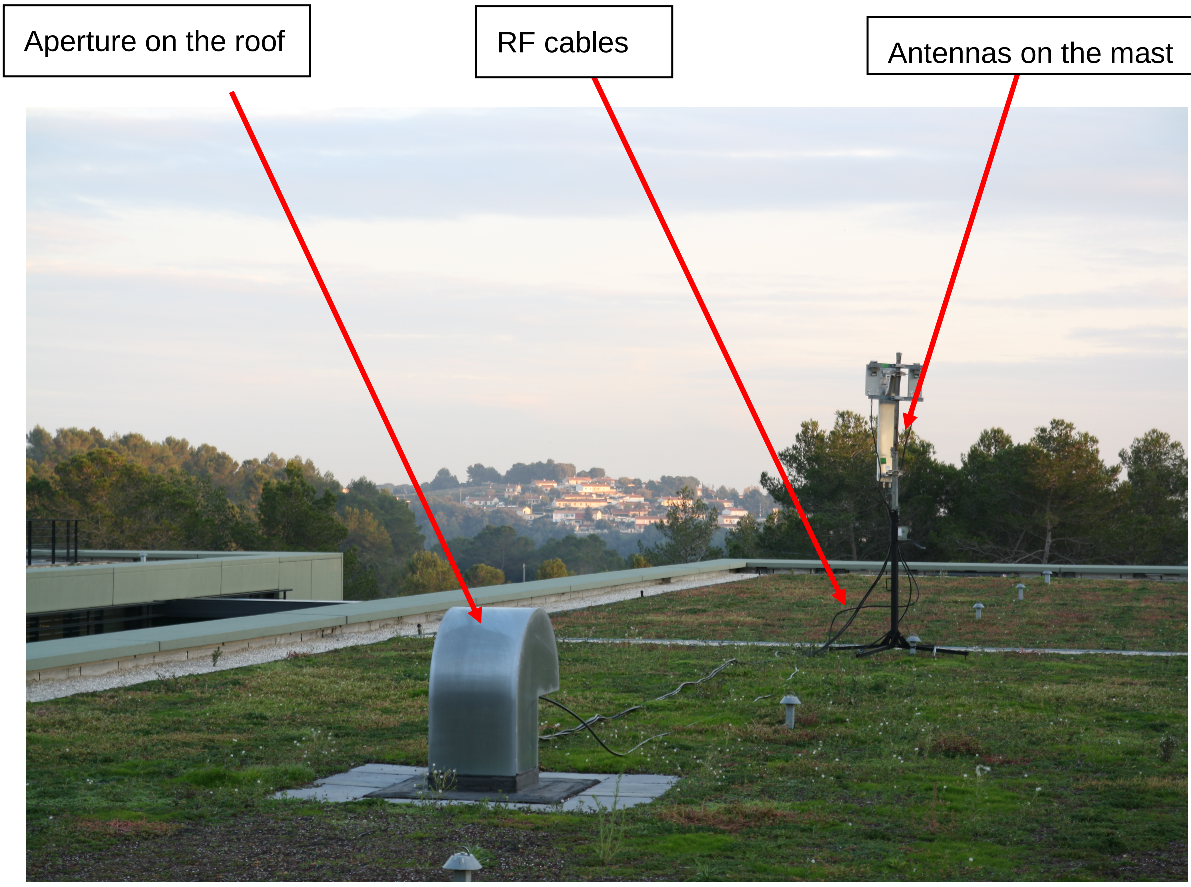

Figure 3-3: mast on the Eurecom building, back view

3.2 PA/LNA SUBSYSTEMS

The antenna subsystems are connected through RF cables to an RF equipment to be installed in the control room beneath the mast, the **PA-LNA Subsystems.** The aim of those elements is to amplify and filter the Signal of Interest both on the RX and TX side. The overall hardware in the control room is depicted in Figure 3-4.

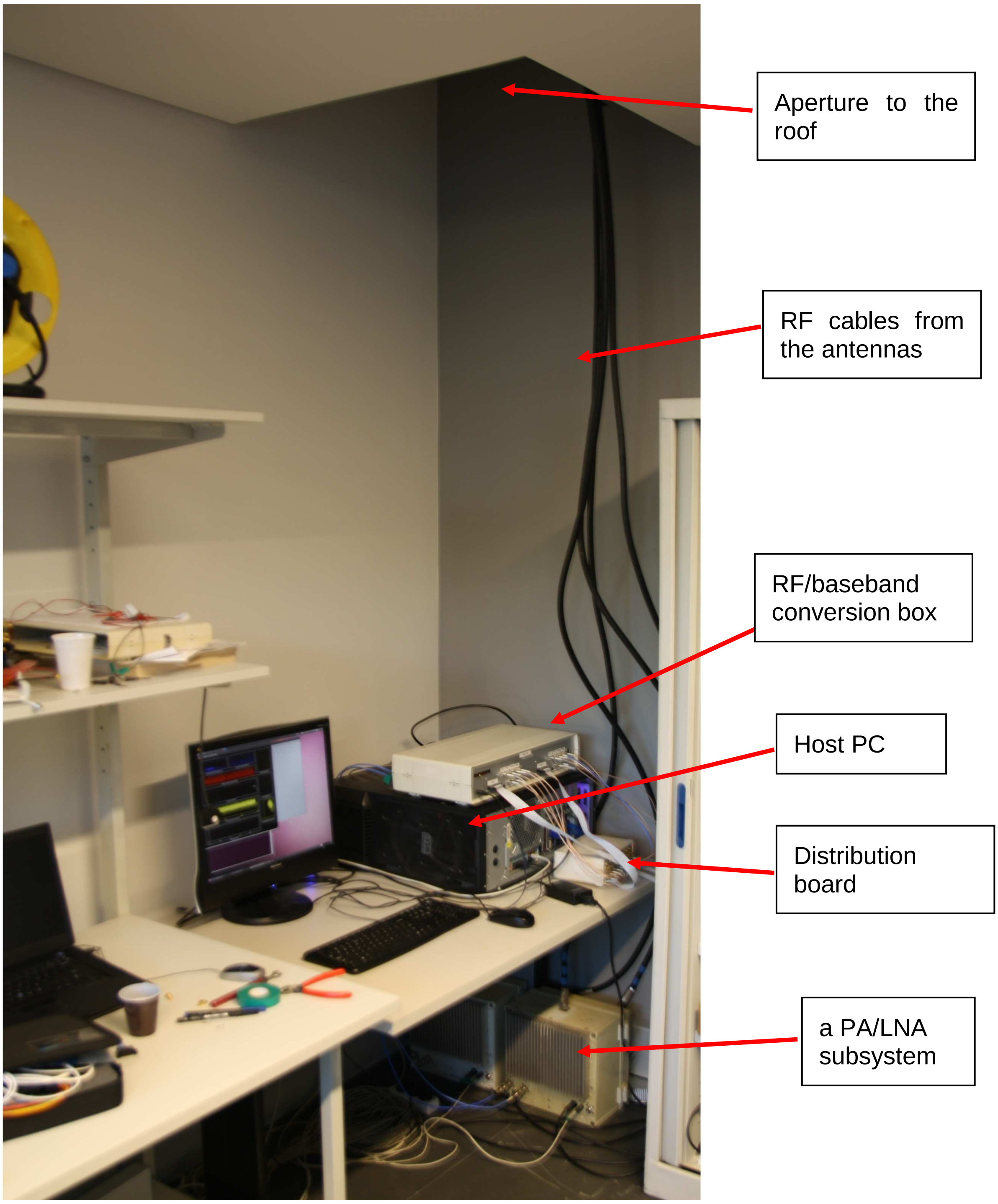

Figure 3-4: overall hardware in the control room

There is one PA/LNA subsystem per band, one for the 2.6 GHz and one for the TVWS. The 2 subsystems are described in the following sections.

3.2.1 2.6 GHz PA/LNA subsystem

The PA/LNA subsystem is in the control room. As described in Figure 3-5, the TX signal is received from the RF conversion box at a relatively low level (- 22 dBm). The signal is amplified by a 3-stage PA sub-system and feeds the duplexer. On the RX side, the signal is received on the antenna, is separated from the TX signal thanks to the duplexer, and filtered and then amplified.

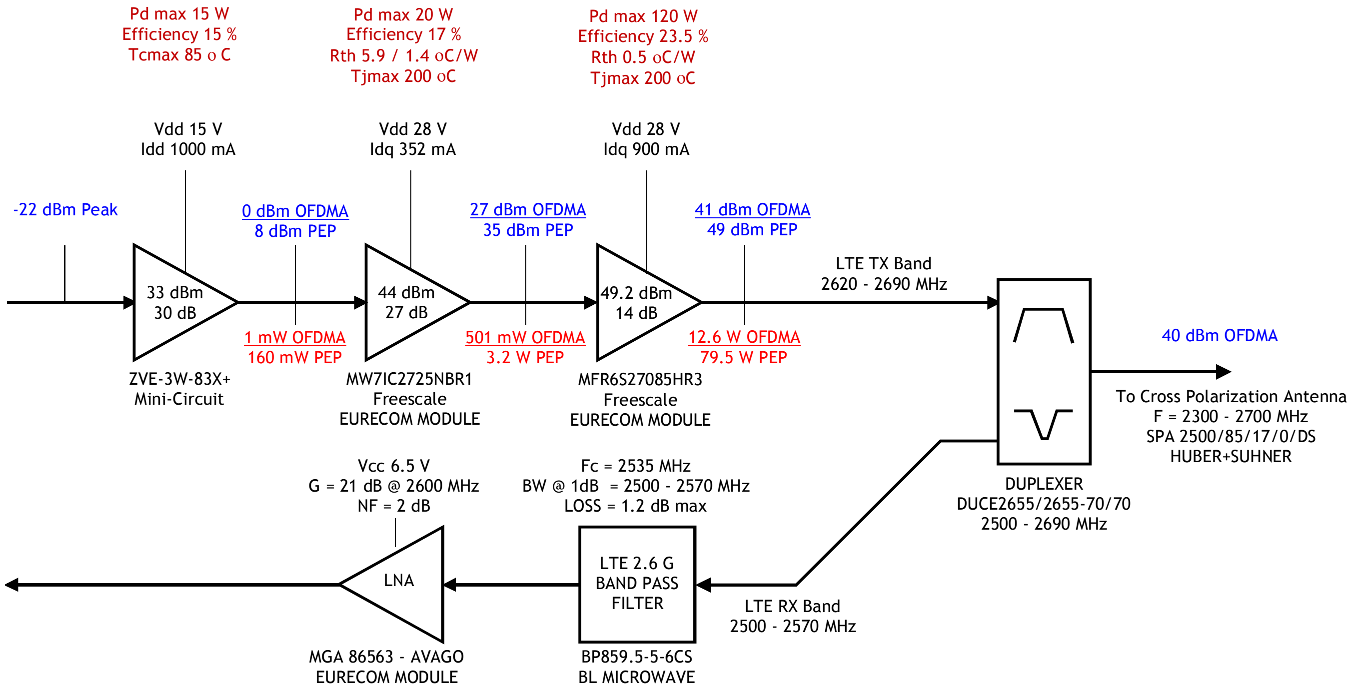

Figure 3-5 : 2.6 GHz PA/LNA subsystem, block diagram

The PA/LNA subsystem comprises 2 RF chains (2 RX and 2 TX paths). The subsystem is put in a box, as illustrated in Figure **3-6**.

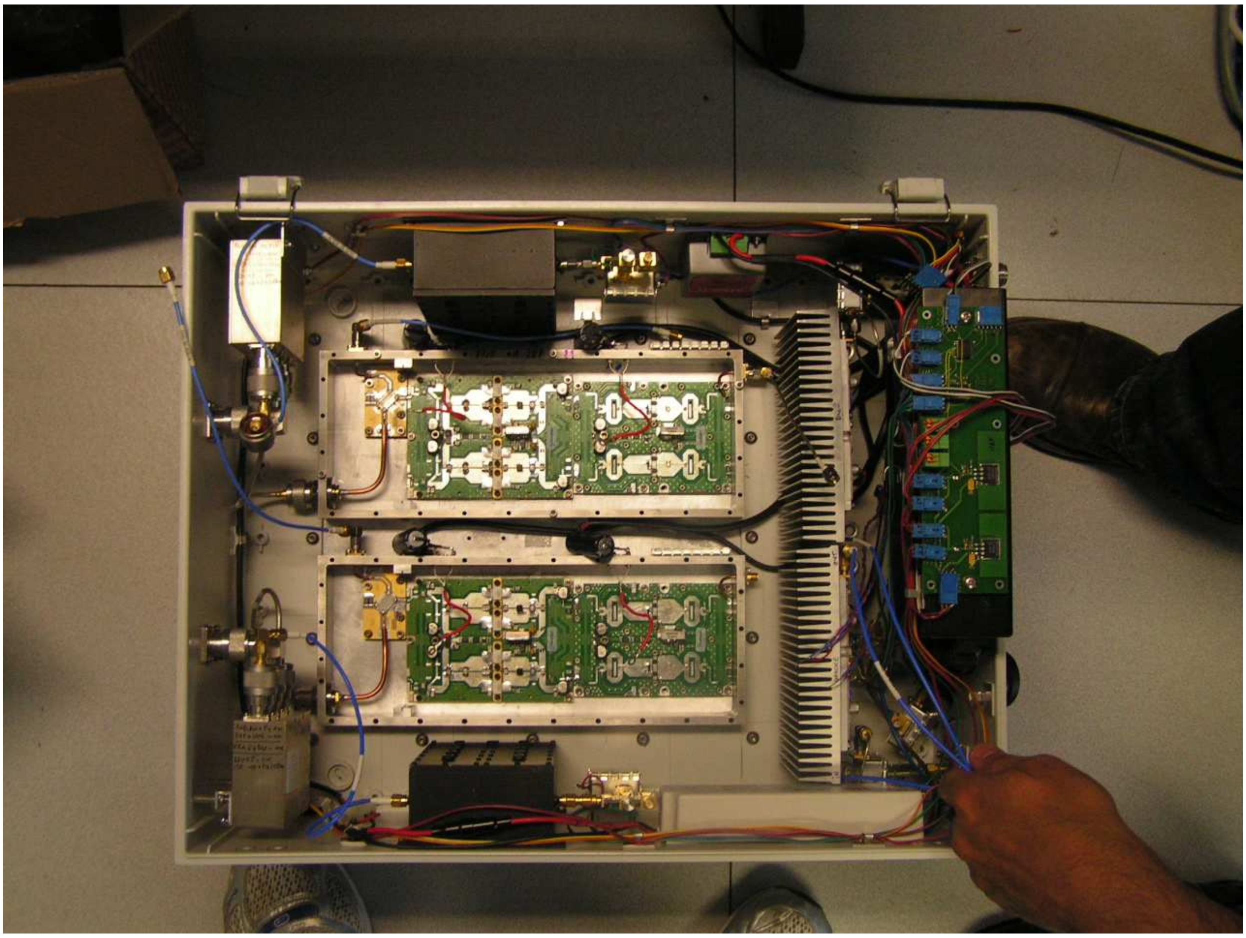

Figure 3-6: 2.6 GHz PA/LNA subsystem

3.2.2 TVWS PA/LNA subsystem

As described in Figure 3-7, the TX signal is received from the RF conversion box at a relatively low level (- 9 dBm). The signal is:

- filtered (SAW filter TFS746)
- amplified by a high gain amplifier block (ZHL-1000-3WX)
- The output signal feeds 2 switches (2 switches are needed in order to have a good isolation from the TX path to RX, so that the sensitivity of the receiver is good enough).

On the RX side, the signal is:

- received on the antenna
- is separated from the TX signal thanks to a switch (HMC784)
- filtered (SAW filter)
- Amplified (LNA).

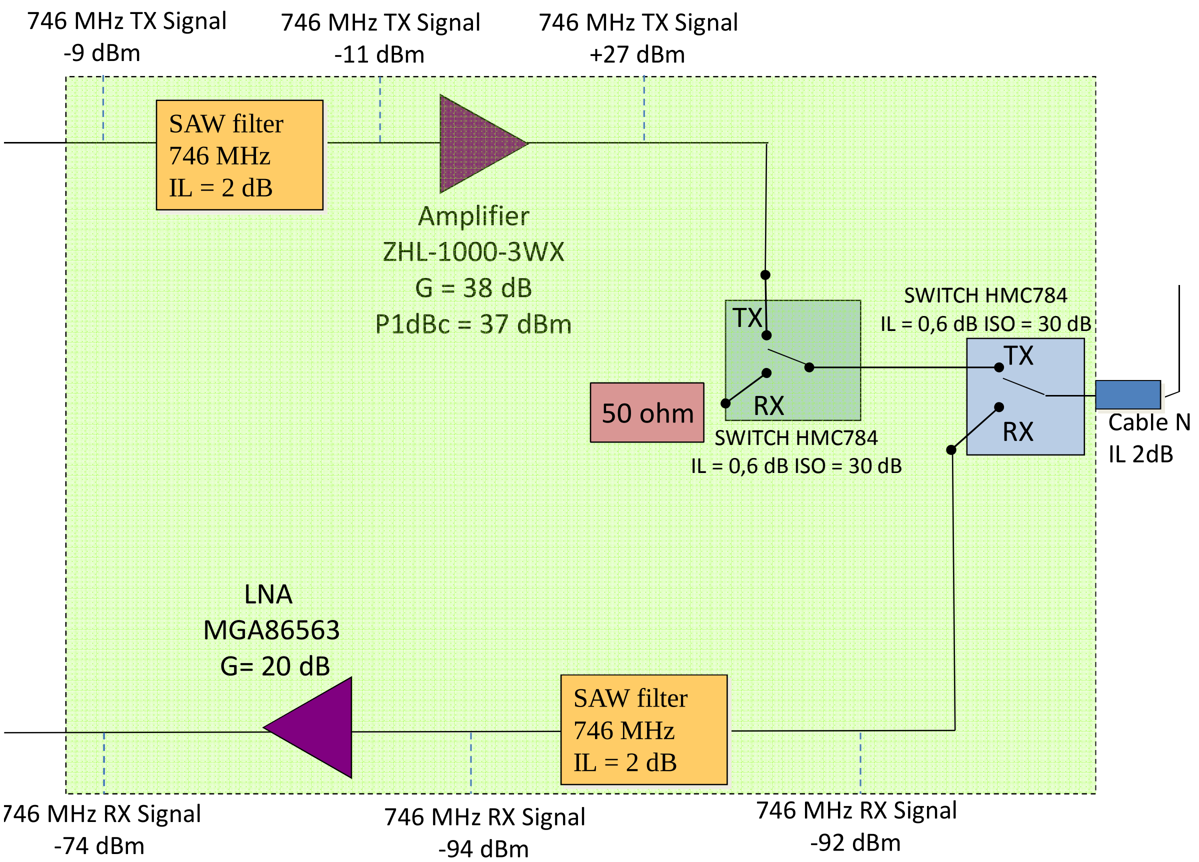

Figure 3-7: TVWS PA/LNA subsystem, block diagram

The PA/LNA subsystem comprises 2 RF chains (2 RX and 2 TX paths). The subsystem is put in a box, as illustrated in the following picture.

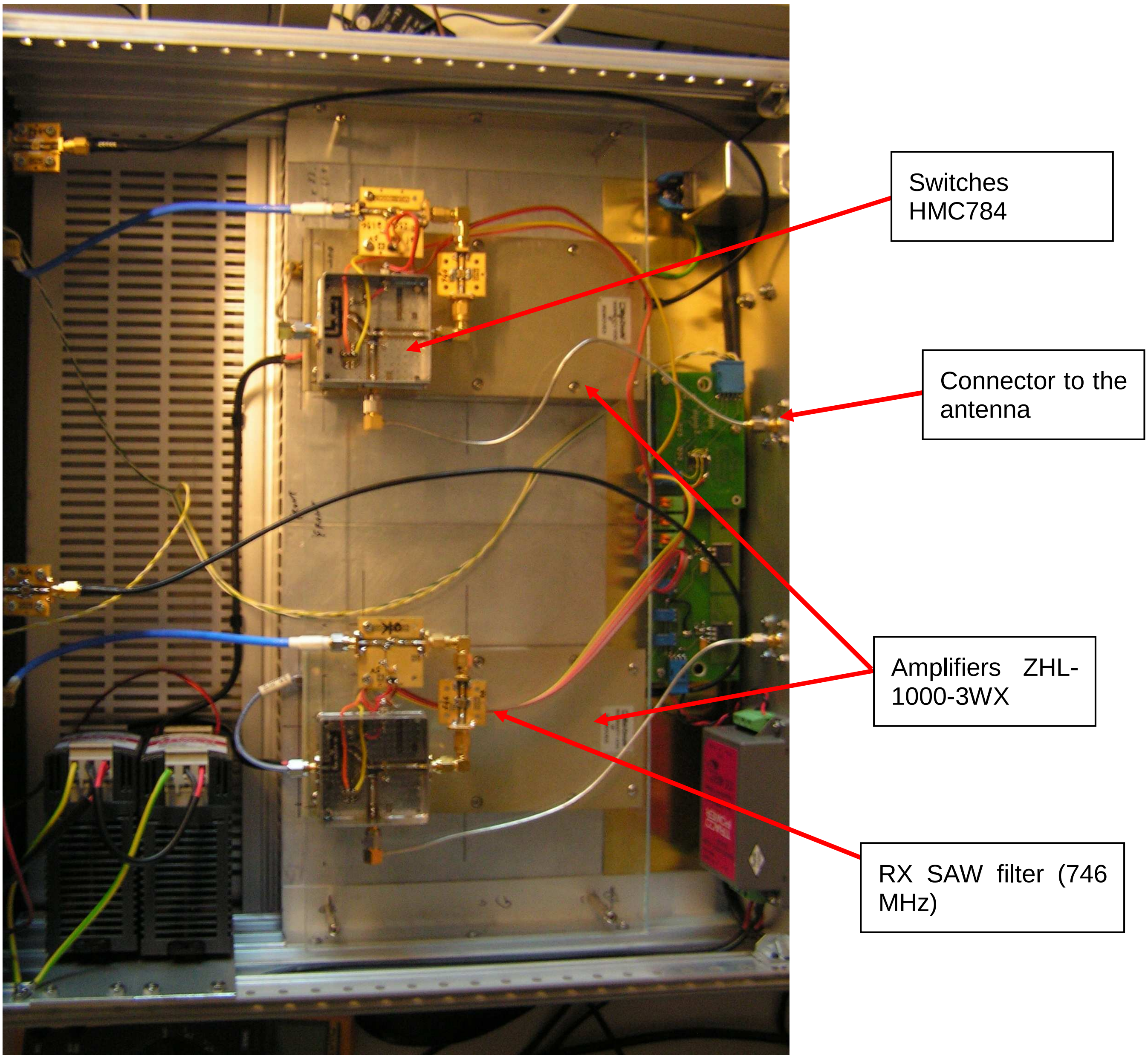

Figure 3-8: TVWS PA/LNA subsystem box

3.3 RF/BASEBAND CONVERSION BOX

The figure below gives an overview of one RX/TX path in the RF/Baseband conversion subsystem. This module is based on the LIME LMS6002D evaluation board. This part is based on 4 LIME LMS6002D evaluation boards [6]. LMS6002D is a fully integrated multi-band, multi-standard single-chip RF transceiver for 3GPP (WCDMA/HSPA and LTE), 3GPP2 (CDMA2000) and WiMAX applications.

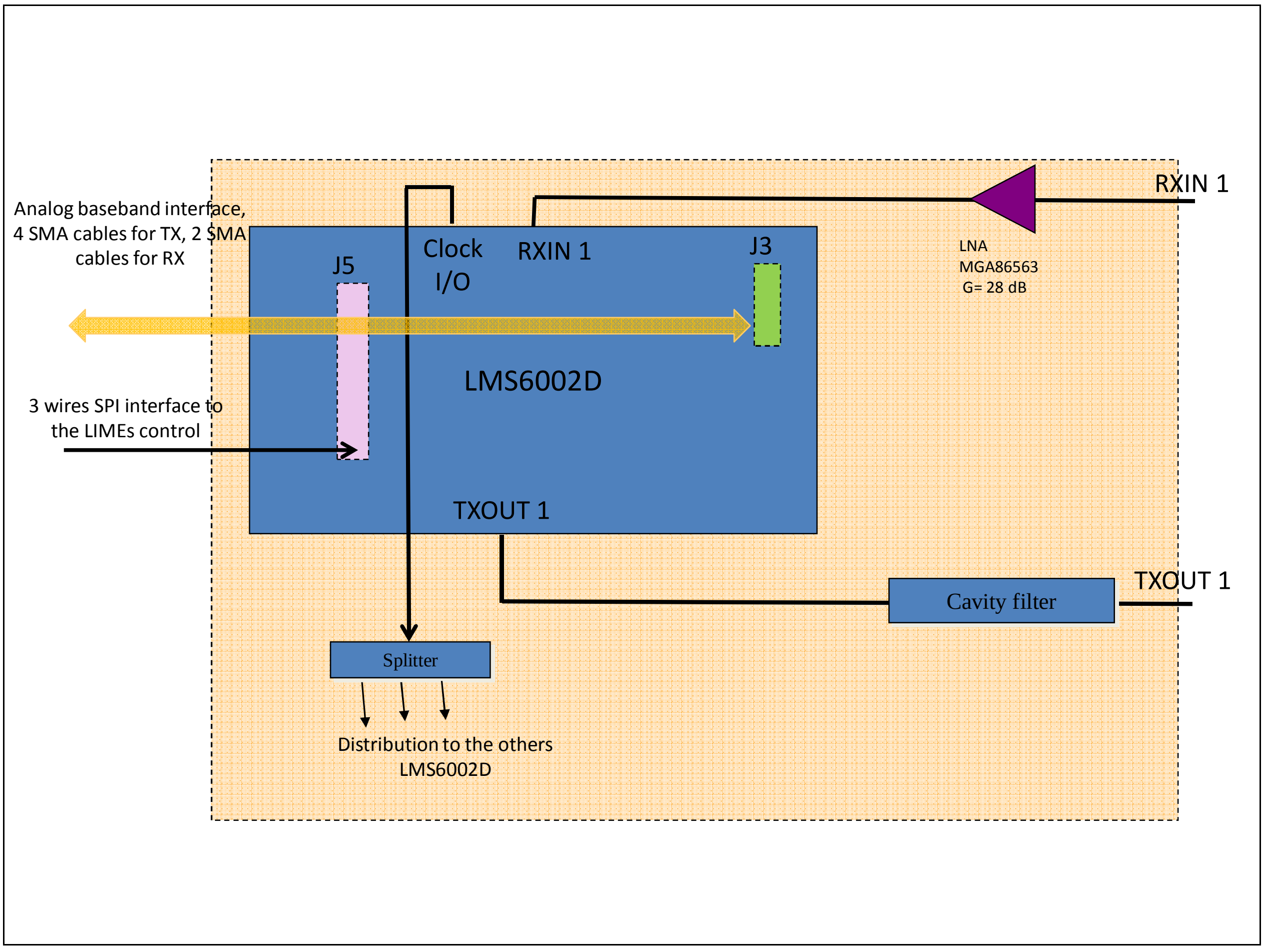

Figure 3-9: RF/baseband conversion TX/RX

The RF conversion box (that includes the 4 TX/RX paths) is illustrated in Figure 3-10.

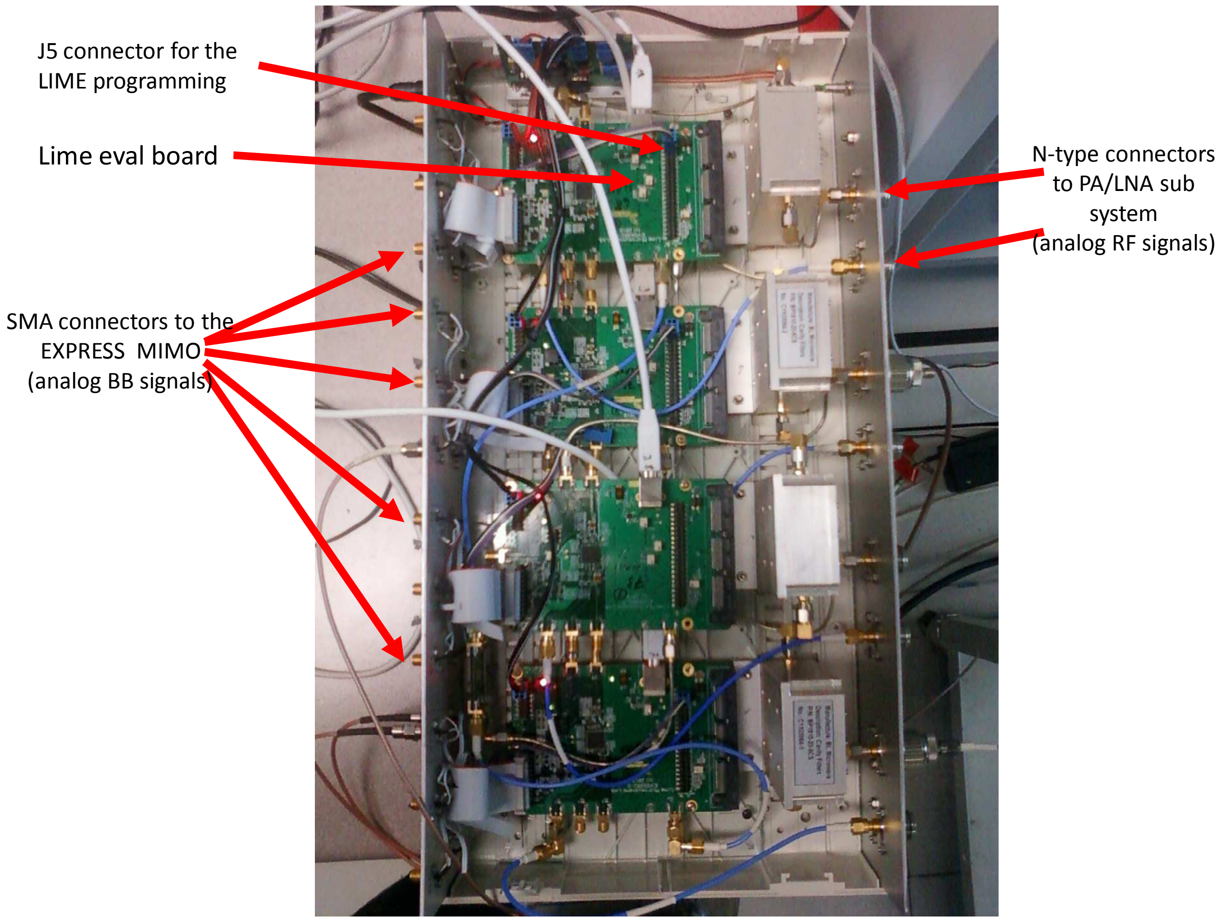

Figure 3-10: RF conversion sub system

3.4 DISTRIBUTION BOARD, EXPRESS MIMO 1 AND HOST PC

The RF/base Conversion box is connected to a distribution board (which aims to put all the RF signals and controls into one single connector to ExpressMIMO) and to ExpressMIMO. ExpressMIMO is a FPGA-based board dedicated to Base Band processing. The protocol stack of the eNodeB is done in a host PC, connected though a PCIexpress interface.

3.4.1 Brief Overview of ExpressMIMO

The OpenAirInterface ExpressMIMO platform [15] was developed jointly by Eurecom and Télécom ParisTech. Its hardware potentially supports a wide range of different standards like GSM, UMTS, 802.11, DAB, LTE as well as their multimodal processing and Time / Frequency Division Duplex (TDD / FDD) modes. It should be noted that to-date the only considered air interfaces for which a subset of the air-interface procedures have been implemented are LTE, 802.11p and DAB. The platform is used primarily for architecture exploration in SDR studies.

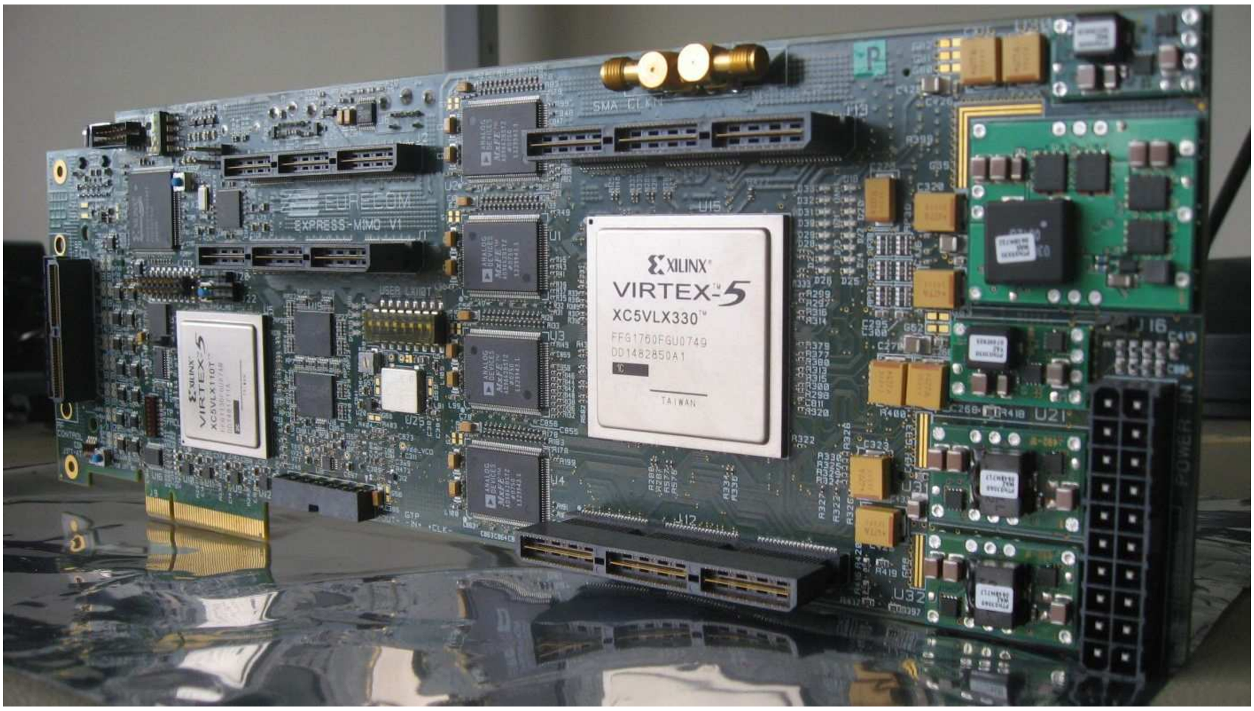

Figure 3-11: The ExpressMIMO board

The platform is capable to process up to eight different channels simultaneously (four in reception, four in transmission) by reusing the same HW resources. As each channel may support a different wireless communication standard, the main design challenge is the synchronization of these resources by providing a maximum accuracy and by meeting all the real-time requirements. ExpressMIMO is used for experimental purposes only. Therefore the chosen target technology are FPGAs which come with a reduced design time, higher runtime flexibility, simple ease of use and lower costs for small quantities when compared to other solutions. Nevertheless ASICs are considered in a future version once the whole baseband design has been validated. In contrast to the previously presented solutions, the current design of the ExpressMIMO platform is split over two different FPGAs from Xilinx: (1) a Virtex 5 LX330 for the baseband processing and (2) a Virtex 5 LX110T for interfacing and control as shown in Figure 3-12. To simplify testing on the platform, the two FPGAs can run stand-alone if required. Another difference is that the baseband processing which is responsible for the signal processing of the transceiver is split over different DSP engines. The underlying hardware architecture further allows to process four receive and four transmit channels in parallel by using the same resources.

The interface and control FPGA transfers the signal coming from / going to the MAC layer and contains the main CPU (SPARC LEON3 processor) being responsible for the main control flow of the system. The two FPGAs are connected via an AMBA / AVCI DSP bridge while the different DSPs on the baseband side are connected via an AVCI crossbar. As only seven DSPs plus the VCI RAM and the main CPU are connected with each other, the performance of this crossbar is sufficient for the design of the ExpressMIMO platform.

The available memory space is distributed in a non-uniform way. Each DSP engine has its own memory space that is also mapped onto a global memory map. This global map is provided to the main CPU and to the DSPs and is consulted in case of DMA transfers between the DSPs or between the two FPGAs. For internal processing, the DSPs apply a local addressing scheme. In addition, an external DDR memory is available for mass storage on the baseband side and a

DDR2 memory (size 16 MByte) contains the LEON3 program code and can be used for mass storage on the control side.

Currently the whole design is running at a frequency of 100 MHz but the target is to increase this frequency to the maximum possible one of the main CPU (133 MHz) in the future. It is now likely that the entire embedded system will be ported to the new Xilinx ZYNC technology which will allow for much higher processing speeds.

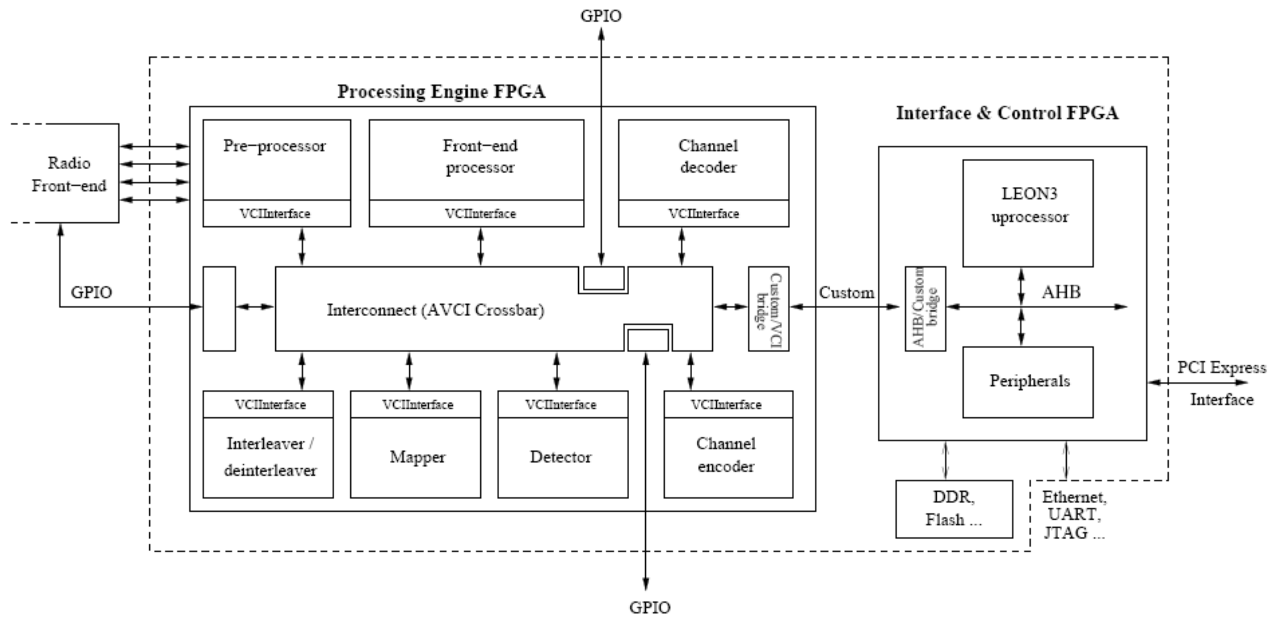

Figure 3-12: ExpressMIMO Baseband Engine

4 UE PARTS

For the SACRA experiments, we have used the developed SACRA modem, as described in D4.4[20] The following components are included at the SACRA modem for the experiment setup:

- Laptop and mobile phone antenna (antenna sub-system)
- RF analogue front ends
- Digitally tuneable filter (tBPF-600v01, plug and play)
- Motherboard
- A PC.

The SACRA modem that is used can be seen in the Figure 4-1:

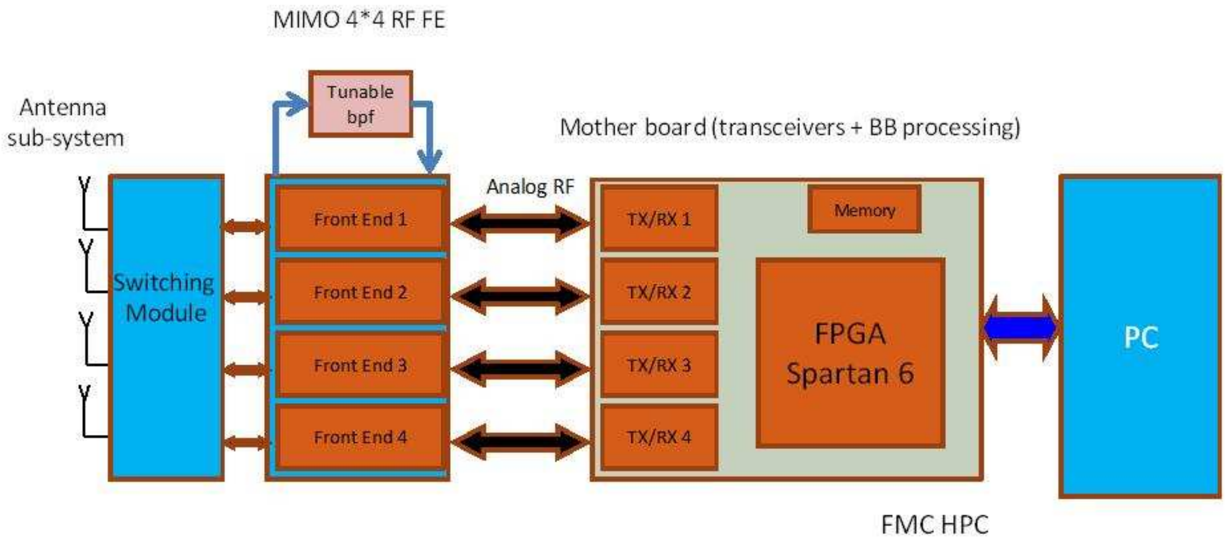

Figure 4-1 Block diagram of the whole SACRA modem including the integrated RF components

A detailed description of the SACRA modem can be found in Deliverable 4.4 of the project. It shall be noticed that the developed modem corresponds to the specifications that were given at the beginning of the project in D6.1.

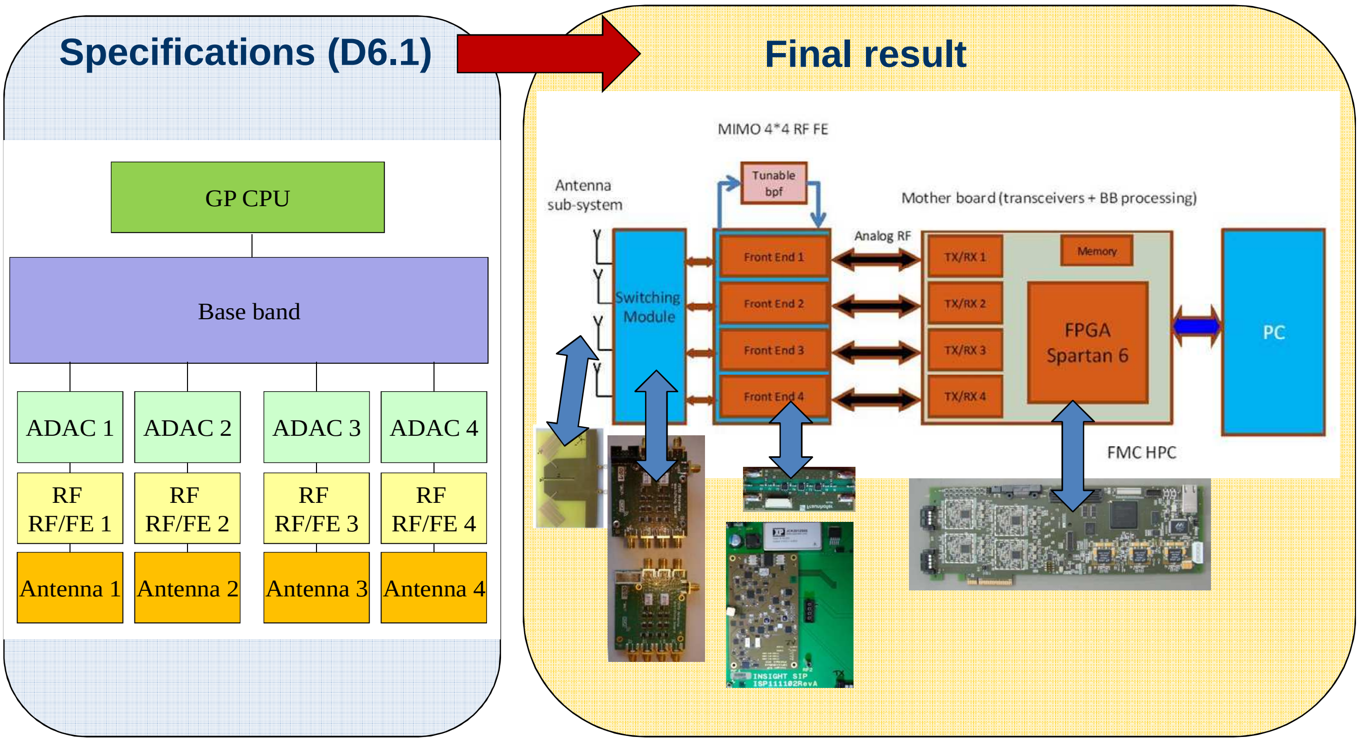

Figure 4-2: Specifications and final results for the SACRA terminal

As depicted in Figure 4-2, the target terminal according specifications has been defined as a 4 antennas modem, with 4 independent RF Front Ends (RF FE) and a General Purpose CPU for the processing. The final result on the right side of the figure is compliant with the specifications. The modem includes 4 antennas and 4 independent RF FE.

5 SOFT MODEM AND PROTOCOL STACK IMPLEMENTATION

As explained in the technical annex of the project, SACRA does not aim at developing protocol stack. In order to implement full over-the-air communications between the eNodeBs and the SACRA terminal, we have reused the Open Air Interface (OAI) protocol stack (http://www.openairinterface.org/) developed by Eurecom.

The OAI initiative develops open-source modem and protocol stack implementation for the ExpressMIMO baseband engine and x86 PC targets. These implementations currently target LTE and 802.11p air interfaces. The LTE implementation, OpenAir4G, provides a standard-compliant LTE Rel-8 implementation of PHY and MAC for a subset of the specifications (36.211 [8], 36.212 [9], 36.213[10], 36.321[11], 36.322[12], 36.323[13], 36.331[14]). The gnu-C implementation (with x86 SIMD hardware acceleration) can be made to run under any GNU environment, although x86 Linux and RTAI-based targets have only been considered.

An overview of the currently supported physical/transport channels and transmission modes is given in the following tables. Compliance of the implementation is being validated in conjunction with various industrial partners and is summarized here. Basic compliance at the PHY is determined using standard LTE test and measurement equipment from Rohde-Schwarz and partners' industry-grade equipment. It shall be noticed that many Acronyms are used in the next sections. Their definition can be found in the corresponding 3GPP specifications.

Physical Channel	Functionality	LTE Compliance
PSS	TX/RX	Validated for 1 antenna port at eNB (implemented for 1,2)
SSS	TX/RX	Validated for 1 antenna port at eNB (implemented for 1,2)
Cell-specific Reference signals	TX/RX, Modes 1,2,3,4,5,6 1-2 antenna ports at eNB	Validated for 1 antenna port at eNB (implemented for 1,2)
PBCH	TX/RX 1,2 antenna ports at eNB	Validated for 1 antenna port at eNB (implemented for 1,2)
PCFICH/PDCCH	TX/RX 1,2 antenna ports at eNB All 5 MHz DCI Formats	Validated for 1 antenna port at eNB, DCI Format 1,1A (TDD/FDD), (implemented for 1,2)
PHICH	TX/RX 1,2 antenna ports at eNB	Validated for 1 antenna port at eNB (implemented for 1,2)
PDSCH	TX/RX 1,2 antenna ports at eNB TX Diversity, 2-antenna Precoding (Mode 4/5/6))	Validated for 1 antenna port at eNB (implemented for 1,2)
PUSCH + UCI	TX/RX 1,2 antennas ports at eNB	Validated
PUCCH	TX/RX formats 1,1a,1b	Validated
DRS	TX/RX, 1-2 antenna ports at eNB	Validated
SRS	TX/RX, 1-2 antenna ports at eNB	Not validated yet, implemented
PRACH	TX/RX, 1-2 antenna ports at eNB	Validated (formats 1-3)

Table 1: Physical Channel Support in OpenAirInterface.org (3GPP 36.211)

Coding Methods	Functionality	LTE Compliance
Tail-biting C. code, ,	TX/RX	validated
Turbo code	TX/RX	validated
rate-matching (C. code)	TX/RX	validated
Rate-matching (turbo)	TX/RX	validated
segmentation	TX/RX	validated
CRC 24-bit	TX/RX	validated
CRC 16-bit	TX/RX	validated
CRC 8-bit	TX/RX	validated
BCH	TX/RX	Validated
DCI	TX/RX, 5 MHz TDD/FDD formats	Validated (format 1,1A,1D,1B)
DLSCH	TX/RX	Validated
ULSCH/UCI	TX/RX	Validated (subset of UCI formats)
CQI	TX/RX	Validated
CFI	TX/RX	Validated
HI	TX/RX	Validated

Table 2: Coding and Multiplexing (36.212)

Procedure	Functionality	LTE Compliance
Random-Access	TX/RX, full procedure, Connection Establishment, handover, data transfer	Validated
Random-access response	TX/RX, full procedure	Validated
PDCCH procedures	TX/RX	Validated
DL/UL HARQ procedures	TX/RX, TDD, no PHICH	Not validated
CQI/PMI/RI reporting	TX/RX, HLC and Subband PMI on PUSCH	Not validated
PUCCH	Implemented (formats 0,1a,1b)	

Table 3: Physical Layer Procedures (3GPP 36-213)

5.1 OPENAIR4G PROTOCOL STACK

OpenAir4G provides a full real-time protocol stack for a gnu gcc environment implementing a subset of LTE Rel. 8/9 of access stratum as shown in Figure 5-1 and includes the following blocks:

- Linux Network device driver (kernel)
- MAC/RLC/PDCP/RRC and IP
- PHY procedures

Moreover, the above blocks :

- Can be integrated with openair4G MODEM or abstraction of physical channels, MODEM is abstracted along with propagation
- Can be vectorized for multiple instances (multi eNodeB, multi UE, combined eNodeB/UE, multiple component carriers for carrier aggregation)

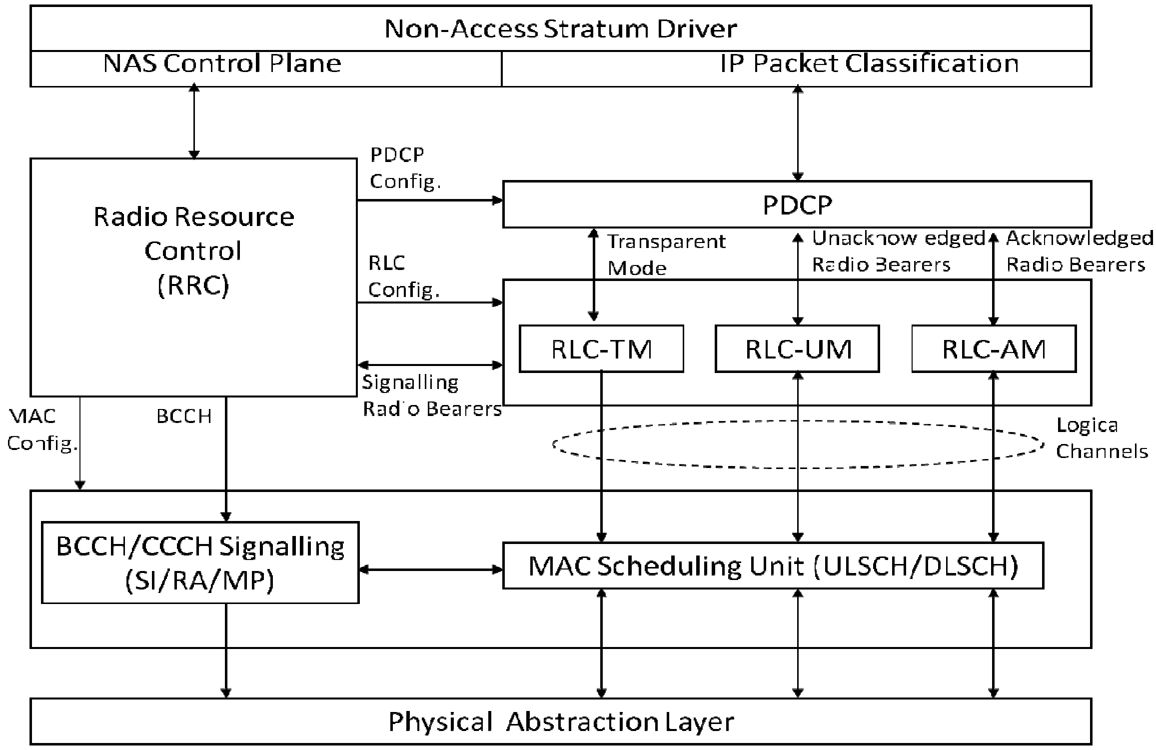

Figure 5-1: OpenAir4G protocol stack

5.1.1 NAS

The direct inter-connection between LTE and IPv6 is performed using an inter-working function, located in the NAS driver and operating in both the Control Plane and the Data Plane. This function provides the middleware for interfacing IPv6-based mechanisms for signalling and user traffic with 3GPP-specific mechanisms for the access network (e.g. for mobility, call admission, etc.). It is developed as an extension of a standard IPv6/IPv4 network device driver. It implements the EPS bear association with the one RB, which is associated with the one PDCP entity.

5.1.2 RRC

The RRC layer, shared between the UE and the ENB, performs the control of the radio interface. It is based on 3GPP 36.331 v9.2.0. The control procedures available in the LTE platform are the following:

- System Information broadcast
- RRC connection establishment
- Measurement configuration and reporting
- the signalling data transfer
- Connection reconfiguration (addition and removal of radio bearers, connection release)
- the measurement collection and reporting at UE and eNodeB
- EUTRA handover is under integration

These procedures are being extended to support MBMS for multicast and broadcast.

5.1.3 MAC

The MAC layer implements a subset of the 3GPP 36-321 release v8.6 in support of BCH, DLSCH, RACH, and ULSCH channels. The eNodeB MAC implementation includes:

- RRC interface for CCCH, DCCH, and DTCH
- Schedulers
- DCI generation
- HARQ Support
- RA procedures and RNTI management
- RLC interface (AM, UM)

UE MAC implementation includes

- PDU formats: all control elements and logical channels
- RLC interface AM,UM, TM
- RRC transparent interface for CCCH and BCCH
- Buffer status reporting and scheduling request procedures
- Power headroom reporting.

5.1.4 PDCP

The current PDCP is header compliant with 3GPP 36-323 Rel 10.1.0 and implement the following functions:

- User and control data transfer
- Sequence number management
- RB association with PDCP entity
- PDCP entity association with one or two RLC entities

5.1.5 RLC

The RLC layer implements a full specification of the 3GPP 36-322 release v9.3 for all three modes: transparent mode (TM), unacknowledged mode (UM), and acknowledge mode (AM) with the following characteristics:

- RLC TM (mainly used for BCCH and CCCH)
  - Neither segment nor concatenate RLC SDUs
  - Do not include a RLC header in the RLC PDU
  - Delivery of received RLC PDUs to upper layers
- RLC UM (mainly used for DTCH)
  - Segment or concatenate RLC SDUs according to the TB size selected by MAC
  - Include a RLC header in the RLC PDU
  - Duplication detection
  - PDU reordering and reassembly
- RLC AM, compatible with 9.3
  - Segmentation, concatenation, and reassembly
  - Padding
  - Data transfer to the user
  - RLC PDU retransmission in support of error control and correction
  - Generation of data/control PDUs

5.2 SPECIFIC EXTENSION OF OPENAIR4G IN THE CONTEXT OF SACRA

A specific extension to the OpenAir4G software environment has been integrated (still in progress during drafting of this report) in the context of the project, addressing different issues related to distributed interference management. It concerns integration of some aspects of the Release-10 specifications dealing with spectrum-aggregation of multiple LTE component carriers. Distributed algorithms for dynamic spectrum allocation will be considered using this development in 2013.

5.2.1 Overview of Carrier Aggregation in Release-10 LTE

The primary reason for introducing carrier aggregation in LTE is to provide larger bandwidths for end-users under the constraint of spectrum fragmentation. Due to its basic waveform description, LTE is a scalable bandwidth system, allowing for bandwidths covering 1.4, 3, 5, 10, 15 or 20 MHz per carrier. In Release-10, any combination of up to 5 component carriers, depending on the UE capability, can be considered. It is thus theoretically possible to accurately cover an area with a sparse yet wide total bandwidth (100 MHz). The second important aspect is, as is common in cellular systems, that backward compatibility is ensured. LTE guarantees that each Release-10 compliant component carrier can be used transparently by a Release-8/9 UE. The third aspect is that carrier aggregation facilitates support of heterogeneous network deployments through cross-carrier scheduling. The latter is made possible by using “clean” primary carriers for signalling and essential services in conjunction with “dirty” secondary carriers for more opportunistic data transmission with the help of robust HARQ mechanisms. The combination of these two features will allow for much higher throughput to end-users and improved quality-of-service for essential services. This makes the cognitive radio paradigm extremely relevant for mainstream wireless technologies.

In order to guarantee backwards compatibility with Release-8 UEs the physical layer does not aggregate packets at the level of the code word. This is a task of the MAC layer scheduler at the eNodeB which decides how to schedule traffic on the different component carriers offered by the physical layer. The PHY can now transport 2 N_{cc} code words in one sub frame, N_{cc} is the number of CC configured for the UE. Aside from signalling in the RRC, the protocol elements above the MAC layer (i.e. RLC, PDCP) see no impact other than higher throughput. The physical layer replicates its procedures (aside from basic signalling which only occurs on the primary CC) on all carriers. From a software perspective, this can be seen simply as a vectorization of the physical layer procedures.

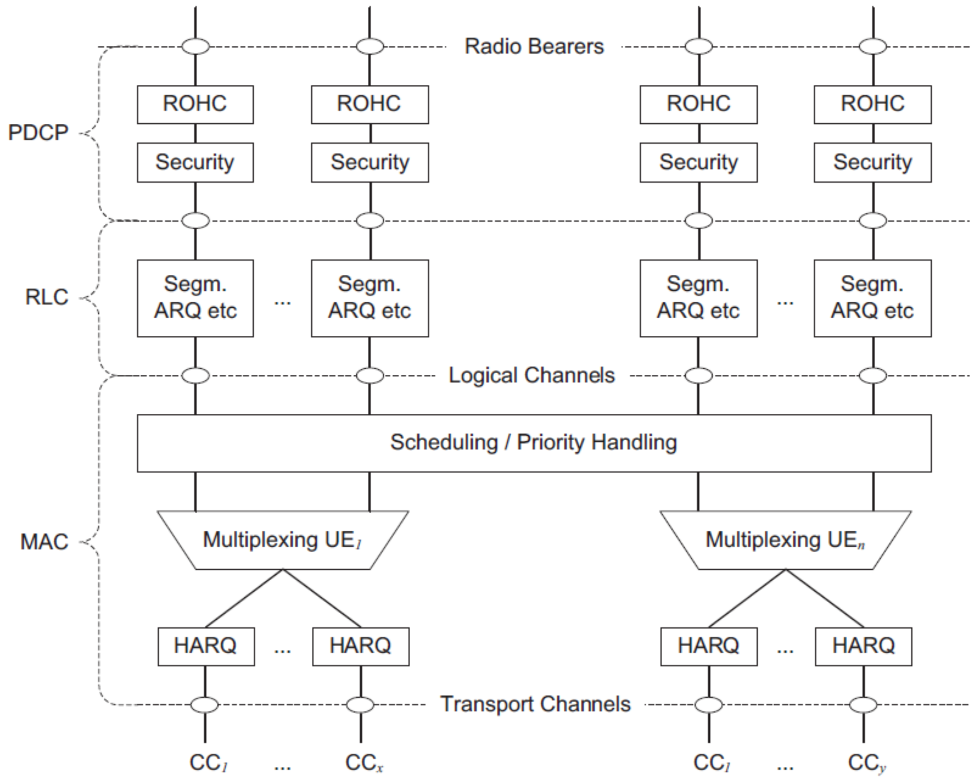

Figure 5-2: Carrier Aggregation Protocol Replication at eNB

5.2.2 Overview of OAI extensions for Carrier Aggregation

The extension is concerned with enabling Carrier Aggregation capabilities on the OpenAirInterface protocol stack. This requires changes to the RRC, MAC and PHY entities both for the eNodeB and UE. The RRC module was extended to add, delete and modify CCs and perform other control signalling specific to Release-10 UEs such as cross-carrier scheduling, CA-specific measurement configuration, secondary cell search etc. The MAC needs to be extended to support multiple (up to five) CCs at the eNodeB and UE. Regular MAC functions like scheduling, HARQ handling, power control, processing of CQI and ACK/NACKs should include multiple CCs. The scheduler in particular needs to be carefully designed to allow for globally optimal user selection. The current scheduler in OAI is a barebones implementation which does not yet take into consideration issues such as user fairness, metric computation, UE-level QoS etc. The PHY processing is replicated for each CC both in the downlink (eNodeB) and uplink (UE). So each CC will have its own HARQ process (per UE), separate modulation, coding and other PHY processing prior to transmission (see Figure 5-3).

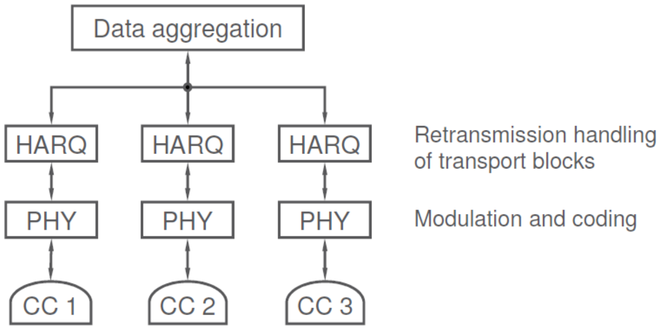

Figure 5-3: PHY replication for aggregated CCs

This extension currently implements only a subset of the RRC extensions required to fully support CA in OAI. Specifically, a provision to add one secondary CC to a UE has been implemented. Configurable parameters for the secondary CC allow it to be changed as per the scenario to be tested.

The extended implementation makes it possible to configure one secondary Component Carrier using the parameters according to the requirements. It is also easily possible to extend this to add/modify up to four CCs. This is the starting point for enabling full support for carrier aggregation in OAI. Extension of the MAC to support multiple CCs is being completed at the time this report was drafted. The latter is non-trivial since the scheduler has to be designed from scratch and the scheduling algorithm must be sufficiently flexible to test different scenarios. Furthermore, extending the scheduler to multiple CCs will add to the complexity. Besides the scheduler, other functions of the MAC such as power control, HARQ processing, measurements reporting and link adaptation will have to be extended for multiple CCs.

Changes to the MAC required modification of the PHY entity – the easiest (and most natural) approach was to replicate (vectorize) the PHY for each CC as described earlier. All PHY-layer processing will occur independently for each CC both in the downlink (eNodeB) and the uplink (UE). The MAC keeps track of which CCs are active for each UE and pick a globally optimal set of UEs from all CCs to schedule in a given scheduling interval (sub frame).

6 EXPERIMENTS PERFORMED

This Chapter depicts the experiments that have been conducted in the frame of the SACRA WP6. Those experiments have been conducted near the Eurecom Building, in Sophia Antipolis, France.

6.1 OVERALL SETUP

The overall setup comprises:

- An eNodeB located in the Eurecom building, with capabilities in TVWS band (TDD duplexing mode) and 2.6 GHz (FDD duplexing mode).
- A terminal that is put in a car, as illustrated in Figure 6-1.

Figure 6-1: Equipped car for the SACRA experiments

6.1.1 ENodeB specifications

The following table illustrates the specifications for the eNodeB.

TX transmitted power	+25 dBm (per path) in the TVWS (734 – 758 MHz) +30 dBm (per path) in the 2.6 GHz band
Noise figure	6 dB
Operated TX frequency band	TVWS : 734 – 758 MHz 2.6 GHz band: 2500 – 2570 MHz
Operated RX frequency band	TVWS : 734 – 758 MHz 2.6 GHz band: 2620 – 2690 MHz
Maximum input power	-30dBm
Maximum attenuation between antenna and PA-LNA module (due to the 20 m cables)	3 dB

6.1.2 Terminal specifications for the chosen bands

The following table illustrates the specifications for the terminal for the chosen bands (the SACRA terminal has more capabilities, as described in D4.4).

TX transmitted power	+20 dBm (per path) in the TVWS (734 – 758 MHz) + 20 dBm (per path) in the 2.6 GHz band
Noise figure	7 dB
Operated TX frequency band	TVWS : 400 – 790 MHz 2.6 GHz band: 2620 – 2690 MHz
Operated RX frequency band	TVWS : 400 – 790 MHz 2.6 GHz band: 2500 – 2570 MHz
Maximum input power	-30dBm

Figure 6-2: car (including the SACRA terminal) on the road near Eurecom

6.2 COVERAGE TEST

The aim of this first experiment to get a estimation of the eNodeB coverage at 746 MHz and 2.6 GHz. The test is done around the Eurecom building, as illustrated in Figure 6-3.

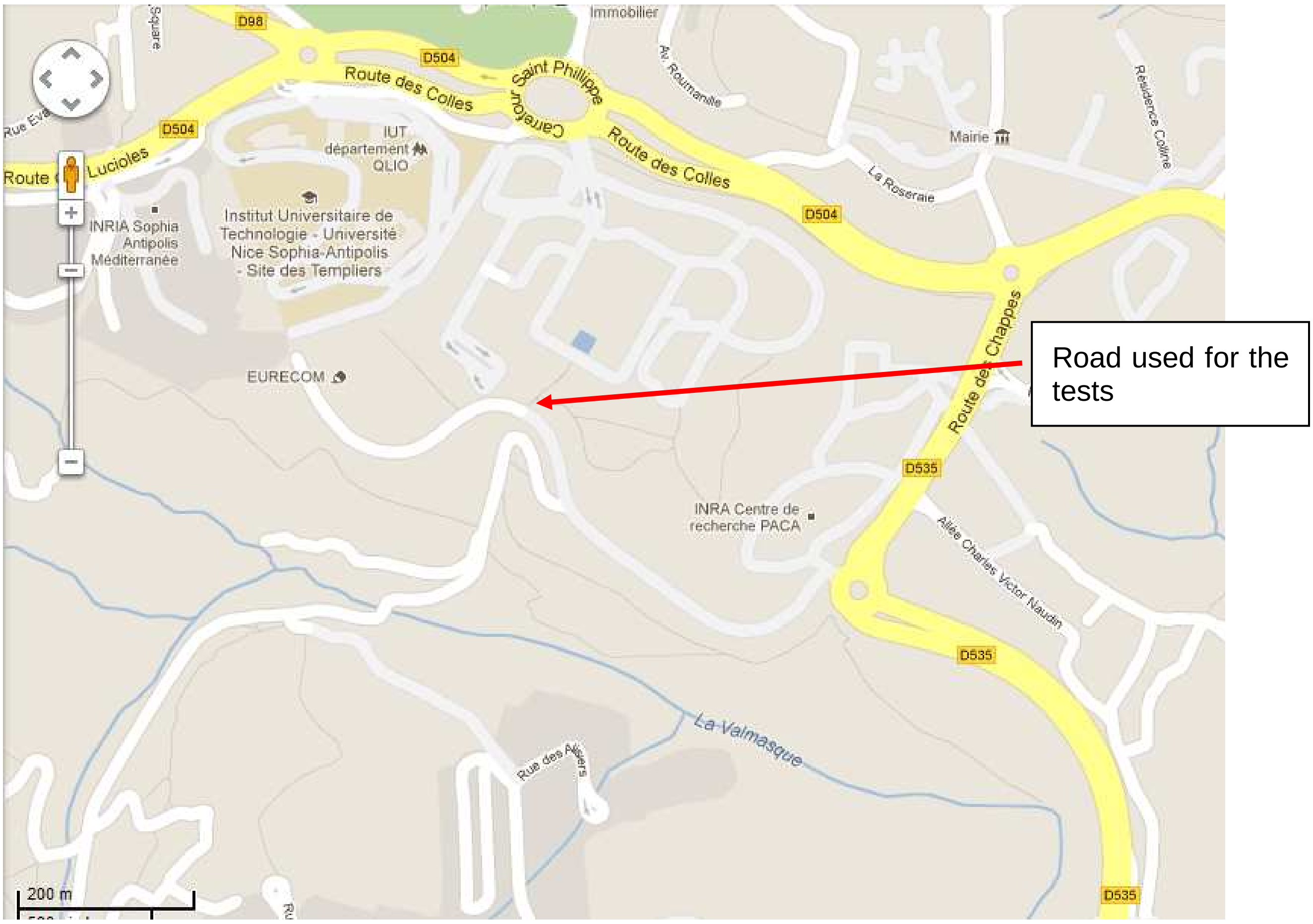

Figure 6-3: Location of the experimentations (map)

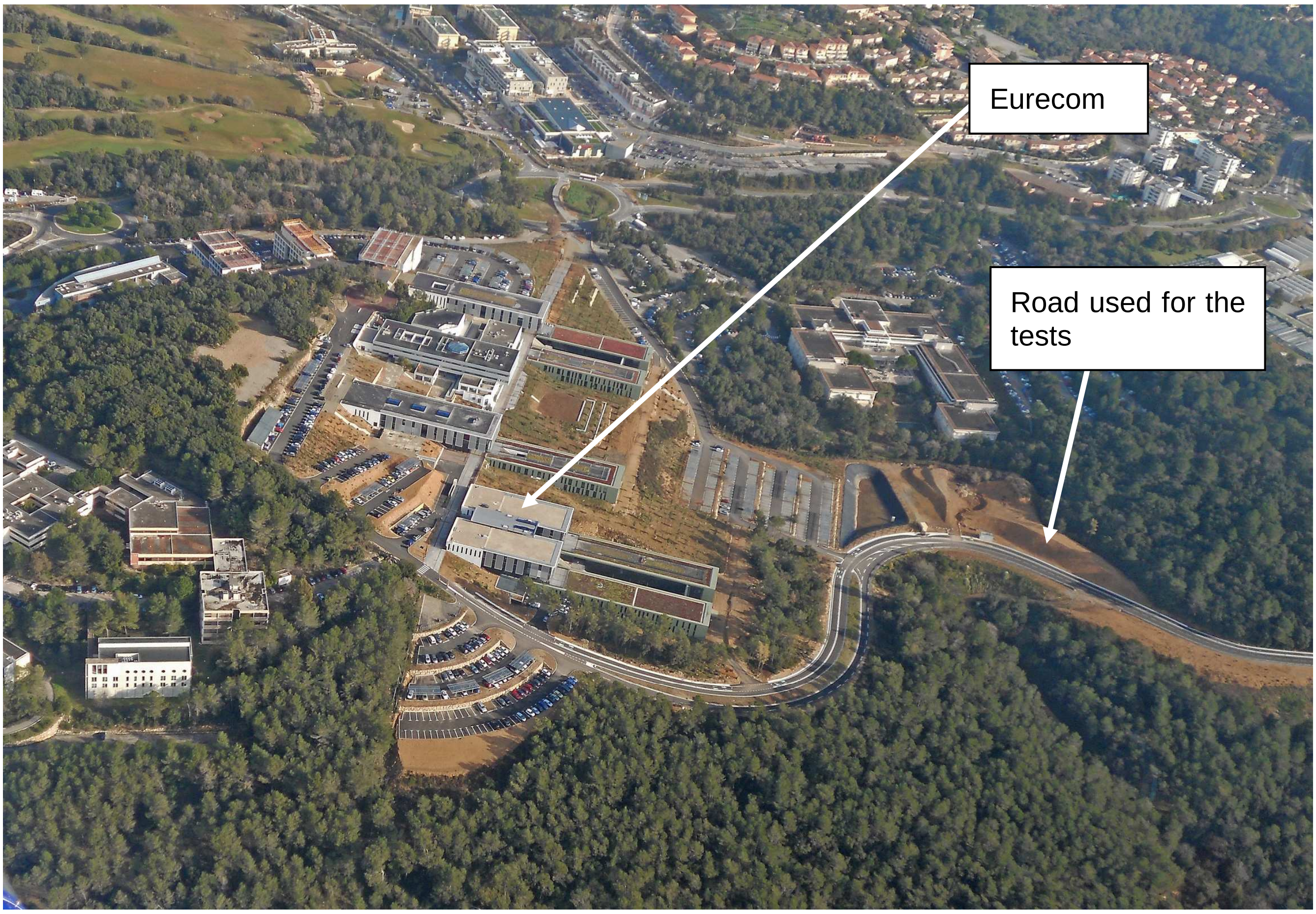

Figure 6-4: Location of the experimentations (photo)

For this test, the eNodeB transmits a sinusoid with a specified frequency, 746 MHz for the TVWS band, and 2.655 GHz for the 2.6 GHz band.

6.2.1 2.6 GHz coverage

Table 4illustrates the level received by the UE (Downlink) in various places of the road. The levels are given in dBm. The transmission is done by the eNodeB, the signal is a sinusoid at 2535 MHz, with a TX power of + 35 dBm. Only one antenna is used for both transmission and reception.

The measurements are done as follow:

- The eNodeB is transmitting a sinusoid with a calibrated power of +35 dBm (input of the antenna)
- The receiver is put in a car, using the antenna provided by IIS in the WP4. The antenna is connected to a receiver with a calibrated gain of 25 dB at 2.6 GHz. The level is measured with a FSQ spectrum analyser.

	Measured level (FSQ input)	Ampli. gain(+25 dB)	Path loss (Pout-Prec)
1	-46	-71	106
2	-49,5	-74,5	109,5
3	-48	-73	108
4	-33	-58	93
5	-40	-65	100
6	-46	-71	106
7	-32	-57	92
8	-51	-76	111
9	-65	-90	125
10	-49	-74	109
11	-59	-84	119
12	-68	-93	128
13	-79	-104	139
14	-48	-73	108
15	-56,5	-81,5	116,5

Table 4: 2.6 GHz coverage measurements

One can see that the level of signal received by the terminal can vary from a very low level (-104 dBm) up to a very large one (-57 dBm). This test is therefore representative of many realistic situations of reception.

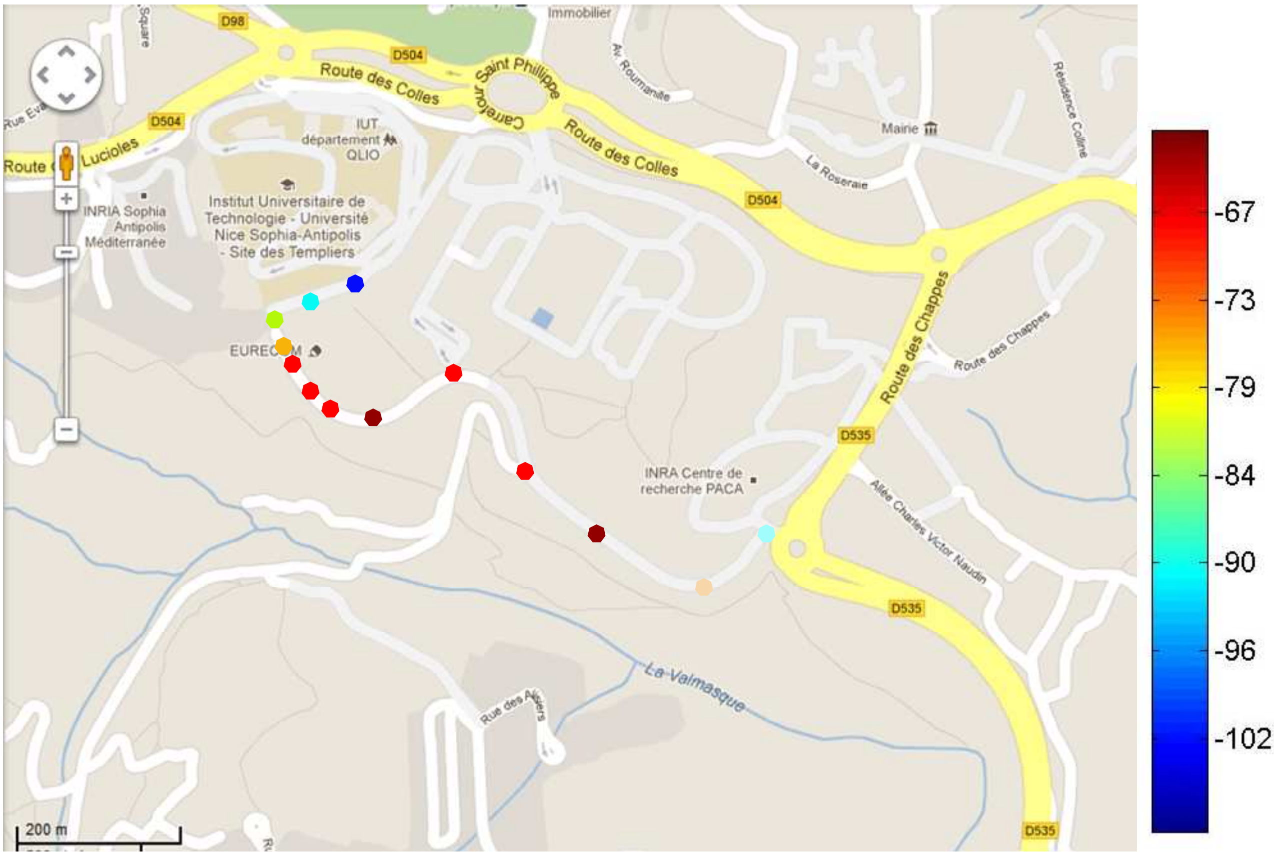

Figure 6-5: level received by the UE in various places of the road (2.6 GHz)

6.2.2 TVWS band coverage

Table 5illustrates the level received by the UE (Downlink) in various places of the road. The levels are given in dBm. The transmission is done by the eNodeB, the signal is a sinusoid at 746 MHz, + 25 dBm. Only one antenna is used for both transmission and reception.

The measurements are done as follow:

- The eNodeB is transmitting a sinusoid with a calibrated power of +25 dBm (input of the antenna)
- The receiver is put in a car, using the antenna provided by IIS in the WP4. The antenna is connected to a receiver with a calibrated gain of 21.3 dB at 746 MHz. The level is measured with a FSQ spectrum analyser.

	Measured level (FSQ input)	Ampli. Gain (+21,3 dB)	Path loss (Pout-Prec)
1	-49,2	-70,5	95,5
2	-44	-65,3	90,3
3	-47	-68,3	93,3
4	-53	-74,3	99,3
5	-70	-91,3	116,3
6	-58	-79,3	104,3
7	-70	-91,3	116,3
8	-71	-92,3	117,3
9	-92	-113,3	138,3
10	-57,6	-78,9	103,9
11	-64	-85,3	110,3
12	-69	-90,3	115,3
13	-83	-104,3	129,3
14	-48	-69,3	94,3
15	-32	-53,3	78,3

Table 5: 746 MHz coverage measurements

One can see that the level of signal received by the terminal can vary from a very low level (-113 dBm) up to a very large one (-53.3 dBm). This test is therefore representative of many realistic situations of reception.

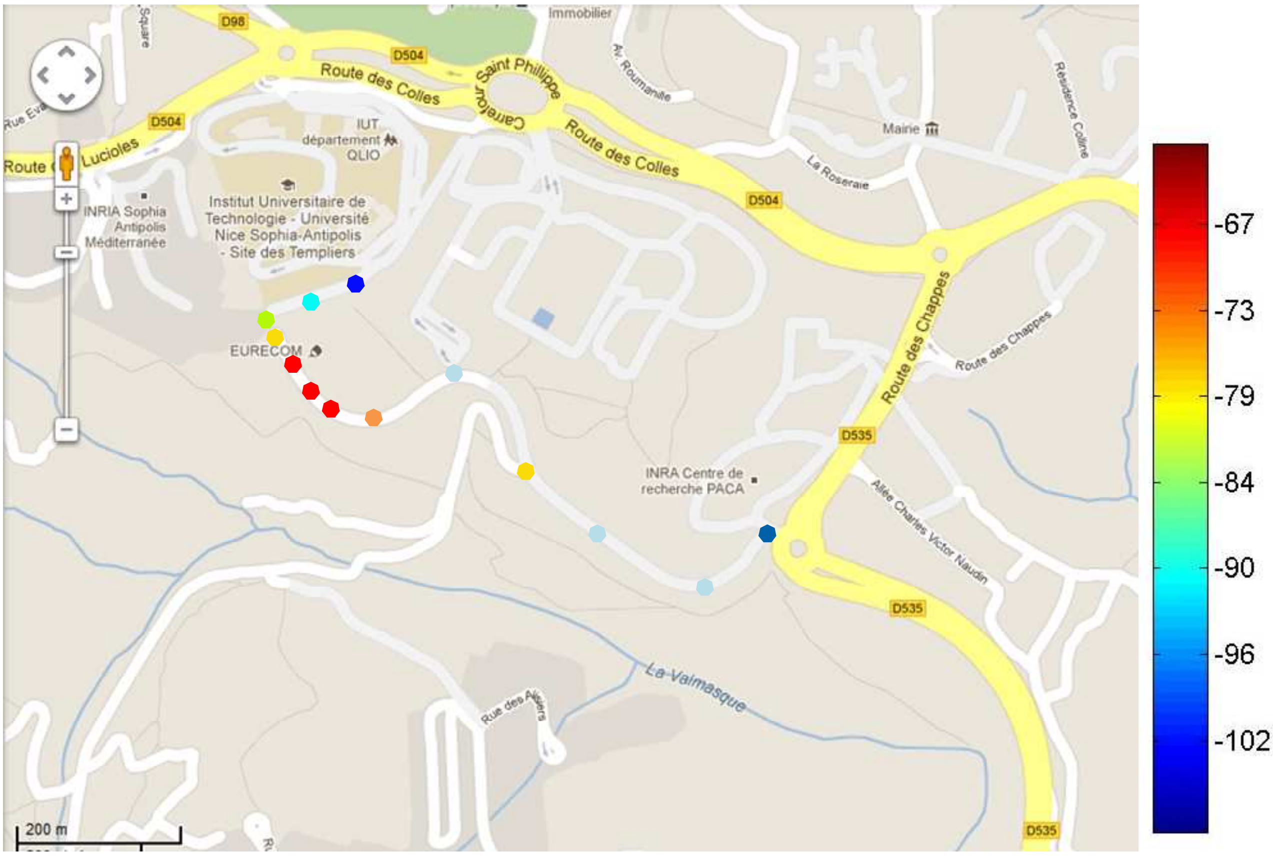

Figure 6-6: level received by the UE in various places of the road (746 MHz)

6.3 DUAL BAND DOWNLINK AND RECEPTION

In this test, the eNodeB transmits a LTE signal (rel. 8 compliant) on the 2 bands, 2.6 GHz and TVWS. The details of the signals are the following:

- LTE Downlink signal
- BW = 5 MHz
- Modulation scheme for data : QAM-4
- TX power (2.6 GHz band) at 2535 MHz : +35 dBm
- TX power (TVWS band) at 476 MHz : +25 dBm

The 2 signals are received by the SACRA terminal, the antenna from IIS has been used. The test has been done in the laboratory (the laboratory is located in the room below the antennas, so the received signal is relatively high).

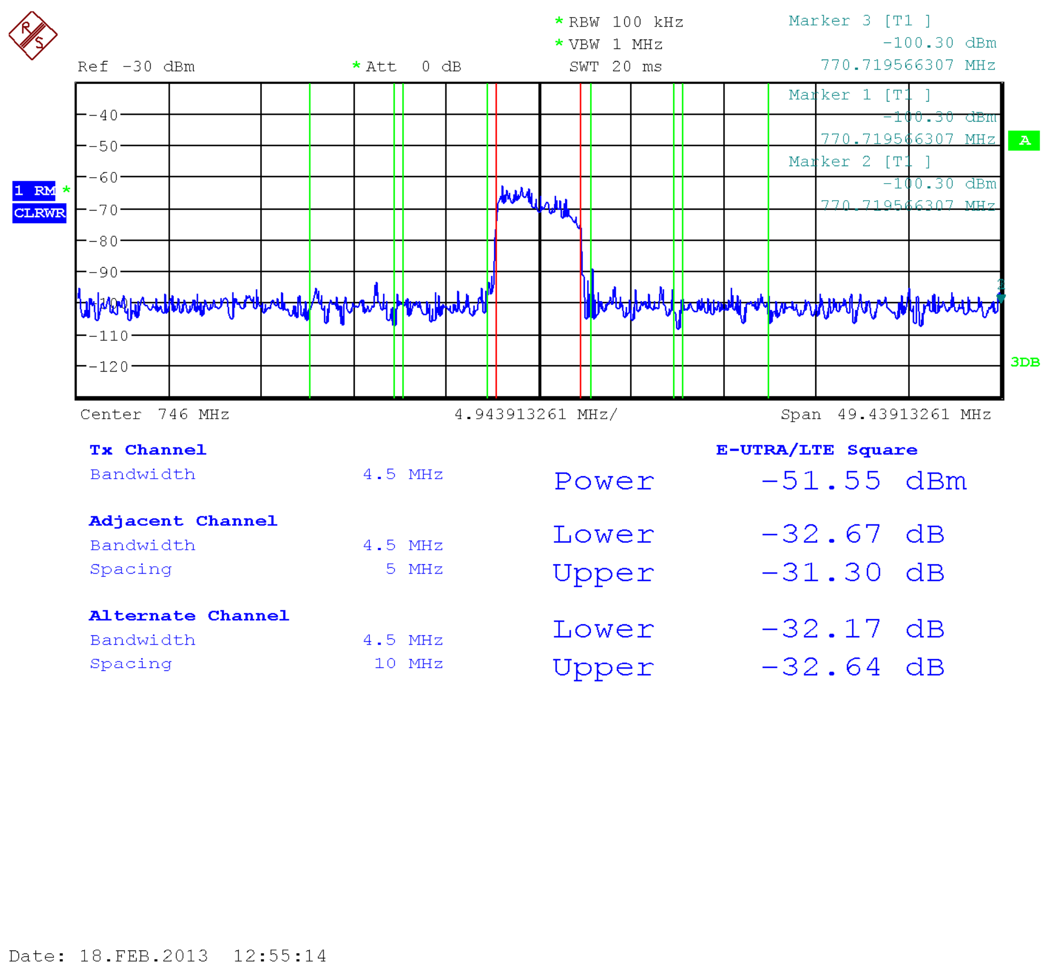

Figure 6-7: Downlink, reception at 746 MHz

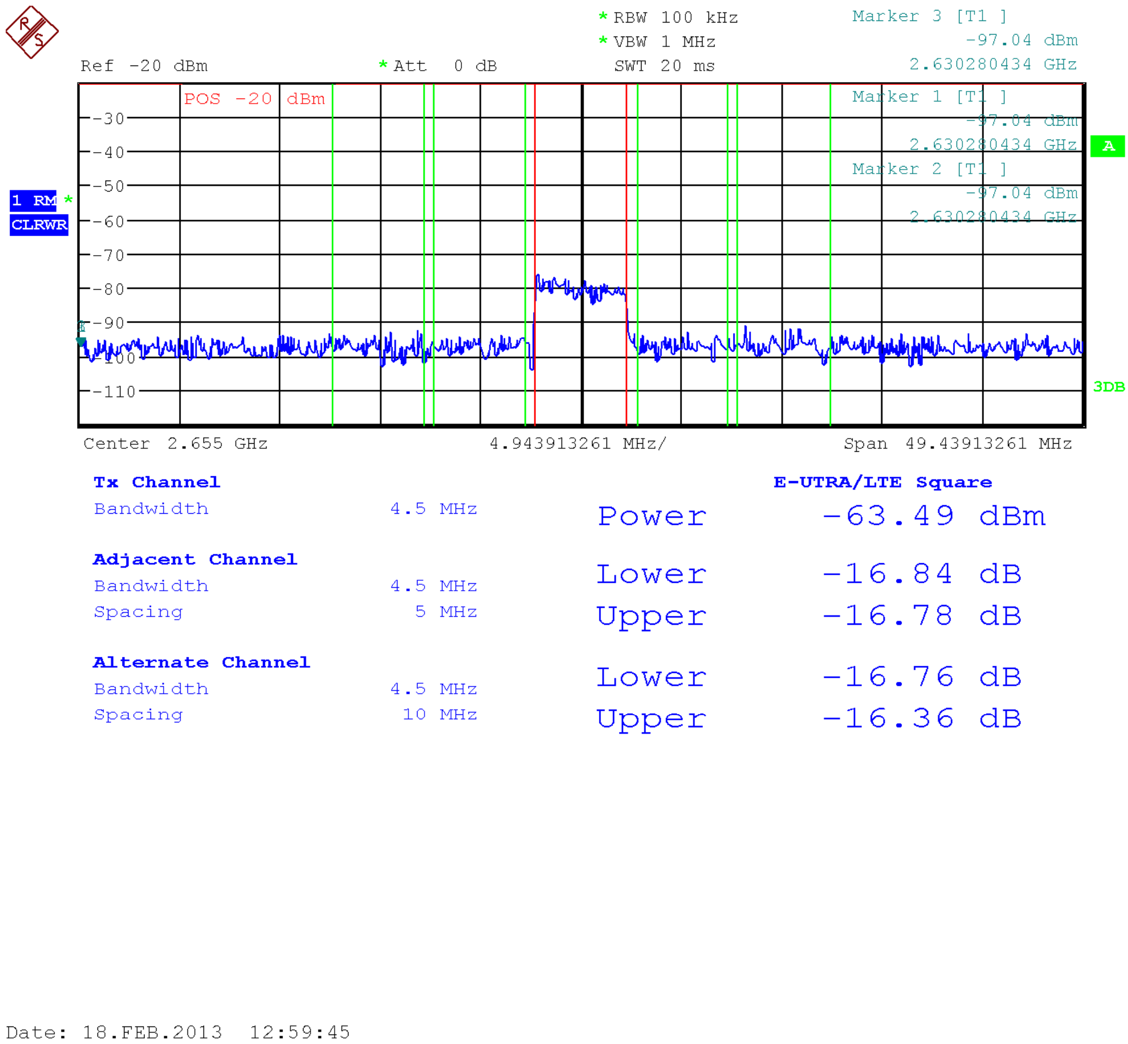

Figure 6-8: Downlink, reception at 2655 MHz

6.4 PRIMARY USERS DETECTION IN THE TVWS

The scenario for the SACRA project includes the sensing of potential primary systems and the evacuation of the band. The goal of this test is to validate the emulation of a primary user for this scenario. In this test, we verify at first the occupancy of the TVWS band around the chosen frequency (746 MHz). The eNodeB receiver is enabled, and we analyse the received signal thanks to a spectrum analyser. The setup is the following:

- Centre frequency : 746 MHz
- Frequency span: 50 MHz
- Gain of the eNodeB receiver: 20 dB.

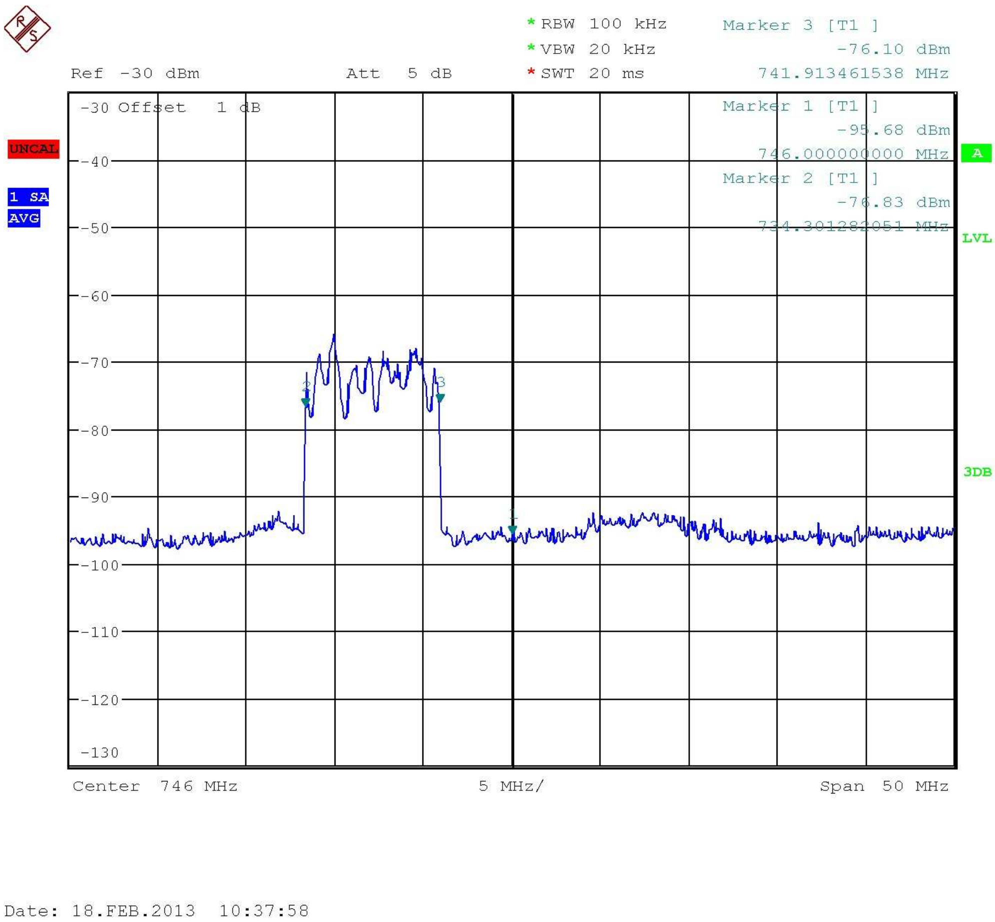

Figure 6-9: TVWS band occupancy

Clearly, the TVWS is occupied between 734.3 and 741.9 MHz. The bandwidth of the signal is 7.6 MHz. For the sensing tests in SACRA, the presence of an actual primary signal is very interesting, since it allows the validation in a realistic environment.

In a second step, we generate an emulated primary signal thanks to a signal generator. This test will allow us to make a dynamic demonstration thanks to a non-permanent primary signal. The following set up is used:

- Spectrum analyser : centre at 747 MHz, span of 100 MHz
- Emulated primary user : sinusoid, at 749 MHz, +12 dBm

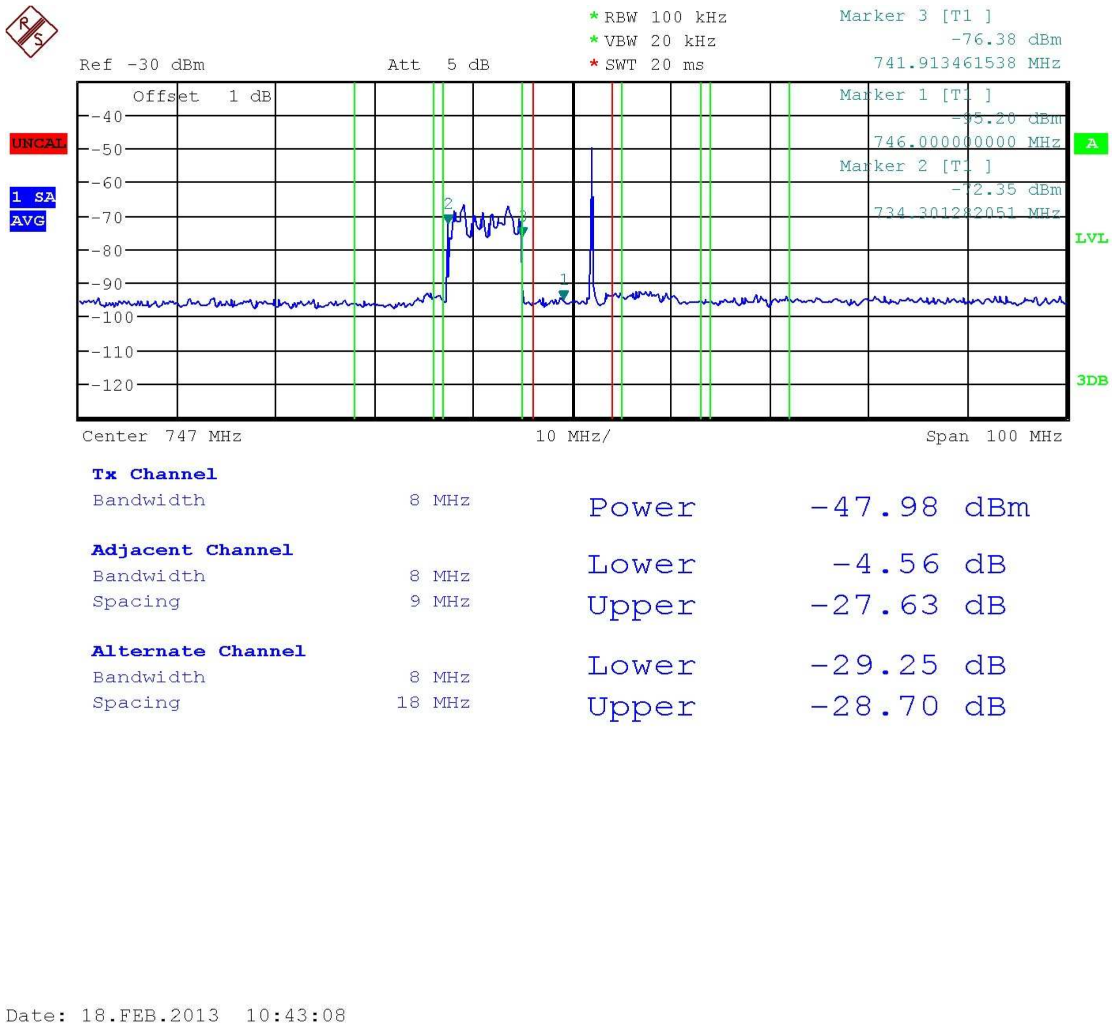

Figure 6-10: emulation of a second primary user signal

The level of the emulated primary user is -68 dBm (-47.98 – Gain of the receiver). The test is successful, since we are able to put a signal in an arbitrary frequency with a significant level, in order to stimulate the sensing/classification algorithms. One can notice that the actual primary signal is received with a level of – 72.56 dBm (-68 dBm – 4.56), which is also a high level.

6.5 UPLINK VALIDATIONIN THE PRESENCE OF AN ADJACENT PRIMARY USER

The goal of this test is to verify the uplink in the case of a communication in the TVWS band. For this test, the setup is the following:

- The SACRA terminal is put in the lab; the antenna from IIS is used.
- The transmitted signal is at 746 MHz, LTE rel8., BW = 5 MHz, Modulation scheme for data: QAM-4, TX power = +12 dBm
- The uplink is received by the eNodeB, a spectrum analyser is used at the output of the PA-LNA subsystem.

The Figure 6-11 and Figure 6-12 illustrate the reception and the demodulation of the uplink signal.

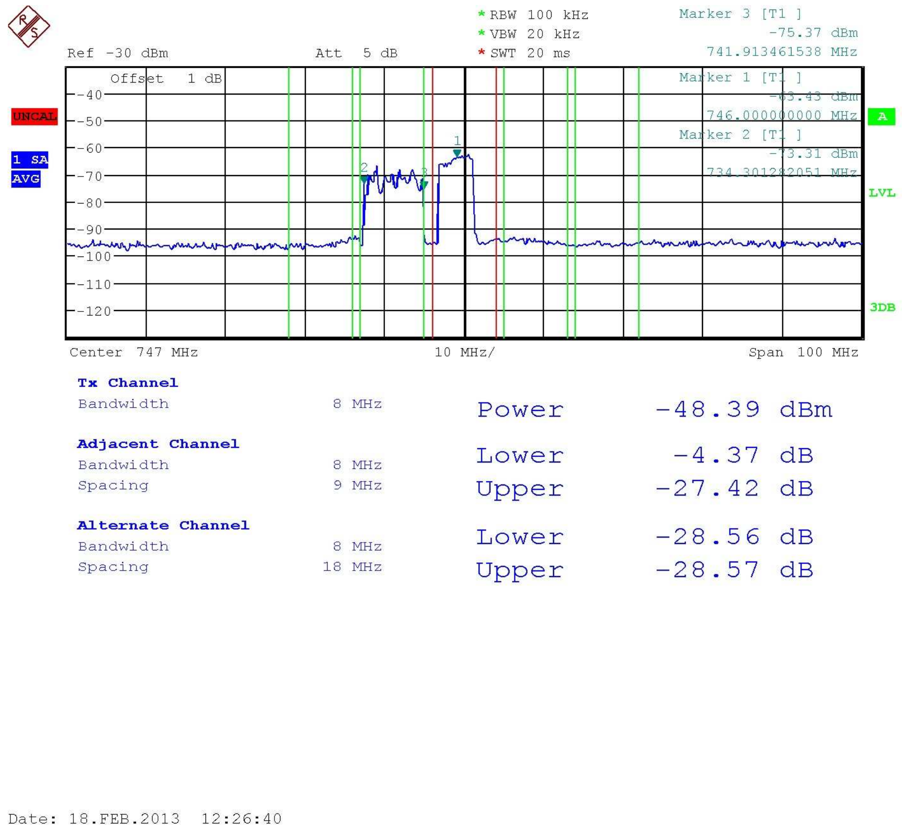

Figure 6-11: reception of the uplink signal

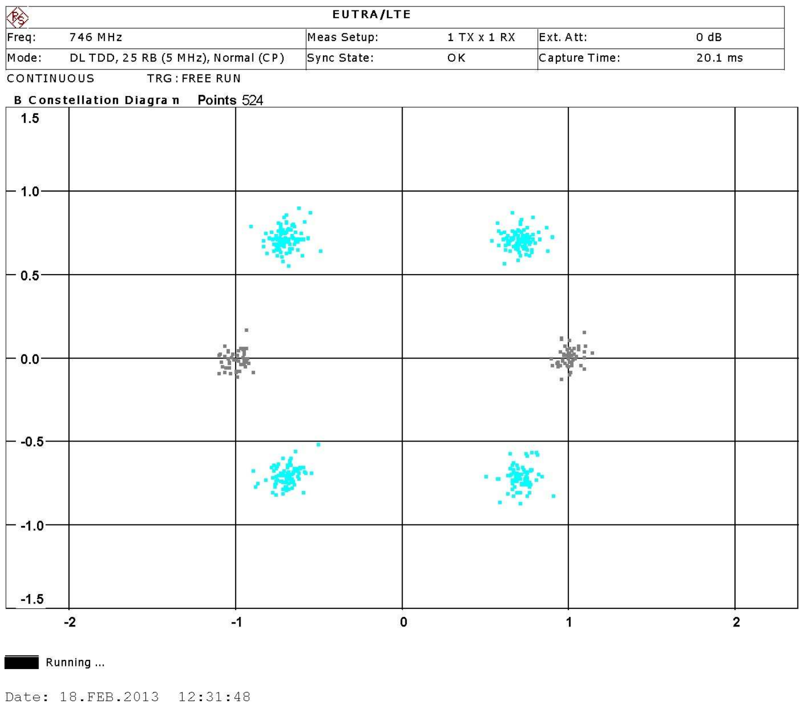

Figure 6-12: demodulation of the uplink signal

6.6 NEXT STEPS

As illustrated in the above sections, real field experiments have been done for the preparation of the SACRA final review and demonstration. The next steps will consist of:

- The implementation of the real time SACRA demonstration for the review
- Use of the results for dissemination of the SACRA project.

Beyond and after the SACRA project, many parts of the SACRA terminal will be used in others collaborative projects or in a point-to-point R&D program. Currently, 20 ExpressMIMO2 (mother boards) are being fabricated (reception April 2013). Moreover, 10 RF Front ends will be fabricated (reception may 2013). This material will be used in FP7 projects CONECT, NEWCOM#, WHERE2 and ACROPOLIS. Moreover, others projects will use the results, namely SPECTRA and SHARING (Celtic), CORRIDOR and SYMPA (French funded projects). Finally, several R&D entities have expressed their interest for a point-to-point R&D program. We have contacts with Agilent China, Orange labs and Alcatel Lucent.

7 CONCLUSION

In this document, we have described the real time trial activities of the developed platform. This document illustrates the demonstration and trials activities that have been conducted to implement the intra-cell Spectrum Aggregation scenario around the Eurecom building, in Sophia-Antipolis, France.

In Chapter 2, we have given an overview of the demonstration. The hardware parts of the eNodeB and the UE have been discussed in Chapter 3 and 4. In Chapter 5, the soft modem has been described as well as the protocol stack implementation. Finally, the experiments that have been performed are discussed in Chapter 6.

The results of this deliverable illustrate that the developed Hardware platform allows the implementation of the SACRA scenarios and the validation of the SACRA concepts. As stated in the technical annex, written before the beginning of the project; the demonstrator is a major objective and visible result of the project. At the end of the project, we can say that the demonstrator exhibits the features that have been designed in the technical annex. Beyond the demonstrated scenario, it is clear that the developed hardware is capable to validate other new concepts in wireless systems such as advanced relaying, sparse Carrier Aggregation, Device to Device communication. Indeed, the developed prototype has:

- Multiband antennas
- A flexible Front End part with up to 4 paths for RX and TX
- A programmable base band
- A PC-based protocol stack running in real time thanks to a real time OS.

Clearly, this prototype can be used for an advanced terminal in CR scenarios, but also as a relay or a Femto BS.

Beyond the SACRA project, the developed demonstrator will be reused in several frameworks (FP7 projects, CELTIC, French funded projects, point-to-point R&D programs). The main features of the demonstrator (antennas, flexible RF, programmable baseband and protocol stack) are interesting for many studies on SDR, cognitive radio, network topologies, etc.

As a conclusion, we can state that the developed demonstrator is a powerful tool for the validation of beyond-4G concepts such as green ICT, relaying, D2D communications and many others.

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9 ACRONYMS

ADC	Analog Digital Converter
BB	Baseband
BS	Base Station
CA	Carrier Aggregation
CAF	Cyclic Autocorrelation Function
ChX	Channel X
CPU	Central Processing Unit
DAC	Digital Analog Converter
DL	Downlink
DSP	Digital Signal Processor
DVB-T	Digital Video Broadband Television
eNodeB /eNB	Enhanced Node B
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FFT	Fast Fourier Transformation
FPGA	Field Programmable Gate Array
HW	Hardware
JRRM	Joint Radio Resource Management
LNA	Low Noise Amplifier
LTE	Long Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
OAI	Open Air Interface
PA	Power Amplifier
PHY	Physical layer (protocol stack)
PMSE	Program Making and Special Events
PU	Primary User
QoS	Quality of Service
QP	Quiet Period
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RRM	Radio Resource Management
Rx	Reception
SA	Spectrum Aggregation
SDR	Software Defined Radio
SNR	Signal to Noise Ratio
SU	Second User
SW	Software
tBPF	tunable Band Pass Filter
TDD	Time Division Duplex

TVWS	TV White Spaces
TX	Transmission
UC	Use Case
UE	User Equipment
UHF	Ultra High Frequency