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European NoE on Cognitive Communications

SEVENTH FRAMEWORK PROGRAMME

Advanced coexistence technologies for radio optimisation in licensed and unlicensed spectrum

(ACROPOLIS)

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Report on Global Trends and Major Developments Roadmap

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Abstract:

The purpose of this Deliverable is two-fold. First, it aims at gathering, sorting, summarising and presenting in a uniform way the major global developments of Cognitive Radio Systems in the main domains of interest, i.e., commercial, civil security and military, research, standardisation and regulation. Then, the adherence of the different activities within the ACROPOLIS Network of Excellence to the identified global trends and developments is assessed, with the aim to enhance the collaboration among the partners, streamline all the joint research activities to the degree possible, enhance its relevance to the broader happenings and maintain a high level of impact within the ecosystem.

Keywords: Cognitive Radio Systems, Harmonization, Regulation, Standardisation

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Executive Summary

Deliverable D4.1 is the first Deliverable of ACROPOLIS Work Package (WP) 4. Its aim is to document observations regarding technology harmonization within Europe as well as globally. A roadmap explaining the current state of Cognitive Radio (CR) standardisation and regulation efforts, as well as the expected near and medium term developments is also presented. The project's adherence to the identified global trends and developments is assessed, with the aim to enhance its relevance to the broader happenings and to maintain a high level of impact within the ecosystem.

The Deliverable is organised as follows:

Section 2 provides an overview of the global trends for Cognitive Radio Systems (CRSs). It first describes the market trends and the respective business opportunities that are derived by the exploitation of CRSs in the commercial domain, as well as the application of the CR concepts and technologies in the civil security and military domains. Then, it presents a review of deployment scenarios for CR networks, based on both the ACROPOLIS activities and international research and standardisation activities. Its main purpose is to provide a complete view of the directions taken in the deployment of CRSs. The broad global scenarios identified are: (i) Multi-Nets (multi-Radio Access Technology or/and multi-tier or/and multi-operator), (ii) Hierarchical Spectrum Access on Licenced Bands, and (iii) Spectrum Sharing on Unlicensed Bands. Special attention is paid on the description of the standardisation and regulation activities in the area of CRSs, with the description of a CRS development and outlook medium term roadmap.

Section 3 reviews the status of the current and recent research activities in the area of CR networking in the different parts of the world. First, an overview of the research activities in Europe is provided. The main achievements of the major European (EU) projects in the CR area and the IC0902 COST and IC0905 Actions are presented, emphasizing on the research activities that are related to the ACROPOLIS research interests. Then, a brief overview of the research in national projects in Europe, as well as in the rest of the world, e.g., United States of America (USA), Asia, and Australia, is provided.

The objective of Section 4 is to assess how well ACROPOLIS adheres to the CR networking global trends and major developments that were identified in the previous sections, and to propose a *harmonization procedure* which will ensure such a maximization of relevance and impact. To this end, it describes the harmonization framework that aims at maximizing the adherence of the project to the global trends, maximizing the impact to the outside world, enhancing the collaboration among the partners, and streamlining all the joint research activities to the degree possible. The joint research topics proposed in the ACROPOLIS technical WPs are also summarized and mapped into the aforementioned framework. Then, the different Joint Research Activities (JRA) reported previously are presented in a comprehensive and conceptually unified way. Finally, the future steps of the ACROPOLIS project are described.

Section 5 concludes this Deliverable.

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1. Introduction

The present Deliverable, as per its title and scope, reports on the observed and reported global trends, the major developments (business, technical, etc.), as well as the main perceived technical challenges that may affect the specification, development, deployment and exploitation of systems meant to ease the introduction of advanced radio-coexistence technologies into the marketplace for the benefit of the consumer, the manufacturer, the provider, and the society at large. Such technologies are viewed as a major contributor to promoting flexible and rational use of spectrum, namely the further widespread dissemination of wireless broadband services in society. The impact of “broadband” on societal productivity, mobility, opportunity and growth is by now undisputed, therefore any technology facilitating its spreading is viewed as critical. Given the even-increasing scarcity of spectrum, it follows that its balanced, flexible and adaptive use is of paramount importance -- hence this ACROPOLIS Network of Excellence (NoE). As will be documented below, the surrounding techno-economic and regulatory environment is complex and rapidly evolving. It thus behoves the researchers of ACROPOLIS (and not only) to understand this environment and harmonize their research contributions within it for maximum benefit and impact.

As per the Technical Annex, the purpose of this Deliverable is two-fold: First, it aims to gather, sort, summarize and present in a unified manner the major global developments of CRSs in the key domains of interest, namely commercial and military scenarios and applications, associated research efforts, standardisation processes and regulation frameworks. Subsequently, it attempts to devise and enforce novel procedures and means, by which the different activities within the NoE adhere to these identified global trends, in order to maximize the impact to the outside world, enhance the collaboration among the partners and streamline all the joint research activities to the degree possible. To do so, the project devised a procedural flow, depicted in Figure 1-1 below, a flow which has also been mapped directly to the contents of the Deliverable. The flow follows the natural “water-path” from the outside to the inside, from the global to the local, from the broad to the specific: it first reviews the scenery on broad directions, existing and forthcoming systems and envisioned scenarios where such technology will most likely be applied (in close relationship to the restrictions posed by standards and regulation); it then reviews and summarizes how the broad world plans the research around the topic, with special emphasis on European Information and Communications Technology (ICT) projects but not only; and finally takes a close inside look into ACROPOLIS, its research collaborations and themes, their individual rationale, their hoped value proposition on the research scene, how they stack up against the state of the art, and what they hope to achieve going forward. All such joint research activities are assessed against the backdrop of the aforementioned global trends (the “adherence” arrow) as well as against other research efforts (the “similarities/deviations” arrow). Because of the complexity and dimensionality of the subject matter, multiple views and profiles are under-taken and analysed, each highlighting a different side of this “CR prism”. Finally, in the last section on “future steps”, the Deliverable proposes specific ideas for properly harmonizing all efforts and bringing about maximum effect in the remaining life of the project.

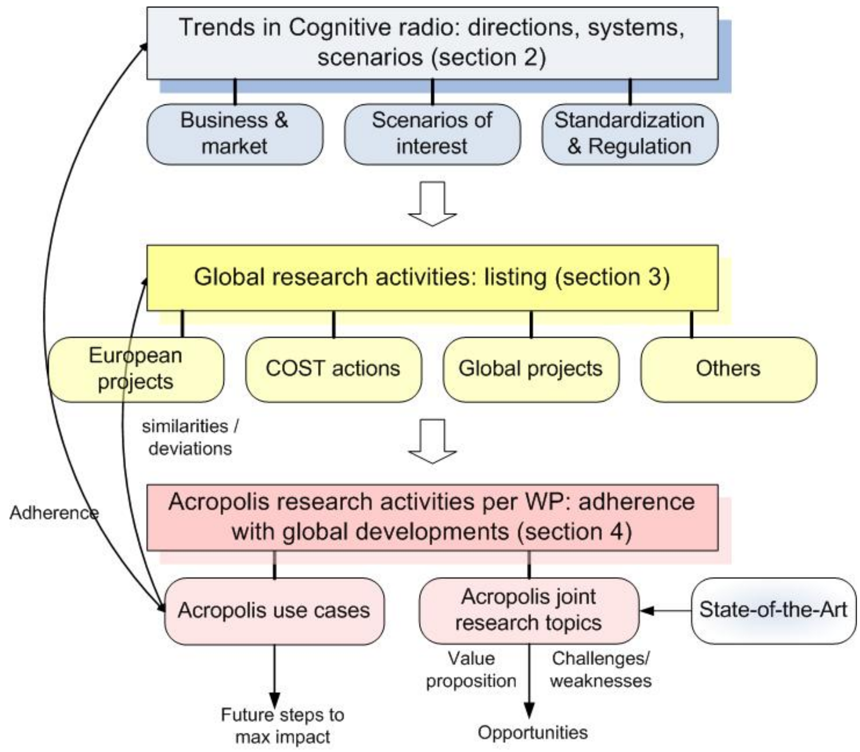

Figure 1-1: Procedural flow and associated structure of the Deliverable

To be more specific on the individual Sections:

Section 2 provides an overview of the global trends for CRSs. It first describes the market trends and the respective business opportunities of CRSs in the commercial domain, and the different applications of the CR concepts and technologies in the civil security and military domains. A review of deployment scenarios for CR networks, based on both the ACROPOLIS activities and international research and standardisation activities is also provided. The regulation and standardisation approaches in the area of CRSs are also summarised, while a medium term roadmap of the CRS developments and outlook is presented.

Section 3 reviews the current status of the research activities in the area of CR networking in the different parts of the world. First, an overview of the research activities in Europe is provided. The main achievements of the major European projects in the CR area and the IC0902 COST and IC0905 Actions are presented, emphasizing mainly on the research activities that are related to the ACROPOLIS research. Then, a brief overview of the research in national projects in Europe, as well as in the rest of the world is provided.

The objective of the overall-coordinating Section 4 is to assess the ACROPOLIS adherence to the global trends and major developments in the area of CR networking that were identified in the previous sections, and to propose a harmonization procedure, in order to guarantee the maximization of relevance and impact. To this end, it describes the harmonization framework that aims at maximizing the adherence of the project to the global trends, maximizing the impact to the outside world, enhancing the collaboration among the partners, and streamlining all the joint research activities to the degree possible. The joint research topics proposed in the ACROPOLIS technical WPs are also summarized and mapped into the aforementioned framework. Then, the different joint research activities reported previously are presented in a comprehensive and conceptually unified way. Finally, some future proposed steps for the harmonization process of the project are provided.

Section 5 concludes this Deliverable.

2. Global Trends for Cognitive Radio Systems

This section provides an overview of the global trends for CRS. The scope is to identify the broad directions, forthcoming systems, applications and envisioned scenarios where such technology will most likely be applied. A short summary on standardisation and regulation activities is also presented, along with a medium term roadmap of the CRS developments.

2.1 Market applications and trends

2.1.1 Commercial domain

The exploitation of CR systems creates new market trends and business opportunities. A complete analysis of these opportunities can be found in ACROPOLIS Deliverable D6.1 "Report on Business Model and Market Report". In this section four market trends and foreseen applications are identified and discussed.

The first trend refers to the *"secondary spectrum market"*. This is related to dynamic trade of spectrum rights among holders of the spectrum, targeting at encouraging the latter to actually use this spectrum. Spectrum leasing is the most expected business opportunity that comes out of this trend while basic customers of this market are expected to be organizations and/or enterprises whose products are directly depended on spectrum (i.e., cellular providers, equipment vendors, etc.). However, in such a case, attention should be paid when identifying the way that the cost of this service will be calculated so as spectrum holders to be encouraged to share the spectrum they hold under fair conditions.

Another market trend that arises from the appearance of CR systems refers to the *applications* that will be offered. Such applications may be machine-to-machine communications and self-organizing networks (such as vehicular networking and wireless sensor networks). TV White Spaces (TVWS) or other idle bands will potentially be able to back up either home or business use of spectrum, especially in busy periods, offering them a higher Quality of Service (QoS) and/or by augmenting the users that can be served at this period. TVWSs are also suitable for the provision of wireless broadband (IEEE 802.22 Wireless Regional Area Networks – WRANs [1]) since they are capable of providing Internet connectivity up to 100 km without limitations imposed by buildings, obstacles or environmental conditions. However, CR systems inefficiency to convince regulators regarding their sensing capability in TVWS has made the latter to support a geolocation/database approach for real time spectrum coordination.

A third market trend is the *femtocell* deployment. Femtocells are small base stations, which are especially designed for residential and small-enterprise environments for addressing the interference and the spectrum scarcity by exploiting the existing infrastructure. In particular, they may be used in order to guarantee the provision of the required QoS in terms of extending the network capacity even when the basic infrastructure is overloaded or congested.

The last but not least market trend that is presented hereafter, concerns *Opportunistic Networks* (ONs). ONs are networks that are dynamically created as an extension of the existing infrastructure in cases such as:

- opportunistic coverage extension, to serve devices that are out of coverage of the infrastructure or are not capable of operating at the provided Radio Access Technology (RAT);
- opportunistic capacity extension, where ONs are exploited to offload service areas with high traffic;
- infrastructure supported opportunistic *ad hoc* networking exploiting the closeness of location of application end-points so as to reduce application traffic;
- opportunistic traffic aggregation in the radio access network where only a sub-set of ON terminals exchange data with the infrastructure; and
- opportunistic resource aggregation in the backhaul network, where backhaul bandwidth is aggregated to match the bandwidth of wireless access technologies towards the user.

In this way, operators are able of providing applications and services in the above challenging situations while users are benefitted by gaining access in services in which alternatively they would have been blocked. Moreover, this temporary extension of the infrastructure can be formed when and where needed without demanding large investments, i.e., keeping the total cost low for the operator.

2.1.2 Civil security and military domains

CR concepts and technologies have been explored in both the civil security and military domains, in the USA and Europe.

The main drivers for the application of CR in the civil security domain are the following:

- Traffic patterns in civil security could be quite different from the commercial domain. Routine operations (e.g., patrolling) have predictable traffic usage patterns, but an emergency crisis or natural disaster can create unexpected needs of traffic and capacity in the specific areas affected by the crisis. A spectrum management approach, which is flexible both in time and space can be more efficient than the traditional “command and control” approach.
- At least in Europe, it is increasingly difficult to identify new harmonized bands for civil security. Below 1 GHz, there is a fierce competition among different stakeholders: civil security, military, digital broadcasters and cellular telecom operators. A flexible spectrum management or multi-band radio equipment devices could mitigate this challenge.

The use of “spectrum sharing” for public safety has been proposed by J. M. Peha in [2] and by the European Telecommunications Standards Institute (ETSI) in [3].

The following options for spectrum sharing can be defined:

- **Sharing between military users and public safety users.** In this case, spectrum bands usually allocated to military organizations, but rarely used (e.g., training bands) or used only in specific areas, are usually allocated to public safety organizations for non-mission critical applications. Military is the primary user and public safety is the secondary user. Within a notification time, military organizations can re-obtain the bands if they need them.

- **Spectrum sharing between public safety users and commercial users.** In this case, spectrum bands allocated for emergency crisis/disaster management are owned or managed by public safety organizations. The spectrum bands can be used by commercial users in "normal" conditions (e.g., crisis) or in the area not affected by a crisis. In case of a natural disaster, public safety organizations will re-obtain the bands (e.g., pre-emptive assignment) to support the exceptional needs for traffic capacity and broadband connectivity in the disaster area. A similar approach can also be used when the commercial infrastructure is degraded and destroyed in the disaster area because of the crisis itself. In this case, the spectrum would be idle and it can be used by public safety organizations.
- **Secondary access by public safety organizations.** In this case, applications with low priority and no availability requirements can be secondary users of commercial primary users for broadcasting or communications. For example, an environmental sensor could collect data and transmit to the public safety Head Quarters (HQ) by using the fallow bands in Digital broadcasters, i.e., Digital Television (DTV) white spaces.

In all of these cases, mission critical applications will still be based on spectrum bands allocated in the conventional way (i.e., fixed static spectrum allocation), while spectrum sharing and secondary access could be used for non-mission critical applications.

The application of CR to civil security has also been investigated by the Wireless Innovation Forum for two special use cases: the London Bombing [4] and the incident in a chemical plant [5]. Both use cases have shown that CR can produce a significant benefit, both in the time needed to resolve the crisis and the decrease of the damage to assets and people.

An investigation of CR for civil security is also provided in [6].

In the military domain, CR has been investigated in many projects including the neXt Generation program or XG [7], which is a technology development project sponsored by the Strategic Technology Office of the Defense Advanced Research Projects Agency (DARPA), with the goals to "develop both the enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms in order to provide dramatic improvements in assured military communications in support of a full range of worldwide deployments".

CR will offer various capabilities in the military domain:

- the ability for radios to sample the surrounding environment, determine where interference and electronic warfare jamming are blocking certain frequencies, automatically choose the best frequencies on which to communicate and set up an ad-hoc network on the fly to make best use of those clear frequencies. In this sense, CR can be seen as an evolution of electronic warfare.
- Improve spectrum utilization in tactical scenario. At the moment, military forces deploy the radio systems with rigorous spectrum management. The concept of CR says if I have a congested spectrum, I can sense the spectrum, use areas of the spectrum in real time, and find a channel not being used. Today's tactics and logistics of the Army don't allow that.

The application of CR will also introduce new challenges. If spectrum can be "shared", the usage of this resource should also be conformant to existing hierarchies or operational contexts. The challenge is not simply to find unused frequencies, but to also determine how to rank the allocation of spectrum in order of importance from the highest-priority radio (e.g., a general or front line combat) to the low-priority radio (e.g., soldier or troops, which are not engaged).

Most of the projects and the activities in the military field do not disclose their research results. As a consequence a detailed analysis of the projects in this area is quite difficult. In Europe, the European Defense Agency (EDA) has financed a project called CORASMA (COgnitive RAdio for dynamic Spectrum Management) [8]. The purpose of this project is to develop a simulation platform for demonstrating the application of CR for military use.

2.2 Deployment Scenarios

This Section presents a review of deployment scenarios for CR networks, derived from both internal ACROPOLIS inputs (e.g., scenarios identified within ACROPOLIS activities and reported in other deliverables, such as Deliverables D9.1 [9], D10.1 [10] and D12.1 [11]) and external sources. Sources that were considered for the identification of relevant deployment scenarios include:

- activities within COST Action IC0902 and in particular IC0905 [12], where Working Group 1, led by ACROPOLIS partners Uniroma1 and KCL, focuses on use cases and scenarios;
- standardisation efforts within the Institute of Electrical and Electronics Engineers (IEEE) and ETSI.

The goal of this Section is not only to review and list the different scenarios, but also to organize them in order to provide a better view of the directions taken in the deployment of CR systems. The identification and classification of potential (and in some cases actual) deployment scenarios is in fact a key step in the analysis of trends for CR systems. Following the approach proposed in [11], a classification can be carried out based on the degree of coordination and integration between the networks involved in the definition of the scenario, leading to the definition of three broad global scenarios of interest in the analysis of CR solutions:

- **Multi-Nets** (multi-RAT or/and multi-tier or/and multi-operator), including sub-scenarios dealing with the integration of cognitive functionalities in existing traditional networks, with specific attention to cellular networks;
- **Hierarchical Spectrum Access on Licensed Bands**, focusing on sub-scenarios dealing with coordinated/coexisting cognitive networks with different priorities;
- **Spectrum Sharing on Unlicensed Bands**, including sub-scenarios on ad-hoc and opportunistic cognitive networks, and specifically without spectrum access priorities.

2.2.1 Multi-Nets (multi-RAT or/and multi-tier or/and multi-operator)

This category encompasses scenarios where cognitive functionalities are directly integrated within a primary network, either by actually introducing cognitive aspects in the operation and management of an existing network, or by extending and complementing such a network with a cognitive network fully integrated with the existing one, typically in a hierarchical way. Several such scenarios are being investigated within ACROPOLIS and beyond:

- *Integration of cognitive functionalities in cellular networks* - the introduction of cognitive solutions in cellular networks is being widely investigated: see for example in [11], section 4.1.1.2, where the problem of policy derivation and enforcing in a cellular network is proposed;
- *Deployment of femtocells for coverage and bandwidth extension in cellular networks*, with femtocells under control of the cellular network operator – such scenario is presently very popular as it promises network operators the capability of increasing both coverage and bandwidth, thanks to the deployment of a set of low power, low cost base stations [13]. The large number of such base stations and the impossibility to fully control their physical position and the corresponding network topology poses however several new challenges ([11], section 4.1.1.3):
    - Resource allocation and interference management due to simultaneous and potentially overlapping operation of different femtocells;
    - QoS support, taking into account the fact that the connection between the femtocell controller and the operator's core network may use a landline owned by a different operator, without any specific support for QoS for the femtocell-core network link and for the additional traffic it may generate for the landline operator;
    - Timing and synchronization, again considering the latency introduced by the landline connection between femtocell and operator.

Similar sub-scenarios are now getting a significant attention in both industrial and academic research, see for example the BeFEMTO EU project described in Section 3.1.1.17, as well as the QosMOS EU project (Section 3.1.1.7).

2.2.2 Hierarchical Spectrum Access on Licensed Bands

This scenario includes sub-scenarios where a network (or multiple networks) with lower priority, referred to as secondary systems, operate under the constraint of not creating harmful interference to a system with higher priority (primary system), typically using the spectrum based on a licensed scheme.

Scenarios in this category are the most common ones among those investigated in the CR research community at large, also in light of the recent regulatory advances in the USA [14] and, more recently, in the United Kingdom (UK) [15], related to the opportunistic use of TV White Spaces.

Within ACROPOLIS, similar scenarios are considered in several WPs, targeting different research challenges related to the deployment of systems operating under the primary vs. secondary paradigm. In WP9, the problem is addressed in relation to the requirements imposed on sensing, and on the alternative solutions to sensing itself in order to enable opportunistic access by secondary devices (e.g., based on geolocation databases) and a set of related scenarios are proposed, [9], p. 74). The same scenarios are considered in WP10, in this case focusing on the aspects related to the acquisition of awareness on neighbouring devices at both local and network-wide level, by defining solutions for neighbour and network discovery under the coexistence constraints set by the opportunistic access in presence of primary systems [10].

In general, ACROPOLIS is investigating all possible ways to implement solutions for the deployment of opportunistic cognitive networks, with research on the following three approaches:

- Underlay cognitive networks, capable of coexisting with primary systems by limiting the amount of generated interference (see the scenarios on ad-hoc cognitive networks in [10] as well as the case study considered in [11], subsection 4.1.3.2).
- Interweave cognitive networks, where cognitive devices try and detect spectrum holes not used by primary systems, investigated in WP13 [16].
- Overlay cognitive networks, that compensate the interference created to the primary systems by decoding and retransmitting the primary signal, also investigated in WP13.

Outside ACROPOLIS, it is worth mentioning the efforts put in the definition of solutions for opportunistic network scenarios by a wide set of European and worldwide research projects; additional details on specific projects are provided in Section 3.

Scenarios related to opportunistic cognitive networks are also central to the standardisation activities within both IEEE and ETSI. IEEE recently completed the IEEE 802.22 standard, focusing on Regional Area Networks capable of using TV White Spaces to deliver data connectivity in rural areas [1]; the scenario envisaged by IEEE in proposing the standard perfectly fits the category of opportunistic cognitive networks. In the ETSI Reconfigurable Radio Systems (RRS) group [17] the same scenario is considered as well.

2.2.3 Spectrum Sharing on Unlicensed Bands

This scenario includes sub-scenarios where different networks with cognitive capabilities operate with the same priority on spectrum access, and are required to put in place mechanisms for cooperation in the use of the common resources, or at least for efficient coexistence. Scenarios falling under this category are being investigated within ACROPOLIS. See for example the case study on spectrum sharing between operators defined in [11], section 4.1.2.2. In general, several activities are going on worldwide on the problem of spectrum management in so-called “spectrum commons” that may correspond to both unlicensed spectrum portions, or to frequencies licensed to multiple operators under the requirement of allowing for coexistence or explicit cooperation between different networks [2].

A similar scenario is under investigation within the ETSI RRS group, under the name “Fully flexible dynamic spectrum management” [18]. Under the umbrella of this long term scenario, ETSI RRS investigates a wide set of solutions for spectrum sharing, including the following ones:

- Dynamic deployment of RATs by operators, e.g., by means of Software Defined Radio (SDR) implementations allowing flexible, almost on-the-fly reconfiguration by switching between different technologies;
- Trading/exchanging of spectrum between operators according to availability and need;
- Dynamic adaptation of mobile devices.

It should be noted that such solutions are also being investigated by other projects/initiatives. Just to mention a few examples, within ACROPOLIS research activities deal with the reconfiguration of Beyond 3rd Generation (B3G) infrastructure networks, as well as with dynamic network selection and switching by mobile devices [11]. Scenarios where the common spectrum is accessed by systems according to an unlicensed access scheme are addressed as well: see for example the Home Network scenario defined in [10], subsection 4.4.

National regulation and standardisation bodies are also considering scenarios related to spectrum sharing, as for example the Office of Communications (Ofcom) in the UK [19].

2.3 Access networks and systems

It can be noted that one of the most promising applications for cognitive systems and functionalities is to increase performance of access networks: examples of scenarios falling in each of the categories defined in Section 2.2 can be found.

Starting from the scenario category defined in Section 2.2, it can be observed that the integration of cognitive functionalities or entire cognitive (sub)-networks in the existing infrastructure is particularly appealing for operators wishing to improve performance of their access network: the issues of coverage and bandwidth extension mentioned in Section 2.2.1 perfectly fit with the needs of mobile network operators to provide better and faster connectivity to their customers. Among the cellular systems that will be mostly interested in the introduction of cognitive capabilities are the Long Term Evolution (LTE) systems. In particular, scenarios involving femtocell deployment are particularly relevant in the case of LTE systems. Several activities are taking place with regards to this specific scenario, both within ACROPOLIS [11], and outside: see for example talks and contributions on this topic given by researchers active in the framework of COST Actions IC0902 and IC0905 (TERRA) [20].

Access systems that will be interested in scenarios falling in the second category, defined in Section 2.2.2, include the IEEE 802.22 system, as it will inherently work in an opportunistic manner, taking advantage of white spaces in the TV bands.

Finally, LTE is also one of the main systems that will be considered in scenarios falling in the category defined in Section 2.2.3. In particular, spectrum sharing and trading between LTE systems and operators will be definitely a hot topic in the near future, and several activities are going on in European projects and in other European initiatives, such as COST Action IC0905 [12], where the problem of spectrum sharing and trading is analysed from both technical and economical/business point of views.

2.4 Standardisation and Regulation trends

Any new technology might be manufactured by a range of different manufacturers. In various areas of consumer electronics, new solutions imply requirements such as the sharing of media and information, and particularly in the case of mobile/wireless technologies the ability of networks/devices to communicate with each other and coexist. This poses a problem: if manufacturers independently develop their own solutions, they won’t be compatible thereby limiting their usefulness; alternatively, if there is one dominating solution manufactured by a particular manufacturer, it will be anti-competitive and cannot be allowed. An agreed structure for the new technology among manufacturers is therefore necessary, allowing any manufacturer to develop equipment conforming to that agreed structure, whereby the equipment of different manufacturers will be compatible. Such a structure is commonly a “Standard”.

Issues are all the more apparent under the deployment of coexistence technologies such as Dynamic Spectrum Access (DSA). Such technologies imply direct/indirect interaction between a range of different systems, primary and secondary, and also between potential secondary systems. These systems must communicate or otherwise be aware of spectrum sharing information and/or availabilities, processes, rules, and generally co-exist, using a commonly understood language and procedures. Although regulatory rules must play a part in organising behaviours of systems/devices, this is only with very broad constraints for purposes such as to maintain the viability of the spectrum through avoiding inter-system/inter-band interference and excessive radiated power. More detail is needed, within the constraints of regulatory rules. Standards are required, specifically for DSA, CR and other such coexistence technologies, allowing systems and devices made by different manufacturers and/or operated by different entities to collaborate, communicate, coexist, form networks/organise, etc., in the realisation of DSA techniques.

The importance of regulation to the success of coexistence technologies such as DSA also cannot be underestimated. Indeed, many DSA concepts such as CR cannot be realised without allowance by regulators and the assurance that such technologies are viable and will not cause unacceptable interference. Further to this, there can be a complex interplay between regulation and standardisation: they often require each other in order to succeed. On the one hand, standards have to be at the forefront of technology in order to be successful, and that forefront (of allowable) technology is often defined by forthcoming regulations, for example, specifying what can be permitted and the safeguards that must be satisfied in the case of secondary spectrum access. Standards therefore require knowledge/expectation of forthcoming regulations, with a reasonably high degree of certainty. On the other hand, regulations require a motivation to be changed, particularly for such a fundamental change as secondary spectrum access, and standards are a very prominent means of demonstrating significant industry drive to achieve something, and therefore assist in determining the economic and social motivation to make a change. A depiction of this interplay, from a high level viewpoint, is given in Figure 2-1.

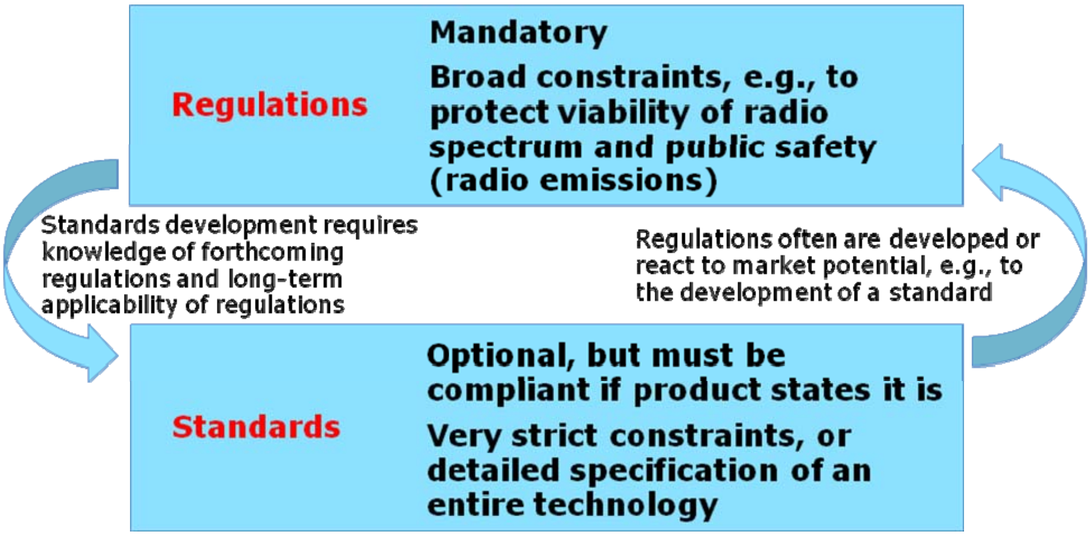

Figure 2-1: The interplay between regulation and standardisation

2.4.1 Regulation activities and the International Telecommunications Union

The regulatory landscape is moving extremely quickly. Recent developments in regulation affect expectations of what future coexistence technologies such as CR and DSA will manifest as, and also affect the realisation of such technologies *per se*. Progress within regulation, an essential prerequisite, is rapidly leading to the situation where such technologies can begin to be realised. However, the nature of that progress is often putting quite different constraints on technologies such as CR that would have been expected even as recently as 2010.

The main trend within regulation is that regulators are steering strongly towards centralised control being necessary for coexistence technologies such as CR. This is manifested by such technologies having to refer to a regulatory database to assess whether spectrum can be locally used in a secondary access fashion, or a managed collection of databases with the regulator at the top of the hierarchy. Such a redirection is the most important trend as referenced in the sections below.

2.4.1.1 The International Telecommunications Union (ITU)

First mentioned is the key international vehicle regarding regulation, the International Telecommunication Union (ITU) [21]. The ITU is an agency of the United Nations which is responsible for international telecommunications coordination. ITU-R is the sector of the ITU dealing with radio communications.

Several study groups within the ITU are looking into SDR, CR and DSA related issues. These include Study Group 1, Working Party 1A (WP 1A) looking into Spectrum engineering techniques, Working Party 1B (WP 1B), looking into Spectrum management methodologies and economic strategies, and Working Party 1C (WP 1C), considering Spectrum monitoring. Also of relevance are Study Group 5, Working Party 5A (WP 5A) on Land mobile service excluding International Mobile Telecommunications (IMT) including amateur and amateursatellite service, and Working Party 5D (WP 5D) on IMT Systems. One key recent work is that of ITU-R WP5A looking at the application of CR systems to the land mobile services [22].

The World Radiocommunication Conference (WRC) is a key meeting of the national regulatory administrations to better coordinate spectrum usage and other radio issues, occurring approximately every four years and managed by the ITU-R [23].

2.4.1.1.1 World Radiocommunication Conference (WRC) 2012

The recent WRC 2012 (23 January to 17 February 2012) was a key event affecting the future trends of coexistence technologies within the scope of ACROPOLIS. The outcome of Agenda Item (AI) 1.19 was for WRC to resolve that “no change” to the regulations is necessary regarding CR and SDR (see, e.g., [24]). This is simply stating that the current international framework is seen to be sufficient to handle the implications of such technologies. Moreover, WRC 2012 passed a “recommendation” COM 6/1 (as the name implies, this is less stringent that a “resolution”) for further study of the implications of CR introduction to continue, in accordance with Resolution ITU-R 58.

One highly important development was the decision to allocate the 694-790 MHz spectrum in region 1 to co-primary access by mobile services, to be put into practice after WRC 2015 (with the lower end of this allocation, and technical conditions for it, to be defined in WRC 2015). Details on key outcomes affecting ACROPOLIS from WRC 2012 can be obtained from [24], among other places, and a useful summary of all key resolutions and recommendations in areas of interest to ACROPOLIS can be obtained from [25].

Regarding the reallocation of spectrum to mobile services on a co-primary basis after WRC 2015, clearly such a reallocation could lead to a significant reduction in the number of secondary spectrum access opportunities in TV bands should this co-primary access be widely taken up. Hence, alternative spectrum for usage on a secondary basis is a key area of interest, as is analysis of the extent of spectrum holes after this reallocation—keeping in mind that the lower bound for this reallocation being as low as 694MHz is a worse-case scenario.

2.4.1.2 The Federal Communications Commission (FCC)

Further to the “Second Report and Order and Memorandum Opinion and Order” of 2008 that defined the need to cross-check with a regulatory database before using a TV band in secondary access fashion [26], the “Second Memorandum Opinion and Order” of September 2010 has now stipulated that the only requirement for such access is to check with a geolocation database thereby almost completely removing the need for spectrum sensing for TV white space access [27] (except for very low transmit power secondary access devices). Furthermore, two channels are reserved for wireless microphones, in an attempt to mitigate the interference issues that such devices may experience from TV white space access. This model has very much driven developments in other regulatory realms, although there was already some indication of those other realms anticipating such as change before September 2010 [28].

It is uncertain the extent to which the severe sensing requirements imposed on TV white space devices by the FCC [26], e.g., a detection threshold of -114 dBm in order for secondary access to be allowed, necessitated a change in rules merely to allow TV white space technologies to move forward. Hence, it is not known the extent to which the poor quality of legacy devices, e.g., in terms of receiver sensitivity and out-of-band interference rejection, as well as requirements to not interfere with low transmit power wireless microphones, led to such stringent constraints being necessary particularly for the case of TV white space. It is therefore uncertain the extent to which the rules for TV white space are different from what would be implied in other bands in which white space might be utilised (such as radar bands, for example). Nevertheless, issues around legacy devices' capabilities are anticipated to still be a problem in other bands.

2.4.1.3 The Office of Communications (Ofcom)

Following earlier indications (see, e.g., [28]), Ofcom has followed as similar approach to the FCC for TV white space in a consultation published November 2010 [29]. However, a key difference of the Ofcom approach is that the allowed transmission power level of white space radios is variable based on path loss and location, given the effect that is would have on possible legacy devices as calculated by the database [29]. This is as opposed to the FCC fixed limit of 4W Effective Isotropic Radiated Power (EIRP). The Ofcom solution is a far more flexible approach that can lead to significantly higher spectral efficiency and more transmission opportunities for white space radios. There are also differences in other rules imposed by Ofcom compared with the FCC, such as the required frequency of access to the database as well as and other issues, although other aspects, such as the "master-slave" form of approach to access of database information, remain.

A recently published summary of responses to the aforementioned consultation and next steps has concluded that the chosen path is correct, although will be refined slightly [30].

A key to understanding the potential for coexistence technologies is determining what demands there will be on spectrum and the nature of potential frameworks to decide the usage of spectrum. Assisting such lines, Ofcom has also published a discussion paper on developing a framework for the future use of TV bands [31]. Such streams of activity should be closely followed.

2.4.1.4 The European Conference of Postal and Telecommunications (CEPT), Electronic Communications Committee (ECC)

The relevant work within CEPT-ECC is done within the Spectrum Engineering (SE) Working Group [32]. Particularly, team SE43 is dealing with CR Systems and White Spaces. This team has recent published ECC report 159, concerned with technical and operational requirements for TV white space (or more specifically, 470MHz-790MHz spectrum) [33].

This report considers a number of different approaches to protection of the range of legacy devices operating in this spectrum. It overviews the various approaches of the FCC, Ofcom and others, and recommends a range of solutions, which might be generally seen as being more in line with the Ofcom database solution, and definitely in line with the use of geolocation databases. For instance, the report calculates that in a number of potential scenarios, protection of legacy TV receivers through sensing requires an impossibly low detection threshold, and protection of PMSE devices is only practical through a geolocation database. Furthermore, it starts that the disabling beacon approach as specified in IEEE 802.22.1, for example, is promising but has a number of unknowns in terms of performance.

2.4.2 Standardisation summary

There are a range of active standardisation activities of relevance to ACROPOLIS coexistence technologies. A complete analysis for the standards of each organization can be found in the ACROPOLIS Deliverable D6.2 “Report on Trends in Standards and Regulation”. The organisations running these standardisation efforts are listed below:

- European Telecommunications Standards Institute (ETSI) [34]
  - ETSI produces a very wide range of standards covering all areas of telecommunications. The group of interest to DSA and other coexistence technologies is ETSI Reconfigurable Radio Systems (ETSI-RRS) [17].
- IEEE Standards Association (IEEE-SA) [35]
  - The IEEE Standards Association oversees various standards covering nearly all areas of electronics and communications. The IEEE 802 LAN/MAN standards committee [36] is developing several standards of interest to ACROPOLIS, but these are generally relevant to specific application spaces (e.g., 802.3 Ethernet, 802.11 Wireless Local Area Networks, 802.15 Wireless Personal Area Networks, 802.16 Wireless Metropolitan Area Networks, etc.). The IEEE DySPAN Standards Committee (DySPAN-SC) [37] is focusing on the wider implications and solutions for DSA, and is relevant for that reason.
- ECMA International [38]
  - ECMA International is a smaller standards body with one interesting standard recently published on TV white space, the ECMA-392 standard for personal/portable devices [39]. ECMA used to be known as the European Computer Manufacturers Association (ECMA), although now just to acronym exists as the title.
- Internet Engineering Task Force (IETF) [40]
  - The IETF handles higher layers of internet communications: e.g., the Internet Protocol (IP) and Transport Control Protocol (TCP) layers, among others. However, the IETF is now also working on “Protocol to Access White Space database (PAWS) information [41], given that the TV white space is now defined as being managed by a database. Given this new reality, higher layers now play an enhanced role in white space and other coexistence technologies.

2.4.3 CRS Technology and Deployment Roadmap

Concerning the current trends of regulation within Europe, Figure 2-2 tries to capture the developments and outlook in a medium term roadmap. There are a number of efforts that will impact the deployment of CR equipment. In US, an approach to certify CR equipment for TVWS access was approved, the certification approach relies on the use of the SpectrumBridge database. At the same time, the EC is on the brink of issuing a mandate for the development of a harmonized standard for the operation of CR and SDR equipment.

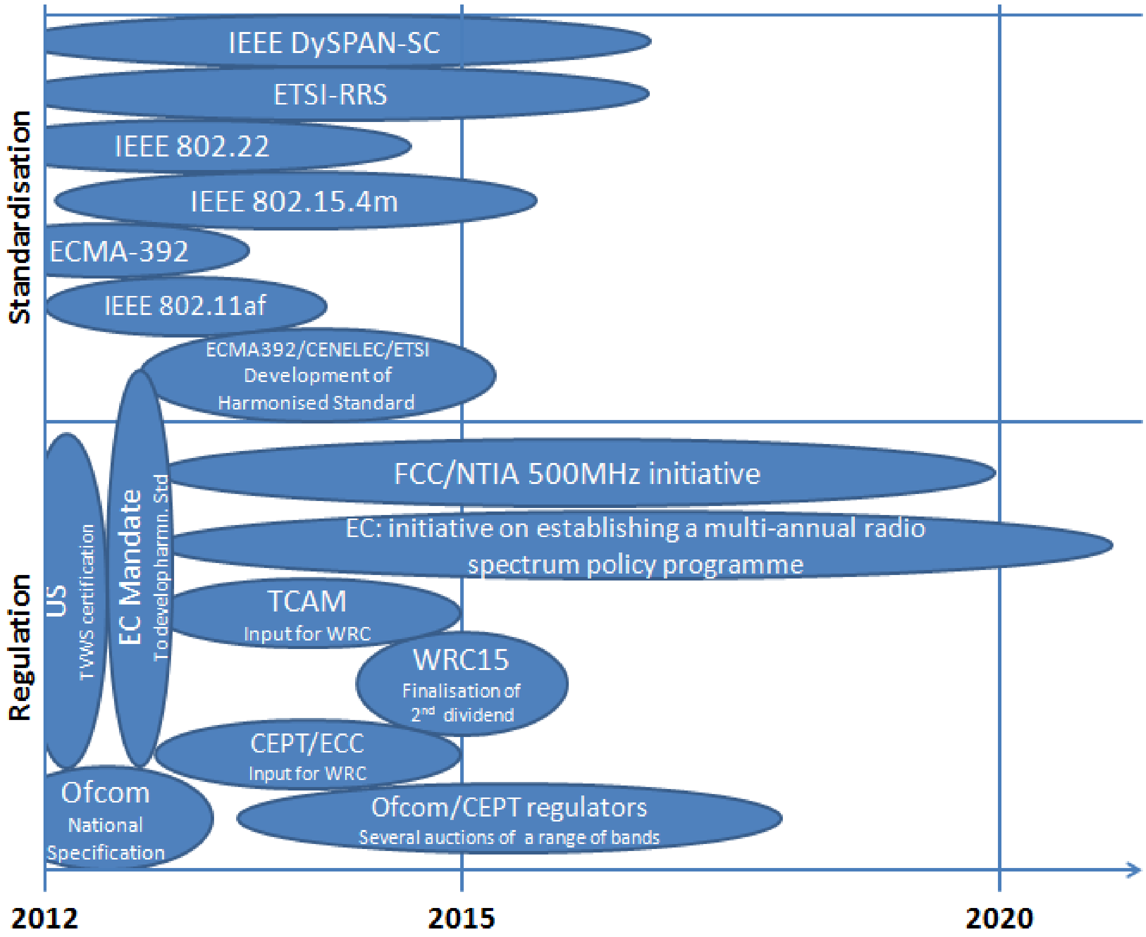

Figure 2-2: CRS development and outlook roadmap

The mandate for such a harmonized standard will be passed to CENELEC and/or ETSI RRS (or both) and the actual standardisation work is expected to start in late 2012, early 2013. At the same time, the IEEE DySPAN and 802 committees will also continue with the development of their standards. At current it is not foreseeable which topics will form the basis of future projects in those bodies, new, or continuation standardisation projects are continuously created.

On the regulation side, the national regulators (at least in Europe) will keep on auctioning spectrum licenses, however with a very much altered set of license requirements which will allow more flexible use and allocation. The European organisations, including CEPT/ECC as well as TCAM will continue their activities, and in particular they can be expected to have a number of activities to prepare the next World Radio Congress (WRC2015). This is of particular interest as the decision taken at WRC12 to consider a second digital dividend at WRC15 may have significant impact on the development, and more on the actual use of dynamic access technologies.

3. Global Research Activities

In this section, the current status of the research activities in the area of CR networking in the different parts of the world is reviewed.

3.1 European activities

In this section, an overview of the main achievements of the major European, both international as well as national, CR related projects and programs are presented. In the first part, a brief description of the main EU funded projects (finished or currently under realization) related to various aspects of CR is provided. In particular, a short summary of each project is presented, followed by a more detailed analysis of the activities realized within these projects that are or can be suitable for ACROPOLIS partners. The second part of this section addresses two leading international COST Actions in the area of CR, i.e., IC0902 and IC0905. Although international in essence, both actions are described in this subchapter since many partners from Europe participate actively in these activities. The third part consists of a concise description of selected national programs and projects. Let us stress that the countries analysed in this report have been chosen arbitrarily and no specific key has been used for their selection. The goal behind such an approach was to show various approaches to the concept of CR among whole Europe. Finally, a brief summary of other European activities related to CR and CR Networks (CRNs) is provided.

3.1.1 European Commission Projects

In this section, an overview and a brief description of the ACROPOLIS related activities of the following projects funded by the European Commission (EC) will be provided:

	Project Name	ACROPOLIS partner involved	Project Website
1	QUASAR	RWTH -PM, KTH, UKIM	http://www.quasarspectrum.eu/
2	FARAMIR	RWTH – Coord.& PM, IASA, UKIM	http://www.ict-faramir.eu/
3	2PARMA	RWTH	http://www.2parma.eu/
4	OneFIT	UPRC -Coord., UoS, EIT+	http://www.ict-onefit.eu/
5	UniverSelf	UPRC, UoS	http://www.univerself-project.eu/
6	Self-NET	KCL	https://www.ict-selfnet.eu/
7	QoSMOS	TUD, UoS	http://www.ict-qosmos.eu/
8	COGEU	PUT	http://www.ict-cogeu.eu/
9	SACRA	EURECOM	http://www.ict-sacra.eu/
10	SENDORA	EURECOM, KTH	http://www.sendora.eu/
11	CREW	TUD, EADS	http://www.crew-project.eu/
12	C2POWER	EIT+, UoS, EADS	http://www.ict-c2power.eu/

	Project Name	ACROPOLIS partner involved	Project Website
13	WHERE2	UoS, EURECOM	http://www.ict-where2.eu/
14	CROWN	EURECOM	http://www.fp7-crown.eu/
15	EARTH	UoS, TUD	https://www.ict-earth.eu/
16	EXALTED	UoS, UPRC, TUD, CTTC	http://www.ict-exalted.eu/
17	BeFEMTO	UoS, CTTC	http://www.ict-befemto.eu/
18	SAMURAI	EURECOM	http://www.ict-samurai.eu
19	SAPHYRE	TUD, EURECOM, EIT+	http://www.saphyre.eu/
20	CogX	KTH	http://cogx.eu/
21	PHYDYAS	CTTC	http://www.ict-phydyas.org/
22	CONNECT	EURECOM	http://www.conect-ict.eu/
23	HELP	JRC	http://www.fp7-sec-help.eu/
24	EULER	JRC	http://www.euler-project.eu/
		Projects with no ACROPOLIS partners	
25	CHRON		http://www.ict-chron.eu/
26	ECODE		http://www.ecode-project.eu/
27	SOCRATES		http://www.fp7-socrates.org/
28	ADVANCE		http://www.advance-logistics.eu/

Table 3-1: European Commission Projects with ACROPOLIS related activities

3.1.1.1 QUASAR (Assessing real life benefits of cognitive radio) [42]

Website: http://www.quasarspectrum.eu/

ACROPOLIS Partners involved: RWTH, KTH, UKIM

Project duration: January 2010 – June 2012

Project Overview

The main objectives of the QUASAR project can be summarized as follows. First, the impact of opportunistic spectrum access on primary system performance is investigated, focusing on moving the community from "detecting spectrum holes" to the regime of "discovering 'real' spectrum opportunities". Next, multi-parameter and utility based assessment of the value of spectrum (opportunities) is derived. Moreover, detailed roadmaps and guidelines on how to apply and analyse new opportunistic spectrum access business models are provided. Finally, specific and reasoned proposals to go beyond the current regulatory framework and to cover the whole value-chain, inspiring interaction between all stakeholders and regulators are investigated.

ACROPOLIS related research activities

QUASAR's research activities are organized in 5 WPs covering many topics that have high relevance to ACROPOLIS. QUASAR’s WP1 has two stages – the first task is to define the models, scenarios, performance measures and to make initial proposals for a number of secondary spectrum access regimes. The assessment of the business impact of the proposed schemes, and the regulatory feasibility is done in the remainder of WP1, which clearly relates to ACROPOLIS’ WP6. QUASAR’s WP2 introduces the concept of spectrum opportunity discovery. These activities are related to ACROPOLIS’ WP9 and WP12. Next, QUASAR’s WP3 studies the impact of the performance of the primary system, in particular the capabilities of the primary receivers to withstand secondary interference This WP relates to ACROPOLIS’ WP7, and more precisely to Activity 7.4. Furthermore, QUASAR’s WP4 studies schemes for accessing the spectrum opportunities and interference impact caused by secondary multi-access, providing models and tools for the performance evaluation. This activity is related to ACROPOLIS’ WP9 and WP14 (Activity 14.1). Finally, QUASAR’s WP5 aim is the development of various methods and tools to assess the spectrum availability (over space, time and frequency) for secondary use. The methodology being developed within QUASAR's WP5 is not directly correlated with any ACROPOLIS WP, but parts of it tackle similar topics as in ACROPOLIS WP9 and WP14.

3.1.1.2 FARAMIR (Flexible and spectrum-aware radio access through measurements and modeling in cognitive radio systems) [43]

Website: http://www.ict-faramir.eu/

ACROPOLIS Partners involved: RWTH, IASA, UKIM

Project duration: January 2010 – June 2012

Project Overview

The main goal of this project is to show how radio environmental information can be measured, collected, and represented efficiently, employing Radio Environmental Map (REM) techniques. The consortium develops the reference architecture and the respective functional entities. Moreover, key-parts of a context-sensitive Radio Resource Manager (RRM) that optimizes heterogeneous networks is developed and demonstrated. The consortium conducts spectrum occupancy measurements in several European sites with different equipments and frequency bands to provide real-world data for the spectrum occupancy modeling community. This data is shared openly and transparently with other technical communities. The data will provide an objective, scientific basis for the quantifiable debate on the availability of “free spectrum”.

ACROPOLIS related research activities

The consortium studies the spectrum sensing technology and the performance of spectrum sensing techniques. In particular, techniques for source localization and transmit power estimation are developed, for a possibly unknown number of sources based on power measurements, along with Time of Arrival (ToA) and Angle of Arrival (AoA) techniques. More generally, techniques for obtaining Radio Environmental Awareness via Radio Interference Field Estimation are investigated. Techniques that aim to characterize the Interference Field directly without characterizing transmitting sources are developed. The consortium also aims to discuss, based on real measurements, some of the applications and scenarios in which spectrum sensing might be used. These activities are related to the activities of WP9 of ACROPOLIS.

Another goal of the FARAMIR project is to develop optimization techniques that utilize the spectrum data to enhance cognition and context-awareness in cognitive wireless networks. More specifically, of interest are the design of novel distributed algorithms and methodologies that exploit advanced REMs, neighbourhood-sensing and interference minimization. It has also proposed a detailed framework to exploit the measured radio environment data. The complexity and feasibility for obtaining and exploiting the empirical spectrum-use parameters (WP3) and neighbourhood-sensing data (WP4) is also examined. Similar activities are examined in WP12 of ACROPOLIS in the framework of interference management and resource allocation.

The scenarios that are investigated are presented in Deliverable D2.2, while the concept of Radio Environment Maps is described in Deliverable D4.1 [44].

3.1.1.3 2PARMA (Parallel paradigms and run-time management techniques for many-core architectures) [45]

Website: http://www.2parma.eu/

ACROPOLIS Partners involved: RWTH

Project duration: January 2010 - December 2012

Project Overview

2PARMA demonstrates methodologies, techniques and tools by using innovative hardware platforms provided and developed by the partners, including the Platform 2012, and an early implementation of Manycore Computing Fabric provided by STMicroelectronics. The selected applications are: Scalable Video Coding, CR and Multi View Image Processing.

ACROPOLIS related research activities

As one of the application cases in 2PARMA project, RWTH investigates component oriented design for flexible CR Physical (PHY) and Medium Access Control (MAC) layers. RWTH aims at defining and exploring critical algorithmic and execution kernels of PHY and MAC layers, which capture their common and key functionalities. These kernels are to be realized on the multicore architectures to enable flexible PHY and MAC solutions with run-time reconfiguration capabilities. RWTH also investigates the implementation of reconfigurable MAC design approach on WARP SDR platform as a proof of concept. The WARP SDR platform is also investigated in the ACROPOLIS project (WP7).

A toolchain for realizing adaptable MAC solutions has been developed. The ACROPOLIS project will hold a hands-on-training session on this toolchain, which certainly eases the development efforts and widens the experimental room for prototyping Cognitive MAC protocols. In the framework of the first ACROPOLIS mini-winter school, RWTH has conducted a joint tutorial on this toolchain and WARP SDR platform with Rice University, USA at the IEEE DySPAN 2011 in Aachen, Germany.

3.1.1.4 OneFIT (Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future InterneT) [46]

Website: http://www.ict-onefit.eu/

ACROPOLIS Partners involved: UPRC, UoS, EIT+

Project duration: July 2010 – December 2012

Project Overview

The main goal of the OneFIT project is to develop and validate the concept of the opportunistic networks that are controlled and steered by the cognitive systems. It aims at satisfying the demand of the end-users through efficient resource provisioning and utilization. In that vision, the opportunistic networks (which are typically operator-governed) are steered by the cognitive management systems by means of dedicated control channels.

ACROPOLIS related research activities

The OneFIT project partners are intensively participating to research activities involving opportunistic networks and cognitive management systems. These research activities include control channels for CR, the functional and system architecture of the OneFIT platform, emphasizing on the building blocks “Cognitive management System for the Coordination of the Infrastructure” (CSCI) and “Cognitive Management system for the Opportunistic Network” (CMON) and the functionality of the “Control Channels for Coordination of Cognitive Management Systems” (C4MS).

Two key Deliverables that are of interest to the ACROPOLIS project are the following:

D2.2 - OneFIT functional and system architecture. This Deliverable presents the OneFIT functional and system architecture for the management and control of infrastructure coordinated ONs. The most relevant building blocks CSCI and CMON are described [47].

D3.1 - Proposal of C4MS and inherent technical challenges. This Deliverable contains a proposal of C4MS, which enables delivery of guidance/assistance information from infrastructure towards the ONs and provides means for the management of ONs. This document defines first messages and elementary procedures for the C4MS as well as a preliminary set of information, which is to be conveyed over C4MS. The Deliverable introduces also the inherent technical challenges related to the C4MS proposal [48].

3.1.1.5 UniverSelf [49]

Website: http://www.univerself-project.eu/

ACROPOLIS Partners involved: UPRC, UoS,

Project duration: September 2010 – August 2013

Project Overview

UniverSelf will consolidate autonomic methods of the future Internet for business-driven, service and network management into a novel Unified Management Framework (UMF) evolving through cognition. The UMF will remove the roadblocks of the original Internet design and of its later patchwork growth; it will seamlessly unite the control and management planes by enabling self-organization of the former and empowering the latter with cognition. This will advance the routine management tasks by humans to the level of governance of the entire network and service ecosystem. It aims at overcoming the growing management complexity of future networking systems, and to reduce the barriers that complexity and ossification pose to further growth.

ACROPOLIS related research activities

The research activities within UniverSelf heavily focus on decision making and optimization with special emphasis given to the incorporation of learning and knowledge building into the various reasoning engines. Focus is also on the detection and resolution of conflicts that may arise in an environment where multiple decision making entities are operating in parallel. The autonomous mechanisms and approaches are relevant to ACRPOLIS, albeit the UniverSelf approach does not explicitly tackle the access networks and access technologies. There are four lines of investigation within the project that can be described as follows: a) *Interactions and coordination of multiple control loops,* b) *Autonomic management of core and access network segments,* c) *Dynamic service management* and d) *Context discovery, diagnosis and prediction.*

3.1.1.6 Self-NET (Self-Management of Cognitive Future InterNET Elements) [50]

Website: https://www.ict-selfnet.eu/

ACROPOLIS Partners involved: KCL

Project duration: May 2008 – December 2010

Project Overview

Self-NET envisaged the Future Internet to be based on cognitive behaviours of its elements with a high degree of autonomy. The project aims "to design, develop and validate an innovative paradigm for cognitive self-managed elements of the Future Internet" [50], and the final target is to achieve a high autonomy of network elements in order to allow distributed management, fast decision making, and continuous local optimization. An architecture is proposed for the operation of self-managed Future Internet elements around a novel hierarchical feedback-control cycle (built around the generic Monitoring, Decision Making and Execution – MDE control cycle model).

ACROPOLIS related research activities

Self-NET provides a comprehensive analysis and various validation results in the area of design and deployment of control cycle driven self-managed Future Internet networks. The principles of such self-managed networks are given in Self-NET [51] for a broad scope of applications in network operations, from wireless access regions to network routing and management functions. Self-NET defines extensive use-cases [52] where the theory of self-management can be realized based on high-level paradigms of self-management and realization of control loops (generically called M-D-E cycle in Self-NET, i.e., Monitor-Decision Making-Execution) and their expansion to practical scenarios and needed additional components of such a formed logical architecture [53]. Applications of this are provided in many practical examples and based on tools for management of knowledge and information modeling [52]. Such examples include validations of self-management in wireless access regions of networks [54] and many test-bed implementations conducted in the project [55].

Various aspects of SelfNET are relevant to the implementation of the cognition cycle in communications, particularly self-management. The project has, however, recently been completed. Lessons can still be learned regarding the self-management concepts studied in SelfNET.

3.1.1.7 QoSMOS (Quality of Service and MObility driven cognitive radio Systems) [56]

Website:	http://www.ict-qosmos.eu/
ACROPOLIS Partners involved:	TUD, UoS
Project duration:	January 2010 – December 2012

Project Overview

The primary objective of QoSMOS is to develop a framework for CRSs and to prove various broadly understood efficiency of various critical technologies using a test-bed. The project focus is on opportunistic use of radio spectrum, e.g., TV White Spaces. Involvement in standardisation bodies and industrial forums is emphasised. It is worth mentioning that the QoSMOS project has an External Advisory Board consisting mainly of regulators and broadcasters, established in order to help steer the project and also to provide paths for exploitation of project results.

ACROPOLIS related research activities

WP3 – "Radio Environment Mapping and Sensing" in QoSMOS is related to WP9 – "Spectrum Awareness" in ACROPOLIS, mainly to Activity 9.2 "Management of Spectrum Information". The main objectives of WP3 include: a) to develop models of the radio environment provided by the TVWS and other bands that provide opportunities for building up a spectrum portfolio, b) to define and evaluate a protocol stack for the sensing components within CR networks and for the exchange of sensing information between cognitive nodes, and finally c) to propose and evaluate algorithms for the acquisition and exchange of radio environment context via the designed protocol stack. Collaborative sensing in ACROPOLIS Activity 9.2 requires the storage and transfer of spectrum information among entities in a centralized or distributed way.

The protocol stack proposed in QoSMOS for the sensing components within CR networks and for the exchange of sensing information between cognitive nodes can be a reference for the framework of collaborative sensing in ACROPOLIS. This reference protocol stack has been described in Deliverable D3.2 "Reference Protocol Stack for QoSMOS Radio Environment Mapping and Sensing" [57]. It is part of the overall system reference model and the basic functionalities and interfaces are described. There is a short survey on the state of the art of protocol stacks and data formats for sensing information. The blocks to be studied in QoSMOS are introduced and sorted in the sensing model. Finally, a first set of requirements of the protocol stack reflecting the different use cases is given.

3.1.1.8 COGEU (Cognitive radio systems for efficient sharing of TV white spaces in European context) [58]

Website: http://www.ict-cogeu.eu

ACROPOLIS Partners involved: PUT

Project duration: January 2010 – December 2012

Project Overview

The main focus of the COGEU project is on providing the effective combination of, first, cognitive access to TVWS and, second, economic aspects applied in the proposed secondary spectrum trading mechanism. Within the framework of this project technical, business and regulatory aspects will be taken into account in order to take advantage of the TV digital switch-over. COGEU will also provide new methodologies for certification and compliance of TVWS devices addressing coexistence with the Digital Video Broadcasting – Terrestrial/Handheld (DVB-T/H) standard.

ACROPOLIS related research activities

Various activities within the COGEU project are related to the ACROPOLIS network. COGEU considers a centralized topology with a spectrum broker trading with players. The spectrum broker controls the amount of bandwidth and power assigned to each user in order to keep the desired QoS and interference below the regulatory limits. In the COGEU reference model, the centralised Broker is an intermediary between the geolocation database (spectrum information supplier) and players that negotiate spectrum on behalf of spectrum users. TVWS characterization and context representation is considered in order to populate the geolocation database. The sensing techniques and their integration with the database access techniques in order to make spectrum opportunity observations available to the CR are considered. The transceiver will make use of the fragmented spectrum opportunities by aggregating the available frequency bands. The transceiver implementation platform (IRIS developed in CTVR, Dublin, Ireland) is being extended through the development of sensing and flexible spectrum shaping algorithms. Furthermore, game-theoretic auction-based spectrum trading mechanisms are considered. Non-identical objects auction rules are tested for their future practical application in the spectrum market to avoid speculation, monopolization and to enable open market to small players (secondary users).

The COGEU project has already achieved a number of important results that can be accessed through its Website in public Deliverables. Among those, related to ACROPOLIS are: a) the measurements of spectrum opportunities in TVWS in Germany and the design of geolocation databases (useful for context representation in ACROPOLIS WP12), b) software radio platform specification and development (useful for ACROPOLIS WP5 and WP7), c) sensing methods implementation and development of the sensing quality metrics (useful for ACROPOLIS WP9), d) dynamic spectrum shaping techniques for the protection of primary users (useful for ACROPOLIS WP7 and WP8), e) game-theoretic approach to dynamic spectrum allocation (useful for ACROPOLIS WP8 and WP12), and finally f) strong links with the regulatory and standardisation bodies, contributions to radio-spectrum cognitive usage consultations and hearings (useful for ACROPOLIS WP6).

3.1.1.9 SACRA (Spectrum and energy efficiency through multi-band cognitive radio) [59]

Website:	http://www.ict-sacra.eu/
ACROPOLIS Partners involved:	EURECOM
Project duration:	January 2010 – December 2012

Project Overview

The key issue addressed by SACRA is to propose a system approach that is based on innovative algorithms and advanced hardware components in order to support opportunistic and flexible communications in interleaved spectrum. The major outcome of the project is to implement, as a proof-of-concept, the multi-band CR technology for energy- as well as spectral-efficient communications.

ACROPOLIS related research activities

Various activities realized within the SACRA project are highly related to the ACROPOLIS NoE. First, SACRA WP1 deals with the specification of the global system requirements (architecture, characteristics, etc.), what is related partially with many ACROPOLIS WPs, e.g., WP8 in terms of context representation or WP12 in terms of target metric definition and generic framework description. SACRA WP2 aims at the investigation of various sensing and access techniques, focusing on advances in space-time polarization codes. This activity is related with at least WP9 and WP12. Furthermore, SACRA WP3 deals with the radio resource and interference management techniques for multi-band operation modes, which is the subject of interest for many WPs in the ACROPOLIS project. Investigation performed in the SACRA WP4 is related to the ACROPOLIS WP5 and WP7 in network, since in this WP the issues of design of antennas and other RF-parts are treated. Also techno-economic and standardisation activities are valued from the ACROPOLIS WP17.

3.1.1.10 SENDORA (SEnsor Network for Dynamic and cOgnitive Radio Access) [60]

Website: http://www.sendora.eu/

ACROPOLIS Partners involved: EURECOM, KTH

Project duration: January 2008 – December 2010

Project Overview

SENDORA, an ICT project on DSA, is already finished. During its lifetime, the possibility of application of Wireless Sensor Networks (WSNs) for supporting the coexistence of licensed and unlicensed wireless users has been widely investigated. Within SENDORA, the so-called Sensor Network aided CR concept has been evaluated.

ACROPOLIS related research activities

The following results or actions undertaken in the SENDORA project are of potential high interest from the ACROPOLIS perspective. First, the *Business Cases and Scenarios* that have been considered (especially nomadic broadband access, with/without spectrum broker, etc.) presented in D2.2 [61] are clearly relevant to the ACROPOLIS WP6. Next, *Collaborative Spectrum Sensing, Protocol Design, and Cooperative Communication* realized by application of WSN is related to the ACROPOLIS WP9. Furthermore, the Deliverables provided by SENDORA WP3 describe a large number of spectrum sensing techniques and evaluate their performance. There is a direct connection to ACROPOLIS D9.1, which should be utilized. The SENDORA D6.2 may be furthermore insightful since it discusses network dimensioning for collaborative spectrum sensing [62]. Dimensioning itself is related with the ACROPOLIS WP7 and WP9. The SENDORA WP5 proposed cooperative communication schemes which were designed to increase the reliability of collaborative spectrum sensing. *(Related WPs in ACROPOLIS*: WP7, WP9, WP13). Various cooperative communication algorithms were developed in SENDORA D5.2 [63] and their performance was evaluated in SENDORA D5.3 [64].

The next area of investigation in the SENDORA project can be entitled as *Interference Management and Cognitive Radio Reconfiguration Management*. In this activity, interference management issues as well as coordination between the sensor network and the CR network, and resource allocation have been considered [65] and are related to WP11, WP12 and WP13 in ACROPOLIS.

Finally, a s*ystem demonstration and integration* task has been developed, which is highly related to ACROPOLIS WP5.

3.1.1.11 CREW (Cognitive Radio Experimentation World) - FIRE projects [66]

Website: http://www.crew-project.eu/

ACROPOLIS Partners involved: TUD, EADS

Project duration: October 2010 – December 2014

Project Overview

The main expected outcome of the CREW project is to establish "an open federated test platform" [66], that will be able to facilitate the research on various aspects of cognitive technologies, i.e., advanced spectrum sensing, CR and networking. The proposed platform takes advantages of four individual testbeds.

ACROPOLIS related research activities

Since the goal of the CREW project is the establishment of the open test platform for advanced spectrum sensing, CR and cognitive networking, such activities are particularly related to the WP5 and WP7 in the ACROPOLIS project. Moreover, aforementioned spectrum sensing techniques are evaluated in ACROPOLIS WP9.

3.1.1.12 C2POWER (Cognitive radio and Cooperative strategies for POWER saving in multi-standard wireless devices) [67]

Website: http://www.ict-c2power.eu/

ACROPOLIS Partners involved: EIT+, UoS, EADS

Project duration: January 2010 – December 2012

Project Overview

C2POWER addresses the problem of development and implementation of energy-saving technologies that could be used for wireless multi-standard terminals. It is considered that such a device shall exploit the combination of various CR techniques and advanced cooperative strategies, thus enabling the required performance (i.e., data rate of QoS level).

ACROPOLIS related research activities

As it was stated above, from the ACROPOLIS point of view, the most relevant and useful activities in C2POWER are related to context awareness, network/neighbour discovery mechanisms as well as cooperative short-range communications. Thus, corresponding research results may be exploited in particular by ACROPOLIS partners involved in WP9, WP10, WP11, WP12 and WP14.

3.1.1.13 WHERE2 (Wireless Hybrid Enhanced Mobile Radio Estimators – Phase 2) [68]

Website: http://www.kn-s.dlr.de/where2/

ACROPOLIS Partners involved: UoS, EURECOM

Project duration: July 2010 – June 2013

Project Overview

The main goal of WHERE2 is developing novel cooperative positioning techniques in order to enhance mobile network assisted positioning accuracy. Moreover, the project is also interested in the efficient exploitation of location information for improving the communication quality. The major novelty of WHERE2 is in the area of localization, such as message passing for cooperative positioning, novel particle filter design, etc. It is assumed that the location information will be linked to a database of physical parameters, which can be helpful to communication techniques such as channel estimation, cooperative relaying and CRs.

ACROPOLIS related research activities

WHERE2 has a location-aided CR task, WP3 Task 3.3, which is related to the ACROPOLIS activities. The key objective of this task is to research how to exploit location information in order to improve the performance of cognitive communications. The primary objective of this task is to improve the efficiency and reliability of CRs through exploitation of location information about network nodes and mobile terminals. The technical focus of this research is on the PHY/MAC layer issues of advanced CRs, such as cooperative spectrum sensing, underlay and overlay DSA, Multiple Input Multiple Output (MIMO) CR, user cooperation, and cognitive multiple-access schemes. The output of this research should reflect the fundamental performance limit of location-aided CRs, novel cognitive communication schemes, and applications in future wireless systems such as LTE, Worldwide Interoperability for Microwave Access (WiMAX), and IEEE 802.22 WRAN.

The research taking place in WHERE2 WP3 is highly related to the ACROPOLIS WP9 activities on Spectrum Awareness as the spectrum sensing accuracy can be significantly improved by the consideration of location information.

3.1.1.14 CROWN (Cognitive Radio Oriented Wireless Networks) [69]

Website: http://www.fp7-crown.eu/

ACROPOLIS Partners involved: EURECOM

Project duration: May 2009 – April 2012

Project Overview

CROWN works towards the realistic implementation of CRs for better, more spectrally and financially efficient wireless communications. The main purpose of the CROWN project is to understand the technical issues of CRs, through a proof of concept demonstrator. The techniques branded as “Cognitive Radio” enable concepts such as dynamic spectrum licensing, where the reconfigurable spectrum radio is able to sense whether a particular band is being used or not and, to utilize the spectrum without interfering with the transmission of other licensed users. The CROWN project’s aspirations place it in a high-risk/high-return regime; it will help to revolutionize the spectrum licensing and efficiency landscape for personal wireless communications.

ACROPOLIS related research activities

Since CROWN is realized as the FET-Open (Future Enabling Technologies) project, its achievements are particularly important for ACROPOLIS. The main goal of the CROWN project is to “understand the technical issues of Cognitive Radios, through a proof of concept demonstrator”. Since FET programs are known to be classified as High Technical Risk but with High Potential reward, all of the Deliverables are significant for the whole ACROPOLIS community.

3.1.1.15 EARTH (Energy aware radio and network technologies) [70]

Website: https://www.ict-earth.eu/

ACROPOLIS Partners involved: UoS, TUD

Project duration: January 2010 – June 2012

Project Overview

The EARTH project is focused on significant, i.e., by a factor of at least 50%, reduction of overall energy consumption of the mobile systems. The goal of making the wireless communication “greener” will be achieved by the investigation of the energy efficient limit whilst still providing high capacity and the required level of QoS. The EARTH project concentrates on cellular systems, mainly LTE and LTE-Advanced (LTE-A), but considers also wireless communications standards from the 3rd Generation (3G) family such as Universal Mobile Telecommunications System (UMTS)/High Speed Packet Access (HSPA).

ACROPOLIS related research activities

EARTH WP4 – Green Radio studies energy efficiency (EE) technologies and components, EE enabling radio interface techniques, and EE enhancements of innovative radio transmission techniques. The main goal of the EARTH project is to significantly reduce the power consumption of cellular networks. The approaches presented affect the performance on component, node, and link level and are complementary to the tracks presented in the document “Most Promising Tracks of Green Network Technologies” (Deliverable D3.1) [71]. New solutions are proposed and analysed in the way to predict the achievable gains for green radios with the main focus on LTE. The most promising tracks presented in this document are addressing MIMO and beamforming techniques, radio interface technologies, and transceiver components and their control. Thereby, one basic approach is to improve significantly the energy efficiency of the radio nodes for low and medium traffic situations, which occur very often, and where traditional solutions show rather low energy efficiency.

The provided results show the quantitative gains expected by the application of the proposed techniques.

3.1.1.16 EXALTED (EXpanding LTE for Devices) [72]

Website: http://www.ict-exalted.eu/

ACROPOLIS Partners involved: UoS, UPRC, TUD, CTTC

Project duration: September 2010 – February 2013

Project Overview

The EXALTED project addresses the concept of laying out "the foundations of a new scalable network architecture" [72] whilst supporting various requirements put on the future wireless systems. The proposed and investigated network architecture would provide secure, cheap (cost-effective) and energy-efficient communication between machines (M2M).

ACROPOLIS related research activities

All of the activities undertaken within EXALTED, which are related to ACROPOLIS, are summarized below. These can be split in two parts, activities related to WP3 and WP4.

WP3 activities:

Task 3.1 Physical Layer - Simplification of signal processing techniques is needed in the LTE-M device in order to reduce energy consumption and cost, as well as a reduction of the Peak-to-Average Power Ratio (PAPR). For this purpose, two new alternative waveforms have been investigated for LTE-M radio access, namely Generalized Frequency Division Multiplexing (GFDM) and Wideband Code Division Multiple Access (W-CDMA)-like waveforms, both providing good spectral characteristics.

Task 3.3 Dynamic Resource Management - Novel sensing mechanisms are considered in this task to optimise parameters such as sensing time, number of sensing devices, algorithm and architecture complexity, energy consumption, etc. A new set of procedures will be defined and developed for spectrum sensing and the exchange of sensed information between the M2M devices (distributed approach) or with the LTE Base Station (centralised approach) for efficient spectrum utilization, while satisfying the diverse requirements of the M2M devices.

WP4 activities:

The End-to-End (E2E) M2M system requires efficient and reliable operations of the capillary networks connected to the LTE/LTE-M access network via M2M gateways, E2E connectivity as well as devices. For this, several capillary network protocols/algorithms have been investigated while considering LTE/LTE-M access network connectivity via M2M gateway(s), and some initial recommendations have been made for cooperative medium access control, network coding for traffic aggregation, energy efficient clustering, lightweight device management, mobility management, and reliable network health monitoring. Moreover an address auto configuration procedure has been proposed for capillary network devices connected to LTE/LTE-M access network.

The EXALTED WP3 activities can be considered in the ACROPOLIS research, mainly concerning Spectrum Awareness activities of WP9, as the sensing mechanisms proposed aim to optimise the sensing time, the number of sensing devices, the algorithm and architecture complexity, the energy consumption, etc.

3.1.1.17 BeFEMTO (Broadband Evolved FEMTO Networks) [73]

Website: http://www.ict-befemto.eu/

ACROPOLIS Partners involved: UoS, CTTC

Project duration: January 2010 – June 2012

Project Overview

As the project name suggests, the main target of the BeFEMTO project is to develop efficient femtocell technologies (mainly based on LTE-A networks), thus enabling the provisioning of broadband services. Various novel usage scenarios are considered, i.e., networked, relay and mobile femtocells. One of the main goals is to have real impact on the standardisation related to the next generation femtocell technologies, mainly based on LTE-A systems.

ACROPOLIS related research activities

Radio Context Based Learning:

In order to efficiently share the spectrum with the macrocell network, femtocells need to strategically learn from their environment using context aware learning mechanisms, while at the same time mitigate interference towards the overlay macrocell network. In BeFEMTO, machine learning tools are used for this purpose. Notably, two strategic learning mechanisms are considered, namely, evolutionary- and reinforcement-based learning mechanisms. In the former, femtocells exchange local information where the dynamics are analysed using tools from evolutionary games; whereas in the latter information exchange is no longer possible among femtocells, and the dynamics are analysed using tools from Reinforcement-Learning (RL). In both approaches, femtocells perceive the state of the environment and subsequently take actions, causing the environment to transit into a new state. The femtocell next receives a reward evaluating the quality of this transition and the process is repeated until eventual convergence.

Docitive Femtocells:

When multiple decision makers coexist in the case of a femto network, the environment is no longer stationary since it consists of other nodes who are similarly and simultaneously adapting. This may generate oscillating behaviours that not always reach an equilibrium and that are not yet fully understood, even by machine learning experts. The dynamics of learning may thus be long and complex in terms of required operations and memory, with complexity increasing with an increasing observation space. A possible solution to mitigate this problem, to speed up the learning process and to create rules for unseen situations, is to facilitate expert knowledge exchange among learners. Even as cognition and learning have received a considerable attention from various communities in the past, the process of knowledge transfer, i.e., teaching over the wireless medium has received fairly little attention to date. We thus introduce an emerging framework for femtocells, referred to as docition, from “docere” = “to teach” in Latin, which relates to nodes teaching other nodes. The femto BSs are not (only) supposed to teach end-results, but rather elements of the methods of getting there. This concept perfectly fits a femtocell network scenario, where a femtocell is active only when the users are at home.

Although the major emphasis of BeFEMTO is on Femtocells, aspects related to CR networks exist as the femto access point has cognitive or learning abilities for smart interference management/radio resource management. Some opportunistic spectrum re-use schemes have also been investigated.

3.1.1.18 SAMURAI (Spectrum Aggregation and Multiuser-MIMO, Real-world Impact) [74]

Website:	http://www.ict-samurai.eu/
ACROPOLIS Partners involved:	EURECOM
Project duration:	January 2010 – October 2012

Project Overview

Similarly to other cognitive-radio related projects, the SAMURAI project concentrates on the cost, energy and spectrum efficiency aspects of wireless transmission. The innovative techniques for multi-user multiple-input multiple-output (MU-MIMO) case will be investigated. Furthermore, issues related to spectrum aggregation will be considered. It is planned that the main attention will be paid to the practical implementation and deployment aspects.

ACROPOLIS related research activities

The SAMURAI project will demonstrate MU-MIMO and SA on real-time testbeds. Such an activity is particularly interesting for WP5 partners. Moreover, the following measurable technical objectives of the project are also of interest for the partners involved in particular research activities in various ACROPOLIS WPs:

- Development of a system level simulation tool (for modeling the impact of MU-MIMO and SA on capacity, average user performance, etc.) and of proof-of-concept (PoC) prototypes;
- Development and assessment of innovative MU-MIMO schemes, investigating practical implementation trade-off;
- Development and assessment of SA schemes, from the practical implementation perspective (hardware and software).

The part of SAMURAI which is most closely linked to ACROPOLIS is the work on SA, which targets decentralized dynamic spectrum management for femto/pico cell deployment using multiple component carriers.

3.1.1.19 SAPHYRE (Sharing Physical Resources – Mechanisms and Implementations for Wireless Networks) [75]

Website: http://www.saphyre.eu

ACROPOLIS Partners involved: TUD, EURECOM, EIT+

Project duration: January 2010 – December 2012

Project Overview

SAPHYRE focuses on demonstrating the advantages of equal-priority resource sharing in wireless networks. In particular it describes the benefits of equal-priority resource sharing in wireless networks understood as the improvement in spectral efficiency, enhancement of the coverage, increase of user satisfaction and revenue for operators.

ACROPOLIS related research activities

The SAPHYRE WP2 - Fundamental Limits is related to WP8 - Fundamental Research Methods and Tools in ACROPOLIS, and specifically to Activity 8.3 - Information Theory and Activity 8.4 - Game Theory and Optimization.

Activity 8.3 surveys the case studies provided by the information theory literature. The most relevant models will be covered and their results will be interpreted in context of the target applications of ACROPOLIS.

Activity 8.4 summarises the basic results from game theory and discuss their applications in the related scenarios of ACROPOLIS.

The results in the area of information theory and game theory from WP2 in SAPHYRE can be a reference for WP8 in ACROPOLIS.

3.1.1.20 CogX (Cognitive systems that self-understand and self-extend) [76]

Website: http://cogx.eu/

ACROPOLIS Partners involved: KTH

Project duration: May 2008 – June 2012

Project Overview

The CogX project focuses on the challenge of how “to understand the principles according to which cognitive systems should be built if they are to handle novelty, situations unforeseen by their designers, and open-ended, challenging environments with uncertainty and change” [76]. One of the main goals of this project is to investigate a unified theory of "self-understanding and self-extension" of the cognitive system. In other words, the project tries to create a theory "evaluated in robots" of how a cognitive system can model its own knowledge, use this to cope with uncertainty and novelty during task execution; extend its own abilities and knowledge; and extend its own understanding of those abilities.

ACROPOLIS related research activities

The concept of self-understanding and self-extending of the cognitive system, in CogX referred to robots, is of the highest interest to the ACROPOLIS partners. In particular, the achievement of the CogX project in the area of decision making can be important for partners working in WP12 in ACROPOLIS. Since the learning phase of the cognitive cycle is also investigated in the CogX project, the results achieved in this area are of particular interest to the ACROPOLIS partners.

3.1.1.21 PHYDYAS (Physical layer for dynamic spectrum access and cognitive radio) [77]

Website: http://www.ict-phydyas.org/

ACROPOLIS Partners involved: CTTC

Project duration: January 2008 – June 2010

Project Overview

A physical layer best suited to the new concepts of dynamic access spectrum management and CR is needed for future efficient wireless and mobile radio networks. The requirements of high data rates and flexible spectrum allocation are met by multicarrier techniques, which can approach the theoretical capacity limits in communications. The scheme used so far, Orthogonal Frequency Division Multiplexing (OFDM), is a block processing technique, which lacks flexibility and has poor spectral resolution. In contrast, a filter bank-based multicarrier (FBMC) technique offers high spectrum resolution and can provide independent sub-channels, while maintaining or enhancing the high data rate capability. In the project, algorithms for single and multi-antenna terminals, scalability and adaptivity, and multiple access were developed and demonstrated. The impact on CR was also investigated.

ACROPOLIS related research activities

The main research activities unexplored in PHYDYAS and related to ACROPOLIS are focused in WP7. More specifically in the ACROPOLIS Activity 7.2 titled: "Reconfigurability and Flexible Radio Systems", where different reference architectures will be considered, but at least one of the key baseline architectures will be OFDM based flexible radio architecture. In this context we will also consider FBMC as a basis for a possible flexible modem in CR network.

A more wide performance analysis between different filter bank schemes, Isotropic Orthogonal Transform Algorithm (IOTA), PHYDYAS FBMC, Non-Orthogonal Frequency Division Multiplexing (NOFDM), etc., is needed, mainly in more realistic environment assumptions. A unified and flexible structure, which encompasses almost all specificities of the above mentioned schemes, would be very beneficial. Complexity analysis between OFDM and FBMC schemes are more than recommended.

3.1.1.22 CONECT (Cooperative Networking for High Capacity Transport Architectures) [78]

Website:	http://www.conect-ict.eu/
ACROPOLIS Partners involved:	EURECOM
Project duration:	May 2010 – April 2013

Project Overview

The main goal of the CONECT project is to propose a holistic network design approach by unlocking the potential of broadcast wireless medium. Contrary to the typical approach, the received signal is not split into desired and interfering parts. Such an approach should lead to achievement of close to optimal end-to-end throughput, while energy consumption is significantly reduced and other performance metrics such as delay can be controlled.

ACROPOLIS related research activities

In the CONECT project, the information and communication theory, as well as protocol design engineering are considered from the perspective of cooperative information forwarding strategies and data fusion. These aspects are of interest for various WPs in ACROPOLIS, i.e., WP8, WP12. As the OpenAirInterface platform is used in both projects, results from the implementation activities in CONECT could be valuable for the ACROPOLIS community, especially for WP5 and WP7.

3.1.1.23 HELP (Enhanced Communications in Emergencies by Creating and Exploiting Synergies in-Composite Radio Systems) [79]

Website:	http://www.fp7-sec-help.eu/
ACROPOLIS Partners involved:	JRC
Project duration:	February 2011 – May 2012

Project Overview

HELP is working towards the establishment of a comprehensive solution framework for supporting public safety communications aspiring to significantly enhance the communication resilience and responsiveness in emergency situations. The solution framework is being built on two pillars: network sharing and spectrum sharing. Network sharing refers to the shared use of a network, or a part of it, by multiple users. Spectrum sharing is the application of technical methods and operational procedures to permit multiple users to coexist in the same region of spectrum.

ACROPOLIS related research activities

HELP is a Coordinated and Support Action project that focuses on two main aspects: network and spectrum sharing. Various approaches are identified and analysed in the framework of this action. Since the coexistence of multiple users in the same region of spectrum is considered, the achievements from this project can be significant for all WPs in ACROPOLIS.

3.1.1.24 EULER (EUropean Software Defined radio for wireless in joint security operations) [80]

Website: http://www.euler-project.eu/

ACROPOLIS Partners involved: JRC

Project duration: March 2009 – February 2012

Project Overview

The EULER project aims “to define and actually demonstrate how the benefits of SDR can be leveraged in order to drastically enhance interoperability and fast deployment in case of crisis needed to be jointly resolved” [80]. The activities considered in this project span various topics, i.e., proposal of a new high-data-rate waveform for homeland security, strengthening and maturing ongoing efforts in Europe in the field of SDR standardisation, implementation of SDR platforms, etc.

ACROPOLIS related research activities

One of the main goals of the EULER project is to propose the new waveform for emergency and security operations. Such an activity is crucial for all ACROPOLIS partners that deal with the CR physical layer. Moreover, the standardisation activities undertaken in the framework of this project are interesting for WP17. Finally, various hardware implementations were considered during the project lifetime, thus those issues are significant for ACROPOLIS WP5 and WP7.

3.1.1.25 CHRON (Cognitive Heterogeneous Reconfigurable Optical Network) [81]

Website: http://www.ict-chron.eu/

Project duration: July 2010 – June 2013

Project Overview

The CHRON project addresses the challenge of controlling and managing the next generation of heterogeneous optical networks supporting the Future Internet. Such networks will be of a highly heterogeneous nature, ranging from a wide variety of classes of services with different requirements, to wide physical layer diversity in optical transmission techniques and optical switching paradigms. The focus of the project is on the essential elements of the proposed cognitive network, in particular a cognitive decision system; an intelligent monitoring system; and a cognitive control system.

ACROPOLIS related research activities

The topics covered within the CHRON Project are related with the ACROPOLIS WP5 and WP7, where the various aspects of platform architectures are considered. Some aspects, although not directly, of the heterogeneity of various networks and systems are also considered in WP9 till WP12. From the ACROPOLIS point of view, the most important will be the area of cognitive management of the developed optical network and all algorithms used for decision making, learning, monitoring, etc. From that point of view all research WPs of ACROPOLIS network are related to the CRHON project.

The CHRON project provides a comprehensive view of the fundamentals of cognitive management of the optical networks. It will be excellent from the ACROPOLIS point of view to compare the results obtained within the both projects (ACROPOLIS and CHRON) and draw some conclusions, such as what are the differences between application of the flexibility (cognition) idea in the wired and wireless communication networks.

3.1.1.26 ECODE (Experimental Cognitive Distributed Engine) [82]

Website: http://www.ecode-project.eu/

Project duration: September 2008 - August 2011

Project Overview

The main goal of the project is to "develop, implement, and validate experimentally a cognitive routing system that can meet the challenges experienced by the Internet in terms of manageability and security, availability and accountability, as well as routing system scalability and quality" [82]. This goal has been reached by the consortium by combining various aspects of the networking and CR concepts, mainly semi-supervised, online and distributed machine learning. As it can be deduced from the project web-page the resulting cognitive routing system revisits the capabilities of the Internet networking layer.

ACROPOLIS related research activities

The results of the ECODE project are highly important for the ACROPOLIS project, especially issues related to machine learning and decision making. Moreover, implementation issues of the cognitive routing system could be the subject of interest for the partners working on cognitive networks.

3.1.1.27 SOCRATES (Self-Optimisation & self-ConfiguRATion in wirelEss networkS) [83]

Website: http://www.fp7-socrates.org

Project duration: January 2008 - December 2010

Project Overview

The SOCRATES project addresses a crucial problem of future communications networks, i.e., the self-organisation, comprising the self-optimisation, self-configuration and self-healing. The goal behind such an approach is to reduce the operation expenditure (OPEX) by diminishing human involvement.

3.1.1.28 ADVANCE: (Advanced predictive-analysis-based decision-support engine for logistics) [84]

Website: http://www.advance-logistics.eu/

Project duration: October 2010 – September 2013

Project Overview

ADVANCE will develop an innovative predictive-analysis-based decision support platform for novel competitive strategies in logistics operations. The following aspects will be employed: data mining, machine learning and optimisation techniques to aggregate structured but locally confined data, and extract actionable information to improve local dispatching decisions.

ACROPOLIS related research activities

Since the ADVANCE project is only slightly related with the ACROPOLIS NoE, only some aspects related to intelligent management, machine learning and decision making issues are interesting from the NoE point of view – thus covering problems investigated in WP11, WP12 and WP13.

Since the main outcome of the project is to deliver the open-source platform and solid background material, it will be beneficial to verify the practical implementation of various decision making algorithms.

3.1.2 COST Actions

3.1.2.1 IC0902 COST Action on Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks [85]

Website: http://newyork.ing.uniroma1.it/IC0902/

ACROPOLIS Partners involved: KCL, Uniroma1, RWTH, CTTC, EIT+, UPRC, PUT

Project Overview

The main objective of the COST Action IC0902 is to integrate the cognitive concept across all layers of communication systems, resulting in the definition of a European platform for CR and networks. The Action proposes coordinated research in the field of CR and networks.

The cognitive concept applies to coexistence between heterogeneous wireless networks that share the electromagnetic spectrum for maximum efficiency in resource management. Several efforts are currently in place in European research centres and consortia to introduce cognitive mechanisms at different layers of the communications protocol stack. This Action goes beyond the above trend by integrating the cognitive concept across all layers of system architecture, in view of joint optimization of link adaptation based on spectrum sensing, resource allocation, and selection between multiple networks, including underlay technologies.

ACROPOLIS related research activities

IC0902 Activity	ACROPOLIS Mapping
Working Group 1 – Adaptation and configuration of a single link according to the status of the external environment: the group activities focus on spectrum sensing and link adaptation, as well as on platforms, testbeds and hardware	WP5, WP7 (Activity 7.2 on reconfigurable radio systems) WP9 (Activity 9.1 on spectrum sensing) WP13 (Activity 13.1, especially for signal processing)
Working Group 2 - cooperation-based cognitive algorithms, that take advantage of information exchange at a local level: group activities focus on cooperative solutions for spectrum sensing, relaying and network coding in cognitive networks, as well as of the definition of representation languages for information exchange at local level	WP8 (Game theory) WP9 (Cooperative spectrum sensing) WP10 (Cooperation at local level in general)
Working Group 3 - Definition of network-wide mechanisms for enabling the cognitive approach. Group activities focus on the definition of end-to-end algorithms and protocols, including routing and admission control.	WP10
Working Group 4 - Definition of mechanisms for intersystem coexistence and cooperation: group activities focus on the design of solution for intersystem cooperation and coexistence, e.g., by defining common channels. The Group also acts as the collecting point for regulation and standardisation related issues.	WP10 (Activity 10.3) WP6, WP17 both for standardisation and regulation aspects.
Working Group 5 - Definition of a cross-layer cognitive engine: the group activities focus on the definition of a cognitive engine capable of taking advantage of cross-layer information, multiple RAT. Artificial intelligence and learning techniques are also investigated in this group.	WP12 (decision engine) WP8 (Activity 8.1 on Machine learning)

Table 3-2: IC0902 COST Action ACROPOLIS related research activities

Research assessment and suggestions

Activities in IC0902 are proceeding along the directions set by the 5 Working Groups described above. Among other activities, the following results and initiatives, mainly related to work carried out in Working Groups 1 and 2, are particularly appealing from the point of view of ACROPOLIS:

- Creation of a knowledge platform on Cognitive testbeds, to be made available at the beginning of 2012 on the Action IC0902 website, summarizing the characteristics of the testbeds available to IC0902 participants and, at a later stage, providing a critical overview and analysis of all main cognitive testbeds.
  Action for ACROPOLIS: take in to account the initiative and liaison with IC0902 to ensure complementarity in testbeds-related activities (WP5/WP7).
- Several sub-activities have been started in WG2, namely:
  - Cooperative spectrum sensing;
  - Signalling techniques to alleviate interference in space and beamforming;
  - Cooperative relaying schemes;
  - Resource allocation / Network self organization/Game theory.

  Action for ACROPOLIS: explore the possibility of joint work on these topics, particularly relevant for WP8 and WP9.

New trend(s) and the main direction(s) of the IC0902 actions with respect to the rest of the community

The main goal of the IC0902 project is to create a European platform for CR, encompassing all aspects related to CR and networks. So far, the activity mainly focused on testbeds, physical layer and link layer aspects (as shown by the amount of contributions submitted for WG1 and WG2 sessions at the Action workshops, see above) but it is expected that in the second half of the 4-year life span of the Action aspects related to cross-layer information integration and inter-network coexistence mechanisms will be further explored as well. Solutions developed within the Action will be organized and made available in a wiki-like tool under preparation that will be reachable from the Action website.

3.1.2.2 IC0905 COST-TERRA Techno economic regulatory framework for radio spectrum access for CR/SDR [12]

Website: http://www.cost-terra.org/

ACROPOLIS Partners involved: KCL, Uniroma1, RWTH, CTTC, EIT+, UPRC, PUT

Project Overview

COST-TERRA is a forum to bring together technical and economic experts for spearheading a regulatory break-through for European development of CR and SDR technologies.

The project was launched in May 2010 and will run until May 2014, with the main focus on the coordination of technical and economic studies towards the development of a harmonized European regulatory framework for CR and SDR. It is hoped that this framework will propel forward the realisation and deployment of CR and SDR systems, while maximising their potential in Europe and elsewhere.

The Action is organized into 4 Working Groups:

- Working Group 1 “CR/SDR deployment scenarios”: WG1 has the goal of collecting and classifying deployment scenarios provided by both the technical/engineering and the business/economics communities; the result of WG1 activity should be a set of potential scenarios to be evaluated by other WGs in the project.
- Working Group 2 “CR/SDR co-existence studies”: WG2 focuses on the evaluation of technical aspects in deployment scenarios identified in WG1, aiming at finding a subset of scenarios suitable from a technical point of view.
- Working Group 3 “Economic aspects of CR/SDR regulation”: this WG has a twofold goal; first, it will complement WG2 in evaluating the scenarios identified in WG1, focusing on economic aspects; second, it will analyse the potential impact of regulations proposed in Europe and worldwide for CR/SDR operations, aiming at identifying suitable rule sets capable of favouring the development of a market for CR applications.
- Working Group 4 “Impact assessment of CR/SDR regulation” will build on the work carried out in WGs 1-3 by identifying the most promising sets of regulations that could make CR/SDR feasible from both technical and economic point of views, and carrying on an assessment of such sets of regulation.

Several ACROPOLIS partners play an active role in COST-TERRA. Uniroma1 has a representative on the Management Committee, and holds the chair of WG1; KCL has a representative of in the MC as well, and acts as Vice-Chair of the Action, and Vice-Chair of WG1.

KCL is very active within two recently-establish CR-related COST actions: IC0902 and IC0905. KCL has a representative on the Management Committee of both COST efforts, and acts as Chair of the Special Interest Group on “Information Representation Languages” within IC0902. KCL acts as Vice-Chair of IC0905, and Vice-Chair of Working Group 1 on “CR/SDR Deployment Scenarios” in IC0905.

3.1.3 National Programs

In this section, various national activities are presented. Let us highlight that the selection of the projects (and their respective countries) was made arbitrarily, without any political preferences, etc. The presence of the particular projects was conditioned also by the ability of getting solid information.

3.1.3.1 Cognitive wireless systems (GERMANY) [86]

Website: http://www.pt-it.pt-dlr.de/de/CognitiveRadio.php

Cognitive Wireless Systems is a broad activity, which can be described as three collections of twenty projects realized between 2012-2015; total volume 11 Mio €.

Program overview

The growing demand for bandwidth by the mobile use of the Internet cannot be met by the use of any new frequencies. Strong absorption by the atmosphere makes the use of frequencies above 5 GHz impossible for larger distances. A significant additional potential can be tapped by the most efficient and uniform utilization of the frequency resources forehand. These technologies for on-demand allocation of frequencies are required.

The aim of the joint project CoMoRa is the demonstration of a concept for dynamic spectrum management, in which today's rigid spectrum allocation (e.g., exclusively for mobile, broadcasting and wireless event technology) is deliberately abandoned. In this innovative concept of cognitive wireless communication systems, valuable resources are used economically and efficiently and allow several competing radio services to operate in parallel in previously inefficiently used spectrum bands.

In the project KogLTE, an innovative radio for in-home mobile radio applications constantly examines the variable radio environment looking for the optimum frequency for wireless communication.

The subject of the joint project KUSZ is a radio system for the wireless networking equipment industry, which independently identifies the free radio channels of the individual radio stations. This will both prevent interference with other wireless devices effectively and allows for optimal utilization of the available frequencies without license costs incurred. The control of industrial plants sets special demands on the reliability, speed and reliability of data transmission.

3.1.3.2 DFG focus research program COIN (communication in interference limited networks (GERMANY) [87]

Website: http://www.coin-dfg.de/

COIN is another big program started in Germany. A short description of its main targets and considered research problems is provided below.

Program overview

Information and communications systems are the technological foundation of the modern information age. One of the defining characteristics of the information society of the future will be the technological advance of wireless communications systems. In wireless communication networks, of which the physical basis is the propagation of electromagnetic waves in free space, the control of interference phenomena—interference is the strongest limiting factor in radio communications—will play a key role.

Comparable approaches in conventional communication systems are based on cellular network topologies and the principle of orthogonal access, thus ideally eliminating mutual interference between information carrying signals. The realistic physical properties of the transmission channel as well as the underlying network topologies, however, require strategies and concepts beyond the current state of the art, especially considering the demand for highest data rates, QoS criteria, and flexibility. The object of these novel strategies is the joint, and possibly distributed, processing and coding of information, as well as the cooperation of all nodes of the network; they result in radically novel approaches in the treatment of communications problems that must be reflected in fundamentally new mindsets.

The goal of the program is to develop these new paradigms. A first, already initiated, change of paradigm consists of no longer attempting to avoid interference at the expense of resources (energy, bandwidth, etc.), but to systematically control and coordinate it, and to finally rethink the meaning of the term interference. The second change of paradigm supported by COIN is based upon an alternative theory of communications that supersedes the conventional transport model and is predicated on an evidence based model: “A bit is not a car!”

ACROPOLIS related research activities

Interference management and cooperative strategies: Investigation and development of innovative concepts for the optimization of communication processes in cellular and alternative network topologies based on distributed algorithms, in particular with regard to control and coordination of interference as well as cooperative strategies using methods of distributed coding and signal processing.

Evidence based methods: Fundamental research for the development of evidence based communication techniques that combine the latest approaches in the areas of Distributed Network Optimization, Network Coding, and Relaying, and thereby initiate a change of paradigm in the area of communications.

3.1.3.3 E3 National Participation (GREECE)

Project Duration: 27/7/2010 – 23/11/2011

E3 project National Participation, funded by the General Secretariat of Research and Technology (GSRT) of the Greek Ministry of Development, is a project dedicated to the diffusion of the results of End-to-End Efficiency (E3) EC project. As a result, it is a project based on E3 project and basically targets at disseminating its results. This may involve conferences, papers, tutorial, lectures or even courses.

3.1.3.4 Analysis and modelling of dynamic spectral resource management in cognitive radio networks (SARUMAN) – (FYROM)

SARUMAN is financed by the Faculty of Electrical Engineering and Information Technologies (FEEIT), UKIM. It focuses on research and development of techniques for increasing awareness on spectrum availability and utilization in today’s wireless systems. This will be achieved through a development of a measuring methodology and intensive measurement campaign on two different locations (urban and rural) in the F.Y.R.O.M. using state-of-the-art measuring equipment. The measurement results should reflect on the temporal and spatial variations in the spectrum utilization, i.e., to give an insight into the (under)utilization of the available radio spectrum in today’s wireless systems which employ static allocation of radio spectrum. In this manner, the notions of DSA and CR will be introduced and justified. SARUMAN's measurement results will also allow the derivation of empirical models for spectrum utilization and creation of spectral maps by nodes which, potentially, have cognitive capabilities and can dynamically use the spectrum. Moreover, SARUMAN will develop solutions and algorithms for cooperative exchange of spectral maps among different cognitive nodes, which will increase the efficiency of the spectrum utilization monitoring process. The end goal would be to develop a system architecture that uses the concepts of dynamic spectrum access and CR. It will contribute to the promotion of these concepts in the national standardisation process and the development of future wireless systems.

3.1.3.5 Assessment of available spectrum for secondary access in the Republic of Macedonia (PROSPEKT) – (FYROM)

PROSPEKT is a project funded by the Ministry of Education and Science.

The PROSPEKT project focuses on the research and development of an innovative methodology for assessment of available spectrum for secondary usage in F.Y.R.O.M. The methodology will comprise several steps: 1) analysis of relevant scenarios of interest (e.g., secondary cellular access in TVWS), 2) defining relevant performance metrics (e.g., spectrum availability, primary user protection, etc.), 3) development of a simulation model that comprises modelling of locations and characteristics of primary systems, 4) a measurement campaign on two different locations (urban and rural) in F.Y.R.O.M. for checking the validity of the developed simulation model and 5) analysis of the obtained simulation results and assessment of the available spectrum for secondary access. The final goal of the PROSPEKT project is to give an insight whether there is an available spectrum for secondary access in specific scenarios in F.Y.R.O.M. and, if any, to what extent. At the same time, PROSPEKT will promote these concepts in the standardisation process on national level and will facilitate the development of future wireless systems.

3.1.3.6 DiRecTRadio: All-Digital Reconfigurable System-on-Chip Transmitter for Cognitive Radio Systems (PORTUGAL) [88]

Website: http://www.it.pt/project_detail_p.asp?ID=1545

Project duration: July 2011 – July 2012

Project overview

In this project the main objective is to study, design, prototype and evaluate innovative System on Chip architectures and synthesizable models for flexible, all-digital and fully integrated transmitters for CR systems. Building all-digital flexible transmitters requires traversal competences on different areas, namely, reconfigurable digital systems, signal processing and RF design.

ACROPOLIS related research activities

The research conducted in the DiRecTRadio project is relevant to the hardware-related activities of ACROPOLIS in WPs 5 and 7.

This project tackles various issues regarding the building of transmitters for CR systems. The results of this research and the knowledge gained can be considered in the hardware related issues of ACROPOLIS project.

3.1.3.7 OPPORTUNISTIC-CR: Opportunistic Aggregation of Spectrum and Cognitive Radios: Consequences on Public Policies (PORTUGAL) [89]

Website: http://www.it.pt/project_detail_p.asp?ID=1433

Project duration: January 2011 – January 2013

Project overview

The OPPORTUNISTIC-CR project intends to design, implement and demonstrate "cooperative networking and optimization strategies" for next generation networks that will provide a significant step towards network convergence in a truly heterogeneous environment. Multi band-common radio resource management strategies are considered, assisted by a prediction tool/algorithm that provides the future position and traffic demand of a mobile node for maximizing network resources utility and QoS delivery. By assuming a secondary usage of the spectrum, the spectrum utility maximization is ensured. These visions will be complemented by a business feasibility study, and will include innovative graphical cellular planning tools.

ACROPOLIS related research activities

The activities of the OPPORTUNISTIC-CR project are highly related to the ACROPOLIS project. Issues such as radio resource management, spectrum aggregation, QoS provision, spectrum utility maximization are among the common topics addressed in both projects.

The research results of the OPPORTUNISTIC-CR project can be considered in most areas of the ACROPOLIS.

3.1.3.8 TACCS: Cognitive Radios Adaptable Wireless Transceivers (PORTUGAL) [90]

Website: http://www.it.pt/project_detail_p.asp?ID=1264

Project duration: January 2010 – January 2012

Project overview

This project aims to study most of the physical layer issues of CR, starting from agile Radio Frequency (RF) front ends, but also considering digital implementations, either Field-Programmable Gate Array (FPGA) based, but also Digital Signal Processing (DSP) based.

ACROPOLIS related research activities

The research conducted in the TACCS project is relevant to the hardware-related activities of the ACROPOLIS project in WPs 5 and 7.

This project tackles various issues regarding the physical layer in CR systems. The results of this research and the knowledge gained can be considered in the hardware related issues of the ACROPOLIS project.

3.1.3.9 APOGEE: Analyse et oPtimisatiOn des systèmes d'après 3èmeGEnEration (FRANCE) [91]

Website: www.openairinterface.org/projects/page1046.en.htm

Project duration: February 2008 – April 2010

Project overview

The objective of APOGEE is to propose physical layer technologies (MIMO schemes, advanced detection, channel coding) and multiple-access techniques (resource allocation) in keeping with the different versions of the on-going 3rd Generation Partnership Program (3GPP) standardisation process in order to attain uplink spectral efficiencies of 2.5 bits/s/Hz at minimal user terminal implementation complexity and power consumption. In addition, validation of the considered technologies is carried out through experimentation using a hardware demonstrator made up of two terminals and a base station including MIMO RF front-ends working in real-time.

ACROPOLIS related research activities

The APOGEE project mainly concerns 3GPP networks. However, it studied advanced PHY/MAC technologies covering the needs of emerging wireless systems.

Although the main area of interest of the APOGEE project is 3GPP networks, the gained knowledge on advanced Physical and MAC layer issues and the possible applicability of the results in CRNs can be considered by ACROPOLIS.

3.1.3.10 ECOCells: Efficient Cooperating Cells (FRANCE)

Project duration: 2009-2012

Project overview

The Small Cell Networks (SCNs) envisaged in ECOCells provide a transparent plug-and-play infrastructure, which can be deployed in an instantaneous manner and which can evolve on its own (energy and configuration-wise), without any human intervention.

ACROPOLIS related research activities

The research of the ECOCells project on the co-existence and cooperation of different systems and the need to address the possible conflicts is directly related to ACROPOLIS, especially regarding efficient interference management techniques and the deployment of appropriate channel models.

The adaptation decisions that need to be taken by SCNs in order to adapt to the rapid changes of the system conditions and combat unacceptable interference are directly related to the ACROPOLIS activities. The derived knowledge can be considered by the members of ACROPOLIS.

3.1.3.11 IDROMel: Impact of reconfigurable equipment for the deployment of future mobile networks (FRANCE) [92]

Website: http://www.openairinterface.org/projects/idromel.en.htm

Project overview

IDROMel aims at developing reconfigurable (SDR) equipment able to communicate through at least two RATs using two different frequency bands. The goals of the project include the design and implementation of a prototype of a universal communication system, comprising a mobile terminal and a base station, the exploring of the possibilities for rapid adaptation of telecommunications equipment, and the development of an algorithm and simulator to test and to optimize the reconfigurability.

ACROPOLIS related research activities

The main area of interest of IDROMel is CR and equipment reconfigurability, which is directly related to the ACROPOLIS activities.

The topics covered in the IDROMel project include reconfigurability issues and the rapid adaptation capability of telecommunications equipment. The gained knowledge can be considered by the ACROPOLIS project, especially in the activities related to SDRs and CR Platforms and Reconfigurability and Flexible Radio Systems.

3.1.3.12 PROTON/PLATA: PROgrammable Telematics ON-board radio (FRANCE) [93]

Website: http://www.openairinterface.org/projects/proton_plata.en.htm

Duration: September 2008 – September 2010

Project overview

The joint PROTON/PLATA project defines the architectural design of a SDR-based low-cost multi-standard radio platform for telematics including demonstration capabilities for dedicated use cases. An SDR communication testbed was developed for vehicular integration to prove actual on-board vehicle communication requirements for safety applications. In particular, the PROTON/PLATA platform is capable of supporting different communication standards simultaneously, e.g., IEEE 802.11x and digital broadcast reception systems, e.g., Digital Audio Broadcasting (DAB) including traffic data services. Hereby, the main focus is based on the definition and investigation of co-existence scenarios for such communication systems.

ACROPOLIS related research activities

The use of SDR as a key technology that enables the implementation of co-existent wireless communication systems within one identical hardware architecture is directly related to the ACROPOLIS activities in WPs 5 and 7. SDR technology provides the appropriate technology framework for maximum flexibility, adaptivity and re-configurability of the system for the future deployment of next-generation wireless and advanced telematics services.

3.1.3.13 Mobile Innovation Centre (MIK) Programs (Hungary)

In 2005, The Mobile Innovation Centre (MIK) of Hungary [94] was founded as a result of the National Office for Research and Technology's call for proposals "The Establishment of R&D and Innovation Centre for Mobile Communication". The Centre is based on the cooperation of universities, an academic research institution, industrial companies, suppliers and organisations dealing with scientific research and innovation, including the representatives of profit-oriented and non-profit sectors.

Below, the main integrated projects related to cognitive communication conducted within MIK are listed and shortly described. The gathered information is based mainly on the MIC Final Report [95].

Medium Radio traffic evaluation, resource management and algorithms for effective transmission in mobile networks

Up till now, the main goals of the project were mainly the evaluation of the performance, transmitted traffic and capacity of the radio interface in current and future relevant mobile systems. The other main objective was the development of different algorithms (radio resource management, coding, medium access) applicable in these networks in order to increase the perceived performance of customers. In several areas, deep theoretical investigations were necessary, but the goal of most development and investigation activities was to provide methods and results with practical use potential, hence the frequent consultation with industrial partners had key importance.

The main result of the project is a simulation software system, that allows the packet level investigation of current 3GPP mobile networks and the radio interfaces of networks that are likely to be deployed in the near future, i.e., UMTS, High Speed Downlink Packet Access (HSDPA), LTE. Besides 3GPP standards, the IEEE 802.16 WiMAX and 802.16e mobile WiMAX systems are also implemented in the software package. In the latter case, mobility and multicell operation is also incorporated.

ACROPOLIS related research activities

a) in WP8, methods for improving the transmission efficiency (adaptive coding and modulations, radio resource management), and b) in WP5 the software simulation platform.

Emerging wireless technologies

The aim of the project is to gain complex knowledge on the physical layer and improve it, from modern modulation methods through adaptive antennas to general multi antenna techniques. Participants examining both traditional mobile frequency and the prospective future millimetre range wireless systems from a link and a system point of view. They are emphasizing research on MIMO systems, mainly from antenna and propagation aspect, but also paying attention to applications and performance analysis. One of the main goals are developing a channel sounder based on software radio technology for measuring real MIMO channels.

ACROPOLIS related research activities

a) for WP7 and WP8, modulation schemes and adaptive antennas, and b) for WP5, applications of adaptive antennas systems.

Intelligent Workspace

The "Intelligent workspace" integrated project, in its present form, was introduced during the second project year, combining the work from four previous sub-projects. The "Integration of sensor and mobile networks" sub-project aimed at designing applications that would provide the bridging between WSNs and different mobile networks. Besides that, pursuing research activity related to the communication of WSNs was also an important goal. Researchers tried to answer questions related to the load balancing and the extension of network lifetime in setups with one or more mobile sink nodes that move adaptively in function of the current events in the network. The "Optimization of WSNs" sub-project started with similar goals, putting special emphasis on routing issues, packet classification algorithms, and on designing a health and environment monitoring system. The general purpose of the "Digital Rights Management" sub-project was to develop or adapt protocols and algorithms that are able to provide Digital Rights Management (DRM) functionalities for mobile devices of a heterogeneous wireless network. Finally, the main goal of the "Real-time multimedia information transmission" sub-project was to create an intelligent multimedia distribution network, which supports both the currently used and the future access technologies.

The activities of the above described four sub-projects were merged into an integrated project that aimed at developing applications that can be related to an intelligent workspace. Such applications are: gesture recognition and gesture- based control, information panel, virtual post-it, or indoor climate monitoring.

ACROPOLIS related research activities

a) the algorithms controlling the adaptive movements of mobile sink nodes in WSN in order to improve energy efficiency (WP8, WP11, WP12), b) neighbouring users position estimation by the received signal strength (WP8, WP10).

Integrating heterogeneous wired and wireless networks

The project focuses on the security, QoS, billing and compatibility problems rising in an integrated IP Multimedia Subsystem (IMS) based Next Generation Network (NGN) environment. The results of the project enable new types of telecommunication services, to be provided with the same quality, regardless of the users' type of network connection (e.g., wired or mobile wireless).

One of the important project results is the multi-gateway mesh network testbed allowing the testing and validation of protocols for multi-gateway operation. In order to support the fast handover between the mesh access points, a fully decentralized, fast mesh client authentication protocol, which supports the multi-operator environment was designed and implemented. The protocol is based on certificates issued to the mesh clients and verifiable by the mesh access points in an off-line manner. The execution time was optimized through evaluation and selection of signature algorithm.

ACROPOLIS related research activities

a) QoS and security aspects in heterogeneous radio environment (WP14), b) vertical handovers (WP12, WP13).

Investigation of User Behaviour

The main goals of the projects are: the identification of user behaviour patterns and user groups, which entails the examination and development of processing of data available on users and their behaviour patterns; the examination of the interactions between users and their mobile phones and the design and use and also the further developmental possibilities of user interfaces; and the examination of the restructuring of content production, dissemination and consumption patterns.

ACROPOLIS related research activities

User behaviour patterns, theoretical examinations and measurements of data traffic (WP8, WP11).

Trends and research directions

As it was stated above, research directions in Hungarian scientific institutes are steered by the Hungarian government. Regarding wireless and mobile telecommunications the main national initiative is MIK fostering collaboration of several academic and industry research institutes/companies. As the strategy of MIK is to develop and investigate technical issues in existing and approaching telecommunication systems, the CR technology is not taken into account as a whole concept. Instead of that, several integrated projects face the particular problems emerging in modern wireless communications. Relevant investigations are related to algorithms and methods improving the transmission efficiency, modelling of users' data traffic and behaviour, and general issues emerging from integration of heterogeneous wireless 3G and B3G systems.

3.1.4 Other projects and activities

3.1.4.1 Mobile VCE [96]

Website: http://www.mobilevce.com/

ACROPOLIS Partners involved: KCL, UoS

The Virtual Centre of Excellence in Mobile & Personal Communications Limited (Mobile VCE) is a collaboration of academia and industry, whereby companies subscribe to participate in the collaboration with a number of associated benefits such as access to Intellectual Property Rights (IPR) resulting from the academic work therein. The universities perform the research in Mobile VCE, and industrial companies advise on appropriate research directions and learn of interesting results and progress through participation in "Technical Steering Group" meetings and other means.

Mobile VCE Core 4

KCL has performed a range of work within Mobile VCE Core 4 on CR and Spectrum Sharing paradigms, within the scope of the "Delivery Efficiency" work area. This has included interference management concepts for CR (underlay access in line with the "Interference Temperature" concept), definition of multiple-access approaches appropriate for CR, game theory in resource sharing, spectrum management, among other areas. UoS has also heavily participated in spectrum sharing concepts within Core 4, such as sharing between UMTS operators.

Mobile VCE Core 5

Within the "Green Radio" work area of Mobile VCE Core 5, KCL has been working on various solutions to save energy through DSA paradigms. These have included methods for the dynamic collection of services to operate within certain bands to maximise reuse of radio equipment in those bands and allow sleep modes for other radio equipment. Work has also looked at spectrum usage optimisation to save transmission energy in the light of propagation characteristics and traffic load variations, and opportunistic transmission bandwidth switching modes to save necessary transmission energy. Moreover, energy saving though maximising the use of offloading to Wi-Fi has been investigated, including offloading to Wi-Fi services deployed in TVWS.

3.1.4.2 NATO group IST077-RTG035 Cognitive radio in NATO [97]

Website: http://www.cttc.es/en/projectState/ongoing/project/100705-ist077-rtg035-co.jsp

ACROPOLIS Partner involved: CTTC

CR is a futuristic radio system that is able to survey its radio environment, understand the radio propagation conditions and adaptively transmit according to user demands in momentarily free spectrum gaps. Essentially, a CR node must be capable of locating itself, sniff its surroundings, analyse the usage of the captured spectrum through a cognitive process, and transmit data without interfering other transmissions while satisfying the users QoS requirements. To ensure non-interference, the CR node must exploit holes in the frequency, time, spatial and/or code dimensions where no transmission is detected. The proposed work of the IST task group is:

- To make a review and synthesis of the CR Technologies explored within NATO countries in the military field.
- To make a review of Civilian Technologies available for Military CR now and at mid long term.
- To investigate the techniques and technologies which could be implemented at mid long term in a CR and provide a technology roadmap planning.
- To analyse the benefit of CRs integration in NNEC NII architectures.
- To propose to the NATO community relevant axis of works on CR.

3.2 Projects in the rest of the world

3.2.1 Projects in the Americas

Extensive research has or is being carried out in North America. Within the USA, it is perhaps fair to say that a significant amount of the research has been funded for military and public safety purposes. A major driver of such projects is DARPA. Two key efforts under DARPA are the XG project [7], which is now completed, and the Wireless Network after Next (WNaN) project [98].

3.2.1.1 The neXt Generation (XG) Project

The objective of XG was to "develop both the enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms in order to provide dramatic improvements in assured military communications in support of a full range of worldwide deployments" [7]. XG work was on policy-based decision making for CR, whereby the primary product of the XG programme was not a new radio, but a set of advanced technologies for DSA. XG aimed to develop a de facto standard for CR, and progressed in three phases:

- Technical investments (2002-2003),
- System and protocol design (2003-2005),
- System development and demo (2005-2008).

Although XG is completed, it is notable for its advancement of CR technologies. In particular, a key demonstration of CR in operation was reported at DySPAN 2007, involving multiple moving XG radios forming a network and dynamically changing transmission frequency in response to changing interference dynamics based on movement [99].

3.2.1.2 Wireless Network after Next (WNaN) Project

WNaN aims to develop and demonstrate technologies and system concepts enabling densely deployed networks in which distributed and adaptive network operations compensate for limitations of the physical layer of the low-cost wireless nodes that comprise these networks [98]. WNaN networks will manage node configurations and the topology of the network to reduce the demands on the physical and link layers of the nodes.

The objective of WNaN is to achieve reliable and highly-available communications at low system cost, and to develop a prototype handheld wireless node that can be used to form high-density ad hoc networks and gateways to the Global Information Grid. The project also aims to develop robust networking architecture(s) that will exploit high-density node configurations from related DARPA programs. It is aimed to culminate in a large-scale network demo of inexpensive multi-channel nodes. A major capability of WNaN nodes is DSA; WNaN implies wireless ad-hoc networking between CRs [100].

3.2.2 Projects in Asia

3.2.2.1 Japan

A number of projects of relevance to CR and DSA are being carried out in Japan by the National Institute of Information and Communications Technology (NICT). These are primarily under the Smart Wireless Laboratory (SWL) [101], and specifically the Cognitive Wireless Communications group. The work therein involves all aspects of such communications, from sensing, to physical and MAC layer design, and to learning mechanisms and knowledge management, among other areas.

CR is a technology which is expected to be a remedy for serious spectrum scarcity in highly developed and crowded Japan. Rapidly increasing customers' demand for high-speed Internet connections and new wireless services lay solid foundation for extensive investigations in ITC sector.

Governmental radio policy

In September 2000, the Japanese government announced the “e-Japan” policy and according to this policy, “e-Japan strategy and program” was drafted in 2001 [102].The main target of the e-Japan program was to deploy high speed communication environments and make Japan the most advanced country in the world in the end of 2005. According to the e-Japan program, the Ministry of Posts and Telecommunication (MPT), currently Ministry of Internal Affairs and Communications (MIC), started several study committees and councils on future wireless technologies and systems, advanced wireless systems and new policy of frequency allocations.

The e-Japan policy was followed by u-Japan policy in 2006 [103], whose main target was to realize a "ubiquitous network society" based on broadband networks. In ubiquitous networks, a seamless ubiquitous network environment should be created, in which people can receive services without being conscious of the networks, either wired or wireless. From a technical point of view, this will be realized by CR networks. According to these main ICT policies and strategies, MIC has many committees and study groups to draft future visions and technologies to be realized and developed. In the following the study groups most closely related to CR were listed.

- Study group for "Future visions of radio utilizations" under Radio policy committee" (2008.10-2009.4) - the mission was to draft future visions of radio systems, applications, and technologies to be realized in 2010s; further, the study group discussed the technical and political matters of effective use of frequency resources in 2010s;
- Study group of "Advanced ITS radio systems" (2008.10-2009.6) – the main missions was to discuss future visions and technologies of advanced Intelligent Transportation Systems (ITS), which will provide safety and comfortable transportation systems. CR was identified as one of the key technologies to realize the advanced ITS. Communication characteristics of moving vehicles change from time to time and place to place. When CR technologies are adopted, it is greatly expected to improve communication quality and to reduce interferences with other systems.
- Study group for "Future vision of new radio utilizations" (2009.12-2010.7) – the main mission was to discuss how to use and how to promote "white space" radio resources. As to the new technologies such as CRs, the final report published in July, 2010 concluded that: (1) Research and Development (R&D) and systematic operational experiments based on R&D should be continuously carried out, (2) in order to strengthen world's competitiveness, Japan should actively contribute to standardisation organizations such as IEEE, ETSI and ITU and (3) based on these activities, Japan should search for the deployments in other countries.

Research programs and projects related to cognitive communications

Below, the most important Japanese national programs related to CR are introduced.

MASCOT

MASCOT (Mobile Access Signalling Card On Telecommunication systems) (1997-2000) was the first R&D project related to the present CR systems. The project was proposed by representatives of CRL (Communications Research Laboratory), Ministry of Posts and Telecommunications, present NICT: National Institute of Information and Communications Technology. The key point of MASCOT was to propose a novel basic mobile access system, which may realize personal mobility in mobile communications independent of services and frequencies. The MASCOT system used a small radio card for bi-directional low-bit-rate data communications, and provided only signalling function and location registration function using a dedicated out-band common signalling channel.

MIRAI

MIRAI (Multimedia Integrated network by Radio Access Innovation) project (2000-2005) as a part of the "e-Japan" program succeeded MASCOT project in 2002 to develop new technologies to enable seamless integration of various wireless access systems for practical use by the year 2005. In the MIRAI project, the requirements on a new-generation wireless systems (in 2002, the forthcoming 4th Generation systems were targeted) were discussed. The fundamental goal was to make the existence of heterogeneous networks transparent to users. Another goal was to design a system architecture that is independent of the wireless access technology. These considerations lead to the requirements, which are almost the same requirements for the present CR systems (multi-service user terminal, wireless system detection, wireless system selection, mobility management, location update and paging, personal mobility).

CWC

NICT has carried out the R&D of cognitive wireless systems since 2005 after MIRAI project. In these years, the project is called "CWC (Cognitive Wireless Cloud)". This term refers to CR systems which are working with cooperation with networks [104].

In CWC, a Network Reconfiguration Manager (NRM) collects measured data of each terminal such as data speed, delay time, throughputs and signal strength. The NRM analyses the collected data and feedbacks the optimized information to the terminal to allow it to access to the most appropriate wireless system in a more efficient and effective manner.

In CWC, radio equipments with multiple different air interfaces autonomously utilize the most appropriate infrastructure wireless networks/spectrums, and configure their own reconfigurable wireless network by:

- sensing context information from available wireless networks/spectrums,
- storing the context information in the cloud network as database,
- analysing available context information,
- dynamically making spectrum access decisions on the most appropriate configuration
- t(s) / spectrum (s) that can fulfil user's and/or network operator's policy such as
    - Maximization of throughput or capacity,
    - Minimization of radiation of interference,
    - Highly-maintained co-existence between wireless networks managed by CWC,
- reconfiguring themselves seamlessly to the selected set(s).

R&D programs by the fund of "Spectrum User Fee" System

In April 1, 1993, MIC introduced the Spectrum User Fee System in order to secure the fair use of radio waves. This is to secure a radio user environment without mixed or obstructive signals, and also to digitalize licensing procedures and promote a more efficient way of radio use, in order to cope with the enormous increase in radio stations. As stipulated by the Radio Law, some parts of spectrum user fees have been used by projects for establishing the technical standards of radio equipment using technologies that contribute to efficient utilization of radio waves.

These projects are not R&D, however, since 2005, the revenue of spectrum user fees have been used for R&D projects because of enormous increase of subscribers of mobile phones and base stations. In these R&D projects, CR and related technologies have been expected to contribute to develop new frequencies, efficient use of frequency resources, and co share frequency bands with different systems.

One of the R&D project granted by the Spectrum User Fee System was "**R&D project of Key technologies for advanced frequency shares in mobile communication systems**" (December 2005 to March 2008). This project consisted of five sub groups of which the sub-project and members are as follows:

- Key technologies to realize CR terminals (involved partners: NICT)
- Cognitive wireless communications (involved partners: KDDI, KDDI Laboratories, Hitachi Ltd., Mitsubishi electric company, and ATRI - Advanced Telecommunications Research Institute)
- Efficient use technology of frequency in spatial domain (involved partners: ATR, NTT - Network Innovation Laboratories)
- Super conducting filter technologies (involved partners: Fujitsu, Fujitsu wireless systems, Fuji electric systems, Hokkaido University, Yamagata University)

The typical research themes are network-related CR focusing on: radio resource control, autonomous Inter-base stations networking/network configuration, and routing control for CR networks.

SCOPE (Strategic Information and Communications R&D Promotion Program)

The SCOPE was inaugurated by MIC in 2002 as a competitive-based funding program. The main missions are to realize technical and social innovations in the fields of ICT through supporting focused R&D projects, which will contribute to make world's competitiveness strong, to realize safe and secure Society, and to realize healthy and rich ubiquitous networked societies. Since the start of SCOPE program, there are very few R&D projects related to CR technologies, because such key technologies as SDR, networking, and devices have been mainly carried out by the big-size R&D programs of MIC and NICT. However, below some examples were listed.

Research & Development on Cognitive MIMO Mesh Networks (2006-2009)

In this project, very high speed wireless mesh networks are achieved over the primary wireless communication system by using DSA, MIMO, distributed power control and advanced radio resource management with network coding techniques.

Intelligent MAC Layer Techniques for Cognitive Radio (2009-2012)

In this project, the aim is to develop intelligent MAC layer technologies to realize autonomous distributed wireless networks in frequency sharing type CR terminals.

Reconfigurable RF circuit to realize cognitive radio (2010-2013)

The main emphasis is put in this project on developing wideband tunable radio circuits by using one Complementary Metal–Oxide–Semiconductor (CMOS) chip. The present radio circuits cover the frequency range of 300 MHz at most; however, it will cover from 400 MHz to 10 GHz frequency ranges.

Research on Analog-Digital Signal Processing Devices for Software Defined Radio (2002-2004)

In this research, analog-digital signal processing devices for SDR was proposed. The proposed devices used an analog filter bank and convert the analog signal to digital signals in parallel. With the analog filter, the resolution of Analog to Digital converter on each filtered band can be adjusted properly. In addition, under-sampling technique was employed in order to reduce the sampling frequency and the power consumption. In the digital domain, the distortion of the analog filter bank was compensated with adaptive signal processing. As a result, high-speed, high-resolution analog-digital conversion could be achieved with the proposed processing device.

Trends and research directions

Research related to cognitive communications in Japan is strongly stimulated by national-wide programs founded by the government and thus being in line with the national strategy of development. As Japan has one of the strongest and highly advanced market economies in the world, also the research conducted in its universities, institutes and commercial companies is very advanced. Projects related to CR are often very elaborated with involvement of several huge and high-ranking players from both the industry and academic sectors. As those projects are pretty matured, many of them already approached phase of proof of concept and implementation. Major Japanese operators and vendors seriously consider deployment of systems with cognitive-like capabilities. It seems that most effort is put now in the topic of white spaces reusing. The most early introduced white space systems will be in the area of one-segment TV services, because of the relatively easy situations of interference. Broadcasting stations are fixed and the mobile terminals never transmit signals. So, interference problems have to take into account only the locations of broadcasting stations.

On the other hand, “white spaces” have been studied to use mobile communications such as ITS. In these cases, interference problems will become very complex to overcome even using cognitive technologies. In cognitive research fields, the present cognitive terminal is assumed to be fixed and their physical locations are considered as a known data measured in advance. However, CR has high potential to be applied to ITS, in which systems cognitive terminals will be installed in moving vehicles. Network control technologies with moving terminals will be one of the most interesting subjects to be researched in CR technologies.

3.2.2.2 China

Extensive research on CR and DSA technologies is also being performed in China under the Chinese national 863 and 973 programmes. The details of these programmes are, however, largely closed to the outside world. Information on these programmes can be obtained by surveying the publications that result. For example, work is being done on the MAC sub-layer [105], on relaying in CR [106], on resource allocation [107], [108], on spectrum markets [109], [110], and spectrum sensing [111], [112]. Extensive highly-cited research on cognitive communications and DSA is also being supported by the National Natural Science Foundation of China. Some example publications resulting from this work are [113]-[119].

3.2.3 Projects in Australia

As Australia is an island with mostly low-densely populated areas, the problem of spectrum scarcity is not as serious as in Europe. Thus, the Australian regulator of electronic communication issues, the Australian Communications and Media Authority (ACMA) [120], is quite passive in the area of CR technology. It seems that the Australian regulator tends to follow results the investigations and arrangements of FCC and Ofcom. As a consequence, there are no national-wide founding programs devoted to cognitive communications and all the related projects are conducted in individual universities under separate grants from the government. However, even these projects usually are focused on specific features of CR instead of encompassing the concept as a whole. Such approach is typical in Australian research institutes, which put strong emphasis on collaboration with industry and are interested in projects handling real issues and towards practical implementations. Below, a selected set of the CR-related national projects from Australian universities is presented.

3.2.3.1 Macquarie University

Website: http://www.mq.edu.au/

Cross-layer Optimisation for Quality of Service Support in Cognitive Radio Networks

The concept of CR networks offers an opportunity for efficient use of increasingly more precious radio spectrum. However, CR networks face the challenge of providing guaranteed QoS support to both primary and secondary users of the spectrum. This project investigates development and optimisation of cross-layer (PHY and MAC) algorithms necessary to meet the requirements of guaranteed QoS support.

ACROPOLIS related WPs and activities:

Spectrum sensing, reliable communication (WP8, WP9, WP13).

3.2.3.2 University of Sydney – Centre of Excellence in Telecommunications

Website: http://www.ee.usyd.edu.au/Research/telecommunications.html

Interference cancellation in cognitive networks

The aim of this project is to design an efficient interference cancellation scheme in a multi-hop cognitive network, and analyse its performance. It is assumed that the CR network is equipped with multi-antennas so that it can deploy pre-coding and/or power control to effectively balance between avoiding the interferences at the PU terminals and maximizing the throughput of the CR link. Some possible methods for interference cancellation and pre-coding that can be applied in such a scenario are zero-forcing and minimum mean square error (MMSE). These schemes are going to be applied to different structures of the multi-hop CR networks and under different assumptions and their performance will be studied and evaluated.

ACROPOLIS related WPs and activities:

Interference cancellation techniques (WP8, WP13)

Game Theory Based Transmission Strategies for Cognitive Radio

In this project, the problem of designing transmission strategies between CR nodes without causing significant interference to the licensed users is addressed by utilizing tools from the game theory. In particular, transmission strategies for transmitter-receiver CR pairs causing acceptable levels of interference to the licensed users will be designed. Both, non-cooperative and cooperative scenarios will be considered.

ACROPOLIS related WPs and activities:

Game theory-based transmission strategies (WP8), knowledge sharing (WP11).

3.2.3.3 University of Technology Sydney - The Faculty of Engineering and Information Technology

Website: http://www.feit.uts.edu.au/

Cognitive Radio Oriented Wireless Networks for Pervasive Information Connectivity

CR Oriented Wireless Networks autonomously organise spectrum sharing of the nodes by means of spectrum sensing and link quality evaluation at each node. The nodes communicate to share spectral sensing and link quality information and make collaborative decisions regarding high spectral efficiency transmission. The networks self organize and adapt to changing node location, network topology, number of active nodes, and transmission propagation conditions. The nodes use cognition of the external radio environment and communication from other nodes to implement an optimal adaptive strategy.

ACROPOLIS related WPs and activities:

Collaborative sensing and decision making (WP9, WP10, WP11, WP12, WP13).

Software Defined Radio Test-bed

SDR systems inherently are highly flexible and well suited for adaptive systems such as CR, adaptive modulation and coding, adaptive power control, adaptive antennas steering, and adaptive network protocols. Very close to theoretical performance can be achieved with the SDR.

ACROPOLIS related WPs and activities:

SDR-based test bed for CR (WP5, WP7).

3.3 Brief summary

Based on the review of the scientific projects, programs and actions presented in this section, some generic conclusions related to research in the area of CR networking can be drown.

A first observation is that the variety of issues connected more or less directly to CR were and still are the object of investigation in many research centres, universities, R&D companies and firms all over the world. Although more than ten years have already passed since the first introduction of the idea of CR, this subject is still a vivid research topic. Most of the projects in this area try to address the main identified problem, i.e., the practical implementation of this concept. In many cases, the issues concerning the real application of the new developed algorithms in testbeds, hardware platforms or prototype systems are highlighted in the projects' description. Moreover, a significant subgroup of the projects focuses on finding the ways of improving the energy and spectrum efficiency in wireless communication systems. Such a trend indirectly validates the correctness of the idea that the application of the CR in the real systems shall lead to more efficient spectrum utilization. A detailed analysis of the global trends from the perspective of the ACROPOLIS project is presented in the subsequent section.

It can also be observed that in all of the aforementioned projects at least one of the stages that constitute the basic cognitive cycle, i.e., environmental awareness, context analysis, decision and execution, has been or is still investigated. Thus, there are several projects that deal with collecting and exchanging sensing information, learning and managing the acquired knowledge, making and executing the appropriate decisions, etc. The main characteristic is that, depending on the main target of each project, more attention is paid on the respective specific stage(s) of the cognitive cycle.

4. Project Adherence to Global Developments

We should recall at this stage that the basic mission of WP4 is a mission to which the present Deliverable contributes: it is to act as the "information-inflow gateway" between the ACROPOLIS project and the larger world around it, the scientific ecosystem within which it exists. To achieve that, the Technical Annex proposed the dual goals of (a) gather, sort, evaluate, summarize and present to the NoE those major developments within the broader ecosystem that could (and should) affect its scientific evolution over time, and (b) devise and enforce procedures and means by which the various particular activities of the NoE conform with these developments, benefit from them and harmonize in the most beneficial way so as to maximize relevance and impact to that outside world. Having in the previous Sections focused attention on the gathering and sorting of the outside information, we now proceed in this Section to assess how well the Project adheres to these global trends and to propose a *harmonization procedure* which will ensure such a maximization of relevance and impact. A visualization of this harmonization procedure and its desired outcome is summarized in Figure 4-1 below:

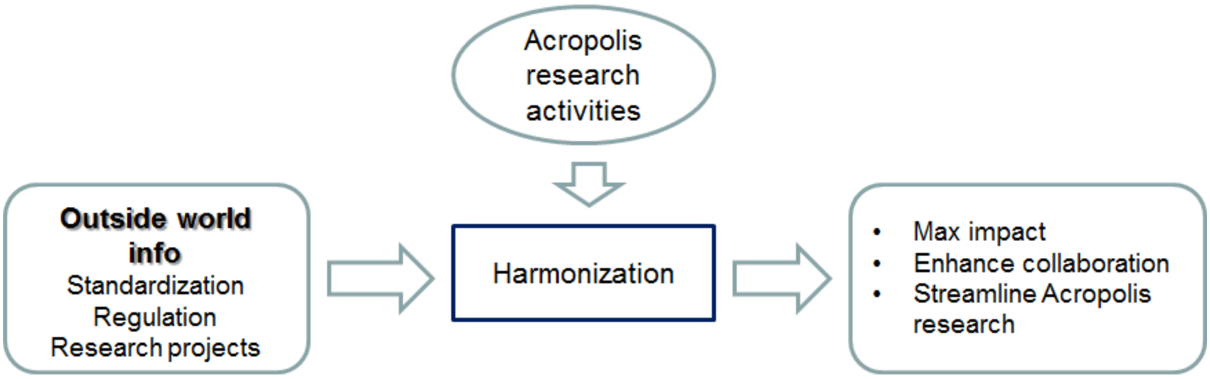

Figure 4-1: Harmonization procedure

Such a procedure is germane to the success of the project and will be the basis for guidelines and suggestions during the second half of the ACROPOLIS project life. It will be applied to each jointly undertaken research activity. The stated objective, again, is to maximize the adherence of the project to these global trends, maximize the impact to the outside world, enhance collaboration among the partners, and streamline all the joint research activities to the degree possible.

A central new element of this harmonization procedure going forward is the creation of a harmonization **framework** for doing such. This framework will be detailed in subsequent sub-sections in great depth. Its mission is to:

- identify relevant scenarios and techniques, as well as their interaction,
- enhance and strengthen interaction between WPs and partners,
- align all research work,
- consolidate the somewhat dispersed landscape of various efforts,
- provide demonstrable and measurable metrics of such harmonization success.

The establishment and operation of such a framework is meant as an on-going, living activity. Monitoring the various research activities should in fact be done on a continuous basis: it has already started at the beginning of the project, accelerated further after the first-year Deliverables and is now reaching a critical stage for the remainder of the life of the project (second half). It will thus be the *main instrument* for this type of important monitoring. The mapping of the various joint ACROPOLIS research activities to this framework can be done in a variety of ways; the present Deliverable below presents some. It is expected to evolve and be refined further as the project and its activities mature. So here, in this Deliverable, we present the first "snapshots" of this holistic evaluation as a result of "running" the framework. The present snapshots will form the basis for further refinements and guidance until the end of the project.

4.1 Assessment and harmonization procedure

4.1.1 Defining the Framework

The first element that instantiates the said framework is the creation of a *matrix* whose rows are the main scenarios of interest in the field of coexisting technologies and CRs, whereas its columns are the various scientific techniques (research "themes", areas) that are brought to bear in the determination of respective solutions to joint research problems.

Regarding the rows of "scenarios", we define them as the different triplets of {service, architecture, technology}. As already discussed in section 2, all the imaginable scenarios in this field can be classified in three main classes (Table 4-1):

- Multi-Nets (multi-RAT or/and multi-tier or/and multi-operator);
- Hierarchical spectrum access in licensed bands; and
- Spectrum sharing in unlicensed bands.

All the ACROPOLIS joint research activities can be classified and mapped to the three main scenarios. When further specificity is necessary, we introduce it under the name of "sub-scenarios". Finally, we define the last granularity of specificity as "use cases", which are scenarios of interest mainly focused on specific applications or systems, with specific constraints and requirements.

Scenarios	**Multi-Nets (multi-RAT or/and multi-tier or/and multi-operator)**	**Hierarchical Spectrum Access on Licensed Bands**	**Spectrum Sharing on Unlicensed Bands**
Sub-scenarios (examples)	a. In-band multi-tier coordinated coexistence b. Self-Configuration of (autonomous) Femto-Cells c.Multi-standard, multi-RAT, multi-operator coexistence	a. Coordinated Spectrum Access between PUs and Sus (Interweave - Overlay) b. Non-coordinated Spectrum Access between PUs and Sus	a. Coexistence of independent (non-coordinated) ad-hoc networks
Use cases (examples)	"Horizontal" sharing between spectrum owners (e.g., sharing spectrum between operators)	LTE IN TVWS, Home Networks (IEEE 802.11af), Out-of-band (cognitive) Femto-cells	Coexistence between WiFi with Bluetooth

Table 4-1: Main scenarios of interest in the research field of the ACROPOLIS project

A second step, as mentioned, is the classification of the joint research topics based on their *main research scientific area* or *theme*. The envisioned main scientific research areas are listed and described in section 4.1.2 where a justification for this selection of themes is provided.

Via this two-step process, all ACROPOLIS joint research activities are categorized according to the technique employed and the scenario addressed, thus resulting in a mapping to the framework matrix. A first visualization of the matrix is provided in Table 4-2, where the individual “matrix cell” entries are the selected ACROPOLIS research topics. For each such activity, an assessment is performed in section 4.2.3 in order to identify the value proposition, the challenges and the opportunities for each such research undertaking, and then finally propose specific actions needed for further harmonization (if necessary).

	Categorization per scientific research area			
Scenarios Sub-scenarios		Acropolis research topic		

Table 4-2: Scenario/research area per topic template

The third (conceptual) step is the identification of the common set of principles which underwrites all the ACROPOLIS research activities. In section 4.3 these identified principles are explained and illuminated via specific examples from the ACROPOLIS activities (hence the title “a Unified View”). These three steps conclude the establishment of the proposed framework.

4.1.2 Main scientific research areas (the matrix columns)

In general, a system is designed so as to meet the requirements of the applications/services that it is expected to accommodate and to comply with the characteristics of the environment that it operates in. CR systems are expected to accommodate a large number of diverse applications provided to the end user, with a multitude of requirements linked to the user QoS or Quality of Experience (QoE). Additionally, CR systems are meant to operate in highly diverse radio environments; these may include various co-existing radio networks with fixed or variable band allocations, with multiple degrees of freedom in defining a user connection and which exploit the different offered connection opportunities. This complexity poses specific requirements at the network management plane, and requires the establishment of a suitable architecture that will enable the exploitation of the diverse connection opportunities with the least possible complexity.

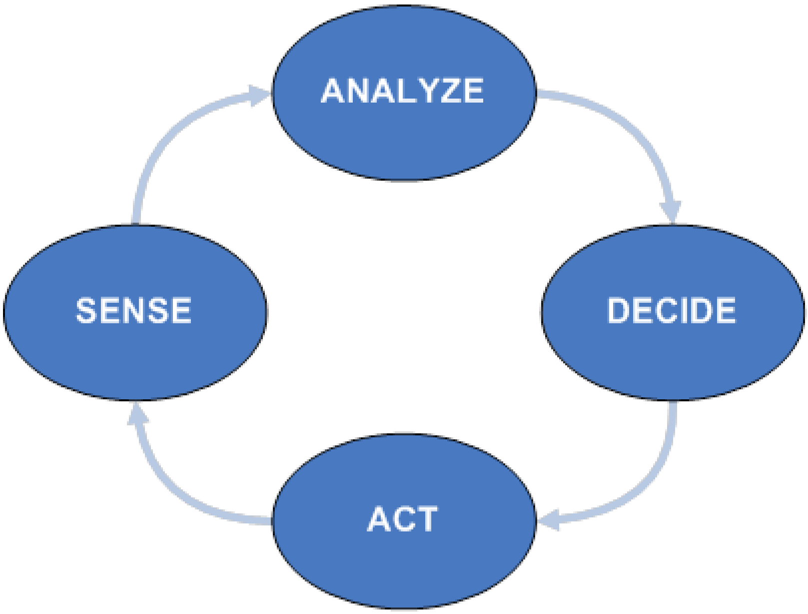

Figure 4-2: Simplified Cognition Cycle [121]

The basic steps/mechanisms encountered in a typical CR system are summarized here. They form the so-called Cognition Cycle (Figure 4-2):

- **Environment awareness (SENSE)**: These are the mechanisms that allow any radio node (both on the terminal and the network sides) to gather context information concerning its surrounding radio environment, its neighbouring nodes, proximal network capabilities, etc. This awareness may be achieved either by actual measurements conducted by the node (e.g., sensing) or by the exchange of related information between neighbouring nodes or between nodes and a specific information server that contains such information. The context information may include a multitude of direct radio measurements, e.g., received power, received Signal-to-Interference-plus-Noise Ratio (SINR), perceived throughput, perceived block error rate, of other node-specific perceived indications (e.g., location information, mobility status, battery level, terminal capabilities, etc.), of neighbourhood-specific perceived indications (e.g., proximal nodes, service advertisements, etc.) and of existing policies/directives that may be put in place in order to regulate the actual co-existence of the different networks and other nodes within a CR environment.
- **Context Analysis (ANALYZE):** This includes all the mechanisms that are used to process the abovementioned context information in order to assess the current terminal and network status and to identify the connection opportunities that may be available, either in terms of reconfiguring the existing network connection (e.g., modifying the link characteristics, updating the resource allocation or changing the spectrum band occupancy, etc.) or in terms of changing the current network connection(s) and handing (them) over to another (other) radio access network(s). The context analysis will drive the reasoning process, by determining the metrics that will trigger the corresponding policies. These policies may then be used to determine the actual network management decision(s).

- **Decision (DECIDE):** This stage includes all the different available algorithms and optimization techniques that are employed in order to implement the selected policies. These techniques may belong to different layers (e.g., networking, MAC, PHY algorithms) or may be cross-layer, involving parameters and elements from different layers.
- **Execution (ACT):** This stage involves the actual employment of the abovementioned decision schemes on the terminal or network platforms. It involves the required hardware/software partitioning for the efficient execution of the selected schemes as well as the flexible operation of the baseband/IF/RF transceiver bands in order to enable the required link or network adaptation or reconfiguration.

Based on the aforementioned concepts, a fully-CR system must operate via a *policy-based network management logic*. Policies are sets of rules (of the type EVENT-CONDITION-ACTION) that are used to control the behaviour of the nodes in a network (either cognitive or not). To guarantee the optimization of the system performance and maximization of the resource usage efficiency, policies have to be dynamic, in order to effectively adapt to the continuous variations of the system conditions. A policy may be used to modify accordingly the elements of a resource management algorithm, e.g., to either modify a cost function (used for resource allocation) in terms of the function expression itself or in terms of the constraints related to this function. Reasoning is inherent in any policy-based management system (both cognitive and non-cognitive). If the policies may be changed at run-time based on the experience gained by assessing past policies (which requires a proper knowledge base to store the results of this assessment), then the system can be enabled to learn from its past actions.

In order to further categorize the ACROPOLIS research activities, the main distinct scientific research areas are identified. These areas interact in the framework of the Cognition Cycle, as discussed above, but each one has specific mathematical tools and evaluation metrics:

- Sensing/discovery techniques
- Position-location techniques
- Databases
- Learning mechanisms
- Context representation and policies
- Access techniques and modeling
- Decisions/optimization
- Execution/platforms
- Management/architectures

4.1.3 Mapping of EU research projects to framework

In order to assess the relationship between the ACROPOLIS research work and the research taking place in the outside world, we first place the EU research activities (presented and summarized in section 3) in the abovementioned framework. The purpose is to highlight the European main scientific areas and scenarios of interest and then examine whether the ACROPOLIS research activities are focusing in the same areas or not. Then, we may propose some re-focusing if necessary (this is performed in section 4.2). The projects are mapped into the scenario/research area matrix based on their main technological areas (up to four per project) of interest. These areas were selected based on the main focus for innovation per project— and do not represent all the projects' activities. The results are shown in Table 4-3, and related conclusions are drawn in Figure 4-3 and Figure 4-4.

EU Research Activities									
Scenarios	Scientific Research area								
	Sensing/discovery techniques	Position-location techniques	Databases	Learning mechanisms	Context representation and policies	Access techniques and modeling	Decisions/ optimization	Execution/ platforms	Management/ architectures
Generic & applicable to multiple scenarios	FARAMIR, WHERE2, EXALTED, COST IC0902 WG1/WG2	WHERE2, SOCRATES	FARAMIR, ADVANCE	UniverSelf, CogX, CHRON, ECODE, SOCRATES, COST IC0902 WG2	UniverSelf, CogX, COST IC0902 WG2	2PARMA, WHERE2, SAMURAI, PHYDYAS, COST IC0902 WG3/4	FARAMIR, UniverSelf, Self-NET, CROWN, EXALTED, CHRON, SOCRATES, COST IC0902	2PARMA, Self-NET, CROWN, SAMURAI, CONECT, CHRON, ECODE, COST IC0902 WG1/4	FARAMIR, 2PARMA, UniverSelf, Self-NET, EXALTED, PHYDYAS, CONECT, HELP, CHRON, SOCRATES, ADVANCE, COST-TERRA
1. Multi-Nets (multi-RAT or/and multi-tier or/and multi-operator)						EARTH, EULER		EULER	EARTH
1.a. In-band multi-tier coexistence		BeFEMTO		BeFEMTO			BeFEMTO		
1.b. Multi-standard, multi-RAT, multi-operator coexistence				C2POWER	C2POWER	SACRA, C2POWER, SAPHYRE	SACRA, SAPHYRE	SACRA	
2. Hierarchical Spectrum Access on Licensed Bands	QoSMOS		QoSMOS, COGEU		COGEU	QUASAR	QUASAR, COGEU	QoSMOS, CREW	QUASAR, COGEU
2.a Coordinated Spectrum Access between PUs and SUs						OneFIT			OneFIT
2.b. Non-coordinated Spectrum Access between PUs and SUs	SENDORA					SACRA	SACRA, SENDORA	SACRA, SENDORA	
3. Spectrum Sharing on Unlicensed Bands								CREW	

Table 4-3: EU research per Scenario/research area

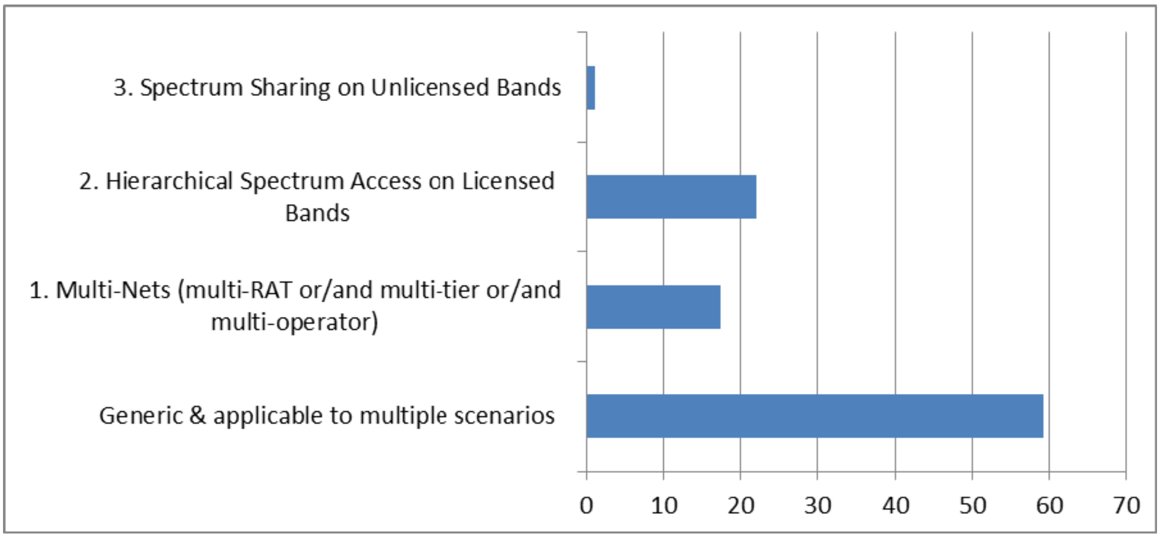

Figure 4-3: EU research scenarios profile (%)

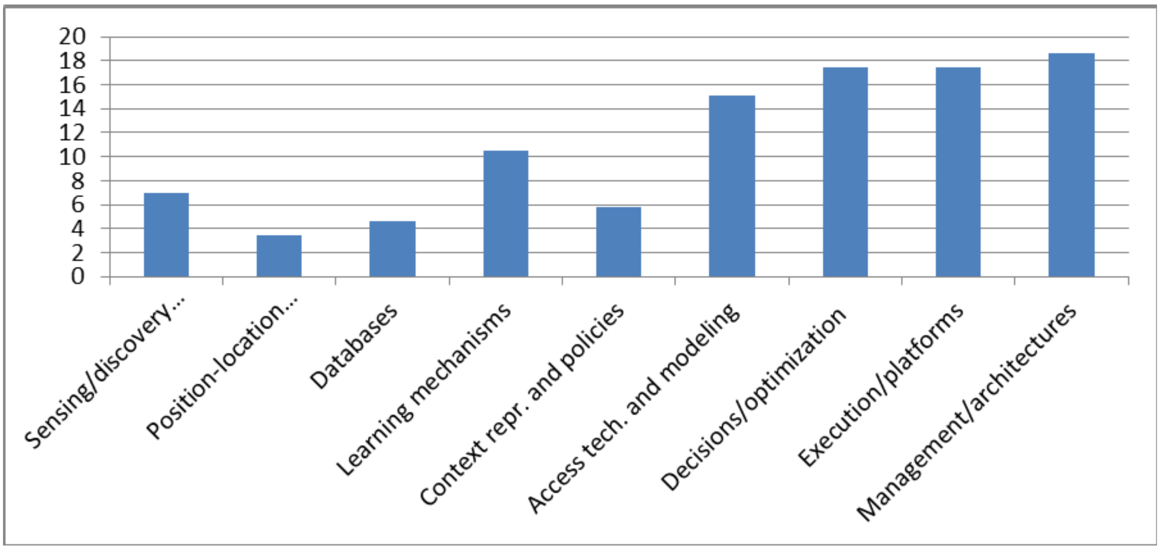

Figure 4-4: EU scientific research areas profile (%)

We note that the majority of the projects do not focus on a single main scenario but propose solutions applicable to all or multiple scenarios. For example, in the Faramir project, the work on the creation and practical use of Radio Environment Maps is examined and demonstrated in a variety of use cases that span all the main scenarios. In some projects the main research focus is on the development of new system-level approaches to cope with a specific objective (e.g., the development of a robust emergency network) which encompasses almost all the scientific areas in the matrix. In this case, the selected main scientific area for mapping is chosen to be “management and architectures”, because such instruments coordinate all other scientific techniques towards achieving these new objectives.

4.2 ACROPOLIS project research activities

Here, the joint research topics proposed in the ACROPOLIS technical WPs are summarized and mapped into the aforementioned framework.

4.2.1 Joint research activities

In the following table the joint research topics are listed, along with their relation to the ACROPOLIS WPs. The topics are segregated into two categories. The first category includes the activities that have already reached a mature point and they can be assessed (in section 4.2.3), while the second category includes activities that are still under development to establish their value proposition.

	Joint research topics	WPs								
		5	7	8	9	10	11	12	13	14
1	Application-specific instruction-set processor (ASIP) for digital front-end processing in wireless communications (WP5/7 - EURECOM, RWTH)	X	X							
2	Application of the Multirate Filterbank-based Multicarrier (FBMC) Modulation and Non-Orthogonal Frequency Division Multiplexing (NOFDM) in the cognitive radio (WP7 - CTTC, PUT)		X							
3	Resource allocation vs. NS-3 / LENA (LTE system level simulator) (WP8/10/11 - CTTC, EIT+)			X		X	X			
4	Spectrum occupancy and use measurements (WP9 - KCL, RWTH, UKIM, IASA)				X					
5	Common simulation platform for spectrum awareness based on the IEEE 1900.6 architecture (WP9/10 - EADS, Uniroma1, KCL)				X	X				
6	Dynamic Spectrum Access, Cognitive Radio and Spectrum Awareness for Energy Saving (WP9/10 - KCL, PUT)				X	X				
7	Radio Environment Mapping: spatial map of radio characteristics, using observations at certain points on {space, frequency, time} and processing capabilities (WP9 - RWTH, UKIM, IASA)				X					
8	Estimation-based noise-robust and energy-efficient sensing (WP9 - IASA, PUT)				X					

9	Interference localization and transmit power estimation in lognormal fading environment (WP9 - IASA, RWTH)				X					
10	Test Beds for Implementation of Spectrum Sensing Schemes (WP7/9 - UKIM, KCL, EURECOM, IASA)		X		X					
11	Beacons for Spectrum Awareness (WP9/10 - KCL, Uniroma1)				X	X				
12	Cognitive Radio through Beamforming to Secondary Users under Interference Limits (WP10/WP9 - KCL, Uniroma1)				X				X	
13	Location-based routing with beamforming (WP10 - Uniroma1, KCL)					X				
14	Common Access Channels for Cognitive Radios (WP9/10 - Uniroma1, KCL, UPRC)				X	X				
15	Common architecture and simulation platform for cognitive applications (WP5/10 - EADS, KCL, Uniroma1)	X				X				
16	Information exchange during the neighbor discovery phase (WP10/11 - Uniroma1, UPRC, KCL, EIT+)					X	X			
17	Admission control based on interference management (WP10/13 - JRC, Uniroma1, EADS)					X			X	
18	Context aware interference management in 2-tier networks (WP12 - IASA, PUT, RWTH, UoS)							X		
19	Policies for cognitive radio systems (WP12 - UKIM, UoS, PUT)							X		
20	Distributed power control for cognitive radios with primary protection via spectrum sensing (WP12/13- UoS, TUD)							X	X	
21	Spatial Shaping in Multiple Antenna overlay CR (WP8/13 - PUT, KTH, TUD)			X					X	
22	Comparison of Underlay and Overlay Spectrum Sharing Strategies in MISO Cognitive Channels (WP8/12/13 - PUT, KTH, TUD)			X				X	X	
23	Crystallized Rate Regions in the Secondary Interference Channel (WP8/12/13 - PUT, KTH, TUD)			X				X	X	
24	Admission control for Cognitive Radio Networks based on aggregated interference (WP10/14 - JRC, Uniroma1, EADS)					X				X

25	Geo-location database for incumbents with known emitter position (WP6/14 - JRC, Univleeds)									X
26	Secure policy framework for Hierarchical Spectrum Access on Licensed Bands (WP12/13/14 - UKIM, JRC)							X	X	X
27	Implementation of collaborative spectrum sensing on USRP platforms (WP7/9/14 - UKIM, JRC)		X		X					X
28	Learning User Preferences and Network Capabilities for enhancing decision making in Cognitive Radio Systems (WP11 - UPRC, UoS)						X			
29	Learning and Knowledge Management Toolbox for Cognitive Radio Network Applications (WP11 - UPRC, CTTC, UKIM, UoS)						X			
30	Distribution and storage of information (WP11 - UPRC, CTTC, UKIM, UoS, RWTH)						X			

Table 4-4: Joint research topics per WP

	Joint research topics	**WPs**								
		5	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Machine learning based self-organizing networks (WP11 - CTTC, UKIM)						X			
2	Analysis of flexible & reconfigurable radio platforms: design space & fundamental limits & extension of the platform capabilities and their analysis (WP5/7 - RWTH, IASA, PUT)	X	X							
3	Possible architectures and system approaches for realization of the cognitive cycle (WP7 - RWTH, EURECOM, all)		X							
4	Abstraction Scenario and Link with Collaborative Sensing Information (WP9/WP10 - Uniroma1, EADS, KCL, UPRC)				X	X				
5	Centralized Control Channels for Spectrum Information Acquisition (WP9/WP10 - UPRC, Uniroma1, KCL)				X	X				
6	Geolocation Databases and Information Handling for Spectrum Availability Information Acquisition (WP9 - RWTH, IASA)				X					

7	Decision Rules (WP9/WP12 - UKIM and Uniroma1)				X			X		
8	Dynamic spectrum masks, adaptive spectrum shaping of the secondary transmission for primary protection (WP12)							X		
9	Network organization (WP10/12 - EADS, UPRC, Uniroma1, KCL, EIT+)					X		X		
10	Resource Allocation in Cognitive Radio relaying environment (OFDM vs. FBMC) (WP7 - CTTC, TUD)		X							
11	Rendezvous-MAC protocol for asynchronous CR nodes (RAC2E-gQS) (WP7/10/12 - UKIM, RWTH)		X			X		X		

Table 4-5: Joint research topics under development per WP

As seen from the table, in most joint activities there is collaboration among different WPs. This was encouraged from the beginning in order to streamline the actual research and to avoid parallel uncoordinated efforts on the same topic from different partners.

The Table 4-6 below depicts the numbers of joint activities on the matrix of main scientific research areas and scenarios. Since some of the activities are linked to more than one scientific area, the most important one was selected. The purpose of this table is to provide an overview snapshot of the ACROPOLIS research work and compare it with the similar snapshot of the current EU research activities (Table 4-3).

ACROPOLIS Joint Research Activities									
Scenarios	Scientific Research area								
	Sensing/ discovery techniques	Position-location techniques	Databases	Learning mechanisms	Context representation and policies	Access techniques and modeling	Decisions/ optimization	Execution/platforms	Management/ architectures
Generic & applicable to multiple scenarios	**4**	**1**	**3**	**3**	**1**	**2**	**3**	**4**	**1**
1. Multi-Nets (multi-RAT or/and multi-tier or/and multi-operator)	**1**								
1.a. In-band multi-tier coexistence							**1**		
1.b. Multi-standard, multi-RAT, multi-operator coexistence						**1**			
2. Hierarchical Spectrum Access on Licensed Bands					**1**		**3**	**1**	
2.a Coordinated Spectrum Access between PUs and SUs	**1**						**1**		
2.b. Non-coordinated Spectrum Access between PUs and Sus	**1**	**1**				**2**			
3. Spectrum Sharing on Unlicensed Bands						**1**	**3**	**1**	

Table 4-6: Scenario/research area per topic

We see that in the areas related to the sensing and analysis part of the Cognition Cycle (sensing, localization, databases, learning), the majority of the research activities can be applied to multiple scenarios of interest. This is expected since, for example, the development of a technique for the discovery of a transmitter and for the estimation of its location can be used in a scenario where the Secondary User (SU) wants to protect a Primary User (PU) (scenario 2), while it can also be used in a multi-tier scenario (1.a) where one femtocell performs resource allocation based on this information. Within ACROPOLIS, both generic and scenario-specific techniques have been proposed. In the decision part of the Cognition Cycle (access techniques, decision/optimization, policies), there is a natural shift to more scenario-specific techniques. This is expected since optimization algorithms and approaches are usually demonstrated and evaluated in specific systems with specific performance metrics. In the execution and action part of the Cognition Cycle, again the developed techniques can be applied to most of the scenarios since – most of the times – the limitations and constraints are from the hardware platform and not from the scenario assumptions.

In Figure 4-5 below, the number of joint activities per scientific research area is depicted. As expected, the decision and optimization is the most active area. WP12 is the key WP which coordinates the decision-making process. We note that the joint activities in this area are usually inter-WP collaborations, so that the produced results are reported in different WPs.

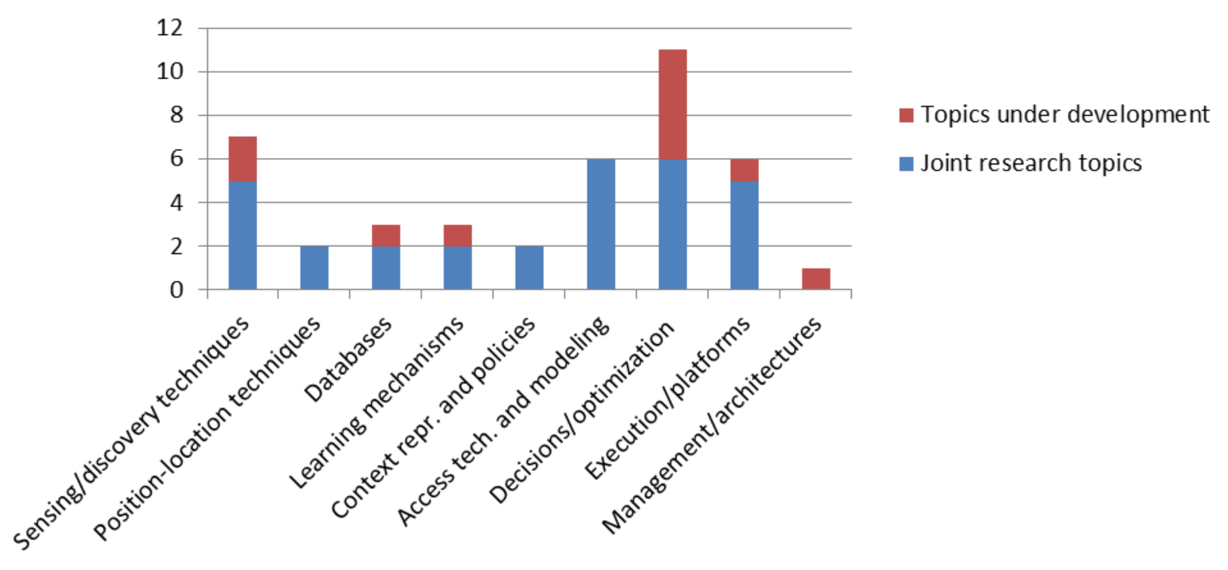

Figure 4-5: ACROPOLIS research technology profile

In comparison with Figure 4-4 and the mapped scientific profile of the EU-funded projects, we can discern both similarities and deviations. In ACROPOLIS there is a strong focus on the development and assessment of sensing and discovery techniques that somewhat exceeds the corresponding percentage of EU research projects. This is a reflection of the specific interests of the ACROPOLIS partners. Furthermore, we recall that sensing and position-location techniques can be used in the creation of databases (e.g., in the form of Radio Environment Maps) which are gaining equal research attention in both ACROPOLIS and the outside world. Also, in the research area of access techniques and modelling, decision/optimization, and execution/platforms, there is conformity with the corresponding percentage of the European activities. The increased number in platforms-related research in EU projects is due to the fact that, in recent years, the Commission has steered interest to the demonstration and experimentation side of research ("experimental research"). ACROPOLIS is following this trend, as shown in Figure 4-5, but with a lower percentage since the focus – as per the Technical Annex – has been planned with equally emphasis on all scientific areas.

4.2.2 ACROPOLIS-specific scenarios of interest

In the *sensing* part of the Cognition Cycle, a variety of research topics that are focused on practical use cases are examined that can be mapped to the main scenarios. In the Multi-Nets scenario (#1) there is work on the introduction of femtocells in a CR network architecture, and on the resulting issues in neighbour discovery and coexistence between mutually independent femtocells in the same geographic area. This use case can be considered as an example of CR solutions applied to cellular networks. In the Hierarchical Spectrum Access In Licensed Bands (scenario #2), the work on cooperating primary-secondary networks entails a primary network and a set of secondary networks, each equipped with a base-station plus one or more secondary users. This use case considers the definition of a common random access channel for spectrum and neighbour awareness, and it is an example of cooperating primary-secondary networks.

Regulation and standardisation trends have been followed by ACROPOLIS partners and do play a role in affecting the ongoing activities. As an example, the work in opportunistic (secondary) access of locally/temporally available spectrum (overlap technique) coincides with current trends in regulation for TV white spaces and the associated standardisation. In the underlay approach, a range of methods are proposed (for example, beamforming to secondary users under interference limits to the primary, localization and power estimation to limit interference). In this case there is no significant coincidence with current global trends due to interference concerns; however, this research is still highly applicable in some current scenarios (e.g., where there is prioritized access in unlicensed spectrum). Also, it is applicable to cases such as CR Ultra Wideband (UWB) (extension to the 802.15.4 work that is currently being standardized).

In the considered scenarios above, sensing capabilities must be assumed for cognitive devices to operate. This is somehow different from the current trend led by FCC that relies primarily on registration and consultation with geolocation based databases for ensuring coexistence with legacy devices. However, the scenarios considered are still relevant to coexistence between different secondary networks built on different technologies, and can be definitely used to deploy solutions relevant for standardisation working groups, in particular belonging to the 1900.x family (e.g., 1900.4 and 1900.6). Also, these activities share research topics with several active research projects within the EU, in the field of energy efficiency in network operations, neighbour and network discovery solutions, common communication channels and inter-network coexistence/coordination solutions, and position-based optimization of services.

In the *analysing* part of the Cognition Cycle, which includes databases, learning mechanisms, context representation/policies, and access techniques and modeling, the research work is more focused on generic techniques that are applicable to most of the main scenarios. For example the work on *policies for CR systems, dynamic spectrum masks, adaptive spectrum shaping of the secondary transmission for primary protection* are all applicable to many use cases and it is highly compatible with the general architectural requirements for the policy-based control of dynamic spectrum-access radio systems, as described in the recently published IEEE 1900.5 standard.

In addition, there is ongoing scenario-specific research. In the multi-nets scenario there is work on independent primary networks with common control channel specification which foresees the presence of multiple networks sharing the definition (and possibly the use) of a common control channel for making network information available to mobile devices. There is also a research activity on a secure policy framework for Hierarchical Spectrum Access on Licensed Bands (scenario 2), and work on admission control based on interference management related to scenario 3.

In the *decision* part of the Cognition Cycle, the joint work is more focused in specific use cases which cover a very wide area of interest, being relevant to all aspects of the deployment of CR networks and covering all levels of coordination between the involved radio networks. Therefore, many similarities with global research activities in the area of CR networking can be identified. For example, *Context aware interference management in 2-tier networks* is applicable to scenario 1 on multi-tier networks. This activity addresses the vital issue of inter-system (and intra-system) interference avoidance, which is one of the central requirements of all regulatory bodies, in the case of femtocell deployment within macrocells. Significant research effort can be seen in a European, as well as global level, regarding multi-tier/operator co-existence. Examples of related EC projects are FARAMIR, BeFEMTO and SAPHYRE, while the issue of interference management is addressed in global research activities, as well as COST actions. One example of scenario 2 is the activity on *Distributed power-control and spectrum sharing - analysis of the achievable rate regions for SUs*. Significant amount of ACROPOLIS work in the decision/optimization scientific area has been devoted to scenario-3 applicable techniques. One example is the work on *Reconfigurable UAVs network*. This use case foresees a set of mobile devices that cooperate in exchanging information and deliver it to a central base station; the network is required to operate in presence of an alien network that, intentionally or not, creates interference. It can be seen as an example/extension of an ad-hoc/coverage extension scenario; it is also suitable for a more general ad-hoc use case without mobility.

In the *execution and action* part of the Cognition Cycle, again the majority of the developed techniques can be applied to most scenarios, since, most of the time, the limitations and constraints are from the hardware platform and not from the scenario assumptions. Research on the development of test-beds and simulators through the collaboration of ACROPOLIS partners is ongoing. As an example of a scenario-specific activity we can refer to the development of a common simulation platform for spectrum awareness based on the IEEE 1900.6 architecture.

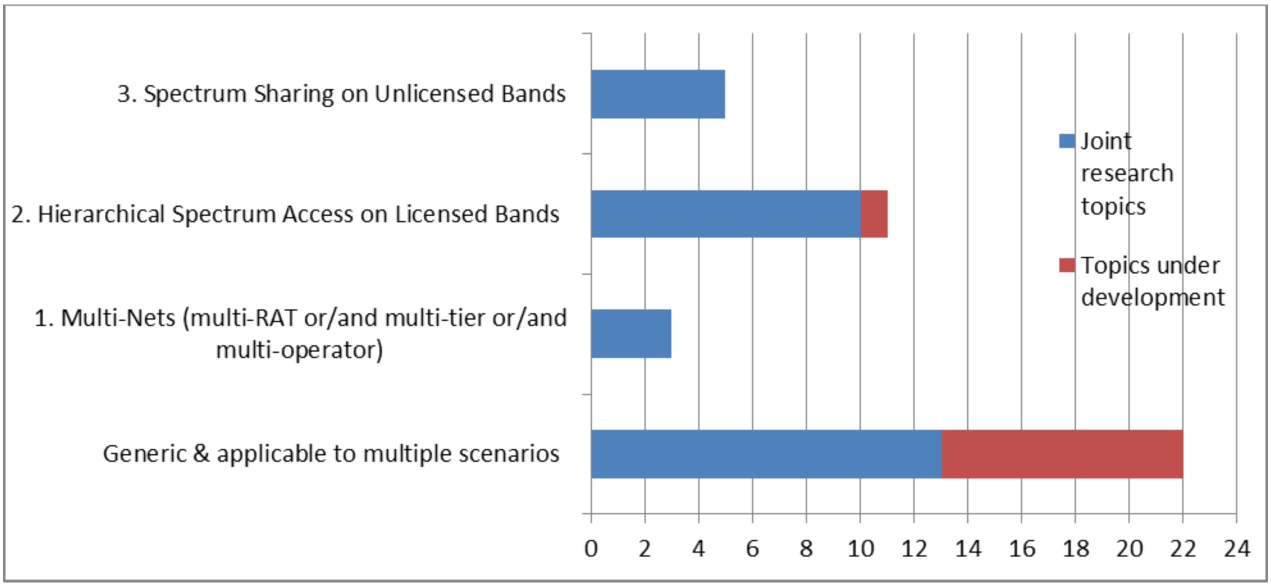

Figure 4-6: ACROPOLIS scenarios of interest profile

The ACROPOLIS scenarios profile is shown in Figure 4-6. In comparison with Figure 4-3, we notice that the research on multi-nets coexistence is rather limited within the ACROPOLIS project with respect to the other EU projects, while the opposite is true for the case of spectrum sharing in unlicensed bands. General research applicable to multiple scenarios is the most popular category in ACROPOLIS, similar to broader EU activities. In conformance to the European activities significant percentage in ACROPOLIS research work is focused on Hierarchical spectrum access scenario.

4.2.3 Joint research activities: SWOT analysis

In this section a short SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) for each mature joint research activity is performed.

4.2.3.1 Application-specific instruction-set processor (ASIP) for digital front-end processing in wireless communications

Description: An Application Specific Instruction-Set Processor (ASIP) for the OpenAirInterface Platform has been designed. The ASIP replaces the existing Front-End Processor (FEP) which is responsible for the different functions at air-interface level. These functions comprise among others time synchronization, channel estimation and data detection. In this context we focus not only on the architectural design of the ASIP but also on a throughout comparison with the custom implemented version of the FEP (C-FEP).

Value proposition: The ASIP replaces the vector processing unit and the microcontroller of the C-FEP. Compared to the C-FEP, internal latencies have been reduced and multiple instruction processing as well as fast pathers for general purpose instructions are supported. In contrast to the C-FEP whose performance excellent when operating on large vector sizes, the ASIP performs excellent for all types of standards. Thus, an efficient processing even of standards with short data sets on the OpenAirInterface platform can be guaranteed.

Challenges:

- The ASIP performs better than the custom implemented version of the FEP when standards with short data sets are processed
- Similar performance when processing standards with long data sets
- The ASIP replaces the vector processing unit and the microcontroller of the C-FEP
- The ASIP does not include a Discrete Fourier Transform (DFT)/Inverse DFT (IDFT) unit

Opportunities: The ASIP improves the performance of the OpenAirInterface Platform when processing standards with short data sets (e.g., 802.11a/p).

Proposed actions: No further actions planned once the submitted paper is accepted, expect possible submission to the second annual ACROPOLIS workshop (28 June 2012).

Collaborations: This is a joint work between EURECOM and RWTH and it is related to WP5/7. The work is placed in the technological area of “Execution/Platforms” and it is related to multiple scenarios.

4.2.3.2 Application of the Multirate Filterbank-based Multicarrier (FBMC) Modulation and Non-Orthogonal Frequency Division Multiplexing (NOFDM) in the cognitive radio

Description: Different approaches are analysed using FBMC and NOFDM and the performance is compared with conventional OFDM. In order to consider the presence of the licensed (primary) users the special interference masks has been proposed. The shape of that mask is defined arbitrarily (thus it can be modified and adapted to the actual situation) taking into account that the strongest interference induced to the primary users comes from the pulses of the FBMC frame that are localized at the boarder of the transmission frame on the time-frequency plane. Due to the application of such 2D masks the SINR of the boarder pulses will be decreased thus less power will be assigned to these pulses. An objective is to include developed adaptive algorithms for link adaptation in FBMC and Generalized Multicarrier (GMC) in a common simulator for testing.

Value proposition: The proposed analysis targets in the implementation of adaptive carrier shaping in Multicarrier waveforms systems (FBMC and NOFDM), transmitting in frequency holes. These schemes are more suitable than conventional OFDM system to be applied in CR in general and TV white space in particular. Furthermore, the technique analysed will include adaptive modulation and coding.

Challenges: The technique requires numerical tools which can increase complexity and cause converge issues, mainly with the use of high modulation order. It also requires knowledge of the fading characteristics which are in some scenarios not known or partially available.

Opportunities: When high order modulation complexity issues are solved it is a useful, accurate and adaptive technique for solving adaptive power (modulation) and frequency allocation in CR environment.

Proposed actions: Future steps include reducing the complexity and extending to more dynamic channel settings is a challenging extension of the proposed technique.

Collaborations: Joint work between CTTC and PUT, related to WP7, and it is in the scientific area of access techniques and modelling. This activity is related also with the IEEE 1900.7 standardisation activity and current regulation which looks for the benefits of using adaptive carrier shaping for TV white space. The research activity is related with EC-funded project PHYDYAS and with running activities of QoSMOS project. QoSMOS actually analyses different multicarrier waveforms (different to OFDM) for its efficient use in TV white space. Related references are [122], [123].

4.2.3.3 Resource allocation vs. NS-3 / LENA (LTE system level simulator)

Description: In Admission Control schemes for 3GPP, when Guaranteed Bit-Rate (GBR) and non-GBR traffic are present, the main problem is how to guarantee QoS of on-going sessions (GBR and non-GBR), while maximizing resource utilization by accepting new calls. Critical problems with current analytical approaches: (i) How to take into account non-idealistic environmental condition, (ii) Cognitive Admission Scheme, eNodeB learns from its past experience, so the main question is how the environmental condition influences on resource utilization.

The developed Cognitive Admission Scheme will be evaluated in LENA simulator, which is LTE extension of ns-3 simulator developed by CTTC. EIT+ is looking the resources allocation in the spectrum sharing scenario, where two network operators are participating in the auction, constructed in order to allocate radio resources based on the valuations received from different players. Such scenario will be adapted to LENA simulator.

Value proposition: Identification of Learning Techniques that can be successfully applied to CR and which will satisfy following conditions:

- Good generalization performance (function approximation, pattern recognition)
- Low computational complexity
- Compact model
- Stability in real usage

- Feasible software implementation

Challenges: A more realistic scenario should include traffic configuration and schedulers, taking buffer size as the basis for valuation of shared spectrum; this will make the LEA integration more complex.

Opportunities: To test on LENA system level simulator different learning approach using different types of traffics and scenarios (Macro+small cells), and to include more complete performance metrics (delay, buffer state, traffic class, etc.) and schedulers for optimal resources allocation.

Proposed actions: In further steps, the concept was planned to be developed towards the dynamic algorithm, considering various valuation functions (i.e., various performance metrics) and self- optimization. Its application within single, heterogeneous network shall be also applicable after slight model modifications.

Collaborations: Joint work between CTTC and EIT+. Related to WP8-WP10/WP11 and belongs to the execution/platform research area. Useful information can be found in [124], [125].

4.2.3.4 Spectrum occupancy and use measurements

Description: Measurements of spectrum usage in different locations and at different times have been conducted, including measurement in Athens, London, and Skopje. The analysis of the data and consideration for further measurements is ongoing.

Value proposition: Although the underutilization of the spectrum bands has been pointed out and has generated a strong research interest on dynamic spectrum access, there is still a lack of scientifically collected data to show in quantified manner how much there are opportunities. The current published measurements are limited in their geographical scope and/or data is collected only for a short period of date. Moreover, quite much of data has been U.S. centric, and there is a lack of understanding situation better from European perspective. The measurement data has intrinsic value for regulatory discussion, but can be also used to test and verify various research ideas that have been generated by the CR community.

Challenges: Spectrum measurement campaigns are challenging to do as they require specialized hardware and access to different locations. Due to this even energy detection measurements are challenging to conduct, and feature detection based methods are even harder to do (partially due to large parameter space).

Opportunities: The better understanding of how spectrum usage varies for a range of countries and times, can lead to new insights. It will definitely contribute to the European discourse on spectrum regulation, and collected data is also useful to test out different CR proposals. Joint work between different groups is required in order to guarantee access to different location and to share expensive equipments and knowledge on measurements. NoEs, such as ACROPOLIS, are almost unique vehicle to enable this sort of work and leverage measurement capabilities to much for further than any single national group or small European STREP projects could hope to do.

Proposed actions: To analyse the existing data, and discuss possible further measurements.

Collaborations: The measurement work has been coordinated and lead by RWTH, and there has been a lot of collaboration in measurements between RWTH, KCL, UKIM, and IASA. Work is mostly related to WP9. The work is place in the technology area of "sensing/discovery techniques", and it can be useful in almost all scenarios. The results of this work are reported in [126].

4.2.3.5 Common simulation platform for spectrum awareness based on the IEEE 1900.6 architecture

Description: This topic proposes a simulation platform for awareness of spectrum opportunities, based on the IEEE 1900.6 architecture for collaborative sensing purposes, which attempts to incorporate the capabilities of different simulation packages to achieve a realistic assessment of performance, particularly regarding physical layer aspects which are often neglected in network simulators.

Value proposition: This will add significant accuracy to sensing simulation capabilities, as well as sensing performance assessments in a range of novel scenarios. Can take higher layer considerations and assess performance of a realistic simulator of lower layers.

Challenges: Assessment of which simulation packages and techniques can or should be incorporated.

Proposed actions: Further work on enhancing the OMNet++ simulations with physical layer capabilities, perhaps using MATLAB. Particularly the effects of mobility and spatial correlation have been considered as important to add.

Collaborations: This is a joint work between EADS, Uniroma1, KCL and it is related to WP9 and WP10. The work is placed in the technological area of "Execution/platforms" and it is related to the "Hierarchical Spectrum Access on Licensed Bands" scenario [127].

4.2.3.6 Dynamic Spectrum Access, Cognitive Radio and Spectrum Awareness for Energy Saving

Description: This topic investigates ways in which dynamic spectrum access, CR and greater spectrum awareness can be used to save energy for mobile and wireless networks. Saving is in terms of transmission power (ideally then mapped to "from-the-mains" power), as well as direct "from-the-mains" saving through facilitating subsets of radio network equipment using power saving modes, are considered.

Value proposition: Represents an interesting application related to spectrum awareness and the use of DSA/CR solutions built on top of that. It will save energy and significant money (OPEX) for mobile/wireless operators; is of strong interest in industry.

Challenges: Ensuring that hardware capabilities are able to realise the proposed energy saving schemes, and consideration of holistic aspects (e.g., complexity of some schemes may lead to increased signalling/processing, which may lead to an energy loss "from-the-mains", not saving). Technically, all of the conventional challenges of such spectrum access apply. Moreover, awareness of the implied energy consumption of different spectrum access plans should be achieved. Feedback and prediction mechanisms to understand this awareness have to be created.

Opportunities: Creation and demonstration added benefits of spectrum coexistence, particularly energy saving.

Proposed actions: Attempt to incorporate more "cognition" into the approaches that have thus far been defined in collaborative works of PUT and KCL. Look as ways in which knowledge of the spectrum (e.g., interference potential) are maximised.

Collaborations: This is a joint work between KCL, PUT, Uniroma1, EADS and it is related to WP9 and WP10. The work is placed in the technological area of "Access techniques and modeling" and it is related to multiple scenarios. For additional information please refer to [128]-[135].

4.2.3.7 Radio Environment Mapping: spatial map of radio characteristics, using observations at certain points on {space, frequency, time} and processing capabilities

Description: This topic attempts to develop a spatial map of radio characteristics, such as RF present in certain bands/locations, using observations at certain points on {space, frequency, time} and processing capabilities (including assumptions and learning about propagation behaviours, for example).

Value proposition: Highly relevant to understanding of where and when opportunities will exist, both for overlay and underlay opportunistic access approaches. It can help the operator or another central processing element (e.g., in an ad-hoc cognitive network) to assess how their spectrum might be used opportunistically, and can assist management of the network, among many other solutions. It can help the regulator understand where opportunities for secondary access might exist and where behaviour is not as calculated by the regulator.

Challenges: Understanding of how to process information and generate the map, given a limited set of observations existing in {space, frequency, time}.

Proposed actions: Continued work on mapping and learning capabilities for the central processing element.

Collaborations: This is a joint work between RWTH, UKIM and IASA and it is related to WP9. The work is placed in the technological area of "databases" and it is related to multiple scenarios. Related references are [136], [137].

4.2.3.8 Estimation-based noise-robust and energy-efficient sensing

Description: This research topic addresses spectrum sensing by developing a new framework for Constant-False-Alarm-Rate (CFAR), feature-based detection. The focus is on (but are conceptually not limited to) spatial signal features that arise due to the reception of the signal at different points in space. These features allow detection (*first*, and that is the novelty) as well as subsequent localization of unknown sources based on an estimation pre-processor. The proposed family of statistical tests is based on the appropriate processing of the received samples in order to create successive and statistically independent estimates of signal features that have meaning if and only if a signal is present.

Value proposition: It is well known that noise-modeling uncertainties give rise to a fundamental limit on the sensitivity of energy-based detectors (or related moment-based detectors), also known as the "Signal to Noise Ratio (SNR) wall" (see related references). Similar "walls" appear also when localizing unknown sources for various applications (including CR), since localization techniques are based on tempo-spatial signal features. Low SNR regimes plus vague knowledge of the characteristics of the signal under detection in such applications motivate the exploration of techniques that are robust to such parameter uncertainties and therefore immune to such limits. A simple conceptual framework is proposed herein that naturally generates techniques with such immunity advantages for detecting the presence of an unknown source in broadband noise.

Challenges:

- The solution may be complex and may need higher SNR when the noise level is known (inferior to the known-noise solution, matched filter, etc.)
- It may not apply directly for multiple sources present and may need modification.
- Time related spatial features poses strict synchronization requirements to the sensors.

Opportunities: If solved with reasonable complexity, it can become the standard solution for all such sensing problems due to the universality of the concept.

Proposed actions: Future work should include extensions of the proposed test for more challenging scenarios of multiple sources and sensors as well as realistic system models.

Collaborations: This is a joint work between IASA and PUT and it is related to WP9. The work is placed in the technological area of "Sensing/discovery techniques" and it is related to multiple scenarios. Related references are [138], [139].

4.2.3.9 Interference localization and transmit power estimation in lognormal fading environment

Description: The proposed technique achieves radio source localization and transmit power estimation (for an unknown number of sources) in a log-normal shadow fading environment. The estimation is based on power measurements obtained by sensors of known number and location placed in the geographical area of interest. The technique is based on the maximum likelihood criterion and requires knowledge of the fading characteristics.

Value proposition: The technique is useful and applicable since it requires only power measurements, which can be typically obtained by low-cost infrastructure. It is also very important for problems were the actual number of transmitting sources is completely unknown or can be only upper-bounded.

Challenges: The technique requires numerical tools which can increase complexity and cause converge issues. It also requires knowledge of the fading characteristics which are in some scenarios not known.

Opportunities: When numerical issues are solved it is a useful, accurate and low-cost technique for solving the cumbersome problem of estimating the number, location and power of transmitting source.

Proposed actions: Proposal to reduce the complexity and extending to more dynamic channel settings is a challenging extension of the proposed technique.

Collaborations: This is a joint work between IASA and RWTH and it is related to WP9. The work is placed in the technological area of "Position-location techniques" and it is related to multiple scenarios. Related references are [140], [141].

4.2.3.10 Test Beds for Implementation of Spectrum Sensing Schemes

Description: This topic is about the active implementation and experimentation on spectrum sensing schemes in hardware platforms.

Value proposition: Offers a real-life testing of concepts around spectrum sensing. Most such concepts are relatively easy to implement and test even on quite "dumb" hardware. Analysis and simulation are often very different in performance from testing in reality; hence this topic offers a better indication of the performance of such schemes than can be achieved with aforementioned means.

Challenges: Scalability, in terms of number of devices and testing environments.

Opportunities: A better understanding of spectrum sensing schemes performance and a better understanding of complexity in implementing them on real systems. Ability to assess large-scale scenarios (e.g., collaborative/cooperative sensing schemes), with larger sensor sets than would otherwise be possible.

Proposed actions: Identification of appropriate sets of hardware and sensing algorithms for future tests; combining the sensing implementations with other elements (e.g., learning) for a more complete assessment of CR potential.

Collaborations: This is a joint work between UKIM, KCL, EURECOM, IASA and it is related to WP7 and WP9. The work is placed in the technological area of "Position-location techniques" and it is related to multiple scenarios [142], [143].

4.2.3.11 Beacons for Spectrum Awareness

Description: This topic aims to define mechanisms for the proactive transmission of information by the primary to ward off secondaries, by using, for example, a common random access channel. The concept might also be used for other purposes, such secondary users providing awareness of the potential for connectivity with devices in the locality to form CR links.

Value proposition: Better ability to deal with mobility in secondary spectrum access, especially considering that current approaches (e.g., geolocation databases) are designed for relatively stationary scenarios. Better awareness of channel from secondary to primary, hence better transmission parameterization in underlay and interweave scenarios. Recognizes the fact the interference occurs as the point of reception, which spectrum sensing misses, and the fact that interference is a local phenomenon, that the database approaches miss.

Challenges: Usefulness of implementation and practicality—in which types of bands could be deployed such a concept? Puts a significant burden on the primary; this burden should be properly assessed. It may still require a coordination mechanism to cope with issues such as channel variability.

Opportunities: Vastly increased spectrum opportunity, and a better understanding of the back channel from secondary Tx (Transmitter) to primary Rx (Receiver). Presents the opportunity to better form opportunistic CR links.

Proposed actions: Consideration of potential of such a scheme to reliably cope with issues caused by mobility for example (which other spectrum information acquisition schemes can't really handle); assessment of the added value in terms of additional performance of the concept while protecting the primary compared with other schemes. Consideration of the burden on the primary (processing, energy depletion due to beacon transmissions, etc.).

Collaborations: This is a joint work between KCL, Uniroma1 and it is related to WP9 and WP10. The work is placed in the technological area of "Sensing/discovery techniques" and it is related to the Coordinated Spectrum Access between PUs and SUs scenario [144], [145].

4.2.3.12 Cognitive Radio through Beamforming to Secondary Users under Interference Limits

Description: This topic assesses CR performance through beamforming to secondary users, in terms of achievable secondary access rates, and effect of the primaries. It is relevant in underlay access CR scenarios. Also explores the incorporation of sensing schemes to detect the primaries and secondary user positions, uncertainties therein, and the overall effect on beamforming performance.

Value proposition: Better assessment and understanding of CR beamforming performance given direction of arrival estimation errors. Implementation of interference mitigation in CR beamforming.

Challenges: Practicality and usefulness (Will underlay access be allowed?). Complexity of beamforming optimization schemes in such scenarios, and general practicality of calculation "on-the-fly".

Opportunities: Vastly increased spectrum opportunity, and a better understanding of the effect of realistic angle estimation errors on performance.

Proposed actions: Assessment of estimation errors on performance for alternative angular position estimation schemes; perhaps incorporation of 3-D aspects (e.g., beamforming in both theta and phi); assessment of mobility related aspects; general consideration of protocols for incorporation of position estimation, e.g., effect on MAC.

Collaborations: This is a joint work between KCL, Uniroma1 and it is related to WP9 and WP10. The work is placed in the technological area of "Access techniques and modeling" and it is related to the Non-coordinated Spectrum Access between PUs and SUs scenario. Related references are [146].

4.2.3.13 Location-based routing with beamforming

Description: This work presents a routing strategy for cognitive wireless networks based on the combination of a position-based routing protocol, with position information obtained by means of Direction Of Arrival (DOA) estimation, and a beamforming technique that takes advantage of the position information to maximize Signal-to-Noise Ratio at the intended receiver while minimizing interference towards other cognitive receivers and primary receivers potentially affected by the transmission.

Value proposition: Availability of position information can be exploited at different levels in order to increase the performance of a CR network. In this work two different usages of position information are taken into account: a local use, where position information is used as a basis for point-to-point transmissions thanks to a beamforming technique, and a global use where information on the position of the destination in a multihop connection is used to reduce control overhead in the routing process.

Challenges:

- The solution introduces an overhead related to the retrieval of position information through a distributed approach.
- Mobility can severely reduce performance.

Opportunities: In static/low mobility scenarios the proposed position-based optimizations can heavily increase performance of a cognitive network, while guaranteeing to meet coexistence requirements.

Proposed actions: The goal for the future is to address the following technical issues: 1) Address overhead for positioning 2) Uncertainty in common channel establishment due to spatial variations aspects 3) Actual performance of positioning based on DOA 4) Optimization related to traffic prediction 5) Mobility (take advantage of changing shadowing and proximity).

Collaborations: This is a joint work between Uniroma1, KCL and it is related to WP10. The work is placed in the technological area of “Decision/optimization” and it is related to the use case “Reconfigurable UAVs network” in the “Spectrum Sharing on Unlicensed Bands” scenario [147], [148].

4.2.3.14 Common Access Channels for Cognitive Radios

Description: The work targets to define a common access channel to be used jointly for coexistence between different CR networks and for neighbour discovery within a network. The work will be extended by considering the use of multiple RATs and the potential use of different RATs for control and data exchanges. Interaction of neighbour discovery with routing and dynamic channel selection in multi-hop networks will also be considered.

Value proposition: The definition of solutions for control channels based on out-of-band signalling on license-free bands can provide a simple yet effective solution for addressing neighbour discovery in cognitive networks.

Challenges:

- Using different RATs can lead to different coverage areas and correspondingly to over-reach / under-reach (hidden terminal) problems for control information.
- Determining the common set of RATs in a network can be an issue by itself.

Opportunities: The definition of a common control channel protocol over a RAT common to most devices (e.g., Bluetooth) could be widely adopted to solve the channel selection issues in CRs.

Proposed actions: the following technical issues are important to be examined in the future: (i) impact of different propagation among different RATs on network performance, and comparison with inband control channel solutions; (ii) review of current solutions for joint routing and DSA.

Collaborations: This is a joint work between Uniroma1, KCL and UPRC, and it is related to WP9 and WP10. The work is placed in the technological area of "Access techniques and modeling" and it is related to the use case "Independent primary networks with common control channel specification" in the "Multi-networks, multi-RAT" scenario [149].

4.2.3.15 Common architecture and simulation platform for cognitive applications

Description: The work proposes a novel simulation framework for wireless cognitive networks, based on the combination of the OMNeT++ discrete event simulator with Matlab, designed to assess the performance of wireless cognitive networks in realistic scenarios. Activity focus on both the definition of a cognitive wireless node architecture as well as on the design of interfaces between different functional blocks, based on the work carried out in the IEEE 1900.6 Group.

Value proposition: A dedicated simulation platform capable of assessing performance of all key algorithms and protocols would be a valuable tool in the design of CR networks. Aspects like mobility and spatial correlation modeling in signal propagation would make extensive performance evaluation possible beyond what is currently feasible with testbeds.

Challenges:

- To achieve a good balance between accuracy and complexity.
- Implementation of lower layers in OMNeT++ is heavily depending on accurate models.

Opportunities: A simulation platform shared by several ACROPOLIS partners could become a valuable tool both within the project and beyond, with the release of the source code to the OMNeT++ community.

Proposed actions: Future actions: 1) Introduction of spatial correlation aspects 2) Address mobility modeling issues.

Collaborations: This is a joint work between EADS, KCL and Uniroma, and it is related to WP5 and WP10. The work is placed in the technological area of "Execution/Platform" and it is related to the use case "Reconfigurable UAVs network" in the "Spectrum Sharing on Unlicensed Bands" scenario. Related information can be found in [127].

4.2.3.16 Information exchange during the neighbor discovery phase

Description: This work addresses the impact of neighbour discovery efficiency, and in particular of discovery failures, on algorithms for distributed learning. It is focused on the issue of reduced efficiency in setting up a common communication channel, compared to the "standard" assumption of having a predefined common control channel.

Value proposition: The work will go beyond the assumption (often introduced in works addressing higher layer issues in CR) of having a predefined common control channel for setting up communications and exchanging information required for learning. The impact of setting up such a channel, in particular in presence of terminal mobility, posing an upper bound on the time available for achieving successful set up, can be significant, and should be analysed more carefully than what is happening right now in the literature.

Challenges:

- Define a proper scenario for analysing the problem (e.g., multiple, non-cooperating networks vs. a collection of network that already built up a common control channel).
- Proper modelling of mobility and design of new schemes for neighbour discovery, beyond simple random search.
- Integration of simulation tools between different partners.

Proposed actions: Provide a much more realistic performance evaluation of higher layer solutions, taking into account neighbor discovery and common control channel impact.

Collaborations: This is a joint work between Uniroma1, UPRC, KCL, EIT+, and it is related to WP10 and WP11. The work is placed in the technological area of “Sensing/discovery techniques” and it is related to the use case “Cellular/femtocell cognitive radio networks” in the “Multi-network, multi-tier coexistence” scenario. Related references are [150], [151].

4.2.3.17 Admission control based on interference management

Description: This activity investigates an admission control scheme for secondary cognitive networks. The scheme will work based on interference modelling and management; performance of the proposed scheme will be evaluated by introducing suitable mathematical models and simulations.

Value proposition: The activity will lead to the definition of a new admission control scheme relying on interference models for deciding if new link request can be accommodated, and of a corresponding MAC protocol to support the operation of the admission control module, possibly based on a variation of ECMA-392. The novelty in the approach will also reside in the definition of analytical models for performance analysis based on Markov chains and multiple Markov chains for multichannel networks.

Challenges:

- Definition of a model based on interdependent Markov chains to model multi-channel CR scenario: feasibility to be verified.
- Development of simulative modules related to ECMA-392.

Opportunities: To develop an innovative admission control technique, and contextually define an analytical tool for analysing performance of a multiple-channel secondary cognitive network.

Proposed actions: Definition of the admission control scheme, work on the analytical model based on multiple Markov chains.

Collaborations: This is a joint work between JRC, Uniroma1, EADS and it is related to WP10 and WP13. The work is placed in the technological area of “Access techniques and modeling” and it is related to the use case “Reconfigurable UAVs network” in the “Spectrum Sharing on Unlicensed Bands” scenario.

4.2.3.18 Context aware interference management in 2-tier networks

Description: Because of the aggressive interference situations in two-tier femtocell scenarios (femtocells deployment within macrocells), traditional interference management techniques may not be able to provide effective performance results. This is in part due to the fact that these techniques use only collected data from users (feedback) and static network planning information. On the other hand, because of the progress in hardware and software development, next generation terminals and access points are expected to be able to collect and store a large amount of data compared to the existing equipment. In this activity, this stored rich context information is used by the interference management and resource allocation techniques to enhance their effectiveness. Both co-channel and orthogonal allocation are examined.

Value proposition: The use of rich context information (not only relying to users' feedback) was shown to result in better performance in comparison to the case where this information was unknown. This was demonstrated for both co-channel and orthogonal channel allocation schemes.

Challenges: The results were based on rather ideal assumptions for the accuracy of the available context information. The heterogeneity of the context information, combined with the high variance of the radio environment pose a critical challenge to the accuracy of the estimated parameters. The uncertainty of the available information needs also to be considered and modelled in order to develop more realistic and practical allocation algorithms.

Opportunities: Since the deployment of femtocells in areas covered with macrocells is expected to accelerate in the future, there will be need for practical resource allocation schemes applicable to 3G and LTE femtocells.

Proposed actions: The future work will aim at comparing the described interference management and resource allocation methods (co-channel and orthogonal) in order to identify the related trade-offs for each and to determine the scenarios for which each approach is more applicable. Future work will also aims to robust algorithms that take into consideration the uncertainty of context information.

Collaborations: This is a joint work between IASA, PUT, RWTH, and UoS and it is related to WP12. The work is placed in the technological area of "Decision/optimization" and it is related to "Multi-tier coexistence" scenario [152], [153].

4.2.3.19 Policies for cognitive radio systems

Description: This work considers the utilization of policies which can facilitate efficient and flexible network management for emerging CR networks. The policies impose rules, regulations and constraints that should be respected by cognitive nodes, while accessing and sharing the available wireless resources. They are separated from the radio firmware and hardware and are dynamically changeable and adaptive. An overview of the policy based cognitive networking is provided and three different policy systems, namely XG, ORACLE and ARAGORN, for CR environments were presented.

Value proposition: A general policy system for CR networks should enable policies to be imposed by all stakeholders, i.e., the regulator authority, network operator and/or a user.

Different types of policies handling different aspects of the resource management in CR networks should be provided by the policy system. A policy language with clearly defined and extendable ontologies can supply these requirements.

Challenges: The various hardware constraints and implementation issues that have to be considered for the efficient instantiation of policy frameworks on existing CR platforms.

Opportunities: The identification of the main characteristics and features of existing policy frameworks allows for the provision of guidelines for the use and deployment of policies in CR systems, emphasizing on their potential for optimisation of the system performance.

Proposed actions:

- Definition of the decision making engine (limitations and mechanisms will be described).
- Centralized and distributed approaches will be considered.

Collaborations: This is a joint work between UKIM, UoS and PUT and it is related to WP12. The work is placed in the technological area of “Policies” and it is related to multiple scenarios.

4.2.3.20 Distributed power control for cognitive radios with primary protection via spectrum sensing

Description: Impact of multi-cell, multi-operator interference on the overall radio resources when multiple operators co-exist and share a common pool of spectrum is studied. A centralized DSA scheme that is able to measure the interference level and interact dynamically to minimize interference and enhance spectrum utilization while maintaining a satisfactory level of QoS is derived.

Value proposition: The analysis indicates that a clever centralized programming framework can be applied to match the offered and required spectrum resources to both operators.

Challenges:

- The CRs perform localized spectrum sensing of primary TV signals and make individual decisions about their interference environment and link gains to the primary system.
- Increased number of supported CR users is expected since different constraint is executed at individual terminals rather the same constraint being applied to all CR devices as in the second related reference.

Proposed actions: For the future, extensions of the proposed scheme to other scenarios than TV spectrum will be considered.

Collaborations: This is a joint work between UoS and TUD and it is related to both WP12 and WP13. The work is placed in the technological area of “decision/optimization” and it can be applied in the 2nd main scenario “Hierarchical spectrum access on licensed bands”. Related references are [154], [155].

4.2.3.21 Spatial Shaping in Multiple Antenna overlay CR

Description: Consider the coexistence of primary and secondary links in the context of an overlay CR system. Assuming that the secondary transmitter has access to the message sent by the primary transmitter in a non-causal fashion, this channel model is known as the cognitive channel or the interference channel (IFC) with degraded message sets. One possible strategy is to have the secondary transmitter employ part of its resources to help the communication between the primary users, so that their communication is not disturbed or is even improved (e.g., in terms of rates). The remaining parts of the resources are used for private communication to the secondary receiver. Moreover, with accurate channel state information, the secondary transmitter can use its knowledge of the interference experienced by its receiver to pre-cancel it.

Value proposition: The proposed overlay strategy works also in scenarios where underlay cannot work, e.g., in fully-loaded CR without degrees of freedom.

Challenges:

- Ideal assumptions on channel state information and messages from the primary links.
- Ideal assumptions on the synchronization and cooperation between primary and secondary links.

Proposed actions: For the future more realistic two-phase and three-phase approaches are under investigation.

Collaborations: This is a joint work between PUT, KTH and TUD and it is related to WP8 and WP13. The work is placed in the technological area of “decision/optimization” and it can be applied in both scenarios: “Hierarchical Spectrum Access on Licensed Bands” and “Spectrum Sharing in Unlicensed Bands”. The collaboration so far shows nice combination of coding (KTH), signal processing (TUD) and resource allocation. Related references are [156]-[160].

4.2.3.22 Comparison of Underlay and Overlay Spectrum Sharing Strategies in MISO Cognitive Channels

Description: Consider an extension of the CR channel model in which the secondary transmitter has to obtain (“learn”) the primary message in a first phase rather than having non-causal knowledge of it:

- An achievable rate region is derived for the two-phase communication that combines elements of decode–and–forward relaying with coding for the pure CR channel model.
- The choice of parameters is found that maximize the secondary rate while satisfying the primary rate requirement.

Value proposition: The question when to use underlay and when to learn (and how) and use overlay techniques is addressed.

Challenges: Ideal assumptions on Channel State Information (CSI).

Opportunities: The work is an important step towards more practical implementation of obtaining the message at the secondary transmitter.

Proposed actions:

- Analysis of phase transition between optimality of underlay and overlay.
- Extension to other forwarding schemes.
- Extension to incomplete CSI.

Collaborations: This is a joint work between PUT, KTH and TUD and it is related to WP8, WP12 and WP13. The work is placed in the technological area of "decision/optimization" and it can be applied in the scenario: "Hierarchical Spectrum Access on Licensed Bands". More information can be found in [160].

4.2.3.23 Crystallized Rate Regions in the Secondary Interference Channel

Description: The CR system model is extended to two secondary links in the presence of a primary link, with all the transceivers equipped with multiple antennas. The Vickrey-Clarke-Groves theory has been applied and the regret-matching algorithm has been implemented to find the optimal playing strategy for the two secondary users. New cost function has been proposed that allows for fast convergence of the developed solutions to the optimal or sub-optimal point.

Value proposition: It successfully uses game theory to find reasonable operating points.

Challenges: Analysis is difficult, numerical evaluations are required to show the performance.

Opportunities: The approach can be combined with different physical layer techniques and approaches, e.g., with beamforming schemes or spectrum power allocation.

Proposed actions: On proposal for the future is the extension to other game theoretic solution methods, i.e., generalized Nash Equilibrium (NE) and satisfaction NE, and to other operating points.

Collaborations: This is a joint work between PUT, KTH and TUD and it is related to WP8, WP12 and WP13. The work is placed in the technological area of "decision/optimization" and it can be applied in the scenario: "Spectrum Sharing on Unlicensed Bands" [161].

4.2.3.24 Admission control for Cognitive Radio Networks based on aggregated interference

Description: This research aims at modeling a complex scenario in which a number of secondary devices (CRs) attempt to exploit spectrum resources underutilized by a primary service. Assuming that the secondary devices are aware of spectrum availability (e.g., database and/or spectrum sensing) they coordinate by means of the ECMA-392 distributed beaconing in a common control channel. Secondary devices decide whether a new link can be scheduled by estimating the signal-to-interference ratio (SIR) on the basis of the distance among devices (this information can be acquired from the beacons). In this work a Rayleigh fading model is assumed, aside with a certain reliability constraint which usually comes from the application. In case the SIR of a channel is below a threshold value, new secondary links can be scheduled in overlay on top of the ones already existing.

The study aims at modelling one channel first and the multi-channel case afterwards. The analysis combines Markov chains technique with signals propagation modelling. The ultimate goal is to model the multi-channel case, including also the interference constraints due to the primary service ownership of the bands. Theoretical results should be contrasted with simulations (e.g., OMNET++).

Value proposition: This study aims to bring into a single model secondary access on primary access, as well as secondary access on secondary access. The scenario is complex and simulations are considered of great importance to assess the goodness of the study.

Challenges: The first weakness that clearly arises is that the study will assume the presence of a certain amount of available spectrum. In a real scenario this is strictly depending on the specific environment (urban or rural for instance). Although the overall modelling should enable predicting the number of secondary links which could be scheduled in overlay mode in a certain region of spectrum and space, the idealization introduced in the model (Rayleigh fading, devices' activity) will bias the results.

Opportunities: Estimation of the number of secondary links that can be scheduled over a frequency channels and/or a number of frequency channels. As a matter of fact, the number of secondary links is the payoff of the entire CR techniques.

Proposed actions: For the future the partners will coordinate in order develop the single and multi-channel theoretical framework as well as the OMNET++ simulator of the network. The simulation tool itself might change depending on models availability.

Collaborations: This is a joint research work between JRC-EC, UniRoma1 and EADS. The topic has impact to both WP10 and WP14. The work is placed in the technological area of "access techniques and modelling" and it can be applied in the 2nd main scenario "Hierarchical spectrum access on licensed bands", and more specifically in the "Non-coordinated Spectrum Access between PUs and Sus". Information can be found in [162].

4.2.3.25 Geo-location database for incumbents with known emitter position

Description: This research topic has the objective to identify use cases for opportunistic spectrum access by secondary CR nodes where the position of the primary radio-communication equipment is known beforehand. The research topic extends the case of the white spaces where the position of Digital TV base stations is well known. Impact of aggregated interference will also be investigated.

Value proposition: Regulatory and industry proposal for opportunistic spectrum access are mostly focused to the "white spaces" use cases but there are other cases which are not currently considered. This is not strictly a research topic but an exploratory investigation for commercial exploitation of the opportunistic spectrum access beyond the white space concept.

Challenges: Research content could be limited.

Opportunities: Identification of new business use cases which could support new regulatory and standardisation activities.

Proposed actions: As a next step the identification of specific use cases is proposed accompanied with a description of the trade-offs, benefits and shortcomings.

Collaborations: This is a joint research work between JRC-EC and Univleeds and it is a joint activity of WP14 and WP6. The work is placed in the technological area of "position location techniques" and it can be applied in the 2nd main scenario "Hierarchical spectrum access on licensed bands", and more specifically in the "Non-coordinated Spectrum Access between PUs and SUs". Related references are [162], [163].

4.2.3.26 Secure policy framework for Hierarchical Spectrum Access on Licensed Bands

Description: This research topic has the objective to define a complete secure framework for the definition and secure distribution of policies to regulate the access to radio frequency spectrum.

Value proposition: Complete policy framework in Hierarchical Spectrum Access is still not present: the CORAL mechanism from XG project is the most relevant. In this topic, we will also describe how the policy framework can make the network more robust against security attacks.

Challenges: The policy framework can be quite complex. Scalability can be a potential issue.

Proposed actions: The output can be channelled to a regulation or standardisation activity (ETSI or R&TTE directive).

Collaborations: This is a joint research work between UKIM and JRC-EC and it has relation to WP12, WP13, WP14. The work is placed in the technological area of "policies" and it can be applied in a variety of scenarios and use cases. In this study the 2nd main scenario "Hierarchical spectrum access on licensed bands" is considered. Related references are [164], [165].

4.2.3.27 Implementation of collaborative spectrum sensing on USRP platforms

Description: This research topic has the objective to design and implement a collaborative sensing framework on the Universal Software Radio Peripheral (USRP) platform (i.e., GnuRadio) or similar hardware platform.

Value proposition: Theoretical research in collaborative spectrum sensing has already been carried out in many projects and presented in various research papers. Practical implementation on real platform is still lacking. This project proposal tries to cover this gap.

Challenges: Research content could be limited.

Opportunities: Identification of major trade-offs of theoretical proposal for collaborative sensing when they are applied to practical systems.

Proposed actions: For the future other hardware platforms could be taken into consideration.

Collaborations: This is a joint research work between UKIM and JRC-EC and it has relation to WP7, WP9, WP14. The work is placed in the technological area of "sensing/discovery techniques" and "execution/platforms" and it can be applied in a variety of scenarios and use cases. In this study the main scenario "Non-coordinated Spectrum Access between PUs and SUs" is considered [166], [167].

4.2.3.28 Learning User Preferences and Network Capabilities for enhancing decision making in Cognitive Radio Systems

Description: The advantages and the way that networks gain benefits from cognitive systems is analysed during this collaboration. The focus of this collaboration is placed on machine learning techniques applied both in the network and the user devices side. During this survey-oriented collaboration an extended state-of-the-art of machine learning applied to cognitive systems as coming from the recent research and an overview of three different learning capabilities of both the network and the user device was studied. The techniques that were exploited for this research are the unsupervised learning technique of Self-organising Maps (SOMs) and the Bayesian statistics.

Value proposition: The value of this research comes from the comparison of the two used techniques and the identification of the relationship between the problems of learning user preferences and of learning network capabilities. Comparing the two techniques/ approaches presented for learning network capabilities, Bayesian statistics offer also the possibility of online training. The latter abstracts the necessity of explicitly storing past observations, a feature that doesn't exist in SOM. Additionally, these techniques were found to be interrelated. Their interrelation lies in the fact that the combination of a dynamical learning of context information and user preferences could be exploited in a later stage for the selection of the most appropriate network configuration.

Challenges: Further functionalities/ mechanisms may need to be specified so as to cover a greater variety of more complex scenarios.

Opportunities: A combination of the identified problems solved would facilitate the most appropriate network configuration with respect to user behaviour/ preferences and thus enhance the QoS and QoE perceived from the user.

Proposed actions: Examine more problems and techniques that could provide more learning-based functionalities for any CRS, enhancing its functioning.

Collaborations: This is a joint research work between UPRC and UoS for WP11. The work is placed in the technological area of "Learning mechanisms" and it can be applied in a variety of scenarios and use cases. Details for the outcomes of this study can be found in [168].

4.2.3.29 Learning and Knowledge Management Toolbox for Cognitive Radio Network Applications

Description: As a continuation of the research described section 4.2.3.28, more learning-based mechanisms were examined and analysed. A set of use cases has been described and sets of corresponding functionalities have been derived for: (i) acquiring and learning user and context information, (ii) deriving policies, (iii) learning related to the efficiency of decisions, and (iv) learning as means of optimizing the trade-off between the efficiency of decisions and the convergence rate. For each of these functionalities, several requirements have been identified.

Value proposition: Learning mechanisms are essential for the attainment of experience and knowledge in a CRS. Based on knowledge obtained through the exploitation of such learning mechanisms, decision-making mechanisms can become faster, since the CRS can learn and immediately apply solutions that have been identified as being efficient in the past. Also more reliable and more optimal decisions can be made by exploiting knowledge obtained through learning mechanisms. Moreover, knowledge obtained through learning mechanisms may be shared among nodes of a system.

The value of this research refers to the collection and presentation in an overview paper of such mechanisms so as to design and develop a toolbox towards this direction. For this reason, for each of the specified functionalities for information acquisition, learning and knowledge management, several requirements have been identified.

Challenges: Further functionalities/mechanisms may need to be specified so as to cover a greater variety of more complex scenarios.

Opportunities: Design a toolbox of learning and knowledge management techniques that can be applied to any CRS.

Proposed actions: Further elaboration on implementation options.

Collaborations: This is a joint research work between UPRC, UoS, CTTC, UKIM for WP11. The work is placed in the technological area of “Learning mechanisms” and it can be applied in a variety of scenarios and use cases. More details can be found in [169].

4.2.3.30 Distribution and storage of information

Description: This topic includes: (i) investigation of how the concept of Cognitive Control Channels (CCCs) and corresponding protocols can be exploited for the distribution and exchange of information, and (ii) investigation of concepts for storage of information, such as:

- Reference Context Repository enabling the storage of previously encountered contextual situations in addition to the corresponding solution that was selected by an optimization process for addressing these situations.
- Policy database.
- Radio Environment Maps enabling storage of context and policy information (including statistical information).

Value proposition: For the efficient operation of CRSs), it is essential to complement learning and decision making mechanisms with means that will allow for the exchange and distribution of information as well the coordination between various management entities. In this respect, CCCs have been identified as a key feature required for CRSs. Another vital issue for such systems is the storage of information so as to facilitate and assist various CRS functionalities. Depending on the type of information and how/where this is information is exploited, storage of information may be addressed in a different way.

Challenges: Work within ACROPOLIS has to follow very closely the work in relevant standardisation bodies.

Opportunities: While the concept and role of CCC and information storage in the operation of CRS have been studied from various aspects in research and standardisation activities, the study of actual implementation options is relatively recent. Implementation options for Control Channels for CRSs are currently being investigated within ETSI RRS (i.e., work item DTR/RRS-03008 leading to ETSI TR 102 684), as well as aspects of Radio Environment Maps for storage of information. The investigation of corresponding implementation options is a crucial step towards the realisation of the CCC.

Proposed actions: Further elaboration on implementation options.

Collaborations: This is a joint research work between UPRC, CTTC, UKIM, UoS, RWTH for WP11. The work is placed in the technological area of “databases” and it can be applied in a variety of scenarios and use cases. Related information can be found in [170]-[177].

4.3 A Unified view for the ACROPOLIS joint research activities

In this Section, the different Joint Research Activities (JRA) reported previously are presented in a comprehensive and conceptually unified way. To do that, we perceive the presently-researched CRS as extensions and knowledge-enhanced versions of classic Communication Systems (CS). This viewpoint gives rise to the important question whether there are any fundamental requirements or functionalities that are completely missing or cannot be viewed as mere extensions or modifications of the ones existing in a classic CS. As we will see in this analysis below, the answer depends on the level at which this comparison takes place.

At a highly functional level, CR scenarios (Table 4-1) differ from CS scenarios by the significant need for advanced techniques that must be deployed to ensure the coexistence of different radio systems which must share common channel resources and, at the same time, ensure the target QoS requirements. In classic CS this is accomplished by well-defined signal processing techniques and/or protocols that ensure the orthogonality of the different radios in one or multiple dimensions of the common medium (space-time-frequency-code). In licensed bands, this approach has been employed mostly in a centrally-controlled manner and only by authorized users. The fundamental difference, then, introduced by CRS is the use of licensed bands by unlicensed and/or un-authorized users and all the variations of this novelty. The use of a network’s licenced band from a user not belonging in the same network can be viewed one such variation (multi- Nets/RAT/Tier/Operators scenario). On the other hand, in unlicensed bands, in classic CS, the unavoidable interference has been treated by the use of robust communication techniques which ensure successful communication under mild interference conditions. By following the same principles, in this case, the CRS introduction brings highly increased efficiency in spectrum utilization.

We now examine whether such functional differences also translate to fundamental differences in the techniques and architectures required to implement CR systems. A case-by-case examination of all different ACROPOLIS JRA’s and a comparison with classic Communication (COMM) techniques indicates that current CR techniques and architectures place Interference Management (IM) as the top priority of all design goals. Although classic COMM systems also deal with interference, in CR scenarios the impact of IM is much more significant. Therefore, the role of Radio Environmental Awareness (REA) is also enhanced, since it is, in most cases, the main enabler for successful IM. The block diagram of Figure 4-7 below illustrates this viewpoint.

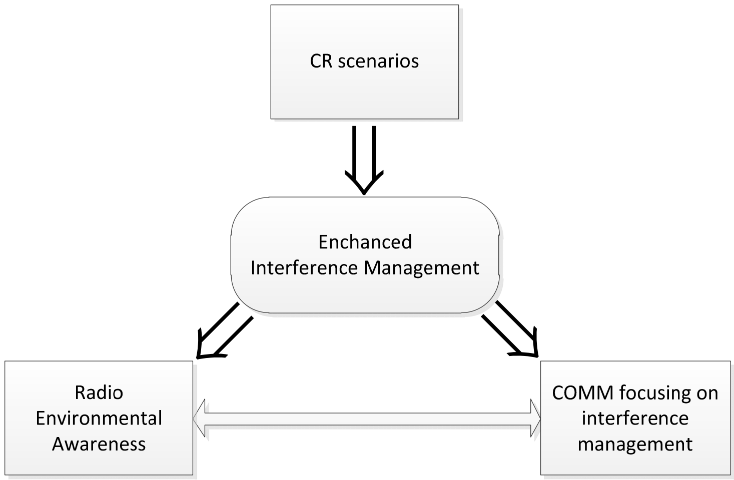

Figure 4-7: CRS main functionalities

The bi-directional interconnection arrow between the two major categories signifies the very significant interplay between the COMM and the REA, the type of interplay and synergy that marks the reason for research in CR systems (as opposed to merely enhanced standard communication systems).

If we focus on the different joint research techniques (algorithms, protocols) investigated in ACROPOLIS, we realize that they belong to one of the two major categories for the most part, while few of them treat the REA and the COMM IM in joint fashion. Regarding the platform development activities, we note that some of them belong solely to the REA category. This fact highlights a fundamental difference of CRS with respect to classic CS, namely that new architectural elements are needed in order to achieve an enhanced REA functionality.

In Figure 4-8 we enrich the categorization introduced in Figure 4-7 and map on it the different JRAs for each category/sub-category: starting from the top layer, “CR scenarios”, JRA4 (Spectrum occupancy and use measurements) investigates the fundamental question for CR networks application: “do spectrum opportunities exist?” JRA25 (Geo-location database for incumbents with known emitter position) targets the identification of new business opportunities and services enabled by the CR’s enhanced REA capabilities (in the form of geolocation databases).

Moving lower and focusing on the two identified major categories of the developed techniques, JRA15 (Common architecture and simulation platform for cognitive applications) targets the development of a common architecture and simulation platform, shared by all acropolis members, in order to assess all the developed algorithms and protocols. JRA6 (Dynamic Spectrum Access, Cognitive Radio and Spectrum Awareness for Energy Saving) goes after energy savings across the whole CR design (algorithmic, protocol, architectural). JRA28 and JRA29 investigate the use of learning and reasoning mechanisms for optimizing the overall performance of the radio. The adopted techniques belong to the research area of machine learning, an approach close to that proposed by Mitola when introducing the CR.

We further sub-divide the REA category into spectrum-sensing (SSe) techniques, REMs and all other techniques that do not fall into the previous two. There is a bidirectional interconnection between SSe and REMs. SSe techniques are helpful in building REMs, while REMs can be used to drive SSe commands. In the SSe class we have JRA8 and JRA9, where robust sensing and passive localization techniques are researched. JRA5 and JRA27 examine simulation and hardware platforms, respectively, for SSe assessment and implementation. A test-bed for SSe experimentation is addressed in JRA10. Distributed power control with primary user protection via SSe is studied in JRA20. Information model representation and learning mechanisms for building REMs using SSe measurements is treated in JRA7. JRA11 investigates the use of beacons, i.e., mechanisms for the proactive transmission of information by the primary in order to ward off secondary radios. This is a different mechanism for enabling enhanced REA, and that is why we classify it as “others”. JRA16 addresses the impact of neighbour discovery efficiency and, in particular, of discovery failures, on algorithms for distributed learning. JRA30 investigates how the concept of CCCs and corresponding protocols can be exploited for the distribution and exchange of information in the scope of ACROPOLIS.

Modulation techniques for transmitting in frequency holes and beam-forming to secondary users under interference constraints are studied in JRA2 and JRA12, respectively. An ASIP for the OpenAirInterface Platform has been designed in JRA1 that replaces the existing FEP which is responsible for the different functions at air-interface level. Underlay and overlay spectrum sharing strategies are under investigation in JRA21 and JRA22, topics that can be viewed as cross-layer techniques between the physical layer and the MAC (resource allocation) layers. Cross-layer techniques that combine routing with beam-forming under interference constraints are under investigation in JRA13. Research concerning policy-based CR networks is done in JRA19 and JRA26. This area can be viewed as the determination and implementation of dynamically changing rules/constraints that are affecting both PHY and MAC layers (which are fixed and hard-coded in classic CS).

Routing and DSA using common-access channels is under investigation in JRA14. Resource allocation techniques and theoretical bounds in interference channels are under investigation in JRA18 and JRA23, respectively. An LTE extension of the ns-3 simulator is employed in JRA3 to assess the performance of admission control and resource allocation schemes when GBR and non-GBR traffic are present. Finally, admission control based on the aggregated interference is the research topic of JRA17 and JRA24.

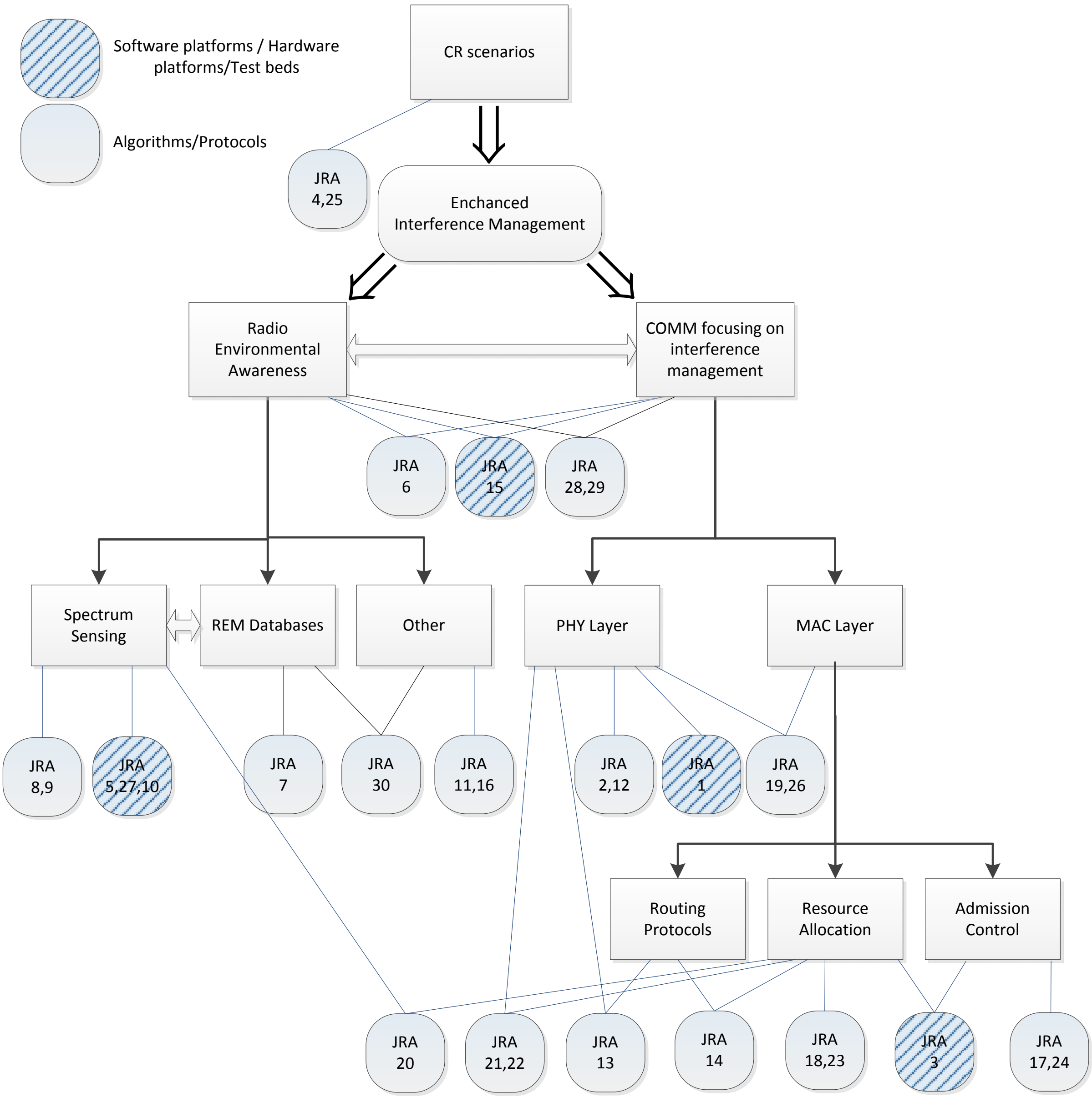

Figure 4-8: Identification of Joint Research Activities on a common conceptual tree

4.4 Harmonization and suggested future steps

The previous extensive commentary on, and placement of, the various JRAs on a common classification tree (Figure 4-8) has concluded the "X-ray" process of the project at its present state. The various JRAs have been initiated spontaneously by partners and elaborated further in a sequence of WP, Cluster and full-project technical meetings, always guided by the directions of the Technical Annex and informed by the partners' initial participation in the respective WP's. Therefore, the formation of the current and forthcoming JRAs has resulted from the initial momentum and conception of the project. The fact that the distribution of the ACROPOLIS research interests is fairly within the prescriptions and profiling of the broader research activities in European and other-continent projects and

R&D preferences must be attributed to the meaningful composition of the initial Technical Annex.

The fact that the business and regulatory dynamics change all the time, that concepts evolve, research results from the global community continue to flow in, etc., means that the JRA themselves must be dynamic and fluid, to accommodate this change in the world scene. To do that (i.e., harmonize not only internally but also cohere with the world flow), there has to be a concept, a guidance, a way for doing so. As a general principle, this can be done in two distinct ways (although following both is also an option): one way is to identify that unique concept, the over-riding topic that permeates all individual JRAs and enhance or amplify research on that topic by collective action. The alternative is to create "virtual mini-projects" within the project, namely a few selected large-scale applications (or scenarios) that call for vertically-integrated synergy between multiple partners, something akin to addressing "large challenges" in science with collective effort.

As far as the first approach is concerned, the previous discussion has highlighted the fact that the main dimension which separates CR research from more ordinary ("classic") radio communication research is the link between communication system design and environmental awareness (see Figure 4-7). Although "knowing thy channel" has been a keystone of every well-oriented research effort in communication and information theory, it is clear that CR greatly expands the notion of the "channel" and makes it the whole environment, the network topology and related architecture, the geo-information of the radio field, the infusion of sensing in addition to communicating, the restrictions from a regulatory and standardisation viewpoint, the limitations of the various platforms involved, policies, and so on. It is the interaction between the universe whose awareness is required and the communication system itself that makes CR research different. Therefore, a single main effort, if chosen, can revolve around that role: what exactly is that environment? What is "context" and what does this contain from a cognitive standpoint? How can that context be learned, known and represented? And, even more importantly, how does such knowledge (regardless of how it is acquired) interact with the radio communication system design? This latter conceptual "filter" is might important to the value of CR research itself. There is massive research in the past and present on general cognitive science, learning, machine learning, and so on, all of which target a better understanding of the surrounding world. All such efforts wish to reduce the uncertainty produced by ignorance. And since "knowledge is power", they all target efficient engineering methods for enhancing such knowledge in order to help and improve the larger task that the engineered system addresses. In the present context, that system is a radio system used to transfer information between nodes in a network. This then begs the fundamental question of exactly what knowledge is needed, how it is acquired and how useful it is *for the purposes of radio networking*. Because collection and processing of environmental information in the process of distilling it to knowledge is a costly enterprise, it is very important that its true value is assessed with precision and always in connection to the job at hand (the facilitation and improvement of the radio engineering job). All these questions do in fact lark behind all undertaken JRAs in ACROPOLIS, to one degree or another, and bringing them to the fore will enhance the clarity of the project as well as motivate deeper synergies between partners.

An alternative is to skip such deeper scientific questions (or at least not focus on the singularly) and, rather, address the design of specific scenarios or applications/deployments. This process of design would then naturally bring to the fore the needed elements for achieving the mission of each design in a natural and "bottom-up" way, i.e., as the qualified need arises, the solution is sought. In Section 4.1 which defined the Framework, it became clear that the three main scenarios identified also represent the main three "application classes" for the said radio systems, and each raises specific needs for environmental awareness. Each also implies a different level of coordination ability between the environment-awareness sub-system and the communication sub-system of the whole CR system. Large-area licensed systems that wish to coexist can possibly afford large-scale coordination of information gathering and processing also. Hierarchical systems in primary/secondary-user licensed scenarios may still need a lot of information and awareness (since protection from interference to the primary is the major mandate here) but how to acquire it in non-fully coordinated or centralized fashion is a challenge. Yet, such challenge must be addressed successfully, for otherwise such systems will not take hold. And, finally, unlicensed co-existing networks face their own challenges, as coordination is at a minimum, but the protection requirements may also be reduced versus the previous systems. It follows therefore that specific mini-projects formed in each such category will necessarily have to identify their respective true needs and thus address the value of contextual information in true engineering perspective.

Going forward, the project will address and determine its preferred harmonization procedure and report it accordingly. As mentioned, a parallel track of both approaches is also feasible.

5. Conclusions

This Deliverable provided an overview of the global trends, the major developments as well as the main roadblocks that affect the definition, development, deployment and commercial exploitation of CRSs. The adherence of the ACROPOLIS project to the identified trends was assessed, and a harmonization framework for the maximization of the project's impact was described.

First, the market trends and the respective business opportunities of CRSs and the different applications of the CR concepts in the civil security and military domains were presented. Then, a review of deployment scenarios for CR networks was provided. The most important standardisation and regulation approaches in the area of CR networking were also presented, while a medium term roadmap was used to capture the relevant developments and outlook.

The current status of research activities in the area of CR networking in the different parts of the world was also reviewed. Research activities in European and national level were presented, emphasizing on their ACROPOLIS related aspects.

The ACROPOLIS adherence to the global trends and major developments in the area of CR networking was also assessed and a harmonization procedure that aims to guarantee the maximization of relevance and impact was proposed. The different joint research activities within the project were presented in a comprehensive and conceptually unified way. Finally, the future steps of the ACROPOLIS project were described.

Glossary and Definitions

Acronym	Meaning
3G	3rd Generation
3GPP	3rd Generation Partnership Program
ACMA	Australian Communications and Media Authority
AI	Agenda Item
AoA	Angle of Arrival
ASIP	Application-specific instruction-set processor
B3G	Beyond 3rd Generation
C4MS	Control Channels for Coordination of Cognitive Management Systems
CCC	Cognitive Control Channel
CEPT	European Conference of Postal and Telecommunications
CFAR	Constant-False-Alarm-Rate
C-FEP	Custom Front-End Processor
CMON	Cognitive Management system for the Opportunistic Network
CMOS	Complementary Metal–Oxide–Semiconductor
COMM	Communication
CPE	Customer Premises Equipment
CR	Cognitive Radio
CRL	Communications Research Laboratory
CRN	Cognitive Radio Network
CRS	Cognitive Radio System
CS	Communication System
CSCI	Cognitive management System for the Coordination of the Infrastructure
CSI	Channel State Information
DAB	Digital Audio Broadcasting
DARPA	Defense Advanced Research Projects Agency
DFT	Discrete Fourier Transform
DOA	Direction Of Arrival
DRM	Digital Rights Management
DSA	Dynamic Spectrum Access
DSP	Digital Signal Processing
DTV	Digital Television
DVB-T/H	Digital Video Broadcasting – Terrestrial/Handheld
E2E	End-to-End

E3	End-to-End Efficiency
EC	European Commission
ECC	Electronic Communications Committee
ECMA	European Computer Manufacturers Association
EDA	European Defense Agency
EE	Energy Efficiency
EIRP	Effective Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
EU	European Union
FBMC	Filter Bank Multi-Carrier
FCC	Federal Communications Commission
FEEIT	Faculty of Electrical Engineering and Information Technologies
FEP	Front End Processor
FET	Future Enabling Technologies
FPGA	Field-Programmable Gate Array
GBR	Guaranteed Bit-Rate
GFDM	Generalized Frequency Division Multiplexing
GMC	Generalized Multicarrier
GSRT	General Secretariat of Research and Technology
HQ	Head Quarters
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
ICT	Information and Communications Technology
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IEEE DySPAN-SC	IEEE Dynamic Spectrum Access Networks Standards Committee
IEEE-SA	IEEE Standards Association
IETF	Internet Engineering Task Force
IFC	Interference Channel
IM	Interference Management
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IOTA	Isotropic Orthogonal Transform Algorithm
IP	Internet Protocol
IPR	Intellectual Property Rights
ITS	Intelligent Transportation Systems
ITU	International Telecommunications Union

JRA	Joint Research Activity
LTE	Long Term Evolution
LTE-A	LTE-Advanced
M2M	Machine-to-Machine
MAC	Medium Access Control
MDE	Decision Making and Execution
MIC	Ministry of Internal Affairs and Communications
MIK	Mobile Innovation Centre
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MPT	Ministry of Posts and Telecommunication
MU-MIMO	Multiple User – Multiple Input Multiple Output
NE	Nash Equilibrium
NGN	Next Generation Network
NICT	National Institute of Information and Communications Technology
NoE	Network of Excellence
NOFDM	Non-Orthogonal Frequency Division Multiplexing
NRM	Network Reconfiguration Manager
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
ON	Opportunistic Network
OPEX	Operational Expenditure
PAPR	Peak-to-Average Power Ratio
PAWS	Protocol to Access White Space
PHY	Physical layer
PoC	Proof-of-Concept
PU	Primary User
QoE	Quality of Experience
QoS	Quality of Service
R&D	Research and Development
RAT	Radio Access Technology
REA	Radio Environmental Awareness
REM	Radio Environmental Map
RL	Reinforcement Learning
RRM	Radio Resource Manager
RRS	Reconfigurable Radio Systems
Rx	Receiver

SA	Spectrum Aggregation
SCN	Small Cell Network
SDR	Software Defined Radio
SE	Spectrum Engineering
SINR	Signal-to-Interference-plus-Noise Ratio
SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise Ratio
SOM	Self-Organizing Map
SSe	Spectrum Sensing
SU	Secondary User
SWL	Smart Wireless Laboratory
SWOT	Strengths, Weaknesses, Opportunities, Threats
TCP	Transport Control Protocol
ToA	Time of Arrival
TVWS	TV White Space
Tx	Transmitter
UK	United Kingdom
UMF	Unified Management Framework
UMTS	Universal Mobile Telecommunications System
USA	United States of America
USRP	Universal Software Radio Peripheral
UWB	Ultra Wideband
W-CDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WNaN	Wireless Network after Next
WP	Work Package
WRAN	Wireless Regional Area Network
WRC	World Radiocommunication Conference
WSN	Wireless Sensor Network
XG	neXt Generation

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