Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum

(ACROPOLIS)

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Report and Analysis on the Existing Platforms for Experimentation

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Abstract:

The present document contains several proposed system scenarios, all falling within the Software Defined Radio (SDR)/Cognitive Radio (CR) domain, in addition to some identified experiments on the hardware and software platforms available to the ACROPOLIS consortium, namely the OpenAirInterface platform, the WARP platform and USRP boards. Although more extensive descriptions are provided in the deliverable D7.1, here we provide brief descriptions of the available platforms and their capabilities. Moreover, the document highlights the details of the training and teaching activities successfully performed towards stimulating the consortium members on to actively exploit the available platforms' facilities. Ongoing and prospective joint research activities in accordance with the identified experiments, which will mainly be realized through the EURECOM's OpenAirInterface platform, are also provided.

Keywords: Hardware/Software Platforms, OpenAirInterface, WARP, USRP, Platform training

Document Revision History

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0.1	14.01.2011	EURECOM	Initial structure of the document
0.2	25.01.2011	EURECOM	Chance in structure of the document
0.3	07.04.2011	EURECOM	ToC and Section 2 is updated
0.4	18.05.2011	RWTH	Included RWTH's first contribution to 2.2.2
0.5	23.05.2011	RWTH	Included RWTH's contribution to 2.2.1, 2.2.3 and 3.3
0.6	25.04.2011	Ioannis Dagres (IASA)	Included IASA's first contribution
0.7	06.06.2011	Aimilia Bantouna, Yiouli Kritikou, Vera Stavroulaki, Panagiotis Demestichas (UPRC)	Section 3.1
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Executive Summary

In recent years, we have witnessed a paradigm shift from digital radio to multi-band multimodal software-defined radios (SDRs), whose computing architectures allow for waveform synthesis and processing functions to be essentially described by a series of software programs (as originally described in 1991 by Mitola). In parallel to this shift, the organizational complexity of emerging broadband radio access networks heightens the need for flexibility in terminals and infrastructure aiming to achieve extremely high spectral efficiency. Some of the main factors that trigger the flexibility need are fragmentation of radio interface standards in all network topologies (cellular, P2MP, LAN, Broadcast, short-range), rapid increase in IP-based traffic (convergence of voice, data and flat-rate broadcast services on mobile terminal), spectrum re-farming and cohabitation of different access-networks on common spectrum. Cognitive Radios (CRs) enable intelligent and flexible solutions towards better utilization and management, and consequently more spectrally efficient use, of radio resources, as opposed to the limited spectrum assumptions of designers of conventional radios, thanks to the enabling technologies such as software defined antennas (agile transceivers or broadband antennas), reconfigurable radio (i.e., SDR).

In order to exploit existing systems in a cognitive sense, an increased multi-modality in both terminals and infrastructures is necessary in order to guarantee both high spectral efficiency and ubiquitous connectivity since many radically different waveforms will have to be synthesized and or detected. For example, different carrier frequency rasters, different baseband symbol times (sampling frequencies) and different interference rejection requirements (narrowband versus broadband systems, WLAN/WMAN versus cellular, etc.) have to be concerned.

In the CR domain, much of the conducted theoretical work related to spectrum sensing (energy detection, cooperative detection algorithms), spectrum management (radio resource management) and spectrum sharing (media access control, neighbourhood discovery) is yet to be considered from a practical perspective by means of experimental prototypes. The primary goal of this deliverable is to provide avenues for experimentation in the context of the NoE in addition to reporting on training activities on various platforms that can be used for such experimentation.

In particular, this deliverable provides brief descriptions of the development platforms and testbeds from different groups in the consortium, namely the OpenAirInterface, WARP, USRP platforms and UPRC testbed. Training activities on these platforms are also provided, in conjunction with WP 3, in order to increase the awareness of the consortium partners on the available platforms and on the hardware/software implementation towards implementing some of the theoretical solutions proposed within the other deliverables. Moreover, this deliverable also involves the description of identified experiments to be carried out in the context of the NoE.

In Section 2, the available platforms and testbeds within the WP5 and their capabilities are concisely presented, while further details and a more extended description of the platforms and testbeds can be found in the deliverable D7.1. In particular some of the basic components of the OpenAirInterface such as Agile-RF prototype used for broadband radio-access and the OpenAirInterface Emulator designed to emulate a medium-to-large scale

networks on one or more machines. Moreover, the basic features of Wireless open-Access Research Platform (WARP) and Universal Software Radio Peripheral (USRP) hardware platforms and UPRC software platform are briefly summarized.

In Section 3, considering the needs of the current wireless communications and the current trends of research in this area, several target CR-related scenarios are introduced and described for joint research and demonstration: spectrum aggregation, use of femto-cells, rapidly-deployable networks, plus white-space exploitation techniques. Pertaining to the described scenarios of interest, a number of CR experiments are identified in order to demonstrate and explore key technology enablers.

Section 4 highlights the details of the training and teaching activities on the available hardware and software platforms successfully performed. Specifically, two training activities, one on the OpenAirInterface methodologies during ACROPOLIS summer school help in Florence, Italy in 2011, and the other on WARP during IEEE DySpan conference, Aachen, Germany in 2011 and one USRP teaching activity in RWTH are given in this section.

In Section 5, the ongoing/planned joint research activities between the partners are provided, where the basis for partners' cooperation is in the design and the implementation/realization of the experiments identified in Section 3.

Finally, this deliverable provides some concluding discussion in preparation for the second year of the NoE in Section 6.

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1. Introduction

1.1 Role of WP 5

The objective of WP 5 is to analyze various existing hardware and software platforms that are available to the ACROPOLIS consortium and can be used for R&D purposes. The work begins by a critical analysis of different platforms (so that it heavily interacts with WP 7) and describes how best-practices are shared between partners to accelerate work in this area. In order to integrate and to enhance the available knowledge and expertise of the participating partners, a network for exchanging software modules and hardware experiments has been set up. Furthermore, several training activities on the available platforms are planned, so as to increase the awareness of the participating partners on the available platforms and to stimulate coordination among them.

One central activity in this area is also the analysis and valorisation of the European OpenAirInterface platform, which will be made available for consortium members by EURECOM. The software tools are provided under open-source policy and hardware elements will be offered to consortium members.

1.2 Purpose of the document

The goal of this deliverable D5.1 is to assess, integrate and provide training on different development platforms available from different groups in the ACROPOLIS consortium. The development platforms include hardware, software and emulation environments.

Here, several target scenarios are described for joint research and demonstration such as: spectrum aggregation, use of femto-cells, rapidly-deployable networks, plus white-space exploitation techniques. All are of interest, considering the needs of the current wireless communications landscape and the current trends of research in this area. Based on the described scenarios of interest, a number of associated experiments are then identified in order to demonstrate and explore key technology enablers. Hardware and software requirements will be investigated using multiple platforms, but mainly the OpenAirInterface platform, which are made available to all the members of ACROPOLIS consortium. These platforms are briefly explained in this document, since their more elaborated descriptions are given in deliverable D7.1.

Regarding the interaction between the identified experiments and the technical WPs, it is expected that as the technical work continues within each WP and new results are being produced and reported, then appropriate changes and additions to the identified experiments (if feasible) will be done to validate the proposed solutions.

Moreover, central to the nature of NoE, this deliverable also provides training/support on the OpenAirInterface radio equipment and development environments, and also on the WARP platform in conjunction with the education and training WP3. Some details on the two training activities conducted till now, one on the OpenAirInterface by EURECOM and the other on the WARP by RWTH, are provided in Section 4.

2. Platforms and Testbeds available to Consortium

In this section, we briefly present the available platforms and testbeds (within the WP5) and their capabilities, while further details and a more extended description of the platforms and testbeds can be found in Deliverable D7.1.

2.1 OpenAirInterface Platform

2.1.1 AgileRF Prototype

Figure 2-1 AgileRF Prototype

AgileRF is an RF front-end prototype for broadband radio-access. An example configuration is shown in Figure 2-1 consisting of a single TDD transceiver operating over the 150MHz-8GHz frequency range. The AgileRF boards comprise the following subsystems:

- RX: This is a generic broadband receiver board (200 MHz – 8 GHz, 20 MHz channels), Quadrature (I/Q) output
- TX: This is a generic quadrature transmitter board operating in the frequency range of 200 MHz – 8 GHz. RX :
- Synth 1: 8.2 GHz local oscillator (used for systems below 4 GHz, e.g. DAB/DMB, LTE/GSM/WCDMA/HSPA)
- Synth 2 : 4-8 GHz local oscillator

The receiver is comprised of a broadband LNA followed by a band-selection filter network. A direct conversion quadrature mixer is used for inputs in the range 4-8 GHz. An additional upconverter to 4-8 GHz is used for input signals in the 150MHz-4 GHz range. The band-selection filters and RF gain levels are controllable via a digital interface (controlled here by ExpressMIMO). Baseband outputs are provided via differential quadrature (I/Q) signals from the baseband engine. The baseband section has maximal baseband channel bandwidth of 20 MHz and a sharp DC block for RF carrier leakage removal. Baseband amplifiers provide

60 dB of gain, which when combined with variable RF attenuators allow for 70 dB of gain control.

The transmitter has maximal baseband channel bandwidth of 20 MHz. Baseband inputs are provided via differential quadrature (I/Q) signals from the baseband engine. Band-selection filters are provided to guarantee image-free outputs in all target bands. The bands are, DC-200 MHz, 200-400 MHz. 400-600 MHz, 600-1000 MHz, 1-2 GHz, 2-3 GHz, 3-5 GHz, 5-8 GHz.

2.1.2 OpenAirInterface Emulator

2.1.2.1 Hardware architecture

The OpenAirInterface emulator makes use of the open-source real-time operating system extension to Linux, RTAI to guarantee hard real-time behaviour. The hardware architecture of OpenAirInterface is shown in Figure 2-2 and makes use of a 64-bit 2GHz Quad-core Xeon cluster with the earlier Linux version 2.6.29.4 (named R4Gx). The clusters are interconnected through a Gigabit switch to enable fast transport of the emulated data traffic. One of the clusters acts as a master and generates periodically the entire emulated parameters for the other clusters. With virtualization of the protocol stack, many instances can reside in the same physical machine.

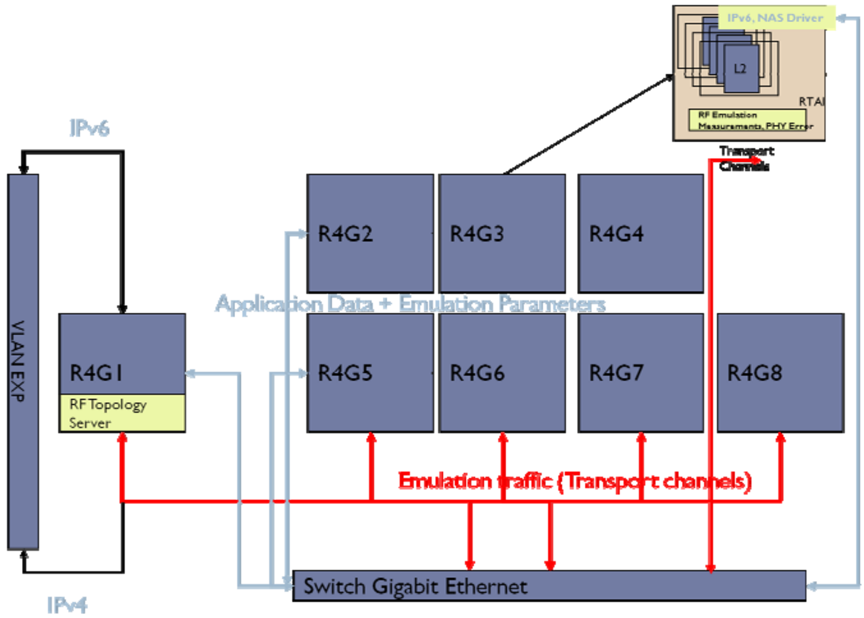

Figure 2-2 Hardware architecture of OpenAirInterface emulation platform

2.1.2.2 Software architecture

Figure 2-3 shows the high level software architecture of the emulated platform itself and the main building blocks. The user scenarios are described using baseline scenario descriptor and then encoded into xml format and dispatched across OpenAirInterface hardware platform according to some predefined rules. Then, the config generator block translates the high level scenarios into low level configuration files understandable for traffic/mobility generator, UE/eNB protocol stack, PHY abstraction and emulation transport medium. The real applications are attached on top of some emulated UE/eNB and the remaining traffic pattern and mobility model will be generated automatically. The behaviour of the wireless medium is modelled using a PHY abstraction unit which emulates the error events in the channel decoder and provides emulated measurements from the PHY in real-time. The remainder of the protocol stack for each node instance uses a complete implementation as would a full-RF system. The Log generator is in charge of recording the emulator activities according to the user defined log level, while the packet trace generator captures the frame (potentially extract on-the-fly the relevant field) and anonymizes the payload before storing it. The result generator produces the user defined test results using the outcome of log generator and packet trace generator to the OpenAirInterface portal accessible by the user.

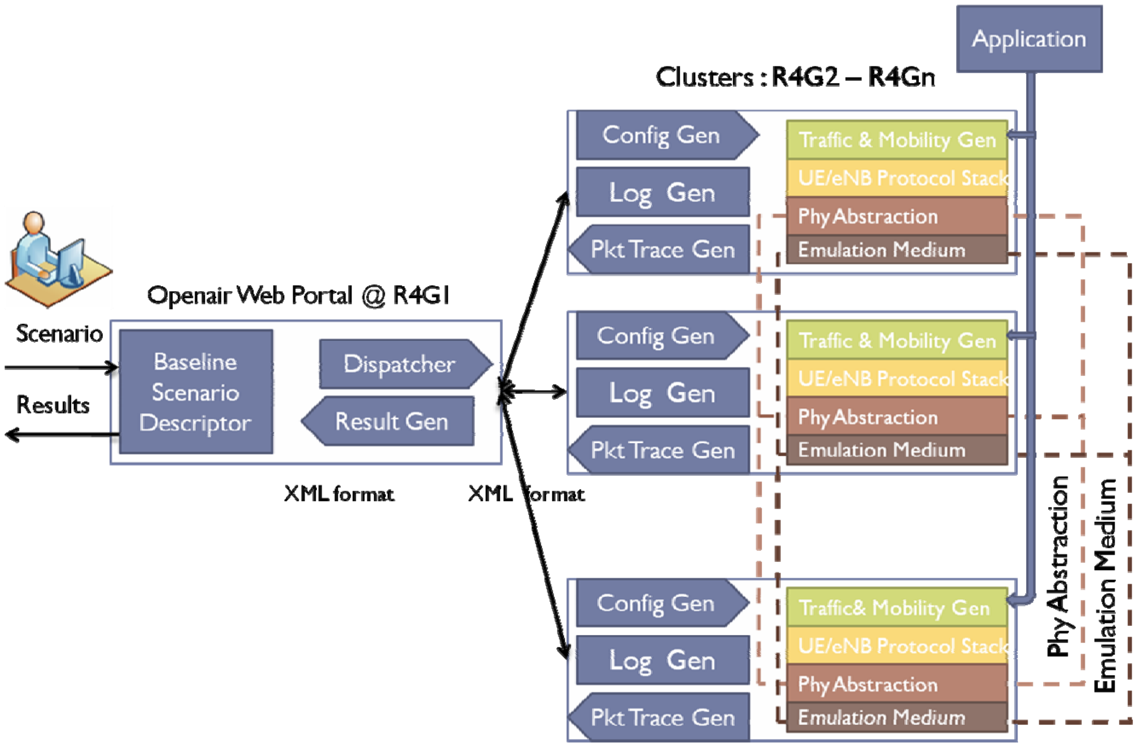

Figure 2-3 Building blocks for OpenAirInterface emulation platform

The OpenAirInterface emulator is designed with the following features in mind:

- allows to emulate a medium-to-large scale networks on one or more machines.
- provides the same conditions that are expected to occur in real-world wireless systems for the network protocols and application.
- accepts real channel measurements or can be based on synthesized channel model
- allows end-to-end IPv4/IPv6 packet transition with QoS support, i.e. any standard application/traffic generator can be attached to any node in the network and possibility to interconnect the emulated networks to live networks or to additional emulated network (on-going).

2.2 Wireless open-Access Research Platform (WARP)

Wireless open-Access Research Platform (WARP) [4] is an SDR platform for research in advanced wireless algorithms and applications. The platform consists of both custom hardware and FPGA implementations of key communication blocks. The hardware consists of FPGA-based processing boards coupled to wideband radios and other I/O interfaces; the algorithm implementations already include a flexible OFDM physical layer [7]. Both the hardware specifications and algorithm implementations are open-sourced and available to the research community. It is gaining its popularity among both research institutes and industry, currently being used by 22 universities and 11 companies.

There are two versions of the WARP platform, v1.2 and v2.2. The WARP v2.2 FPGA board is an 8"x8" PCB built around a Xilinx XC4VFX100FFG1517-11C Virtex-4 FPGA while the WARP v1.2 FPGA board is built around a Xilinx XC2VP70 Virtex-II Pro FPGA. The WARP FPGA Board has four daughter-card slots which ultimately supports 4x4 MIMO communication. The four slots are electrically and mechanically identical. The WARP hardware supports any combination of daughter-cards in the four slots. However, a given FPGA design will require a specific arrangement of daughter-cards once synthesized. On-the-fly reconfiguration of FPGA is not enabled in the current implementations.

There are two major open-sourced software reference designs provided by Rice University for both versions of the hardware platform. These reference designs are commonly used for both research on PHY/MAC designing for software defined radio and educational purposes. Xilinx's Embedded Development Kit is needed to build these designs locally.

The OFDM reference design is a full project with MIMO-OFDM, ALOHA/CSMA MAC and Ethernet hub functionality. The WARP OFDM Reference Design implements a real-time network stack on a WARP node. The design includes a MIMO OFDM physical layer and flexible MAC interface for building custom protocols. This design demonstrates the full MAC/PHY capabilities of WARP. Serial communication is included in the design.

The WARPLab reference design is a framework which brings together WARP and MATLAB. With WARPLab, one can interact with WARP nodes directly from the MATLAB workspace and signals generated in MATLAB can be transmitted in real-time over-the-air using WARP nodes. The users can implement different physical layer algorithms in MATLAB which offers the ease for parameter tuning and modification. At the same time, real-time over-the-air transmission/reception performance can be observed through the WARP nodes. This facilitates rapid prototyping of physical layer (PHY) algorithms. Details about WARP can be found in D7.1.

2.3 USRP (Universal Software Radio Peripheral) Platform

The Universal Software Radio Peripheral (USRP), developed within the Ettus Research™ LLC is one of the most popular SDR platforms for testing of Cognitive Radio implementations due to its various advantages such as low-cost and its simplicity to use for initial experimentation with radio signals. However, on the other hand USRP can not provide strict real-time capacity (due to Ethernet interface between a host-computer and USRP) and complete system implementation.

Basic processing cycles in USRP experimentations work as follows: whole software processing is executed on a host-computer which then samples and sends the processing outcome (via USB or Ethernet) to a motherboard. Then, the motherboard modulates the input signal from the host-computer to the intermediate frequency (IF). Afterwards, the IF signal is converted from digital to analogue form and shifted directly to the certain radio frequency (RF) band on the connected daughter board, and finally sent to the antenna.

2.4 UPRC Testbed

This section focuses on presenting in short a platform developed by UPRC. To begin with, this platform involves the development of a testbed for the integration and the validation of cognitive management systems. These management systems may include one or more of: a) context, b) profile, c) policy and d) learning and knowledge features. For achieving the above, the testbed incorporates a variety (in number and type) of both hardware and software elements. The hardware components include WLAN Access Points, WiMAX base stations, laptops, PDAs, core and access switches, servers and PCs while software elements refer to software blocks which encompass cognitive management of network elements and terminals, traffic generation, network simulation, collection and analysis of measurements, context monitoring and application provisioning. Moreover, the combination of these elements is able of supporting several scenarios and uses cases, especially in terms of executing them and integrating new hardware and/ or software functionalities for different prototyping activities.

Hereafter, it is important to mention that this integration is also supported by a middleware platform that further enables the interaction and cooperation of all involved entities making the testbed flexible and extendable, as well.

Finally, high-level interfaces with various interconnection ways enable experimentation with different problem handling practices, varied hardware and software configurations or even diverse architecture designs. The performance of validation procedures within the UPRC testbed and the collection of results are also possible, while the final experimentation environment is extendable by linking this testbed with other already established European and international testbeds and experimental facilities.

A graphical representation of the UPRC testbed is depicted in Figure 2-4.

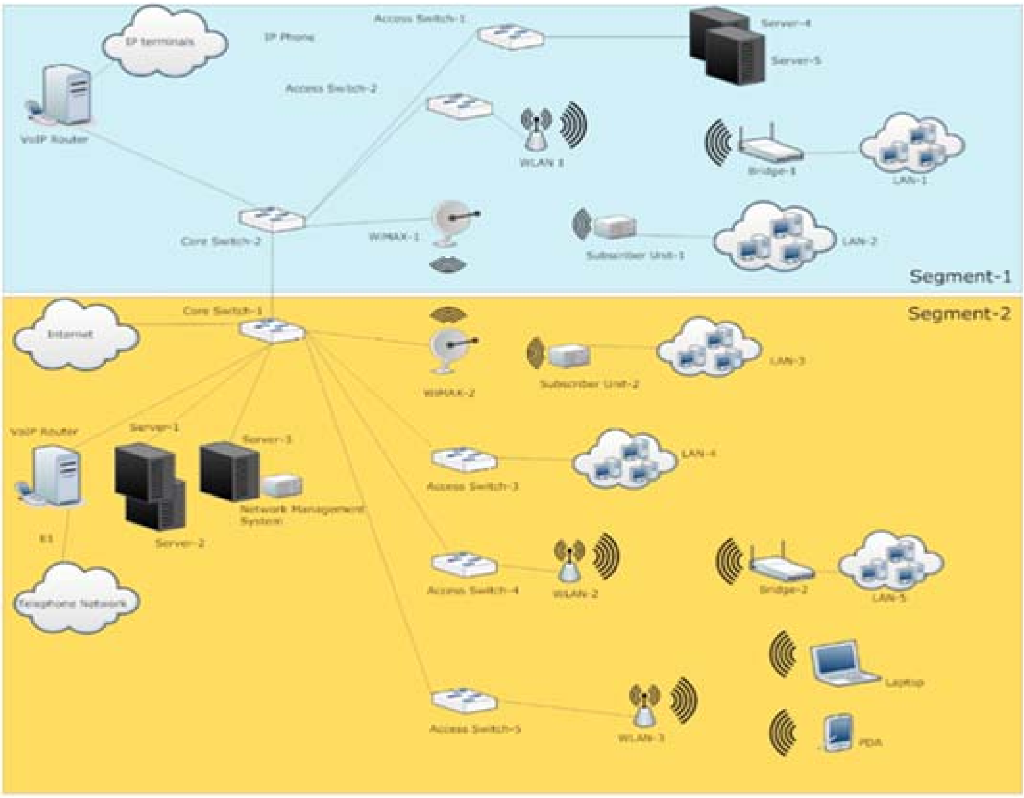

Figure 2-4 Network elements, terminals and topology of the UPRC testbed.

3. Scenarios for Joint Research and Demonstration on Platforms

In this section, scenarios of interest for demonstration purposes of the NoE are identified, in particular as related to (a) civil-protection networks and (b) spectrum aggregation in LTE/LTE-A networks.

3.1 System Scenarios

3.1.1 Spectrum Aggregation

With spectrum allocations differing around the world, it is essential that a communication system provides radio-deployment flexibility. The air interface of 3GPP LTE (E-UTRA) [40],[41],[42] has taken one step in that direction: it facilitates wideband channels up to 20MHz by means of different scalable bandwidths. However, even today, finding spectrum allocations that can accommodate 20MHz E-UTRA carriers in one single band is a regulatory challenge. This will become more complicated for LTE-Advanced system [43] as the very-high peak-data-rate targets can only be fulfilled in a reasonable way by a further increase of the transmission bandwidth of up to 100MHz.

This issue is currently discussed in 3GPP: one solution to free up spectrum is the re-farming of licenses, but it may result in supplementary fragmented spectrum. So, to handle situations where large amounts of continuous spectrum are not available, LTE-Advanced has introduced the concept of “Spectrum Aggregation” over multiple spectrum segments, as shown on Figure 3-1.

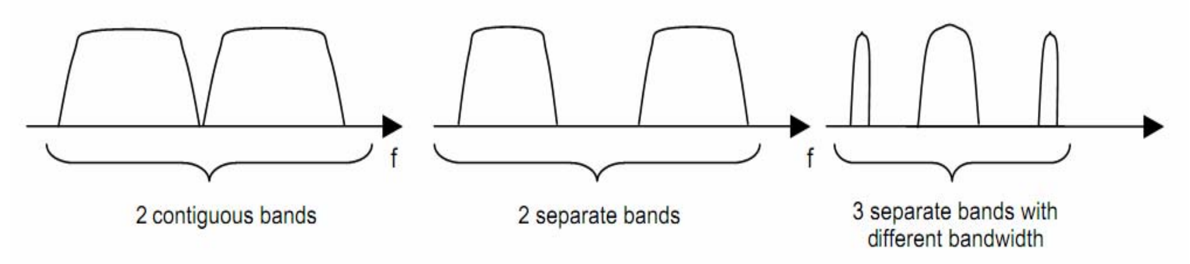

Figure 3-1 Some examples of spectrum aggregation.

A 3GPP work item is currently focused on the intra-RAT and intra-cell cases. The research in this area could go one step beyond by considering a system, based on the LTE-Advanced framework, able to manage the aggregation of spectrum (opportunistic or not) localized in the Digital Dividend (DD) and the TV White Space (TVWS) bands.

In this context, three sub-use cases can be envisioned:

- The most basic one is to deploy an infrastructure using a licensed band at 2.6 GHz and improving its capacity (coverage, etc.) with additional resources available (for secondary use) in the TVWS. This scenario is illustrated in Figure 3-2.
- The second one is a bit more complex and would consider the aggregation of LTE/LTE-Advanced carriers across 2 cells, either co-located (within several sectors) or distant (can be eNodeB (eNB) cells or Relay Node cells), to serve one single User Equipment (UE).

➢ The third use-case is related to the signalling between base stations (or eNBs), which might be access points or cluster heads in the mesh topology, through the use of ISM band (433 MHz) for the purpose of Dynamic Spectrum Access (DSA) at the eNodeBs. In this scenario it is crucial for each UE to sense the environment and to feed this information to the attached eNB. This scenario is illustrated in Figure 3-3.

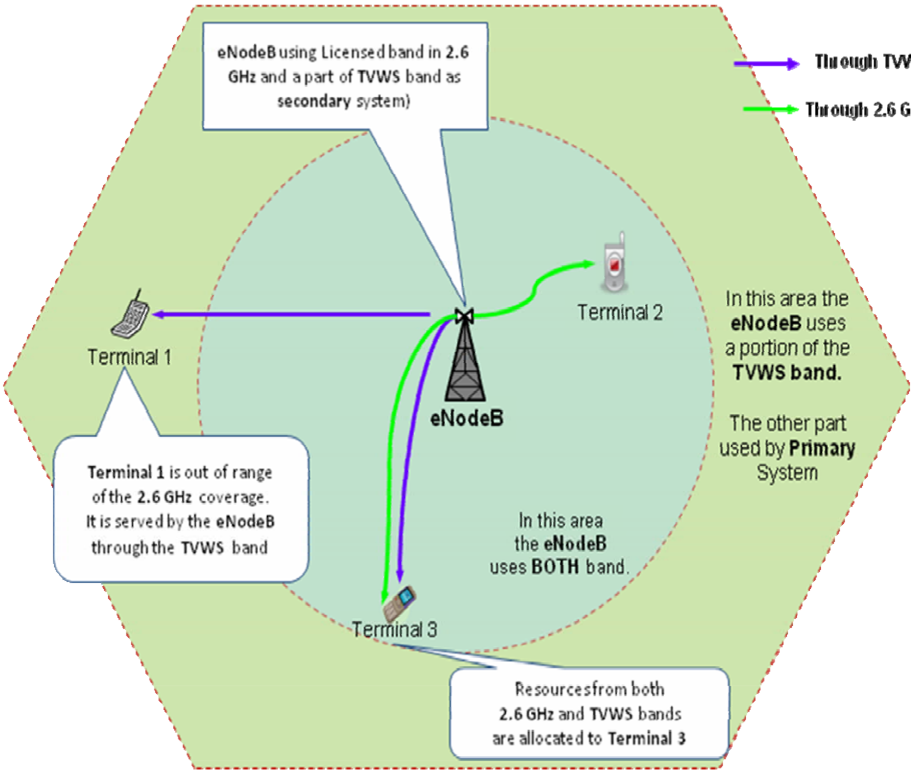

Figure 3-2 Opportunistic intra-cell spectrum aggregation.

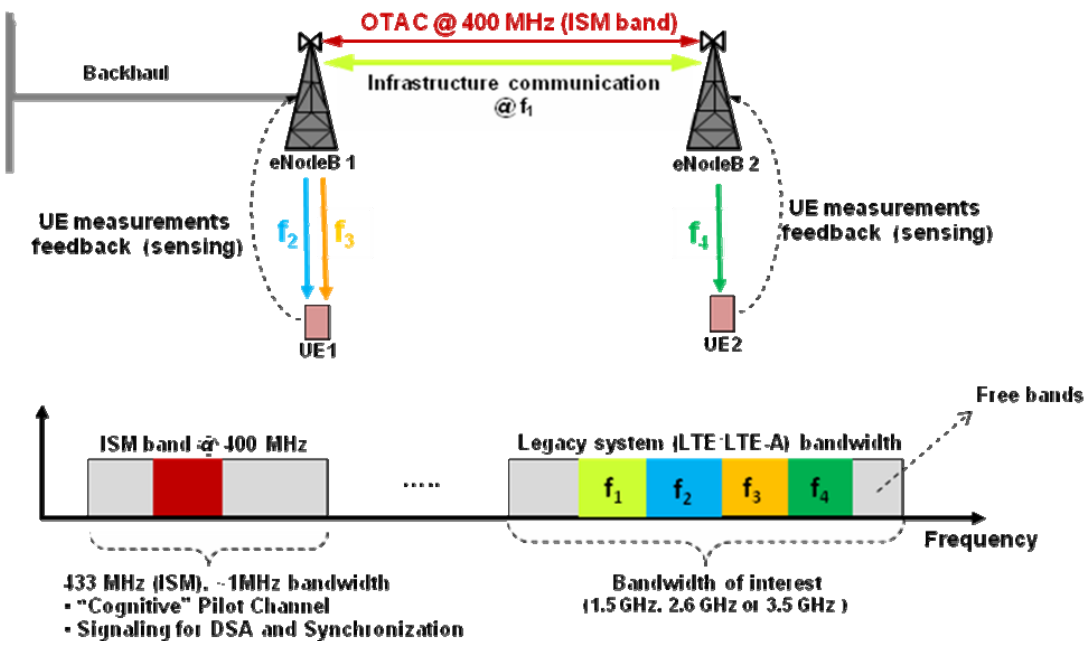

Figure 3-3 Self-configuring Infrastructure: Exploit ISM band for signalling between eNBs.

3.1.2 Femto-cells

The advent of the mobile Internet combined with the rapidly growing use of smart phones with Internet access or data connectivity solution for laptops is stressing the infrastructure of cellular networks. Data traffic is becoming prominent and bandwidth requirements are increasing. Furthermore, end-users are more and more interested in better and improved services, especially indoors. According to [19], more than 50% of all voice calls and more than 70% of data traffic originate indoors in 2007. Typically, indoor environments such as office buildings suffer from poor radio propagation properties and dense areas from insufficient bandwidth resources. Poor coverage additionally decreases the quality of voice and video calls and slows down the adoption of high speed services. The need of expanding the cellular network represents a challenge as new infrastructure is very expensive. However, even though cellular networks are widely deployed and the coverage area continues to extend, full coverage with a high enough signal quality is still a concern. Recently, femto-cells have been proposed as a cost effective solution to expand the coverage and capacity of 3G and beyond networks.

Femto-cells are portable and low-cost base-stations for in-home usage; besides they can be used outdoors to extend the coverage. They are deployed by end-users and are connected to the operator network by a digital subscriber line (DSL), cable modem or optical fiber connection [19],[20],[21]. Femto-cells represent a solution for 4G networks to improve coverage while offering a higher QoS to the user and maintaining full compatibility with the existing handsets and low additional costs. Femto-cells offer significant advantages for both users and operators. While users get indoor coverage and higher data rates at home, operators can scale their networks with reasonable investments by using femto-cells for offloading traffic from the existing cellular network.

The integration and coexistence of large numbers of femto-cells into existing networks creates demanding and severe interference management scenarios [22], [23], [24]. Since femto-cells will be installed by users in an uncontrolled and random manner, this situation represents an enormous challenge for operators to maintain a reliable connection and provide sufficient capacity while preventing interference from reaching unacceptable levels.

Figure 3-4 depicts a typical scenario where the existing LTE network will be overlaid by femto-cells. On the uplink, a macrocell user transmitting at maximum power causes unacceptable interference to nearby femto-cells. On the downlink, femto-cell to femto-cell interference can degrade the performance. Moreover, due to the large number of femto-cells expected to be deployed a centralized deployment could not be the best option from the point of view of network management. In a cross-layer design both the challenges from the physical layer and the QoS demands from the applications have to be taken into account. Rate, power and coding at the physical layer can be adapted to meet the requirements of the applications given the current channel and network conditions.

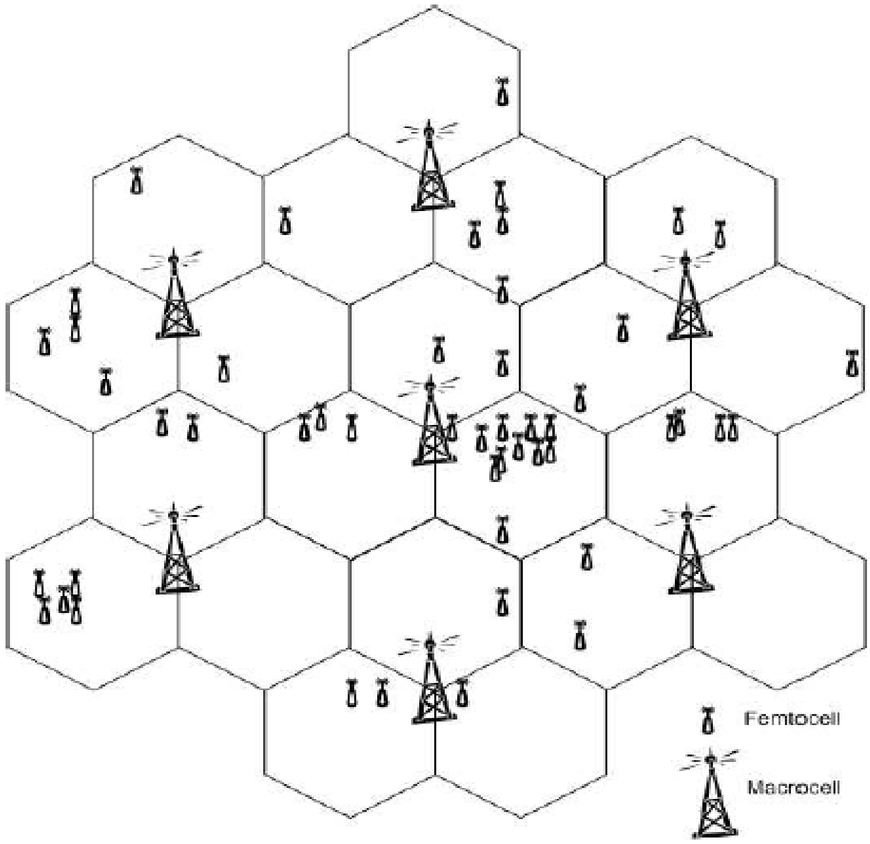

Figure 3-4 A two-tier wireless network where femto-cells overlay the cellular network infrastructure.

3.1.2.1 Radio Resource Management (RRM)

In a bursty interference scenario, the way to allocate the frequency resources becomes of significant importance as to minimize the impact on the adjacent cells performance. One approach is to set aside a portion of the spectrum for deploying femto-cells and use the remaining for the macro network. The other approach is to deploy femto-cells on the same spectrum as existing macrocells. In LTE/LTE-Advanced, the spectrum is divided into a fixed number of Resource Blocks (RBs). In a dense deployment scenario or in a scenario with heavy levels of traffic where resources may not be free, the RBs have to be assigned in an intelligent manner in order to bring the co-channel interference to the lowest possible level. The resources to be used could be negotiated with the neighbouring access points (potential interferers). This could be realised either in a centralized or a distributed manner. The centralized approach is the simplest way to accomplish this by having a centralized entity that coordinates the resource management. The advantage of this approach is that it is simple and the operator retains control. However, in a network with potentially thousands of femto-cells, the resource management by a single centralized entity could lead to instability by introducing significant delays in the assignment of resources and could also limit the scalability of the network. A distributed approach on the other hand is generally fast and accurate as decisions are taken locally. However, it comes with a cost of increased complexity and loss of control from the operator.

Frequency hopping enables femto-cell users to avoid mutual interference. In frequency-hopped OFDMA networks, random sub-channel assignments can be used in order to decrease the probability of persistent collision with neighbouring femto-cells.

LTE power-saving protocols include Discontinuous Reception (DRX) and Discontinuous Transmission (DTX) [27]. Both involve reducing transceiver duty cycle while in active operation. However, DRX and DTX do not operate without a cost: the UE's data throughput capacity is reduced in proportion to power savings.

Autonomous Component Carrier Selection (ACCS) refers to a feature that has been proposed for 3GPP LTE Advanced [25]. Assuming the bandwidth is divided into a number of separate component carriers, each cell selects an active component carrier. Then, the other cells select additional component carriers, depending on the offered traffic conditions, radio conditions, interference, etc. All the carriers not been selected are not used in the cell, therefore, decreasing the co-channel interference and optimizing the frequency reuse configuration.

3.1.3 White-space exploitation

Wireless Regional Area Network (WRAN) or IEEE 802.22 is a standard aiming at using white spaces in the TV frequency spectrum. The development of the IEEE 802.22 WRAN standard is aimed at using cognitive radio (CR) techniques to allow sharing of geographically unused spectrum allocated to the Television Broadcast Service, on a non-interfering basis, to bring broadband access to hard-to-reach, low population density areas, typical of rural environments, and is therefore timely and has the potential for a wide applicability worldwide. It is the first worldwide effort to define a standardized air interface based on CR techniques for the opportunistic use of TV television bands on a non-interfering basis.

IEEE 802.22 WRANs [30] are designed to operate in the TV broadcast bands while assuring that no harmful interference is caused to the incumbent operation, i.e., digital TV and analogue TV broadcasting, and low power licensed devices such as wireless microphones.

IEEE P802.22.1 is a standard being developed to enhance harmful interference protection for low power licensed devices operating in TV Broadcast Bands. IEEE P802.22.2 is a recommended practice for the installation and deployment of IEEE 802.22 Systems. IEEE 802.22 WG is a working group of IEEE 802 LAN/MAN standards committee which is chartered to write the 802.22 standard.

In response to a Notice of proposed rulemaking (NPRM) issued by the U.S. Federal Communications Commission (FCC) [29] in May 2004, the IEEE 802.22 working group on WRANs was formed in October 2004. This project, formally called as "Standard for WRAN - Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and procedures for operation in the TV Bands" focuses on constructing a consistent, national fixed point-to-multipoint WRAN that will use UHF/VHF TV bands between 54 and 862MHz. Specific TV channels as well as the guard bands of these channels are planned to be used for communication in IEEE 802.22.

White-space exploitation might also be applied in wireless access for transportation systems, where both user-specific data and control traffic are conveyed. An example would be that of a wireless backhaul along the railway which exploits opportunistic radio access. In this scenario, both BSs and transceiver unit(s) in a train perform wide-band spectrum sensing and identify spectrum holes and do carrier aggregation across the available parts of the spectrum. In the white-space exploitation (spectrum sensing) phase the determinism in the trajectory of the railway and time schedule of trains' arrivals for more accurate sensing might be exploited. An illustration for the described white-space exploitation scenario is depicted in Figure 3-5.

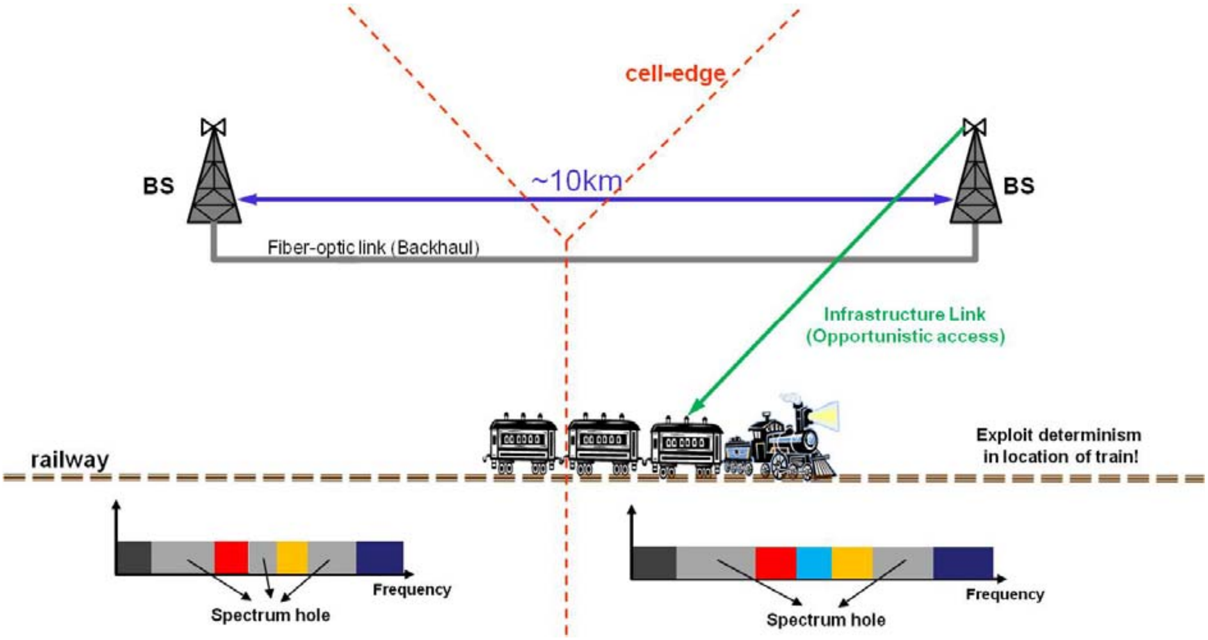

Figure 3-5 A non-LTE White Space Exploitation for opportunistic Radio Access for Railway Infrastructure

3.1.4 Rapidly Deployable Networks

Rapidly deployable networks are one of the technical solutions to reduce the impacts of disasters, such as earthquakes, volcanoes, tsunamis, drought, tornados, forest fires and floods, on population and property. In public safety and emergency/disaster relief applications, the communication system must be highly reliable to allow rescue teams to work and collaborate quickly and efficiently. Such operations are strongly dependent on the availability of the communication links both to rescue operators on the fields and to the central control room. However, in disaster areas, the links and central control are subject to failure, leading to a complete collapse of the network. Hence, the introduction of rapidly deployable inter-operable communication systems for public safety is becoming increasingly important in today's world. Rapidly-deployable inter-operable communication systems reconfigure the network functions according to the system constraints (e.g. radio frequency, bandwidth, authorized transmission power) and network and application characteristics (e.g. traffic and mobility pattern) at the time of deployment. The advantage of the reconfigurable protocols is that no single system is efficient for all emergency situations due to the huge variability in terrains, traffic scenarios, and mobility patterns. For instance, the design of the air interface uses software-defined radio (SDR) principles [26] and can be reconfigurable with respect to PHY and MAC parameters (e.g. frame/slot durations, modulation formats, FFT sizes, preamble lengths, etc.) as well as algorithms designed for specific propagation or traffic conditions (multiple-access and channel coding and synchronization strategies, smart antenna processing, scheduling algorithms). A rapidly deployable network scenario is illustrated in Figure 3-6.

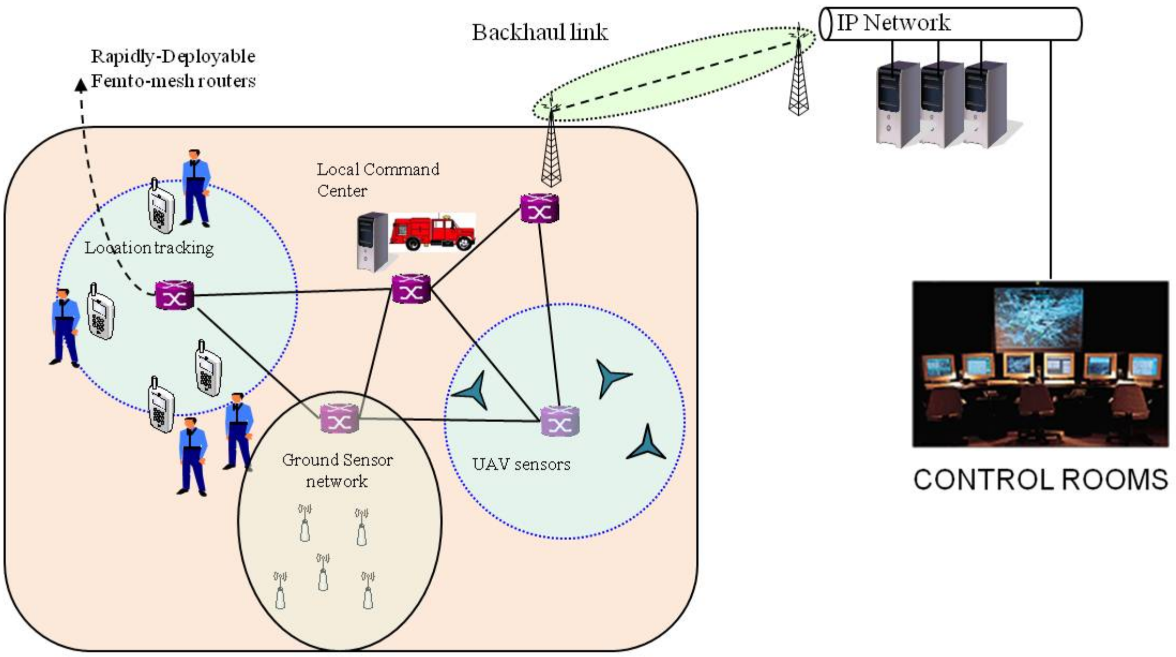

Figure 3-6 A rapidly deployable network scenario: Opportunistic radio access for emergency communications.

3.2 Identified Experiments

Based on the described scenarios of interest a number of experiments have been identified in order to demonstrate and explore key technology enablers. Hardware and software requirements will be under investigation using multiple platforms available to the members of ACROPOLIS consortium. A block diagram depicting the relation of the selected experiments with the scenarios is given in Figure 3-7. A similar relationship between the experiments with the technical WPs is not sufficiently clear at the present time so as to allow them to be depicted in the same block diagram.

In WP7 hardware platforms are under investigation, making it highly relevant to all selected experiments. Similarly, the work in WP8, on fundamental research methods and tools, is related to the work of all experiments. The work in WP9 is closely related to the SS experiment, as well as the RSL and IM, since spectrum awareness and interference prediction is under investigation. Awareness on the network-neighborhood level is investigated in WP10, related to the RP experiment. WP11 addresses the requirements for identification, collection, processing, and distribution of information for a number system scenarios, covering also the ones identified herein. The work in WP12, metric identification, decision making algorithms and solutions, is mainly related to RRM, as well as the RP.

As the technical work continues within each WP the and new results are produced and reported, appropriate changes and additions to the described experiments will be done to validate the proposed solutions.

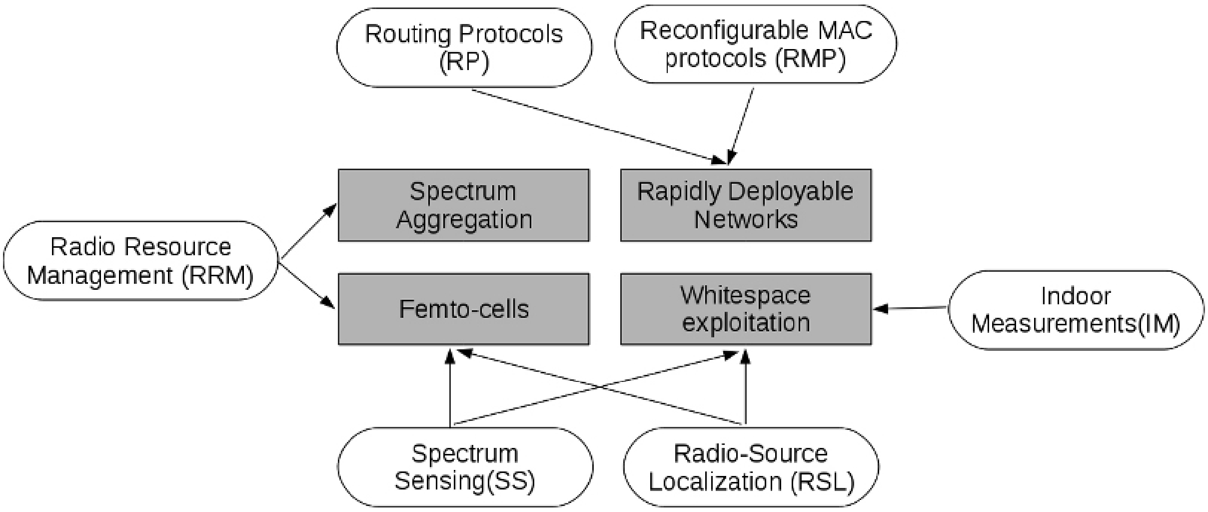

Figure 3-7 Scenarios – Experiments relation

3.2.1 Reconfigurable MAC protocols[1]

RWTH has designed and implemented a tool chain TRUMP on WARP board for rapid protocol realization at run-time and enabling on-the-fly reconfiguration of MAC protocols [1]. TRUMP is built based on a decomposable MAC framework [2] where the most common kernel functionalities have been identified in different MAC-layers. The decomposition of MACs into their building block functionalities is carried out after a comprehensive analysis of existing MAC protocols from different classes of wireless networks. The MAC layer kernel functionalities are identified based on the commonalities among the protocols. The idea is to compose highly dynamic cognitive MAC solutions from a set of these kernel components based on the requirements of the applications and QoS demands. The identified kernel functionalities include *Framing* (for frame formation), *Sending/Receiving Frames, Random Number Generator, Timers, Carrier Sensing* (energy detection, feature detection), radio core control functionalities (setting transmit power levels, setting receiver sensitivity, setting the modes of the radio TX/RX/SLEEP etc.), etc. Based on these basic functionalities, higher level and complex functionalities can be accomplished. Table 3-1 shows a list of defined secondary level MAC components and their compositions.

In order to facilitate fast protocol design and realization using the decomposable MAC philosophy, TRUMP, a Toolchain for Run-tiMe Protocol realization is designed. TRUMP consists of mainly three parts: a Wiring Engine is used to bind the individual components and to coordinate the control and data flow among the decomposed MAC components; a MAC description method for MAC behaviour specification; and a compiler which converts MAC description to executable code for the wiring engine.

[1] This contribution is based on RWTH's published work [1][2][3]

Component	Usage and the *composition*
Random Backoff	Random backoff mechanism *Timer, Random Number Generator, Carrier Sensing*
Expecting Frame	Used when the node is waiting in anticipation of a packet *ReceiveFrame, Timer, Radio Switching, SendFrame*
Send Packet	Called after seizing a channel free *SendFrame, Expecting Frame, Radio Switching, Random backoff*
RTS/CTS/DATA/ACK	Four-way handshake mechanism *Send Packet, Expecting Frame*

Table 3-1 Commonly Used Secondary Level MAC Components [2]

The wiring engine in the MAC-processor allows dynamically linking different MAC-layer components together at the run-time to result in suitable MAC functionalities. This approach allows fast on-the-fly reconfiguration, which is a must for cognitive MACs. The concept of composing MACs using the same set of kernel components is shown in Figure 3-8. The two hypothetical MACs are shown to be realized with appropriate “wiring” of the MAC building blocks.

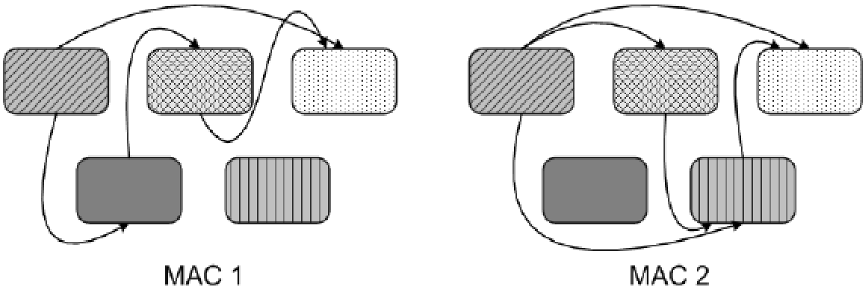

Figure 3-8 MAC composition based on the common kernel functionalities

In addition to the elements binding, we take care of the dependencies among elements and the binding logic by using a Logic Controller as part of the Wiring Engine. The Logic Controller ensures smooth execution of the composed protocol by identifying conflicts between the relationship among components and the execution order. The Wiring Mechanism treats all functional components as independent entities. The sequence of execution of components is managed by the run-time execution manager based on the logical connections. However, in network protocols, some functional components are dependent on each other. In order to reduce design efforts and offer the designer the reassurance that only correctly designed protocol can be synthesized and deployed onto the target platform, the Logic Controller reports erroneous MAC designs and governs the integrity of the executed protocols. Predefined rules have been devised to express interdependencies among components and incorporate them as part of the functional libraries. Based on the dependency table, the framework also explores the opportunity in parallel execution of functions which has a great potential to benefit from multi-core platform architecture.

In order to offer easy access to our component library, two ways to describe a MAC protocol are offered. A meta-language descriptor with very simple C-like language syntax and a grammar consisting of three basic categories of keywords have been designed. With comprehensive analysis and understanding of MAC protocols from various classes of wireless networks, mainly three requirements have been identified in MAC protocol execution: variable declaration, conditional branch and loop. Specifically, six keywords are defined: VAR for variable declaration; IF, ELSE, ENDIF for conditional branching and LABEL, GOTO for describing loops. With the meta-language descriptor, a MAC protocol can be realized in a few lines. In addition to the coding approach, a graphical user interface is provided, where the user can design MAC protocols in terms of a flow chart. The flow chart is then converted to the meta-language. The snapshot of the GUI is shown in Figure 3-9:

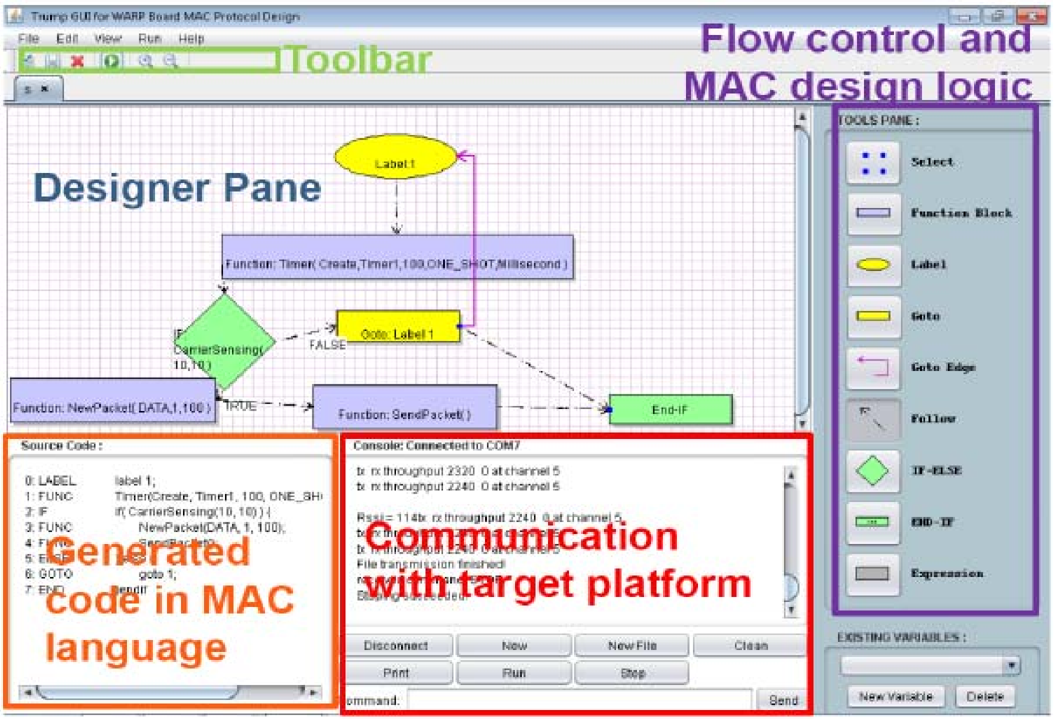

Figure 3-9 A Graphical User Interface for MAC Protocol Designing [3]

To bridge up the MAC description with wiring engine, a compiler is designed for our domain specific MAC language. The compiler is composed of three parts: a scanner to scan the program file to recognize keywords and tokens, a parser to determine the grammatical structure and checks for syntax error and a code generator which generate executable code accordingly for the target platform. There are two basic functionalities of a compiler: convert MAC description to executable code and handling variables. Syntax error will be reported at the time of compilation. This compiler assisted approach prevents potential mistakes in protocol implementation and reduces the protocol development time. It is also integrated to be part of the host machine to further assist the run-time reconfiguration of MAC protocols.

The toolchain has been evaluated in terms of execution time overhead, adaptation response time and MAC performance in terms of throughput with auto-reconfiguration enabled on WARP board. Some selected results are presented. For more comprehensive performance evaluation of the component based re-configurable MAC designing approach and the toolchain, please refer to [1][2][3].

Protocol	*Aloha*	*CSMA*	*SA-MAC*
No. of Nodes in the list	5	11	15
Execution time w/o TRUMP [ms]	1.491	1.503	1.537
Execution time with TRUMP [ms]	1.495	1.518	1.548
Execution time overhead (%)	0.27	1.0	0.72

Table 3-2 Execution time for the implementation based on the decomposed MAC framework on WARP board. All readings are averaged over five samples [1].

Table 3-2 shows the execution overhead of three MAC protocols at different levels of complexity using our toolchain. The overhead caused is in the order of microseconds and within a 1% bound.

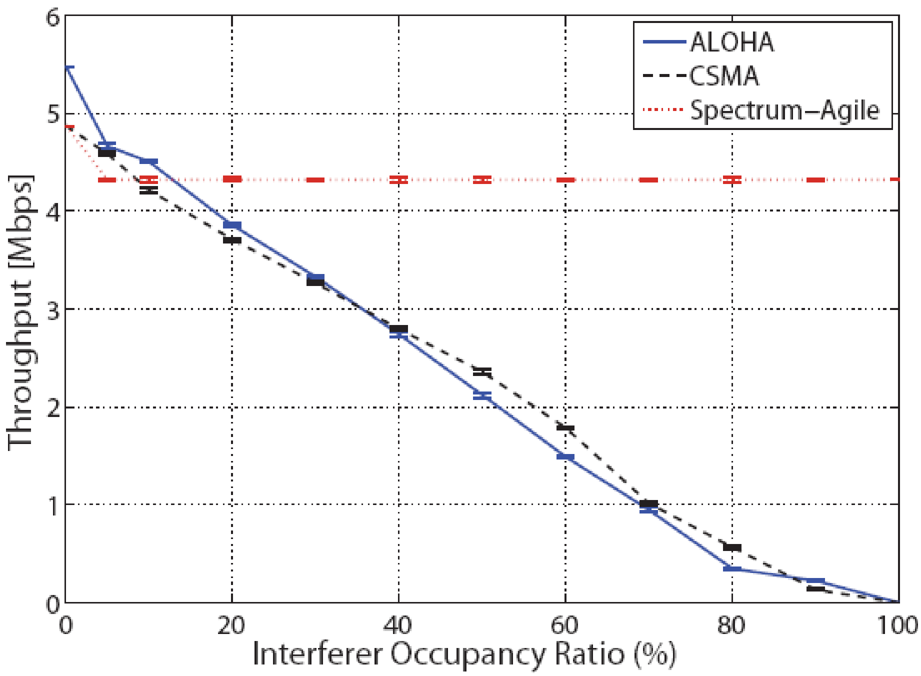

Figure 3-10 Throughput of ALOHA, CSMA and Spectrum Agile MAC protocols running on WARP [1].

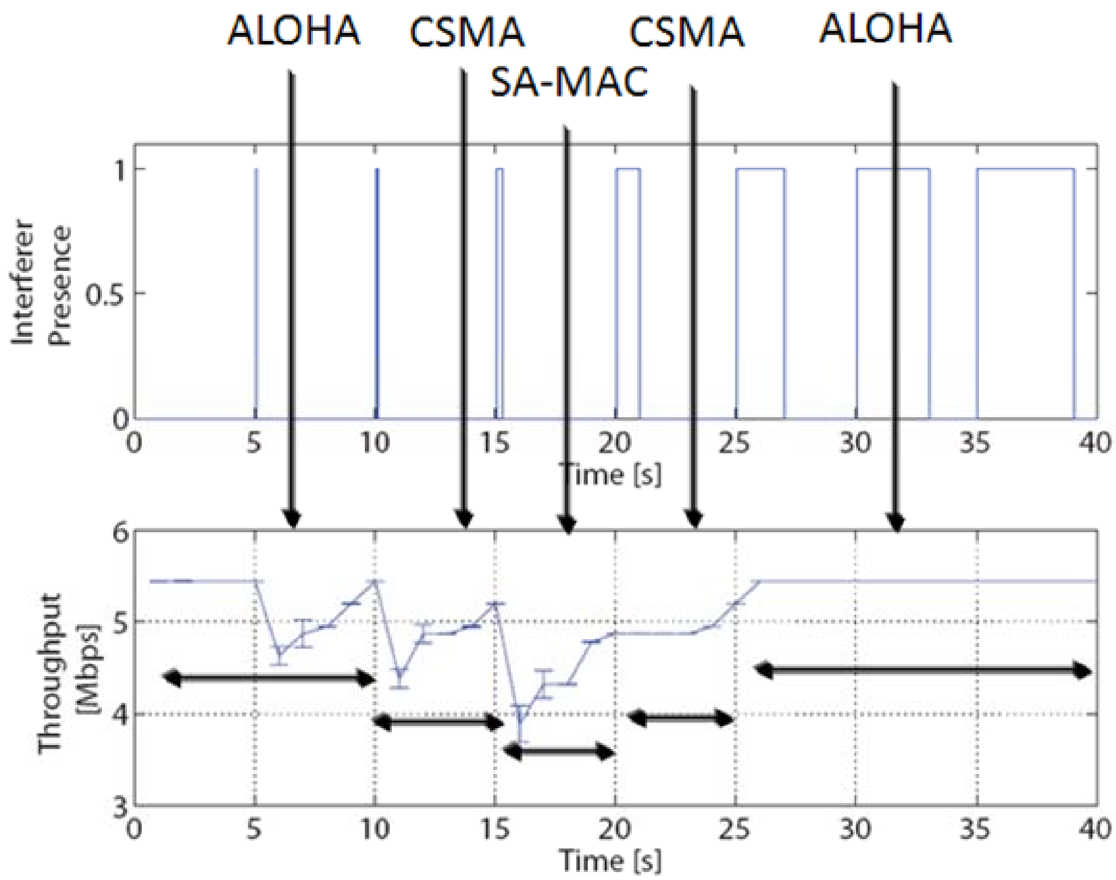

Figure 3-11 The optimized throughput performance with self-adaptive engine [1]

Figure 3-10 shows the throughput performance of ALOHA, CSMA and Spectrum-Agile MAC protocols achieved on WARP board, measured between a single transmitter/receiver pair. The measurement is taken to be fed into the self-adapting decision logic for throughput optimization. Our measurements show that with single channel single transmission flow, when the interference occupancy ratio is below 10%, ALOHA is pretty efficient while when the interferer occupancy ratio is between 10% and 35%, a choice between throughput and packet delivery ratio is to be made. When the performance of either ALOHA or CSMA can suffice, spectrum agility is introduced into the protocol where the protocol starts seeking other free channels. With this as prior knowledge, the experiment is carried out by setting the optimization goal of maximizing throughput. The interferer occupancy radio in a particular channel is varied from 0% to 80% as shown in Figure 3-11. The protocol at compile time is composed with ALOHA-like behavior since assuming the channel is free, it gives the best throughput performance. The throughput was high when the channel is free and experienced an immediate drop when interferer is detected. For the first 15 seconds, the protocol switches between ALOHA and CSMA behavior based on the confidence level of the channel condition. When the interferer occupies the channel for a long enough period of time, the protocol starts to look for the next available channel where an initial downturn of throughput is observed due to the switching overhead. However, since good channel condition is experienced afterwards, protocol switches back to CSMA and then ALOHA behavior for high throughput performance. It can be observed a performance gain up to 400% at the end when the interferer occupancy ratio is up to 80%.

In addition to the publications on the reconfigurable MAC protocols on WARP boards, RWTH has conducted a tutorial of the TRUMP and reconfigurable MAC designing in IEEE DySPAN 2011 in Aachen, Germany. The tutorial material can be found at [5].

3.2.2 A heterogeneous spectrum sensor testbed for indoor measurements[2]

RWTH has designed and deployed a heterogeneous spectrum sensor testbed that allows studying the characterization and modelling of the radio indoor environment by measurements. The testbed is deployed over an area of 240 m^2 and spans over several rooms with both non-load-bearing (paper) and bearing (semi-concrete) walls. The testbed facilitates and enables studying the realistic indoor propagation conditions as perceived by different types of sensor devices at a granular level. The spectrum sensors include WARP boards [6], USRP2 boards [8], and TelosB devices [9]. These devices display a wide range of sensing and processing capabilities and to some extend reflect the characteristics that can be expected from a realistic heterogeneous network deployment.

The spectrum sensing choice clearly falls into three distinct classes with different sensitivity levels and hardware capabilities. WARP board is a high end SDR device providing extremely fast spectral data samples (e.g. 250 µs), USRP2 is a medium grade SDR board, while TelosB represents a low-end device for spectrum sensing. We have carefully profiled and then calibrated all types of spectrum sensors by feeding a referenced signal from Agilent E4438C signal generator directly over a coaxial cable. We have observed that the variances and biases among the same type of devices are quite low. We have also observed that USRP2 devices display non-linear behaviour for low received powers, especially for levels below -80 dBm. Compared to the external monopole antennas for USRP2 and WARP boards, TelosB nodes have slightly higher attenuation due to inverted F type microstrip antenna.

In the current deployment, 60 TelosB nodes, 22 USRP2 boards and 10 WARP boards are used. Figure 3-12 shows the testbed deployment map in the office building consisting of five rooms. Embedded PCs are interfaced to the sensor devices. The embedded PCs are part of the office LAN infrastructure so that the measurements can be controlled centrally through a remote machine without invoking any wireless interference. Furthermore, being part of the backbone, all the machines are synchronized using Network Time synchronization Protocol (NTP) [10]. Figure 3-13 shows a typical deployment setup on an office table. RWTH has developed spectrum sensing applications with flexible controlling APIs for all types of sensors and corresponding software scripts to enable efficient remote testbed control that includes conducting multiple repetitive experiments and gathering of the data in a systematic manner.

[2] This contribution is based on RWTH's published work [11].

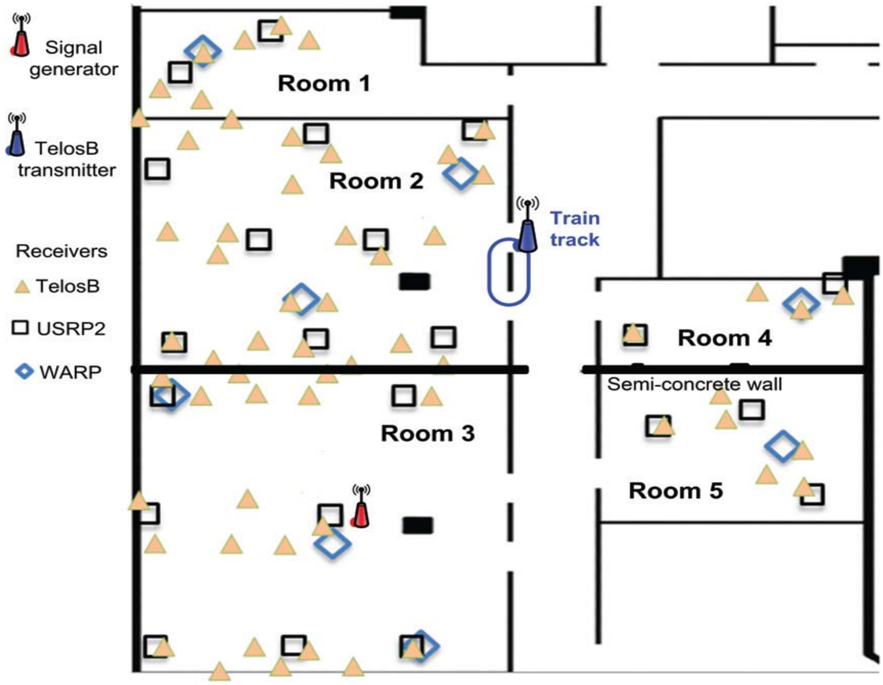

Figure 3-12 The deployment map of different devices in an area of 12m×20m. (The figure is stretched horizontally for better readability) [11].

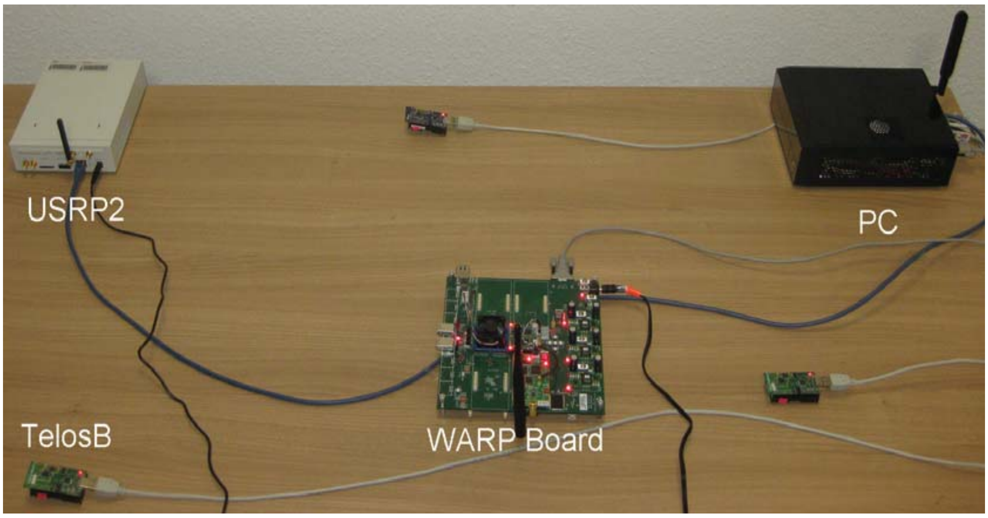

Figure 3-13 Snapshot of a typical setup on an office table with a WARP board, a USRP2 board and three TelosB nodes attached to a PC, which is remotely accessible over the LAN [11].

The testbed fulfils the major requirements enabling the experimental research of indoor radio environment maps. These include: the diversity of the environment (e.g. different structure of the walls, diverse furniture filling of the rooms) and the space covered by the testbed; heterogeneity of spectrum sensors; support for different user activity and mobility patterns; and operation over multiple frequencies, enough to accommodate several independent channels.

The testbed certainly opens the avenue for experimentally studying and understanding various types of indoor propagation measurements at a granular level. Some of the potential experiments include:

- Sensor fidelity, sensitivity, bandwidth, etc.
- Classical power spectral measurements
- Estimating ON-OFF radio activity patterns
- Spatio-temporal correlation measurements
- Cooperative sensing
- Localization studies
- Prediction and modeling
- WLAN network cross-layer optimization studies on host PCs.

The reader may refer to [11], [12] for some of the preliminary studies conducted on the testbed regarding the classical power spectral measurements and ON-OFF radio activity patterns.

3.2.3 Spectrum Aggregation on ExpressMIMO

An experiment is currently under development to highlight technical difficulties in broadband dynamic spectrum access and spectrum aggregation. This reflects the scenarios considered in Sections 3.1.1 and 3.1.3. It is implemented on the newest hardware platforms offered by OpenAirInterface comprising the ExpressMIMO baseband engine which can manage up to four 40-MHz radio channels and the AgileRF RF front-end used for synthesizing and processing 20MHz channels from 150 MHz to 8 GHz. To avoid regulatory issues, ISM bands will be used (433.9 MHz, 2.45 GHz and 5.8 GHz), the lowest of which is used to perform over-the-air coordination between several transmitters. Receivers perform multi-band RF sensing. A key aspect is to show the capacity of the hardware to occupy spectral holes in sparse bands and to perform spectrum aggregation at the physical layer.

3.2.4 Automatic Network Recognition

The two USRP2 platforms recently acquired by Uniroma1 will be used to carry on experiments in the framework of the network awareness activities focusing on automatic network recognition, taking place in the framework of WP10.

The goal of the automatic network recognition activity is to define algorithms capable of identifying and classifying different wireless systems by exploiting knowledge about features of the MAC sub-layer of the different wireless technologies, captured by means of a time-domain packet exchange diagram to be acquired as a result of a simple energy detection scheme.

Early results obtained in the proposed activity highlighted that by means of a careful selection of MAC features for each of the wireless systems of interest a high degree of accuracy in classification of the different systems can be achieved.

The correct interpretation of the packet exchange diagram acquired as a result of energy detection can be hindered by two main factors:

1. The presence of multiple systems operating at the same time on the same frequency range of interest, resulting in a packet exchange diagram composed of partially or totally overlapping packet exchanges by terminals adhering to different wireless standards. In this case the correct interpretation of the diagram and thus identification of the involved wireless systems can be made even harder due to the fact that the different systems may rely on different transmission technologies (e.g. Direct Sequence vs. Frequency Hopping), possibly leading to only partial overlapping in the bandwidth observed by the sensing device.
2. The hidden terminal problem, resulting in the sensing device being capable of listening only part of a packet exchange (e.g., Request To Send sent by a transmitted but not Clear To Send sent in reply by the intended receiver), thus altering the packet exchange diagram with respect to the nominal sequences expected based on the wireless standards.

Experiments based on USRP2 platforms will allow to address the impact of the two factors identified above, and to define potential solutions.

3.2.4.1 Experiment set 1 - Multiple systems

In this set of experiments, the classification process will be tested under a scenario where a single sensing device (USRP2 board) will be operating in presence of multiple wireless systems working in the ISM band at 2.4 GHz, including both systems that are among those to be classified by the classification process (Wi-Fi, Bluetooth, ZigBee) and other systems working at the same frequencies but to be treated as interference, both due to intentional and non-intentional emissions (microwave ovens, analogue wireless Audio/video repeaters, etc.). The set-up is presented in Figure 3-14.

The goal of experiment set 1 is to test the robustness of the classification process to the presence of multiple systems, measured by a correct decision ratio for each of the systems defined in the classifier, as well as misdetection and wrong classification rates.

3.2.4.2 Experiment set 2 - Multiple sensing devices and hidden terminal

The second set of experiments will focus on the impact of incomplete information on packet exchanges due to unfavourable topology, leading to only one side in two ways communications being visible to a sensing device. After a first phase focusing on assessing the performance of a single sensing device under incomplete information, the experiments will take into account the presence of a second sensing device, analysing the improvement made possible by the combination of information collected by each device. A typical set-up foreseen for this experiment set is presented in Figure 3-15.

The goal of the experiment set will be to test the feasibility and to determine the potential advantages in introducing cooperation in the creation of a packet exchange diagram to be used as an input to automatic network recognition.

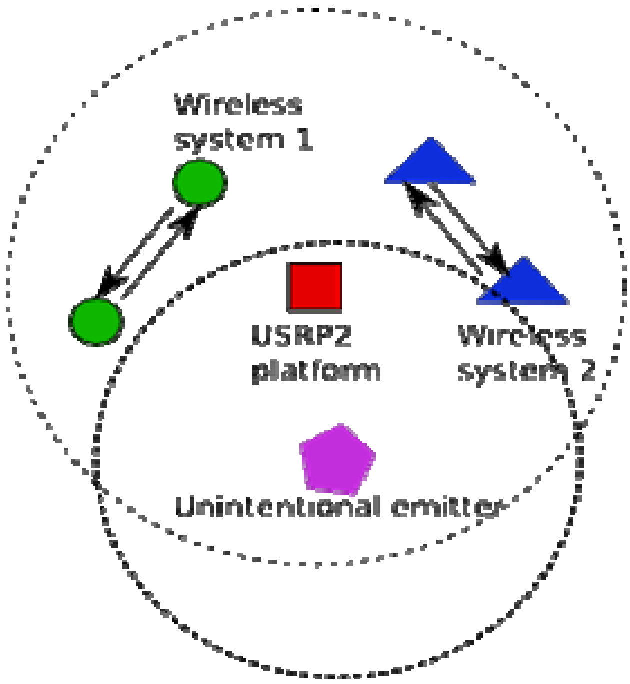

Figure 3-14 USRP experiment set 1: simultaneous presence of multiple wireless systems.

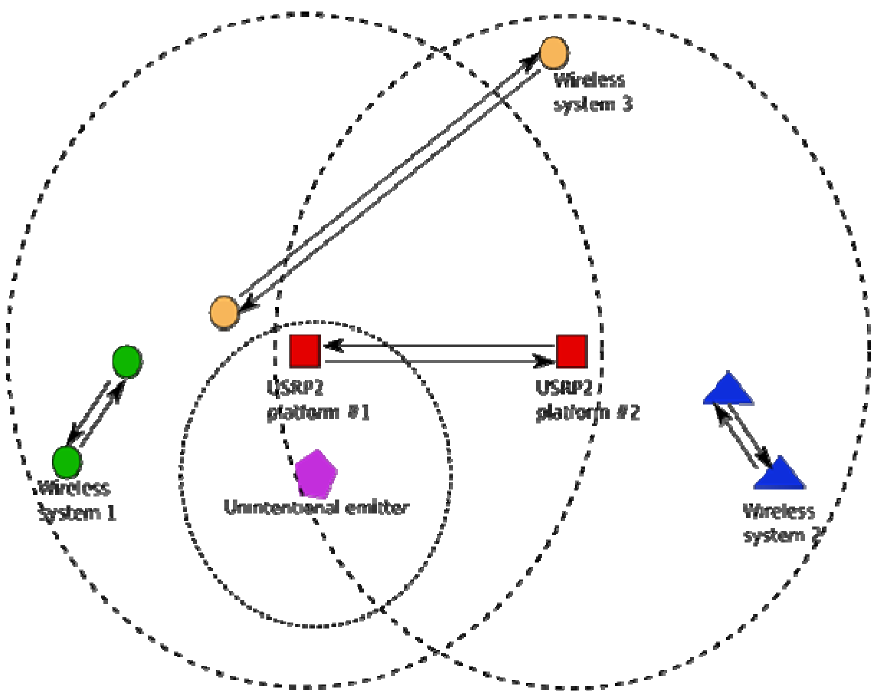

Figure 3-15 USRP experiment set 2: multiple sensing devices and hidden terminal problem.

3.2.5 Spectrum Sensing

Uniroma1 plans to investigate spectrum sensing from the network point of view, focusing on automatic network recognition and classification based on MAC and network layer feature. Automatic network recognition may prove to be an important concept in the framework of cognitive radio and networks. For practical implementations, these operations must be carried out in a simple way by using simple devices and algorithms that require low computational load. Uniroma1 proposes to use MAC sub-layer features for technology recognition purposes where a rudimentary device such as an Energy Detector is used for technology-specific feature extraction. To this purpose, several MAC features reflecting properties, related to the time-varying pattern of MAC packet exchanges, are proposed.

Uniroma1 has already an experimental activity going on for this topic, based on the acquisition of signals in the ISM band by means of experimental data obtained by using the Universal Software Radio Peripheral (USRP) as Energy Detector. The data show that the proposed features are capable of highlighting MAC sub-layer behaviour peculiar to Bluetooth and suggest that these features may therefore lead to successful network recognition.

Uniroma1 proposes to extend the experiments by moving to a distributed acquisition of MAC layer features in order to overcome some of the limitations introduced by using a single point of acquisition (see for example the hidden terminal problem, preventing from acquiring a full MAC exchange, and thus making the recognition of the system more difficult). The OpenAirInterface would thus form the basis for developing a protocol for distributed network recognition and classification.

3.2.6 Radio-Source Localization

A cognitive radio must have the ability of controlling the interference caused to primary users. This implies knowledge of the position of the active radios together with the propagation environment. For this purpose, ranging techniques are used for localizing radio sources (emitters). These techniques provide local information in terms of distance or orientation related to the neighbours of a cognitive radio device. This local information is usually gathered from multiple CRs and combined appropriately to provide location estimates. The most usual types of information used for ranging techniques are the following:

- ***Time of Arrival***: This is the Time of Arrival (ToA) of a known or unknown (Blind ToA estimation) Rx signal. Known signals are usually pilot signals, pre-specified for a specific communication system. Time Difference of Arrival (TDOA) will be treated as a special case of TOA when the sensors are not in sync with the transmitter (as most of the cases in our scenarios).

- ***Angle of Arrival***: This is the Angle of Arrival (AoA) of a known or unknown (Blind AOA estimation) Rx signal. The same assumptions hold as in ToA estimation.

- ***Power (RSS)***: The total power reception of a known or unknown signal. The measurement bandwidth can be narrowband (in order to sense a small number of transmitters) or wideband (for sensing a potentially large number of transmitters). The time horizon of the measurements is also a pertinent parameter.

After estimating the position-related signal parameters, such as RSS, TOA, TDOA and AOA, source position estimation is performed based on various techniques. An extended analysis of these techniques can be found in [14]. In particular, there exist two main categories of techniques:

a) *Geometric* and *statistical techniques* estimate the location of the unknown device directly from the position related parameters estimated from the received signal by using geometric properties and statistical approaches respectively.

b) *Mapping (fingerprinting)* techniques exploit the information from a database [15] that consists of previously estimated position-related parameters corresponding to known locations. The database is usually obtained by a training (*offline*) phase before the positioning procedure starts.

After this very sort overview of the field of radio-source-localization, we will describe two experimental setups that target the two specific areas of IASA's interest.

In the first experiment A below, our target is to evaluate the real performance of TOA based algorithms (either of the classic type or new ones to be developed within ACROPOLIS) and compare it with the theoretical Cramer-Rao performance bounds. Our target is to identify and quantify the effect of all potential imperfections that result from the implementation of any such algorithm on a real platform.

The main target of the second experiment B below is the performance investigation of a proposed statistical technique [16] for the localization of multiple sources. The effect of the real propagation environment is the Achilles' heel of such techniques, necessitating testing on a real environment.

Both experiments can fit multiple scenarios from the proposed list of section 2 as technology enablers. TOA techniques are more suited for long range estimation (outdoors) while RSS for short range (indoor).

3.2.6.1 Experiment A: TOA based localization

In this set of experiments, the ability of resolving the first arriving path on a real propagation environment implemented on a real platform will be under investigation. The focus of this experiment is mainly on the performance evaluation of the RF front end of the receiver platform used for precision location system. The effect on the precision of the location estimate due to RF receiver design imperfections will be assessed and design issues for future platforms design improvements will be devised.

The experimental setup will consist of a generic transmitter of parameterized BW, frequency and pulse shape and a receiver platform that implements the TOA algorithm. Potential platform related parameters that will be studied are listed below:

a) System Gain
b) System Noise Figure
c) System 3rd Order Input Intercept point
d) Receiver Sensitivity
e) Receiver Spurious Free Dynamic Range
f) Time-frequency errors

The performance results will be compared against the Cramer-Rao bound (CRB) analysis carried out in WP9.

3.2.6.2 Experiment B: RSS based multiple source localization

The performance of a proposed technique for multiple sources localization, proposed in [16], [17], will be under investigation. Due to the need of a large number of sensors, OpenAirInterface emulation platform will be used for a complete experimental setup. Specific, proof of concept small-scale experiments will also be contacted that require a small amount of sensors (platforms). Possible collaboration with other experiments within this WP will be also pursuit. Power-based spectrum sensing and shadowing correlation experiments are in direct connection with the technique under investigation.

3.2.7 Routing Protocols

Uniroma1 plans to carry on experiments focusing on the efficiency of a routing function capable of taking into account channel availability in the selection of the best route. Simulation work carried out by Uniroma1 until now focused on the specific case of underlay cognitive networks, where the cognitive devices were characterized by a large bandwidth encompassing several narrowband primary systems, posing the issue of optimizing the selection of a multihop path in the presence of multiple primary emitters and receivers in different position. The goal of Uniroma1 is to test a similar approach experimentally, taking advantage of the capabilities offered by the OpenAirInterface platform.

4. Training and Teaching Activities on Available Platforms

The activities related to training as this is a fundamental part of WP5 and linked to education and training activities in WP3.

4.1 OpenAirInterface Training activities

During the first Acropolis school [39] organized jointly with the COST Action IC0903 by Uniroma1, EURECOM presented the OpenAirInterface platform [18], an open-source hardware/software development platform, created by the Mobile Communications Department at EURECOM, France. Laboratory demonstrations and exposure to experimental design tools were provided in addition to introductory and advanced tutorials presented by Prof. Raymond Knopp, Prof. Navid Nikaein, and Prof. Florian Kaltenberger.

4.1.1 HW + DSP Training

In this part of the training HW and DSP components of OpenAirInterface were briefly explained. Specifically, CardBus MIMO I (CBMIMO1) cards, which are dual-RF (dual-frequency or dual-antenna) systems with both data acquisition and DSP functionality in a very small form-factor (PCMCIA/CardBus), were utilized during the Physical Layer labs sessions. A complete OpenAirInterface modem (5 MHz TDD two-way 2x2 MIMO-OFDM) currently runs on this card where the PC hosts the PHY and MAC-layers in RTAI. Currently, we are running the LEON3/AMBA embedded system from Gaisler Research which is fully open-source and made available with OpenAirInterface so that partners can at least develop code for the embedded system without having to use "closed-source" tools. In Figure 4-1, a CBMIMO1 card along with a PCMCIA Wifi card is shown.

The attendees, PhD students, Post-docs and Professors, had the chance to see the required phases to load modules in order to be able to run the modem. After the introduction of the components of the CBMIMO1 card, a brief tutorial on LTE physical layer specifications and the underlying technologies were also described as the modems are compliant with LTE Release 8. Then, a case-study along with all participants was performed wherein primary and secondary synchronization implementations, as in LTE specifications, were tasks to fulfil. The aim of the case study was to make the attendees familiar with the application development environment and also to attract their interest in participating in development of OpenAirInterface platform.

4.1.2 Networking/Emulations Training

As the next generation wireless systems, protocols, and applications applicable to evolving cellular and Adhoc/mesh networks are becoming complex, their performance evaluation and validation are difficult and in some cases unreliable. This makes the experimental approach necessary in order to validate and compare such systems and protocols. There exist three main approaches in the literature: simulation, emulation, and real testbed. In this training, we present the OpenAirInterface emulation platform and its methodology as well as some real world use cases. The platform allows large-scale networking experimentation in a realistic and controlled environment with a dual objective of performance evaluation for both protocols and applications.

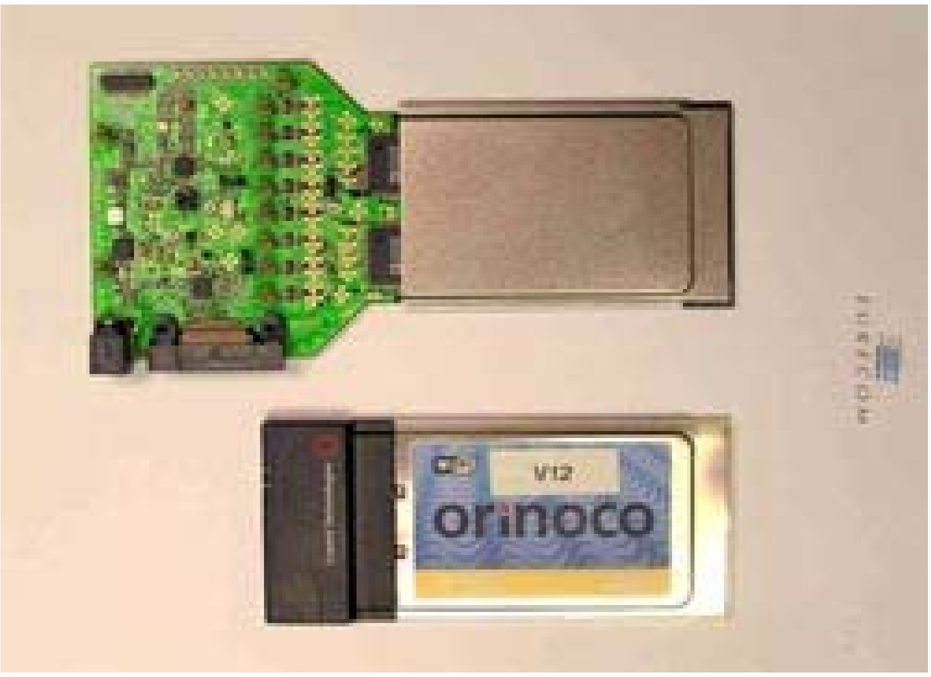

Figure 4-1 A Cardbus MIMO I card with a PCMCIA Wifi card

4.1.3 Radio Network Modelling Training

This training is divided into four parts. The first part covers some basics of radio channel characterization such as wave propagation and statistical channel description. In the second part existing channel models and their implementation are reviewed. Here we also point out the capabilities of the OpenAirInterface platform [18]. In the third part, we presented physical layer abstraction techniques. These methods are useful for large system level simulations, since they provide an accurate model of the physical layer and the channel while keeping the simulation time low. Last but not least we showed how the OpenAirInterface platform can be used to collect channel measurement. Finally we showed some results from a measurement campaign.

4.2 WARP Training Activities

RWTH conducted a hands-on-tutorial on WARP boards together with Rice University, USA at the IEEE DySPAN 2011 [31] conference held in Aachen, Germany. The full day tutorial session was split into two parts. The first part focused on the MIMO OFDM reference design framework [36] conducted by the Rice University while the second part, conducted by RWTH, focused on the flexible MAC design and prototyping for cognitive radio networks. The majority of the participants were researchers from academia.

Spectrum agile and cognitive MAC protocol implementations require flexible control over the PHY/MAC parameters. Without losing the desired level of flexibility and adaptability, real-time constraints in execution of PHY/MAC functionalities are required as well [35]. The Decomposable MAC Framework allows realization of MAC solutions based on a rich set of MAC components using TRUMP [32],[34]. The Decomposable MAC Framework, leveraging from the OFDM Reference Design implementation on WARP boards, advocates software/hardware co-design. This way a component oriented design with interfaces for exposing parameters at a granular level allows a high flexibility while the realization of PHY/MAC components on FPGA satisfies strict timeliness requirements.

Though many MAC solutions have been proposed in the context of CR networks, only a few proposals have been prototyped [37]. This is owing to high development efforts and unavailability of the required functionalities on a platform. One of the main objectives of the WARP tutorial was to highlight the features of WARP as an enabling platform and TRUMP as part of the Decomposable MAC Framework for fast prototyping of MAC solutions.

As part of TRUMP, a MAC meta-language is developed (c.f. Section 2.2.2), which describes an entire MAC protocol in a few lines of codes. The support for a corresponding meta-compiler running on a host WARP board allows realization of a MAC solution autonomously. A GUI based IDE is developed which enables a user to design MAC protocols in the form of flowcharts -- without requiring the knowledge of platform specifics and programming languages. This certainly enhances the user experience, enables fast prototyping and widens the room for experimentation.

During the hands-on-tutorial, the participants designed a spectrum agile MAC protocol. The MAC protocol was able to detect an ongoing activity in the medium and was able to select a free channel. The transmitter and receiver were able to synch on a common communication channel without requiring explicit control information. The hands-on-tutorial was well received by the participants and they shared a common experience of being able to prototype solutions in a fast and easy way. We also showcased an example of enabling run-time reconfiguration by composing MAC appropriate solutions at run using TRUMP [32],[33] at the end of the tutorial. The material for the tutorial is publicly available at [38].

4.3 USRP teaching at RWTH

RWTH Aachen University has included the introduction to USRP into the Bachelor level laboratory on communications engineering. The laboratory is distributed among different departments of the faculty, two of which provide hands-on sessions on building communication systems with a flexible platform.

In a first session, students will build an OFDM transceiver system and conduct a link-level performance analysis of the different performance metrics (BER, SNR losses). Artificial noise, phase and frequency offsets are introduced into the system and their effect on achievable throughput and error rates are experimentally derived.

A second session shifts the focus to the system-level design of communication systems. Students first evaluate a custom-built implementation of a simple FM radio receiver by means of source code analysis and real-world test setups. The students are required to optimize system parameters such as filter configuration and gains to optimize for the best audio quality. The expected learning effect is a better understanding of the relation between the different system components and their effect on the subjective system performance. The second session furthermore comprises the design of a simple packet-based system to transmit an uncompressed wave-audio file between a set of USRP devices. As starting points, students are handed the block-level prototype description of the transmitter from which they need to design a suitable receiver side. The implementation is done in GNU Radio Companion, a graphical front-end to the GNU Radio open-source suite.

5. Review of joint activities between partners

In this section, inputs from the partners on their requirements and wishes with respect to training and joint research activities are gathered and possible collaborations between the partners are initialized.

5.1 EURECOM & RWTH joint activities

There is a joint interest for both EURECOM and RWTH in doing experimentations and measurement campaigns for cellular type of medium-range communication networks (where height of the TX and RX are pretty different as opposed to Ad-hoc scenarios) for shadowing correlation.

Cooperation on architectures for reconfigurable processors (Application-Specific Instruction-set Processor (ASIP) architectures for front-end signal-processing) is underway in the context of WP7. Results from this work in terms of integration in the OpenAirInterface hardware architecture fall under the category of platform expansion as described in the DoW. Concretely, the reconfigurable ASIP designs for the front-end processing component of a reconfigurable radio stemming from the WP7 study are in the process of being integrated in the main stream development of OpenAirInterface.

Furthermore, a joint winter school in February 2012 on OpenAirInterface and WARP is currently being organized and will be held in Sophia-Antipolis at EURECOM's premises.

5.2 EURECOM & Uniroma1 joint activities

Initiation of joint research topics related to network emulation and performance evaluation in conjunction with WP10, and more precisely on network recognition in the ISM band is underway. To kick-start this activity a two-week visit at EURECOM for Uniroma1 PhD students at EURECOM is planned for December.

5.3 EURECOM & IASA joint activities

Discussions with IASA on abstraction methodologies for interference networks as a follow-up of a common activity in the Newcom++ NoE and on radio source localization are initialized wherein OpenAirInterface emulation platform will be used for a complete experimental setup. In addition, the experimental setup by EURECOM in Section 3.1.1 on Spectrum Aggregation is being considered for extension of the studies on ToA-based localization in Section 3.2.6.1. Here, the goal would be to demonstrate the feasibility of increasing ToA estimation through the use of multiple (synchronized) bands spread across a wide bandwidth.

5.4 EURECOM & UPRC joint activities

Initial discussions on research collaboration between EURECOM and UPRC have been started. UPRC has stated its interest in femto-cell and RRM experimentation scenarios, to be performed on OpenAirInterface platform.

6. Conclusion

In this deliverable, a number of CR/SDR scenarios have been described for future joint research and demonstration activities regarding the needs of the current wireless communications systems and the current trends of research in this area, and also the capabilities of the available platforms at hands within the work package. Based on the research interests of each involved partner, a number of associated experiments have been identified in order to demonstrate and explore key technology enablers through the use of multiple platforms, mainly OpenAirInterface platform, available to the members of ACROPOLIS consortium. Moreover, the details of the two platform training activities conducted so far, one on the OpenAirInterface by EURECOM and the other on the WARP by RWTH, have been provided. Stimulated by the training activities, the initialization and coordination for possible future joint research activities among the members participating to this work package have been established.

Glossary and Definitions

Acronym	Meaning
3GPP	Third Generation Partnership Program
ACCS	Autonomous Component Carrier Selection
AoA	Angle of Arrival
BS	Base Station
CR	Cognitive Radio
DD	Digital Dividend
DRX	Discontinuous Reception
DSL	Digital Subscriber Line
DTX	Discontinuous Transmission
eNodeB or eNB	Evolved Node B
E-UTRA	Evolved-UMTS Terrestrial Radio Access
FC	Fusion Centre
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FPGA	Field-programmable Gate Array
LNA	Low Noise Amplifier
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium Access Control
MIMO	Multiple input multiple output
OFDM	Orthogonal frequency-division multiplexing
PCB	Printed circuit board
PU	Primary User
QoS	Quality of Service
RAT	Radio Access Technology
RB	Resource Block
RTAI	RealTime Application Interface
SDR	Software-defined Radio
SN	Sensor Network
SU	Secondary User
TG	Task Group
ToA	Time of Arrival
TRUMP	Tool-chain for Run-time Protocol
TVWS	TV white space
UE	User Equipment

UHF/VHF	Ultra High Frequency/Very High Frequency
WRAN	Wireless Regional Area Network
WSN	Wireless Sensor Network

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