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Towards Cognitive Radio Systems

Main Findings from the COGNAC Project

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Abstract

Cognitive radio systems have recently emerged as potential enablers of more efficient use of various resources in future wireless communication systems. Cognitive radio systems can obtain knowledge of their operational environment and internal state, adapt their operations to optimize performance, and learn from the results. This report presents the main results of the COGNAC project in the field of cognitive and opportunistic wireless communication networks. It identifies fundamental techniques for cognitive and opportunistic networks, summarizes the research activities carried out in the COGNAC project, and provides insight into future research directions.

Theoretical studies in COGNAC have covered various aspects of cognitive radio techniques, e.g., spectrum-sensing techniques for obtaining information about spectrum use, dynamic channel access for adapting operations, interference management using power and frequency control, cooperation among devices using game theory, and learning using stored history data.

Experimental studies were conducted in the form of spectrum occupancy measurements and the implementation of a cognitive radio test bed. Contributions were made to spectrum regulatory bodies to pave the way for the introduction of cognitive radio techniques into the spectrum regulatory framework. Finally, a roadmap for cognitive radio systems was developed.

Preface

This report covers the main results of the Cognitive and Opportunistic Wireless Communication Networks (COGNAC) project, which was a joint effort between VTT Technical Research Centre of Finland and the Centre for Wireless Communications (CWC) from the University of Oulu.

Research into cognitive radio systems was started at VTT in the Channel State Estimation and Spectrum Management for Cognitive Radios (CHESS) project in 2006–2007, funded by Tekes and VTT. The COGNAC project (2008–2011) was established to continue the work of CHESS and strengthen cooperation between VTT and the CWC. The COGNAC project was funded by Tekes, VTT, and the CWC as part of Tekes' Converging Networks (GIGA) program (2005–2010). Professors Matti Latva-Aho (CWC) and Marcos Katz (VTT/CWC), and Research Professor Aarne Mämmelä (VTT) served as scientific leaders of the COGNAC project.

The project steering group had members from industry and the public sector, including Elektrobit, EXFO NetHawk, Nokia, Nokia Siemens Networks, Renesas Mobile Europe, Tieto, the Finnish Communications Regulatory Authority, the Finnish Defence Forces, and Tekes. The support from the steering group was essential for guiding the work in the right directions, and it is gratefully acknowledged. The project had a very active technical group that consisted of VTT and CWC researchers as well as members from the steering group organizations. The technical group meetings were valuable opportunities for information exchange. The continuous support from Kari Horneman, Kari Hooli, and Vinh V. Phan from Nokia Siemens Networks, Juha Ylitalo and Ari Hulkkonen from Elektrobit, Jouko Sankala and Kimmo Määttä from EXFO-NetHawk, Carl Wijting and Niko Kiukkonen from Nokia, Jorma Lilleberg and Kari Rikkinen from Renesas Mobile Europe, Anna-Maria Kähkönen from Tieto, Margit Huhtala from the Finnish Communications Regulatory Authority, Risto Määttä and

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Marja Matinmikko VTT and Timo Bräysy CWC
COGNAC Project Managers

Contents

List of abbreviations

3GPP	Third Generation Partnership Project
ACC	Adjacent Cluster Combining
ACE	(System) Advanced Configuration Environment (Xilinx)
AGC	Automatic Gain Control
APHY	Adaptive Physical Layer
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CaON	Converged and Optical Networks
CCF	Common Channel Framework
CCH	Common Control Channel
CE	Cognitive Engine
CEPT	European Conference of Postal and Telecommunications Administrations
CMA	Cellular Market Areas
CME	Consecutive Mean Excision
COGNAC	Cognitive and Opportunistic Wireless Communication Networks
COST	European Cooperation in the field of Scientific and Technical Research
CPM	Conference Preparatory Meeting
CPG	Conference Preparatory Group
CPU	Central Processing Unit
CR	Cognitive Radio
CR-UWB	Ultra-wideband Cognitive Radio

CRAMNET	Cognitive Radio Assisted Mobile Ad Hoc Network
CRN	Cognitive Radio Network
CRS	Cognitive Radio System
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
CUS	Collective Use of Spectrum
CWC	Centre for Wireless Communications, University of Oulu
DAA	Detect and Avoid
DFS	Dynamic Frequency Selection
DHN	Double-Hop Neighborhood
DSP	Digital Signal Processing
DTV	Digital Television
DySPAN	Dynamic Spectrum Access Network
EC	European Commission
ECC	Electronic Communications Committee
EDK	Embedded Developer’s Kit (Xilinx)
ETSI	European Telecommunications Standards Institute
FA	Functional Architecture
FC	Fusion Center
FCME	Forward Consecutive Mean Excision
FDD	Frequency-Division Duplexing
FI	Future Internet Technologies
FM	Frequency Management
FP7	Seventh Framework Programme
FPGA	Field Programmable Gate Array

FSU	Flexible Spectrum Use
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
GUI	Graphical User Interface
HS	Harmony Search
HTTP	Hypertext Transfer Protocol
HW	Hardware
ICT	Information and Communications Technologies
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IP	Internet Protocol, Intellectual Property
IPR	Intellectual Property Rights
ISE	Integrated Synthesis Environment (Xilinx)
ISM	Industrial, Scientific, and Medical
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radiocommunication sector
LAD	Localization Algorithm based on Double-thresholding
LE-WARP	Linux Enriched WARP
LT	Long Term
LTE	Long Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MME	Maximum-Minimum Eigenvalue
NB	Narrowband

OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimized Link State Routing
OMA	Open Mobile Alliance
OMAN	Opportunistic MAC with Network Layer Information
OMG	Object Management Group
OS	Operating System
OTCH	Opportunistic Traffic Channel
PC	Personal Computer
PLB	Processor Local Bus
PMSE	Programme Making and Special Events
PPC	PowerPC
PSTN	Public Switched Telephone Network
PU	Primary User
PTA	Project Team A
QoS	Quality of Service
RA	Regulatory Affairs
RAS	Radio Access and Spectrum
RBS	Radio Base Station
REAG	Regional Economic Area Grouping
RLAN	Radio Local Area Network
RRS	Reconfigurable Radio Systems
RSC	Radio Spectrum Committee
RSPG	Radio Spectrum Policy Group
RTS	Request To Send
SCC	Standards Coordinating Committee

SDR	Software Defined Radio
SDRF	Software Defined Radio Forum
SE	Spectrum Engineering
SIG	Special Interest Group
SINR	Signal to Interference Plus Noise Ratio
SNR	Signal to Noise Ratio
SQL	Structured Query Language
SS	Spectrum Sensing
ST	Short Term
STF	Specialist Task Force
SU	Secondary User
SVG	Scalable Vector Graphics
SW	Software
TCP	Transmission Control Protocol
TDD	Time-Division Duplexing
TDMA	Time Division Multiple Access
TERRA	Techno-Economic Regulatory Framework for Radio Spectrum Access for Cognitive Radio/Software Defined Radio
TR	Technical Report
TS	Technical Specification
UDP	User Datagram Protocol
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
UWB	Ultra Wideband
VHF	Very High Frequency

VoIP	Voice over Internet Protocol
VTT	VTT Technical Research Centre of Finland
WARC	Word Administrative Radio Conference
WARP	Wireless Open Access Platform
WB	Wideband
WCS	Weighted Cooperative Sensing
WG	Working Group
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WInF	Wireless Innovation Forum
WP	Work Package
WRC	World Radiocommunication Conference
WUN CogCom	Worldwide Universities Network Initiative Cognitive Communications
WWRF	Wireless World Research Forum

1. Introduction

The radio frequency spectrum is a limited natural resource that is divided into spectrum bands. Over the last century, spectrum bands have been allocated to different services, such as mobile, fixed, broadcast, fixed satellite, and mobile satellite services in the Radio Regulations developed by the International Telecommunication Union (ITU). For the mobile service in particular, system development and consequent spectrum allocations have only emerged during the past 30 years, while other services, such as satellite, have wide spectrum allocations dating back to the 1960s. Yet, it is the mobile telecommunication market that is predicted to grow further, and significantly, in the time span 2010–2020 both per user and in terms of aggregate data rates, as stated in (ITU-R 2006).

As all the spectrum bands are already allocated to different services, most often requiring licenses for operation, a fundamental problem facing future wireless systems is to find suitable carrier frequencies and bandwidths to meet the predicted demand for future services. The current license-free bands (Industrial, Scientific, and Medical, ISM) are not enough for future services. A taste of things to come was observed in 2007 at the World Radiocommunication Conference (WRC-07) of the ITU-R, the Radiocommunication sector of ITU, when global spectrum identifications for future mobile communication systems, international mobile telecommunications (IMT) Advanced, were discussed but with a rather limited outcome, see (Takagi & Walke 2008).

Even though the spectrum bands are allocated to certain services, spectrum occupancy measurements, such as (SSC 2011), claim that large portions of the allocated frequency bands are only partially occupied, leading to inefficient overall spectrum utilization. One of the key problems is the low temporal occupation of frequency bands. Although the measurements sometimes give overly pessimistic spectrum occupancy figures for existing systems, they show potential for systems being capable of identifying spectrum opportunities and using them without causing harmful interference to other users, which is the idea behind cognitive radios (Haykin 2005).

To meet the demand for future services, new, novel and more flexible resource management schemes need to be developed for wireless networks. The main emphasis of current research is therefore on the creation of visions and methods for advanced radio and network resource sensing and management schemes for future wireless cognitive and opportunistic networks. The key issues to be addressed include, in particular, when, where, and how a CR node should sense its environment and resource use, how to manage information exchange in the cognitive network, and how to exploit the relevant information to manage the different resources efficiently.

This report presents the main results of the three-year, strategic research project COGNAC (Cognitive and Opportunistic Wireless Communication Networks) carried out by VTT Technical Research Centre of Finland and the Centre for Wireless Communications (CWC) from the University of Oulu in 2008–2011. The project was funded by Tekes, VTT, and CWC. The overall aim of the project was to develop fundamental knowledge on techniques for opportunistic resource use for future wireless networks. The focus was on advanced sensing and management schemes for radio resources.

The topics in COGNAC included: a) the creation of a visionary framework for cognitive networks, b) the development, analysis, and testing of advanced sensing techniques, c) new approaches for centralized networks, d) predictive methods for CRs exploiting a multidimensional resource domain, e) advanced control and management in CR and autonomous networks, and f) the inclusion of cognitive radio systems (CRS) into the spectrum regulatory framework.

This technical report first makes an effort to justify and give motivations for applying cognitive technology in future communication systems. After a definition of CRs, a brief identification of key deployment scenarios and benefits is given. Theoretical and experimental research conducted in the COGNAC project over the three years is then presented and discussed in Chapters 3 and 4, respectively. The emphasis of the discussion is on the adaptation of the result in technology development. A number of promising enabling technologies are also listed and discussed, including obtaining knowledge, adaptation of operations, cooperation, and learning.

One essential aspect of the project has been to disseminate the research results into various formats. Technology demonstration activities were arranged, as discussed in Chapter 4. The spectrum regulatory framework was identified as a major forum for providing input contributions from the project. This aspect and the efforts therein are explained in Chapter 5. Chapter 6 provides a look into the future in the form of proposing a roadmap put together to represent the final summary and conclusions of the project and this report. In the appendix, we list all the published papers that resulted from this project and provide a short summary of each paper.

2. Motivation for cognitive radio systems

This chapter presents a definition of CRSs and outlines potential deployment scenarios and benefits.

2.1 Definition of cognitive radio system

Several definitions for *cognitive radio* can be found from the research domain. The official definition for *cognitive radio systems* in ITU-R developed by ITU-R WP1B in 2009 and published in (ITU-R 2009) states that a *cognitive radio system* is:

> *A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.*

This definition is made generic enough in attempt to select a single term and definition to describe CRS technology under the system of any radiocommunication service. Depending on the specific radiocommunication service in question, it is possible that the identification of unique and detailed characteristics may be required. In the COGNAC project, we adopt the ITU-R definition for CRS.

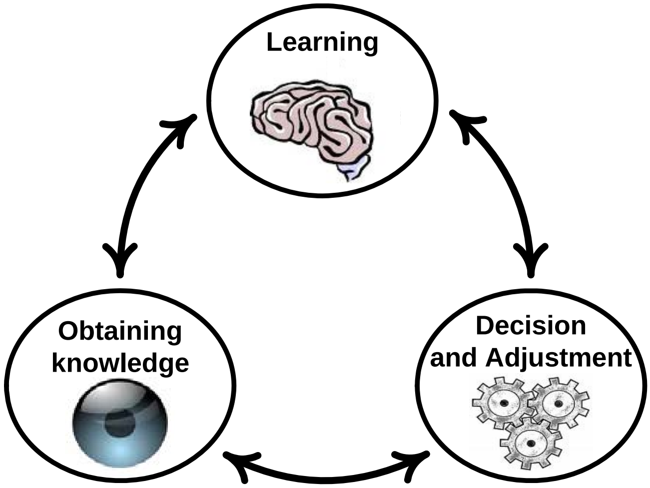

Figure 1. General cognitive cycle.

Figure 1 shows a general cognitive cycle for characterizing the operations of CRS. According to the definition, CRS has the capabilities to obtain knowledge, adjust according to the knowledge, and learn from the results. The definition is broad and the detailed techniques for creating the CRS functionalities are not yet defined. In Section 6.1, we therefore aim to depict a potential roadmap for the introduction of CR features into future wireless systems and describe the different paths.

2.2 Deployment scenarios

CRSs can be used to improve the efficiency of the use of various resources in wireless communication systems. Spectrum has been identified as a scarce resource, and its efficient use is of utmost importance. In terms of spectrum, various deployment scenarios are envisaged for CRSs, depending on the types of spectrum bands considered. Here, we have identified four deployment scenarios:

- licensed spectrum
- unlicensed spectrum
- primary-secondary setting
- bands for CRS on which they coexist.

In the first scenario, it is envisaged that CR techniques will be deployed on licensed spectrum bands by the owner of the spectrum to improve the efficiency of its spectrum use, e.g., to accommodate more traffic on the same band. In this case, CR features could be introduced gradually into future developments of current systems that have sole rights to use the given spectrum. Examples of this include mobile communication systems in which operators could deploy home base stations on the same spectrum bands as their macro cells to accommodate more traffic in the same area. This kind of CR operation does not require any regulatory considerations as it is an internal system issue.

In the second scenario, CR techniques could be employed to improve spectrum use of unlicensed bands such as ISM bands. By using CR techniques, more data could be accumulated on the same spectrum band. Different systems could use the ISM band as an alternative way for, e.g., balancing the load at peak hours by offloading delay-tolerant data to ISM bands with the aid of CR techniques. The current systems using the ISM bands could be enhanced with CR features to improve their performance.

In the third scenario, CRSs could make opportunistic use of temporarily and locally available spectrum that belongs to higher priority systems. Here, the prerequisite for allowing this kind of operation is that the CRS is not allowed to cause harmful interference to the higher priority systems. Examples of this primary-secondary user setting include TV white space discussions in which CRSs could use TV spectrum in the band 470–790 MHz.

In the fourth scenario, different CRSs could coexist with each other on the same spectrum bands following some set of coexistence rules. This is similar to ISM bands in which different systems share the same spectrum but the spectrum use is predicted to be much more efficient, as it has been the major design aim.

In all of these scenarios, the key topic is the coexistence of several systems on a given spectrum band. The systems can have similar or different access technologies, and equal or unequal priority. In any case, a key challenge for the development of CRSs is the development of coexistence techniques and etiquette to optimize resource use. Chapter 3 sheds some light on the various techniques that can facilitate coexistence.

2.3 Benefits

A CRS network can improve spectrum access and utilization significantly, easing the sharing of spectrum among different systems. Spectrum sharing is becoming more and more important in the spectrum regulatory framework as the spectrum is becoming congested. The cognitive radio techniques currently under development can form a toolbox offering new and more powerful tools for spectrum sharing to maximize the value of the spectrum. As the conditions and requirements for spectrum sharing can vary on a band-by-band basis, there will be a versatile set of operational techniques available for the different scenarios. The creation of new etiquette and rules for spectrum sharing using cognitive principles can change the way the spectrum will be used in the future.

The development of cognitive radio techniques can result in new and more efficient ways of interference management. Individual techniques developed in the telecommunication research, e.g. smart antennas and power control, offer a good solution for interference suppression and can be further developed for the needs of cognitive radio systems.

Another aspect is the improved flexibility of the network with the introduction of cognitive radio features. Networks can be enhanced by cognitive techniques to provide capabilities for self-organization and self-healing. Large amounts and diversity of distributed resources offer great potential for cooperation, as well as new services, application functionalities, and capabilities. Moreover, CR techniques increase interoperability between different standards and allow systems to support and change their parameters depending on the policy used (Maldonado et al. 2005).

Finally, the introduction of cognitive features into new application areas can open up completely new opportunities. At the moment, the efforts are focused on the development of cognitive capabilities to be used in future wireless communication networks. Similar principles could also be applied to other industry verticals, e.g., smart energy grids and industry automation.

3. Technical approaches studied in the COGNAC project

The aim of the COGNAC project has been to develop guidelines for applying opportunistic radio resource management in future CRSs. This chapter introduces fundamental techniques for obtaining knowledge, adapting operations, cooperation, and learning that will form the key features of cognitive and opportunistic networks. In particular, it presents the specific research results of the COGNAC project in the aforementioned areas.

3.1 Obtaining knowledge

3.1.1 Resource availability information

A mobile device has many different capabilities and functionalities. Fitzek and Katz (2007) divided mobile smart phone capabilities into five classes:

- radio resources: time, frequency, space, and power/energy
- built-in resources: different hardware-related assets distributed over the network; mass storage, e.g., memory devices; energy sources, e.g., batteries and processing units, e.g., central processing units (CPU); and digital signal processing (DSP)
- user interface resources: typical capabilities integrated into wireless devices, such as speakers, microphones, keyboards, display, cameras, and built-in sensors
- communication interface: typically includes cellular and short-range capabilities

- social resources are considered part of a resource pool distributed across the cooperating entities.

In fact, *connectivity resources* that typically include several cellular and short-range air interfaces can be seen as a sixth resource, as devices nowadays typically have more than one air interface. For instance, smart phones, laptops, and touchpads are often equipped with several communication protocols, such as a global system for mobile communication (GSM)/general packet radio service (GPRS), universal mobile telecommunications system (UMTS), Bluetooth, and Institute of Electrical and Electronics Engineers (IEEE) 802.11. In the future, more technologies, such as worldwide interoperability for microwave access (WiMAX) and IEEE 802.22, are expected to become popular. Some applications may be delay-sensitive, such as voice communications. Others are bandwidth-sensitive, like video streaming, while email transfer mainly requires reliability. Hence, there is no unique solution that can be expected to achieve optimal quality of service for all applications. Learning and inference from interaction with the environment and other users, and from earlier actions and collected history data, are crucial when making decisions about which radio access technique to use in a certain case to achieve optimal performance.

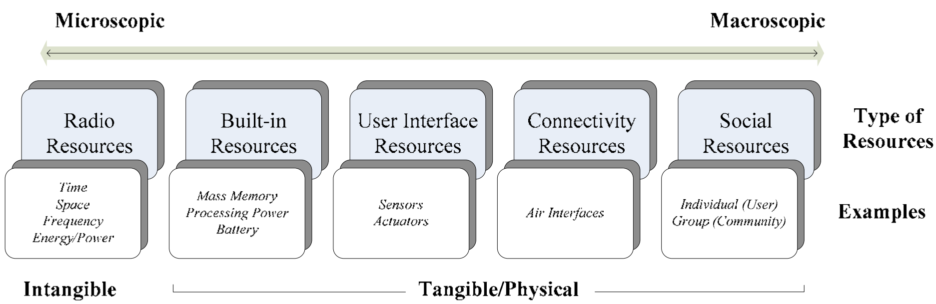

Figure 2. A classification of resources in wireless networks.

Large amounts and diversity of distributed resources offer great potential for cooperation. Figure 2 depicts the described resource classification, showing typical examples of these resources in wireless networks.

Wireless and mobile devices have unique challenges to overcome when building a grid application for them. The devices are characterized based on their limited processing power, storage capacity, energy capacity (battery life), and transmission range (Ahuja & Myers 2006). From a practical point of view, and depending of the scenario in question, it may also be very challenging to convince people to share resources, for privacy and security reasons. In fact, security, privacy, and trust issues of wireless sharing of networks are big concerns for people (McKnight et al. 2005). Thus, in some cases, the end-user may decide with whom to cooper-ate and what resources to share.

In the COGNAC project, the management of radio resources is addressed extensively. Thus the cognitive management of other (network) resources remains mostly outside the scope of the COGNAC project. Nevertheless, the subject has received some attention in COGNAC. In [42], an overview of the distributed resources in wireless networks, focusing on cooperative resource use and resource discovery, is given. A framework for distributed resources and resource sharing in wireless networks by generalizing and combining an environmentally aware CR area and a resource discovery area is defined. A novel classification of different resource discovery methods is provided, motivating the use of cooperation in wireless networks as well as foreseeing future developments in this area. The paper [42] also gives a broad view on cognition in wireless networks, considering awareness and intelligent use of all available resources in a wireless environment. We also note that future aspects of CRSs are introduced in [1] and [2], which are articles directed at a general audience.

3.1.2 Spectrum information

It is a known fact that radio spectrum deployment is growing considerably, and finding unused frequency channels for new applications and services has therefore become the most important and challenging objective. One proposed solution is to implement flexible spectrum use (FSU) in which wireless systems dynamically use unexploited licensed spectrum bands. Flexible spectrum usage requires telecommunication systems to be equipped with an ability to specify unoccupied parts of radio spectrum and adequate logic to make realistic and timely decisions about spectrum use.

One method to identify temporarily unused parts of the radio spectrum is spectrum sensing. This requires CRs to have the capability to analyze the spectrum samples and find and locate free frequency channels. If CRs operate as SUs of the spectrum, they must protect the PUs from harmful interference. In this scenario, the main concern of resource sensing is to avoid interfering with the PUs. When operating in unlicensed bands (such as ISM), the main aim is to avoid the most crowded/heavily exploited spectrum bands and to balance spectrum use among all CR systems. In distributed and/or cooperative sensing, CRs make spectrum sensing and exchange measurement information in order to receive spectrum information with good coverage (in all dimensions) but with lower resource usage per node (low overhead).

Alternative options to spectrum sensing would be to consider a centrally managed spectrum in which the licensee of the spectrum has complete knowledge of spectrum usage in the network and is thus able to provide frequency slots for terminals in an optimal manner. This case also includes the outside policy as an essential element. In a sense, the licensee should be aware of the other spectrum users and their allocated spectrum operating in the area, especially if there is a danger of interference. The centralized approach is not as dynamic and versatile as the solution based on distributed spectrum sensing.

It is also possible for the CRs to obtain their spectrum-sensing/usage information from outside sources, e.g., from some coexisting, sensing-enabled network. For example, in a military environment, the equipment used for electronic warfare may be used to provide spectrum information, as it usually has very powerful sensing devices. Alternatively, the ubiquitous information technology that is currently emerging to provide all kinds of information to users (humans) through its mobile terminals could also be used to provide spectrum information to those terminals (and to CR networks in general).

A hybrid version can be envisaged in which a user terminal can perform its own spectrum sensing and try to find a spectrum slot. If it does not succeed, however, it can ask for a channel from a licensee. The idea is that all users should be guaranteed at least some part of the network resources, even if, for some reason, they cannot find it themselves. This could be called “spectrum management by request.”

In the following, we summarize the COGNAC research performed on different spectrum-sensing methods and principles related to radio resource usage in cognitive systems. Some of the questions to be answered in this research include:

- What are the requirements for spectrum awareness in terms of reliability, timeliness, and accuracy?
- What are the costs of performing spectrum sensing at the required level of accuracy? Costs can be expressed as, e.g., equipment costs, cooperative signaling overhead, system complexities, as well as time, battery, and processing power consumed for sensing.

- How can the balance between requirements and costs be found and ensured? Answering this question may require different models/solutions to be used in different scenarios. Thus, FSU also means flexibility of sensing.

On a very general level, spectrum-sensing problems are addressed in two COGNAC papers. In [17], sensing parameters of time-slotted systems are optimized with respect to false alarm and detection probabilities. Consideration of these measures is of extreme importance in ensuring reliable operation of any spectrum-sensing-based opportunistic spectrum usage system. The topic of unreliable (imperfect) sensing is also studied in [18], in which a simple state-diagram-based analytical approach to model the effect of false alarms and misdetections is developed.

In the COGNAC project, one focus has been on defining and analyzing signal processing methods to perform spectrum sensing by a single observer (a CR). One such method is Welch's periodogram, which can be used for spectrum monitoring and sensing. In [12], a generalization and application of the theoretical analysis of energy detection with Welch's periodogram is presented. The analysis of the methods is further applied to the case of Rayleigh's fading channel in [13]. In [13], a novel performance metric for spectrum sensing, the time between failures in detection, is also presented and analyzed. The time between failures in detection describes how often the CR misses the detection of the presence of a PU, leading to performance degradation for the PU.

Research has also been done on iterative backward and forward consecutive mean excision (CME/FCME) algorithms that are efficient at suppressing and detecting narrowband signals. As they are computationally relatively simple, they can easily be applied to spectrum sensing in CRs. Conventionally, the detection threshold is set assuming that the noise power is estimated from noise-only samples. The FCME algorithm is a method for making decisions automatically based on the decision variables, without estimation of the noise power a priori. In [16], the use of the FCME algorithm with the Welch spectrum estimator is proposed. The performance is shown to improve significantly compared with the previously used periodogram. In [19], the detection performance of the CME algorithms is analyzed using a rectangular signal model approximation. The analysis results provide simple rules to predict whether a signal is detectable. The presented limits of detection can be used in CRSs in which well-defined and predictable performance limits for spectrum sensing are required.

An additional signal processing method analyzed for spectrum sensing purposes is a recently proposed Localization Algorithm based on Double-thresholding (LAD) presented in (Vartiainen et al. 2007). LAD with adjacent cluster combining (ACC) uses the FCME algorithm and is suitable for signal detection. Laboratory and field measurement results with the LAD ACC method are included in [16] to study the detectability of different signal types, including real wireless microphone signals.

The LAD method performs best when detecting narrowband (NB) signals. For complete spectrum sensing, however, which is usually required in CRSs, it is not enough just to detect and localize NB signals, as the PU’s signal could just as well be a wideband (WB) signal. In [15], combining the LAD method with the maximum-minimum eigenvalue (MME) method is proposed. The results indicate that the combined method is able to detect both the NB and WB signals without knowledge of the noise power. The proposed method enables better use of spectrum white spaces in cognitive spectrum use, but it comes with somewhat increased resource utilization for sensing.

The study in [12] is extended to cooperative spectrum sensing, a theme that is further continued in several studies in COGNAC. Cooperative spectrum sensing is one of the key methods to enhance significantly the performance of an autonomously operating CRS that is based on channel detection methods. The most important benefits are related to the enhanced accuracy and efficiency of the sensing. As a trade-off, however, there is an extra overhead in signaling between sensing nodes and possibly for coordination by a central node. In [14], quantized soft combining of decisions (i.e., more than one bit used to characterize the decision) is studied with simulations and compared with hard decision combining and non-quantized soft decision combining in an additive white Gaussian noise (AWGN) channel using Welch’s periodogram. Hard decision combining is considered with three different decision-making rules, and the obtained simulation results are verified with analytical performance results for Welch’s periodogram. The results in [14] show substantial improvement in detection probability when sensing information between the cooperating nodes is shared using two bits instead of one. The results in [12] indicate that cooperation between two radios provides the highest cooperation gain.

The use of fuzzy logic in CRS was studied in [11]. Cooperative spectrum sensing using fuzzy combining of the sensing results from several CR nodes was considered to be beneficial when the operational environment is changes, e.g. CR nodes have different signal-to-noise ratios (SNR).

A fusion-center-based approach is addressed directly in [20], in which a weighted cooperative sensing (WCS) method is analyzed. In WCS, global detection at a fusion center (FC) is performed using weighted local soft decisions given by SUs, and the use of appropriate weight can improve the sensing performance, especially when the SNR of each SU is different. The weight depends on the noise power and the PU's signal power, and, moreover, multiple antenna elements are used to suppress the effect of Rayleigh fading.

A cooperative sensing paradigm is further elaborated in [21]. To reduce the sensing overhead and total energy consumption, it is recommended to cooperate only with the CRs that have the best detection performance. The problem is that those CRs are not known a priori. To this end, methods for selecting the CRs with the best detection performance based only on hard (binary) local decisions from the CRs are proposed. The proposed and analyzed methods are:

- Simple counting: select the CRs that report the highest number of PU detections.
- Partial agreement counting: select the CRs that agree with the FC decision. It is assumed that the FC has a high PU detection probability.
- Collision detection: select the CRs that are able to detect PUs when the FC failed the detection, i.e., a collision occurred.

In [21], simulations are used to evaluate and compare the methods. The results indicate that the proposed CR selection methods are able to offer significant gains in terms of system performance.

In [34], a novel cooperative spectrum sensing technique based on cooperative multi-hypothesis testing was proposed to find the allowable maximum transmit power for the SU, which guarantees the PU performance. The approach allows secondary transmission in the guard bands with low transmit power levels to improve the efficiency of spectrum use.

Finally, the selection of the most suitable spectrum-sensing techniques was studied in [22]. There are a large number of spectrum-sensing techniques with different characteristics in terms of, e.g., performance and complexities. In [22], a simple heuristic decision-making method was developed to select the most suitable spectrum-sensing technique from energy detection, correlation-based detection, and feature detection for a given situation. The input information used for the selection was a requirement of the detection probability, available time for processing, available a priori information about the PU signal waveforms, and operational SNR.

3.2 Adaptive operations

3.2.1 Dynamic channel access

Dynamic channel access and spectrum sharing are key aspects of cognitive networks (Nie & Comaniciu 2005). Selfish and cooperative approaches to spectrum sharing are both possible techniques in CR networks. The fundamental definition of dynamic spectrum access is as follows: "According to the proposed etiquette, the users should listen to the environment, determine the radio temperature of the channels and estimate their interference contributions on their neighbors." Based on these measurements, users should react by changing their transmission parameters if other users need to use the channel (Quote from Nie & Comaniciu 2005). This definition inherently assumes that users in the radio network cooperate in the sense that they respect their status as SUs of the spectrum and restrain from transmitting in a certain spectrum slot if the transmission would cause interference to the legitimate primal user(s). This behavior is essentially an extension of the typical carrier sense multiple access (CSMA) mechanism that is widely applied in wireless networks.

Several factors of cognitive operation make cooperative behavior difficult to implement:

- The spectrum-sensing information sensed by each node is subject to uncertainties, and the timeliness of the information is uncertain.
- The decision-making algorithm required for the dynamic selection of free spectrum slot(s) for access inevitably consumes resources from the nodes (processing capacity and transmission power) and, furthermore, cannot operate in real time, causing additional delays in spectrum access.
- Cooperative users can easily be subdued by selfish users, making the applicability of the whole dynamic spectrum access concept approach questionable in critical applications or whenever guarantees for channel access are needed.
- Spectrum access across the whole network is not easily managed. If nodes report different views of the available spectrum slots (a scenario that is not difficult to imagine in a large network operating in a rich and dynamic spectral environment and a wide frequency band), what is the proper action?

The last point, in particular, stresses the need for a common signaling channel and protocol within the network in order to find a common view (consensus) of the spectrum usage at each moment. It should be noted that any negotiation protocols that are implemented will inevitably further increase the reaction time of the network as well as the signaling overhead. It also stresses the very important fundamental implementation issue of distributed vs. centralized approaches.

In the COGNAC project, the design of the architecture for cognitive networks was studied in [9]. The paper introduced the concept of cognitive wireless mesh network, called CogMesh, in order to meet the future needs of ubiquitous wireless communications. CogMesh aims to enable a uniform service platform by seamlessly integrating heterogeneous wireless networks through the use of advanced cognitive and adaptive technologies under a mesh structure. The context-based reasoning, policy and role-based control model, and distributed trust and security mechanism are used to establish a flexible, reliable, scalable, and adaptive wireless network in complex wireless environments.

The concept and approach of ultra-wideband cognitive radio (CR-UWB) was introduced in [8] to enable CR to self-adapt to the characteristics of the surrounding wireless communications environment using UWB transmission. A common architecture supported by CR-UWB was illustrated and several techniques for dynamic spectrum accessing and sharing were proposed.

The control channel assignment problem in a CR-based wireless network is addressed in [3]. To achieve efficient control channel selection, self-organization based on a swarm intelligence algorithm is proposed. Considering the fact that common channels may temporarily exist among a local group of SUs, the proposed algorithm selects local, common control channels independently by each SU according to the qualities of the detected spectrum holes and the choices of its neighbors. The idea is to use HELLO messages periodically broadcasted by neighbors as the pheromone to rank the common channels, so as to expedite the channel selection process. The algorithm is completely distributed and therefore scalable. Moreover, it is simple, flexible, adaptive, and well balanced for the exploitation and exploration of the radio resources. In [3], the behavior and performance of the proposed algorithm is verified by simulation.

Channel selection by CRs based on spectrum sensing alone have several difficulties, as discussed above. One possibility to ease channel selection is to use the channel measurement over a longer period. History information can give good hints on promising channels for SUs. The topic is further discussed in Section 3.4.

In line with the idea of using history information in channel selection, a simple opportunistic spectrum (channel) access strategy is proposed in [41] for an autonomous, distributed CR network, in which two or more distributed CRs sense the channels sequentially in some sensing order until they find a free channel to transmit on, if one exists. First the performance of the traditional opportunistic spectrum access strategy is shown to be limited by the collisions among the distributed uncoordinated CRs. To reduce the likelihood of collisions among the distributed CRs, an adaptive strategy is proposed in which CRs maintain information regarding past successes (and failures) of accessing the channel. The paper demonstrated that this strategy converges quickly to collision-free sensing orders. Such a strategy is compared against a randomized one after every collision strategy in which a new channel sensing order is randomly selected whenever a CR experiences a collision. The implementation of the proposed strategy is not complex, as it only requires two binary flags for maintaining state information at an individual CR.

As one of the primary goals of CR technology is to enable opportunistic spectrum access, medium access control (MAC) plays a key role in achieving efficient and reliable radio resource allocation, either in centralized or distributed cognitive wireless networks. So far, only a few cognitive MAC protocols have been proposed in the literature, and none of the existing solutions addresses dynamic channel selection, load balancing, multi-channel contention resolution among SUs, and avoidance of PUs at the same time. Further design of MAC protocols capable of using flexible spectrum access in multiple channels is therefore an important topic and was also addressed in COGNAC.

First of all, a general framework for a novel performance analysis method suitable for common IEEE 802.11-based decentralized MAC protocols is presented [24]. Then, in [23], a novel distributed frequency agile MAC amendment for wireless mesh networks is proposed. The proposed method is capable of multi-channel deployment of available frequency opportunities in order to coordinate concurrent multiple data transmissions more efficiently. The root concept is to apply the IEEE 802.11s common channel framework (CCF) to attain two important goals: on the one hand, the proposed scheme improves channel utilization and capacity using the concept of CR and, on the other hand, using the same concept, it leads to lower access delay due to smarter decision-making procedures exploited for link layer connection establishment. The proposed scheme has complete backward compatibility with the legacy IEEE 802.11 and is an extension to the next-generation wireless mesh networks based on IEEE 802.11s.

Another MAC solution suitable for distributed cognitive networks is proposed in [26], in which stochastic channel selection is studied. In particular, a MAC layer load balancing technique for traffic distribution among a set of data channels without centralized control is introduced. The proposed scheme is enabled by a multi-channel, binary exponential back-off mechanism to further facilitate contention resolution in a multi-channel environment. It is shown through simulations that the proposed MAC layer enhancement outperforms well-known multi-channel MAC protocols both in terms of aggregate end-to-end throughput and average frame end-to-end delay.

Design, implementation, and performance evolution of a distributed time division multiple access (TDMA) MAC protocol for wireless ad hoc networks is presented in paper [27].[1] The target platform for the protocol is the wireless open access platform (WARP), a programmable software-defined radio (SDR) platform for prototyping wireless algorithms and protocols. Towards the end of the COGNAC project, the WARP platform has been used to demonstrate several features of CRs, including FSU (see Section 4.2 for further details).

While the first three MAC protocol papers mentioned above were aimed directly at addressing the multichannel cognitive networks, the two remaining papers on the topic were more general. In [25], a novel MAC protocol called eMAC is proposed. Under the proposed scheme, stations maintain double-hop neighborhood (DHN) graphs while exchanging designated eMAC tables to share their knowledge about their neighborhood topology. Using a DHN graph and an adaptive unreachability reporting mechanism, stations are reliably informed about their neighbors' unreachability status. Hence, they avoid establishing link-layer connections with their unreachable neighbors, and, consequently, network resources are not consumed for unsuccessful connection establishment efforts. As a result, the proposed protocol is well suited to any decentralized ad hoc network.

Finally, the channel allocation problem was addressed using a heuristic harmony search (HS) technique in [30]. The technique was used to assign the different channels among coexisting CR links in order to minimize the average bit error rate (BER) over the existing links in the network.

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[1] The distributed TDMA MAC protocol is based on a fairly simple idea: first, the node in the network acquires local neighborhood information from the surrounding nodes. This information consists of neighborhood information and time slot assignment from two hops away from the particular node's point of view. After sufficient local information is obtained, the particular node may allocate a free time slot and start data transmission to the nodes in the network. DTDMA was originally developed outside the Cognac project.

3.2.2 Interference management

CR technology has been invoked to provide a solution for frequency management (FM) in future heterogeneous wireless networks. The aspects of spectrum management have already been examined in several studies. In order to maintain a holistic view of cognitive networks and the relating issues, however, other aspects are also needed. One of the key issues is to control and/or limit the spatial domain of a tagged wireless network. Generally speaking, limiting the interference caused by SUs is an important issue.

In the COGNAC project, the influence of the spatial dimension on the network capacity has been studied. The project has studied the maximum number of users that can be allocated to the same spectrum band, in the case of using beamforming in a transmitter and receiver by simulations. With the use of smart antennas, the spectrum could be used efficiently and, at the same time, the quality of service of SUs increased compared with omnidirectional antennas. The beamforming improvement in spectrum sensing has also been studied. The results indicated that more users can transmit in the same area while fulfilling QoS constraints. The obtained results also stated that beamforming offers great improvements compared with detection by omnidirectional antennas. Beamforming leads to power savings, as transmission power is sent in the desired direction. In addition, directional antennas decrease the time needed for sensing and therefore less energy is consumed than with omnidirectional antennas.

An obvious method to limit the level of interference is to apply transmission power control. It is also worth noting that power control is coupled with frequency allocation due to dissimilar propagation characteristics of different frequency bands. The topic has been investigated in the COGNAC project. Parts of the results are published in [29] in which multidimensional operation in interference management is emphasized and sensing-aided methods for power and frequency allocation developed. A two-step approach is proposed in the paper: 1) selection of operation frequency based on sensing and prediction and 2) adaptive power adjustment in the selected band to meet the required QoS. Power control is used for spatial control. It is shown that the allowed transmission power of an SU scales linearly with increasing primary transmission power. The results illustrate the effect of the antenna height to maximum power: a high-antenna PU transmitter allows more powerful SUs.

Power and frequency control was studied in [32] and [33] where the power control was modeled using game theory. The transmission power level and spectrum usage were negotiated among the SUs adaptively according to the changing networking environment. A study of the effects of nonlinear analog parts in beamforming was also published during the COGNAC project [28].

3.3 Cooperation in autonomous networks

One major trade-off involved in the implementation of spectrum-sensing functionality in autonomous CR networks is the cooperation-processing trade-off. If an increasing number of nodes participate in the spectrum-sensing process and cooperatively share their sensing information, reliable sensing may be performed with high enough accuracy but with lower resource investment/node. In short, this would mean that nodes would need to invest less time in sensing or have lower resolution (=cheaper) sensor technology installed. If centralized handling of sensing information is used, with a base station or similar central node known as a FC polling the CRs in a round robin fashion to report the distributed sensing decisions to the base station, then the cooperation overhead generally increases with the number of cooperating users due to the increased volume of data. This may result in inefficient throughput utilization of the unused licensed spectrum.

The cooperative sensing problem was addressed in the COGNAC project by modeling the group of autonomous CR nodes as players in a game, i.e., game-theoretical analysis was applied. The aims were to analyze different schemes for sensing, sending individual CR sensing decisions to the base station, and comparing their performance in terms of achieved throughput for the CRs. Moreover, novel protocols for throughput-efficient signaling of cooperative spectrum-sensing decisions in CR networks were proposed.

In game-theoretic formulation, wireless cognitive networks are formed from a set of rational devices that interact strategically in order to achieve a specific goal or payoff. Such strategic interaction is already seen in a basic form in a number of different types of networks, when distributed, dynamic bandwidth resource assignment takes place within spectrum allocation. The competition and cooperation seen with cognitive network devices make game theory an ideal for laying down the basic framework for a CR protocol structure. The relationships between short-term losses versus long-term gains in such "games" were studied in [36]. The paper also provides a novel theoretical analysis of cooperation and coordination in the spectrum access games.

The cooperative aspect of autonomous players in games (and thus in theories describing such dynamics) is highlighted in the ability to form coalitions. By definition, a coalition is a set of distinct, autonomous agents or players that may cooperate in order to increase their individual gains (selfish cooperation) or to maximize the overall gains of the group (altruistic cooperation). When applied to spectrum sensing, this means that each CR within a coalition computes its local sensing decision and transmits it to the coalition head over the common control channel. The coalition head combines the local sensing decisions, including its own sensing decision, using the OR decision fusion rule. In [37], it is demonstrated that the altruistic coalition formation solution yields significant gains in terms of reduced average false alarm probability and increased average throughput per CR, compared with the selfish and non-cooperative solutions.

The coalition formation game is further complicated when interference and power allocations are included in the game rules. The strategic decision for any link analyzed in paper [38] consists of an allocation of power across the available bandwidth to maximize the individual data rate. Coalitions are then formed if the coalition participants agree to share (= allocate power over) bandwidth according to certain ratios. A key question is how to coordinate the distributed wireless links with partial channel knowledge to form coalitions to maximize their data rates while also taking into account the overhead in the message exchange needed for coalition formation. Such a system has been shown to be able to evolve into stable coalition structures that yield significant gains in terms of average link rates. The coalition formation games and their analysis in spectrum sensing and sharing of games are also reported extensively in [39].

An alternative aspect of cooperative spectrum sensing is addressed in [40]. By only selecting a subset of the CRs for which to report the spectrum sensing result to the FC, some signaling overhead and bandwidth can be saved. The problem is one of effectively selecting those CRs that are able to provide reliable spectrum information for the FC, if it is assumed that the sensing performance of the CRs is not known a priori.

3.4 Learning

A device uses learning when it changes its behavior based on the data gathered from sensors and the database. Learning can enable performance improvements for the CRS by using stored information to aid the decision-making process. It can use its own actions, and the results of these actions and the actions of PUs in the process. An example learning cycle is shown in Figure 3. When this cycle is compared with the cognitive cycle, it is easy to understand that learning is a natural part of CRSs.

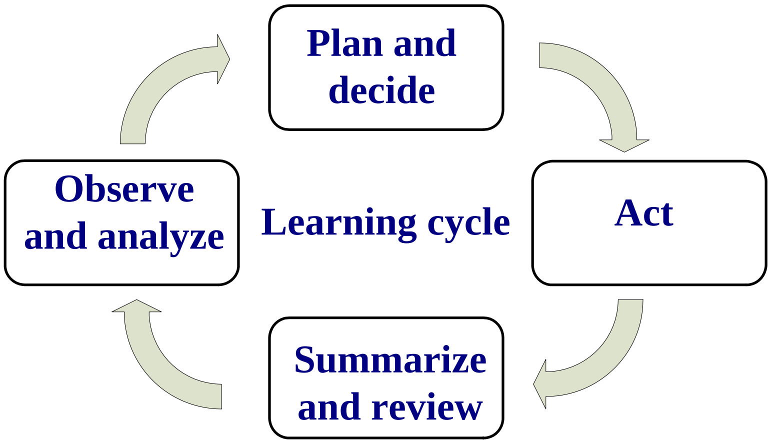

Figure 3. Learning cycle.

Learning techniques can be classified into three main learning schemes: *supervised learning*, *unsupervised learning*, and *reinforcement learning*. Supervised learning is a technique that uses pairs of input signals and known outputs as training data so that a function that maps inputs to the desired outputs can be generated. An example of a supervised learning technique is case-based reasoning in which the knowledge base contains cases that are representations of past experiences and their outcomes. Unsupervised learning techniques aim to determine how the data are organized. Clustering, i.e., unsupervised classification, is an example of an unsupervised learning technique. Reinforcement learning uses observations from the environment in learning. Every action has an impact on the environment and this feedback is used in guiding the learning algorithm. Q-learning is an example in this class.

All these learning schemes can include several specific learning techniques, such as genetic algorithms, neural networks, pattern recognition, and feature extraction. It has also been concluded in the COGNAC project that pattern recognition and classification can be seen as crucial parts of an intelligent system that aims to observe its operating environment and act based on observations. Feature extraction and classification are complementary functions. A very important task is to find good distinguishing features to make the classifier perform efficiently.

One of the key requirements of efficient learning and reasoning is maintenance of the knowledge base. The knowledge base should be able to adapt to the changes in the environment to offer relevant information for the decision-making. The size of the knowledge base should not grow uncontrollably. Rather the size should remain at a reasonable level. All unnecessary information should be taken away from the database on a regular basis. An administrative component may therefore be needed in the system to take care of these tasks and to restrict the changes in the knowledge base to avoid chaotic situations. Moreover, the knowledge base could be tailored to operate efficiently with the specific learning techniques used in the system.

Advantages and examples

Learning makes the operation of CRs more efficient compared with the case in which only information available at design time is possible. Ideally, information gathered during the lifetime of the radio should be used. A majority of CR research focuses on methods that only use instantaneous information about the environment as a basis for dynamic operation.

For example, a CR could recognize the type of the application generating the traffic by looking at the statistical features of the traffic. This would help management of the network, as different applications have different QoS requirements, e.g., voice over Internet protocol (VoIP) and media downloading. This would be particularly good for the optimization of the network itself, i.e., for the network using cognitive principles to improve the quality of the experience for end-users. Learning also helps in fault tolerance. Patterns of faults can be identified as logical sets that can be interconnected as a constraint network or a reactive pattern-matching algorithm. This approach can enable a more efficient fault isolation technique, as it identifies multiple potential causes concurrently and then chooses the most likely one based on precedence and weighting factors.

Results of the COGNAC project

Channel measurements over a long period can lead to several advantages compared with pure instantaneous sensing information. We have proposed methods for exploiting history information in [4]–[6] for which a database is used to collect information about the channels. This information is then used to guide the operation of cognitive users. References [4] and [6] concentrate on predictive operating channel selection and reference [5] on the selection of channels to be sensed.

The method proposed in [5] works as follows. When a CR needs to find an unoccupied channel for a transmission, it sends a query to the database. Based on the information collected in the database, the channels that are most likely to be unoccupied at the time of the request are the best candidates when searching for unoccupied channels, and these channels are delivered to the CR. The CR first performs the power level detection. Based on the power level information delivered from the database, full signal detection is performed next to the channel with a low enough power level to ensure that the channel really is unoccupied. As power level detection can be performed much faster than full signal detection, the latter is only performed for the channel that is most likely to be unoccupied, based on the power level measurements. This saves both time and computational resources, yet maintains reliable sensing results. In [5], it is shown that the use of a history database has benefits over random channel searching, especially when there are a large number of occupied channels.

The idea of database usage is further elaborated in [4] and [6], in which the measurement data are analyzed to find and classify traffic patterns (channel usage patterns) for different channels. Based on the analysis, different prediction rules are created for different types of traffic and channels. These rules can be used to find the best candidate channels for secondary use. In [6], the proposed method is tested with several different traffic models. The method is shown to improve substantially the throughput compared with the system operating based on instantaneous information. From the secondary user point of view, this performance metric, i.e., throughput, is defined as the percentage of time during which the CR system can successfully transmit without colliding with the PU. The classification-based prediction decreases collisions by 60% compared with a predictive system operating without classification. The system model for predictive channel selection is shown in Figure 4.

Both of the proposed ideas above were combined and further developed in [7]. The proposed method brings new aspects to the prior work by joint long-term and short-term database use. The proposed method is not limited to a certain type of traffic but works with a variety of traffic patterns. A long-term (LT) database aids the operation of a CRS and reduces its sensing time by prioritizing channels. A short-term (ST) database allows classification and prediction in the bands of interest. This leads to intelligent channel selection for data and control transmission and thus improves system performance by increasing the throughput of the secondary system and reducing the interference caused to PUs. The combination of the LT and the ST databases makes the operation faster and more efficient than either of these techniques alone.

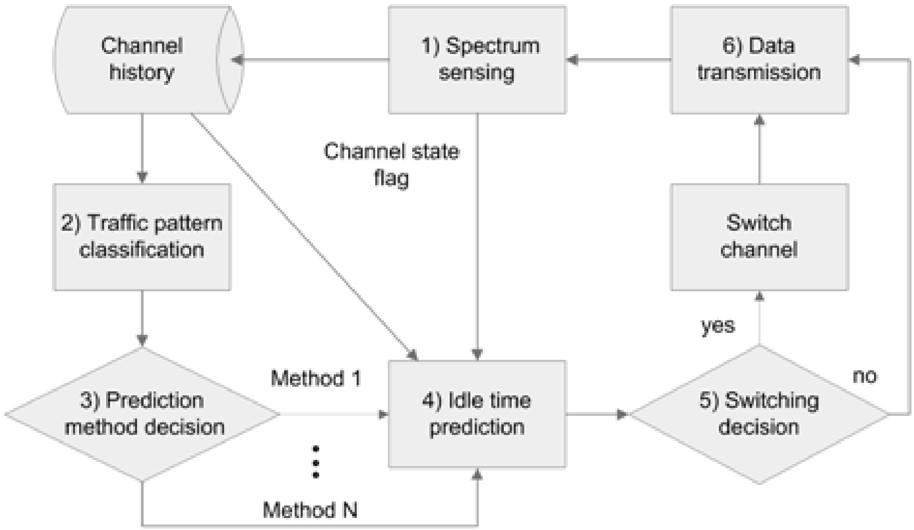

Figure 4. System model for predictive channel selection from [6] (Reproduced by Permission of IEEE © 2010 IEEE).

4. Experimental studies

To complement the theoretical investigations into CR techniques described in Chapter 3, the COGNAC project has also carried out some experimental studies. This chapter summarizes these studies, including directional spectrum occupancy measurements and CRS demonstration using WARP platforms.

4.1 Directional spectrum occupancy measurements

Spectrum occupancy is an important metric for spectrum administrations in the assignment of frequency bands and monitoring of their use. The seminal work of Spaulding and Hagn (1977) defines spectrum occupancy for a channel as the fraction of time that the received power in the channel exceeds a threshold level. This definition for spectrum occupancy has been widely used in measurement studies since then.

Spectrum occupancy measurement studies have identified large temporal and spatial variations in spectrum occupancy on different spectrum bands. The measurements can give hints on which parts of the spectrum band are used inefficiently and thus offer potential for CRS operations. Even the low percentage values for the spectrum occupancy, however, can encompass a large amount of usage that must be detected reliably by the CRS in order to be exploited.

Traditionally, the spectrum occupancy measurements have been conducted using a single measurement device with an omnidirectional antenna as in (Wellens et al. 2007; Biggs et al. 2004). The resulting spectrum occupancy values have presented an average of the overall situation.

In the COGNAC project, we have conducted distributed spectrum occupancy measurements with directional antennas in the 2.4 GHz industrial, scientific, and medical (ISM) band to characterize the influence of the spatial dimension [31] and [35]. Directional spectrum occupancy is defined as the fraction of time that the received power in a channel exceeds a threshold in a given measurement direction. We have used two separately located measurement devices with directional antennas to measure the directional spectrum occupancy in an office area with a heavy traffic load. The results indicate that spectrum occupancy is heavily dependent on the measurement location and direction. The results of [31] showed that for spectrum occupancy, in particular in the ISM band with low-power short-range devices, the influence of the spatial dimension is very important. In [35], the principles of cooperative spectrum sensing were applied to the spectrum occupancy measurements of [31] by combining the measurements from several antennas and measurement devices. We introduced a new metric, cooperative spectrum occupancy, to characterize the resulting spectrum occupancy that is obtained by combining the occupancy measurements from the antennas with different combining techniques such as AND, OR, and majority combining rules.

4.2 WARP demonstrations

4.2.1 LE-WARP: Linux-Enriched Design for Wireless Open-Access Research Platform

Linux Enriched (LE)-WARP is a programmable radio platform that can be configured to build experimental and reconfigurable wireless networks. Through our new design, we propose a system-level modification to WARP, a field-programmable gate-array- (FPGA) based platform design. The achieved end result is a hardware- and software-enhanced WARP design called LE-WARP. It is capable of adaptation across various layers of communication protocols, such as network, transport, and application layers, along with the already supported flexibility at physical and MAC layers by WARP. The design uses novel dual core architecture in which time-critical PHY control and MAC layer tasks are carried out separately in one core, and the other core is equipped with the Linux operating system (OS), which guarantees a flexible network and application layer support in an open source development environment.

4.2.2 WARP architecture

The main component of the WARP board is Xilinx's Virtex II Pro FPGA chip, which is why the WARP system architecture is based on the Xilinx design flow. The Xilinx design tools *Integrated Synthesis Environment* (ISE), the Embedded

Developer's Kit (EDK), and the System Generator add-on for Simulink are used to incorporate the different phases of the HW/SW co-design into one comprehensive system design (Rice 2011). The orthogonal frequency-division multiplexing (OFDM) reference design is an example design that is built with these tools. The design has an OFDM physical layer implemented on the FPGA logic and abstracted away as intellectual property (IP) cores. In addition, the various third-party peripherals that the platform has, such as memory, Ethernet, an RS-232 port, a System Advanced Configuration Environment (ACE), and various other peripherals, are abstracted away as IP cores. The design consists of two different Processor Local Buses (PLB) running at different clock speeds and connecting the IP cores to a PowerPC (PPC) core.

The OFDM reference design also includes a software framework aimed at one of the PPC cores that runs a single thread OS. This PPC core is used to control the peripherals and all the IP cores. Thus, the software framework includes lower level drivers for the IP cores, the abstraction level for physical layer control signaling, and a framework program for MAC protocol implementation. On top of the software framework, a contention-based MAC scheme is presented as an example implementation on the OFDM reference design.

4.2.3 LE-WARP design

LE-WARP adds a fully functional network layer with an IPv4 stack, transport, and application layer to the WARP. The open source Linux enables the use of the Optimized Link State Routing (OLSR) protocol (Tonnesen 2004) or any other routing protocol designed for Linux to be used on WARP.

From the system design perspective, as two PowerPC cores already existed on the FPGA chip of the WARP and only one PPC was used for the OFDM reference design PHY and MAC level handling, it was decided to use the second PPC in the further development. In this design, the PHY controlling and MAC-layer processing are done by the PPC0 core, while the network layer handling is performed by the PPC1 core. The PPC0 core has a more or less similar physical layer and software framework to that of the OFDM reference design. The inter-processor communications between the two cores are carried out by introducing a mailbox and shared memory IP cores to the design. These are connected to both PPC cores via their own PLB buses. The main changes to the system level design are as follows:

- Enabling a second PPC core (PPC1)
- Adding an interrupt controller for PPC1
- Adding a mailbox entity and shared memory for interprocessor communication between PPC0 and PPC1
- Adding two PLB buses and on-chip memory for PPC1
- Moving the System ACE and Ethernet IP cores to the PPC1 side.

By moving the System ACE IP core from PPC0 to PPC1, we have made it possible for the system to boot the Linux OS using the CF card as a root file system and mass memory. The CF card connected to the board also has a dedicated boot sector from which the whole design is started up. The IP core of the wired Ethernet interface is also moved to the PPC1, as that builds the foundation for the Linux OS to control the Ethernet interfaces.

As the LE-WARP design uses two PPC cores and two different OSs, the software architecture becomes more complex. The main changes on the software side were the implementation of the communication protocol between the two PPC cores and adding the Linux OS to PPC1. PPC0 runs the same software framework as the OFDM reference design with a few software additions and changes. On the PPC1 side, the Linux OS kernel (version 2.6.28) (Xilinx 2011) is ported into it. This flavor of Linux OS is a stripped-down version of standard Linux including only the kernel and essential programs needed to coexist in the PPC405 architecture.

4.2.4 Demonstration configurations

4.2.4.1 Centralized cognitive radio network demonstration

This demo scenario presents a centralized way of assigning free data channels for SUs. In addition, spectrum-sensing information from SUs is gathered to a database for further processing that enables coordinated decision-making. With the use of intelligent algorithms, the database enables learning of spectrum occupancy of PUs, and it becomes possible to predict the free data channels available for the SU network (Farkas et al. 2006).

The system demonstration scenario is represented in Figure 5. The scenario comprises one PU node that generates an adjustable OFDM waveform on the 2.4 GHz ISM band. There are four SU nodes and a remote personal computer

(PC) that comprises the cognitive secondary network. The remote PC is the host for the database and graphical user interface (GUI) software. The SUs and PU are connected to the PC via a wired router that can be thought of as a separate control channel used for signaling between the database and the SUs. All the data traffic between the SUs is carried out wirelessly on a 2.4 GHz ISM band.

The PU is implemented on the LE-WARP and has the following GUI-controllable features:

- The 10 MHz OFDM waveform whose center frequency can be adjusted to an accuracy of 5MHz steps on the 2.4 GHz ISM band.
- The waveform can be programmed to sweep the chosen spectrum area or use a repeating random sequence to occupy the spectrum.

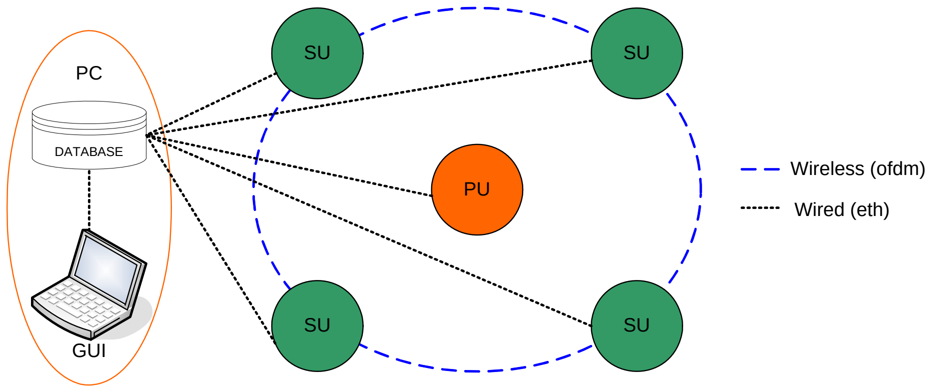

Figure 5. Demonstration scenario of a centralized CRN.

The time that the PU occupies the specific part of the spectrum can be also set from the GUI. The PU features and the remote control from the GUI enable the generation of a diverse spectrum environment for the SU network.

The SUs are implemented on LE-WARPs, which comprise the following features:

- The physical layer is OFDM-based, as described earlier.
- The spectrum-sensing on the physical layer employs distributed energy-based spectrum sensing, with each SU sensing part of the spectrum in a randomized way.

- The MAC layer includes a customized TDMA-based MAC protocol [27] for which different SUs have an individual time slot allocated for data transmission and common time slot spectrum sensing.
- The TDMA-type MAC protocol requires time synchronization between the nodes. This is carried out using distributed time synchronization between the SUs (Vanninen et al. 2008).
- The OLSR routing protocol is used for a sustaining up-to-date topology view of the network.
- Logging software that gathers statistics from the different components, including PHY, MAC, and synchronization and stores it to memory, or relays the information to a remote GUI or database.
- Remote control software for controlling the current data channel or topology from the remote PC, i.e., from a database or GUI.

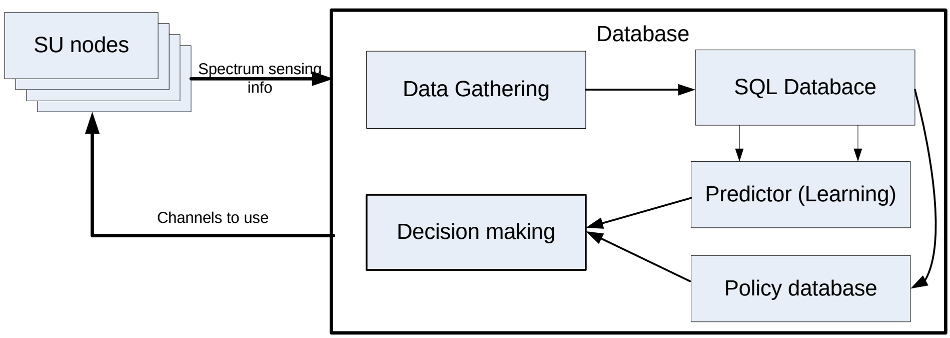

Figure 6. Functional overview of the database and SU loop.

These features allow the SUs to build up a functional secondary network that can detect a PU waveform and carry out data transmission among the SUs while avoiding PU transmission. In addition, spectrum-sensing information is relayed to the database for further processing and remote control of important parameters such as the current data channel.

The database and GUI are implemented with the Java programming language in a Linux environment and run on a remote PC. The GUI functions as an inside view of the demo scenario showing, e.g., individual nodes' instant spectrum-sensing info, PHY/MAC layer statistics in graphical form on a remote PC. The database gathers all the statistics that the SUs and PU relay. The database is illustrated in Figure 6 and includes the following modules:

- Data gathering module that parses the input coming from SUs and the PU into a sensible format.
- Information is stored in a structured query language (SQL) database module for further processing.
- The predictor module uses the gathered spectrum-sensing history with a pattern-matching algorithm based on cross-correlation in such a way that the recurrent PU behavior can be learned and the future behavior can be predicted.
- A policy database module is used to limit the possible spectrum that SUs can use for data transmissions.
- The decision-making module output is the data channel to be used among the SUs. This decision is made from the output of the predictor taking into account the current spectrum policies that are present in the SU network.

4.2.4.2 CRAMNET – Cognitive Radio-Assisted Mobile ad hoc NETwork

The design of CRAMNET involved setting up a MANET using a WARP and adding the cognitive features to the whole system. The aim of CRAMNET was to implement a fully functional system that was programmable at all layers, such as the physical, MAC, and network layers. The design of CRAMNET involved several modules, like spectrum sensing, which provides the spectrum layout; the cognitive engine (CE), which uses the acquired knowledge to come to a logical conclusion; an adaptive physical layer, which assisted in suppressing and expressing OFDM subcarriers and a change of the centre frequencies to fit the bandwidth and frequency that were free to use; and finally the porting of the Linux OS without which the network layer could not have been embedded in CRAMNET.

The most illustrative part of the whole design was that of the GUI, as this gave a very clear picture of the data and control message flow, alongside keeping track of parameters like data throughput, packet loss ratio, request to send (RTS) clear to send (CTS) transfers, channel information like an opportunistic traffic channel (OTCH), a common control channel CCH, the whole spectrum view of the environment in which the MANET is set up, link quality information, routing table information, and many such types of information about the PHY, MAC, radio parameters, etc. This could be achieved, as CRAMNET has the ability to store such information in the compact flash card, and the GUI server would retrieve the information using the hypertext transfer protocol (HTTP) or user datagram protocol (UDP) packet retrieving and processing using a scalable vector graphics (SVG) script running on the GUI server.

The CRAMNET demonstration is implemented entirely on the LE-WARP platform. Every individual LE-WARP platform acts as a wireless node and can be configured as a PU or SU. A PU starts communicating with another PU in the form of a video transmission using UDP on a licensed channel; the channel usage by the PU is performed randomly to provide an opportunity for the SU to use the licensed channel. The SUs use the time synchronization module to acquire network-wide synchronization. Every SU will run the spectrum sensing (SS) at every constant interval of time to obtain the list of OTCHs called the free pool, which is unoccupied by the PUs. Every SU has a CE module that uses information provided in the free pool to direct the adaptive PHY layer module (APHY) to adapt its physical layer according to the free frequency spectrum slots available. The opportunistic MAC with a network layer information (OMAN) module takes care of medium-access-related issues. The OMAN MAC protocol is based on a combination of CCH and OTCH. The CCH is divided into TDMA and random access channel (RACH) parts. The OTCH is used for the actual data transfer and is chosen from the free spectrum slots on which both the transmitter and receiver agree. Every SU has multi-hop routing capability, because the OLSR routing algorithm is primarily embedded in the Linux OS, i.e., in the form of an OLSR daemon that drives the network layer. The block diagram of CRAMNET is shown in Figure 7.

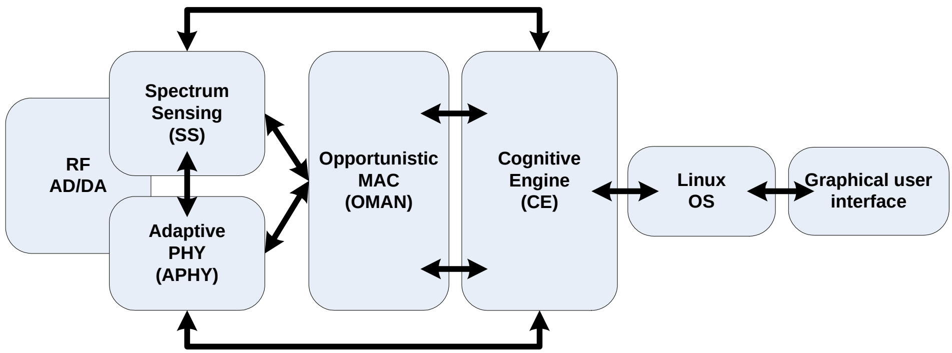

Figure 7. CRAMNET diagram.

The six basic modules of CRAMNET:

- Spectrum sensing on the PHY layer (SS)
- Cognitive engine module (CE)
- Adaptive PHY layer module (APHY)
- Time synchronization module
- Opportunistic MAC with network layer information (OMAN)
- Linux OS as the network layer handler with OLSR and a full IPv4 Transmission control protocol/Internet protocol (TCP/IP) protocol stack running on it.

4.2.5 Demonstration events

SDR'09 Conference, Washington DC, USA

In this demonstration, CRAMNET was able to sense and use the licensed spectrum opportunistically in mobile ad hoc communication among CR-capable wireless nodes, i.e., SUs, and, in the process, form a cooperative set of self-configurable MANETs. The PUs do not cooperate with the SUs, and hence the latter are not aware of the formers' channel usage and have to rely entirely on the spectrum information sensed by their own spectrum-sensing modules in order to find the free channel for SU data transmission. For simplicity of demonstration, the PU network and the six SUs were aligned in such a way that they formed 1-hop, 2-hop, and 3-hop networks. The demonstration was visualized by a graphical user interface showing the network topology, its changes, and the whole data transmission

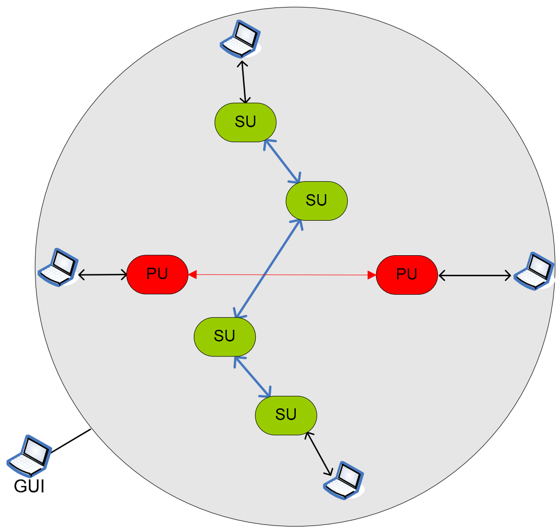

Figure 8. Multi-hop-scenario exhibited at SDR'09.

process from a projector display using TCP/IP applications, such as video conferencing and voice chatting, video transmission, audio transmission, ping, etc. in the demonstration. Figure 8 explains the setup.

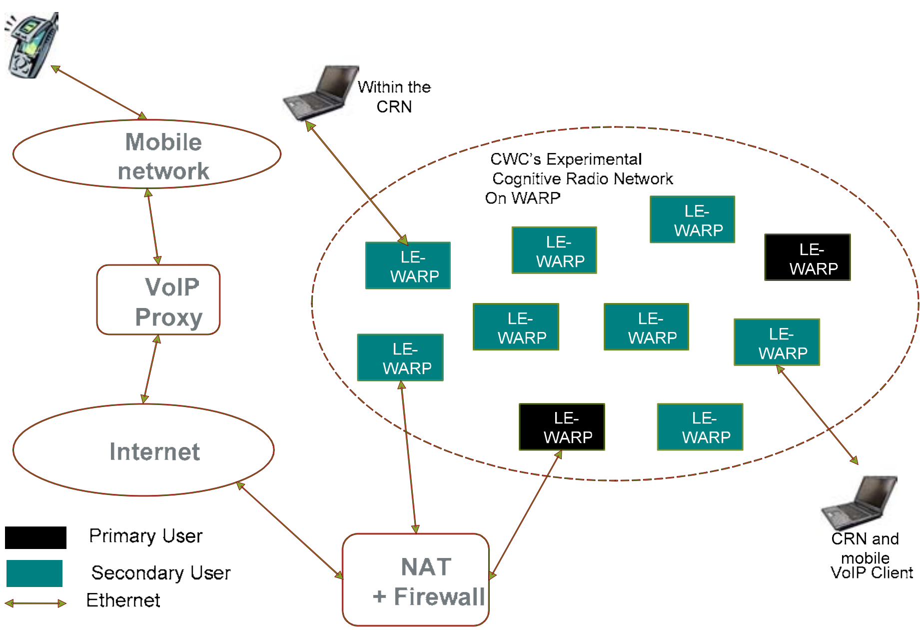

Figure 9. Demo setup for a CR network phone call.

The world’s first phone call over a cognitive radio network, GIGA seminar ’10 Oulu, Finland

The demonstration carried out here proves the capability of CRAMNET to coexist with a commercial network. The main purpose of the demo was to make a VoIP call from an SU as one of the end-users in the CR network that we built, i.e., CRAMNET, via the Internet and the public switched telephone network (PSTN), GSM, or the Third Generation Partnership Project (3GPP) network to another end-user connected to the PSTN/GSM/3GPP network.

The demo setup (at the Public CWC GIGA seminar 2010 [10] in Oulu, Finland in January, 2010), as shown in Figure 9, had four different networks: the mobile phone network, the PSTN, the Internet, the PanOulu open-access wireless fidelity (Wi-Fi) network, and the CWC Experimental Cognitive Radio Network called CRAMNET. LE-WARP has a full IP stack, and hence it was possible to use various applications that used the IP stack over CRAMNET. In this demonstration, the Skype software application was used for VoIP calls.

The VoIP call went through as expected during a 15-minute demonstration session. There were call drops a couple of times, however, due to the fact that the demonstration arena was filled with several users using Wi-Fi from their laptops, and this might have resulted in congestion in the local Pan Oulu open access Wi-Fi network.

Mobicom ’2010, Chicago, USA

This demonstration was similar to the demonstration at the GIGA seminar 2010. The difference was in the increased throughput due to which we could push the number of hops from one to two, and we could also hold a VoIP call session within the multi-hop ad hoc network, compared with the VoIP call between the CR network and the Internet. This demonstration helped us bag the best project award at the prestigious Mobicom’10 international conference.

5. International regulatory, standardization, and research activities

When CR techniques are used to access spectrum bands that have some higher priority users, it is important to protect these users from any potential harmful interference that could arise from a CRS. Activities related to CRSs have recently emerged in regulatory bodies indicating that CRSs are seen as an important topic for the future spectrum management framework. Standardization efforts have also been started to look into the various aspects of CR techniques.

5.1 Regulatory activities

5.1.1 European spectrum regulatory framework

The main players in the European spectrum regulatory framework are the European Commission (EC), and the Electronic Communications Committee (ECC), of the European Conference of Postal and Telecommunications Administrations (CEPT). The EC makes binding decisions on frequency use for EU member countries. The EC has made large investments in CR research.

The Radio Spectrum Policy Group (RSPG) of the EC is a high-level advisory group that assists the EC in the development of radio spectrum policy. The RSPG adopts opinions, position papers, and reports, as well as issuing statements aimed at assisting and advising the Commission at strategic level on radio spectrum policy issues, coordination of policy approaches, and harmonized conditions with regard to the availability and efficient use of radio spectrum necessary for the establishment and functioning of the internal market. The RSPG develops opinions on spectrum topics, e.g., digital dividend, collective use of spectrum (CUS), spectrum trading, etc. For example, CUS allows an undetermined number of independent users and/or devices to access spectrum in the same range of frequencies at the same time and in a particular geographic area under a well-defined set of conditions. In February 2010, the RSPG also finished its report on cognitive technologies (RSPG 2010). The Radio Spectrum Committee (RSC) of the EC assists the EC in the development and adoption of technical implementing measures aimed at ensuring harmonized conditions for the availability and efficient use of radio spectrum, as well as the availability of information related to the use of radio spectrum.

National regulatory authorities have sole responsibility for managing frequency use in their own countries. In Finland, the testing of CRSs is already possible in the 470–790 MHz band if they do not cause interference to other radio traffic.

CR-related activities are on-going in different groups of the ECC. The Conference Preparatory Group (CPG) has been preparing for WRC. The CPG Project Team A PTA has prepared the draft CEPT brief on AI1.19 of WRC-12 on general regulatory and technical issues. The CEPT brief to the agenda item was finished in June 2010. The Working Group Frequency Management (WG FM) is responsible for coordinating the work on CRS issues. A correspondence group (CG CRS) was created to handle this. The Working Group Regulatory Affairs (WG RA) has created an ad-hoc group to identify possible WG RA-related work items on CR, including PT RA1, which looks into associated enforcement issues.

The Working Group Spectrum Engineering (WG SE) has established the group SE43 Cognitive Radio Systems – White Spaces (470–790 MHz). SE43 defines technical and operational requirements for the operation of cognitive radio systems in the white spaces of the ultra high frequency (UHF) broadcasting band (470–790 MHz) to ensure the protection of incumbent radio services/systems and investigate the consequential amount of spectrum potentially available as "white space." SE43 can also provide technical assistance on further issues related to white spaces and CRSs. SE43 published an ECC Draft Report "Technical and operational requirements for the operation of cognitive radio systems in the 'white spaces' of the frequency band 470–790 MHz" in January 2011 (ECC 2011).

In Europe, there has been recent activity in the "digital dividend," which denotes the spectrum resulting from the switchover from analogue to digital TV in the bands 470–862 MHz. The activities in the digital dividend are closely related to CR, as the white spaces in TV bands have been considered a major application scenario and driving force for CR research.

According to the CEPT definition, white space is part of the spectrum which is available for a radiocommunication application (service, system) at a given time in a given geographical area on a non-interfering/non-protected basis with regard to primary services and other services with a higher priority on a national basis (CEPT 2008).

CEPT Report 24 (CEPT 2008), published in July 2008, gives a preliminary assessment of fitting new services into TV white spaces. In Europe, white spaces in the TV bands (i.e., 470–862 MHz) are 8 MHz segments of spectrum between active TV stations in a given area in a given time. The available spectrum from the digital dividend is likely to be more limited in Europe than the US, and far less spectrum will be available than previously with analogue TV. Moreover, the band 790–862 MHz was identified for IMT at WRC-07, and the re-arrangement of this band in Europe will take a long time and cause high uncertainty over the extent of spectrum availability.

The major challenge in applying TV white spaces for communications is that program making and special event (PMSE) services already operate on the TV spectrum on an interleaved basis (e.g., wireless microphones, in-ear monitors) normally on a “tuning range” basis. PMSE services use white space spectrum intensively in certain areas at certain times. Their controlled employment is efficient in spectrum use.

Any new application that is proposed to exploit the TV white spaces is supposed to use CR techniques in order to detect the presence not only of TV signals but also of PMSE users, which is challenging. In addition, an important remark is that any new white space application should be used on a *non-protected, non-interfering basis*, which must be taken into account in CR research. The proposed applications should not only be compatible with other services on the TV bands (e.g., current TV and PMSE equipment) but also with the possibility of evolution of TV planning and technology.

Before any sharing scheme could be applied to the TV bands, it should be carefully assessed and confirmed, including testing. CEPT remarks that it is too early to judge the final capabilities of CR technology, and further studies are needed. The feasibility of cognitive sharing schemes has not yet been demonstrated conclusively. The requirements for CRs should be looked into further, including, for example, interference to TV and PMSE services and the coexistence of different categories of license-exempt usage (e.g., asymmetric power needs).

5.1.2 ITU-R activities

At international level, the ITU-R has finalized the definitions for the CRS and SDR in (ITU-R 2009) in response to the ITU-R Question sent out in November

2007 (ITU-R 2007b). The ITU-R definition of CRS has been adopted by the COGNAC project, and it can be found in Section 2. The work on the measurement of spectrum occupancy is currently on-going in response to the ITU-R Question (ITU-R 2007a).

In particular, the next WRC in 2012 of ITU-R will consider CRs in its Agenda Item 1.19: "*to consider regulatory measures and their relevance, in order to enable the introduction of software-defined radio and cognitive radio systems, based on the results of ITU-R studies in accordance with resolution [COM6/18] (WRC-07).*"

The preparatory work for WRC-12 Agenda Item 1.19 is divided into two parts so that the group ITU-R Working Party 1B (WP 1B) "Spectrum management methodologies and economic strategies" has the main responsibility for the preparations for this agenda item and the group ITU-R WP 5A "Land mobile service excluding IMT; amateur and amateur-satellite service" is responsible for the technical work regarding the agenda item. WP 1B finished its work on this agenda item in June 2010 by finalizing the conference preparatory meeting (CPM) text. For the purpose of facilitating the technical work, WP 5A has been developing an ITU-R report "Cognitive radio systems in the land mobile service." The purpose of the report is to provide an answer to the questions posed by the ITU Radiocommunication Assembly in 2007. The topics to be covered include the following aspects of the CRS: closely related radio technologies and their functionalities, key technical characteristics, requirements, performance, benefits, potential applications, operational implications, capabilities that facilitate coexistence with existing systems, possible spectrum-sharing techniques, and the effect on the efficient use of radio resources. Members of the COGNAC project have actively contributed to the development of the report (see Section 7.2) and participated in the ITU-R WP5A meetings. The report should be finished in November 2011. ITU-R WP 5D is also working on the report "Cognitive radio systems specific for IMT systems." The work was officially initialized in February 2009 and the targeted finalization is in October–November 2011.

The following four scenarios have been identified as possibilities for the deployment of the CRS in ITU-R WP5A and WP 1B.

1) The use of CRS technology to guide reconfiguration of connections between terminals and multiple radio systems. In this scenario, multiple radio systems employing different radio access technologies are deployed on different frequencies to provide wireless access. For example, some terminals are reconfigurable and able to adjust their opera-

tional parameters and protocols to use different radio access technologies. These terminals can obtain knowledge and make decisions autonomously on the adjustments based on the knowledge. Radio systems may also assist terminals in obtaining knowledge and guide terminals in their reconfiguration decisions.

2) The use of CRS technology by an operator of radiocommunication systems to improve the management of its assigned spectrum resources. In this scenario, an operator already owns a network and operates in an assigned spectrum. The operator decides to deploy another network, based on new generation radio interface technology, in the same or other assigned spectrum covering the same geographical area. Due to the non-uniform nature of the radiocommunication needs, an operator running more than one network based on different radio technologies could dynamically and jointly manage the deployed resources in order to adapt the network to the dynamic behavior of the traffic and maximize the capacity globally.

3) The use of CRS technology as an enabler of cooperative spectrum access. In this scenario, information on spectrum use is exchanged among the systems in order to avoid mutual interference. For example, it may be possible to take advantage of parts of the unused spectrum resulting from variations in the occupancy of the assigned spectrum in a specific location and at a specific time. The capability to predict these variations in advance or exchange information among systems/networks on the usage of their respective assigned spectrum may allow operators to share these spectrum resources.

4) Use of CRS technology as an enabler of opportunistic spectrum access. CRS may access parts of unused spectrum in bands shared with other radio systems without causing harmful interference. In this case, the selection of the spectrum to be accessed eventually is made on a real-time basis following, e.g., a radio scene analysis. In this scenario, information on spectrum use is not exchanged among the systems, nor is there “a priori” determination of the spectrum to be accessed.

5.1.3 Example spectrum bands

Section 2.2 has dicussed different deployment scenarios for CRS in terms of spectrum bands. In case of licensed spectrum bands, CRS techniques could be deployed by the owner of the spectrum to improve the efficiency of its spectrum use. CRS techniques could also be employed to improve spectrum use of unlicensed bands such as ISM bands to accumulate more traffic. The primary-secondary user setting could enhance the overall spectrum occupancy by allowing CRS to make opportunistic use of temporarily and locally available spectrum that belongs to higher priority systems without causing harmful interference. Eventually, there could also be spectrum bands for CRS where different CRSs could coexist with each other following some set of coexistence rules.

Most research into CRs focus on TV bands (e.g., 470–790 MHz in Europe), which is an example of the primary-secondary setting. The US has decided to allow license-exempt devices employing geo-location/database access capabilities to access the available channels in the UHF television bands. ISM frequencies are a worldwide frequency band and potential for CRS operations. The use of this band does not require any licenses. Power and antenna beamforming has been restricted so that the range is about 100 meters. There are several ISM bands: 6.765–6.795 MHz, 13.553–13.567 MHz, 26.957–27.283 MHz, 40.66–40.70 MHz, 433.05–434.79 MHz, 902–928 MHz, 2.400–2.500 GHz, 5.725–5.875 GHz, 24–24.25 GHz, 61–61.5 GHz, 122–123 GHz, and 244–246 GHz, whose use can vary in different parts of the world. For instance, microwave ovens, Bluetooth, and IEEE 802.11 devices use ISM bands.

The selection of spectrum band for cognitive networks depends on the application of the network. For example, at lower frequency bands, the antenna size places restrictions, as the antenna sizes cannot be kept very small there. Handheld CR terminals are therefore not feasible at too low frequency bands. At higher frequency bands, the movement of nodes becomes restrictive due the increasing Doppler spread. Mobile CR nodes are therefore not feasible at high frequencies.

The spectrum bands of interest to CRS could be e.g. those identified by the ITU-R for IMT systems. In this scenario, the owner of the spectrum could improve the efficiency of its spectrum use by e.g. deploying small cells with cognitive interference mitigation techniques. The IMT bands may not be feasible for spectrum-sensing types of CR operation, but cognitive capabilities and intelligent spectrum access methods will be developed instead. The latest decisions on

IMT spectrum were made by the ITU-R at WRC-07, where the following bands were identified for IMT:

- 450–470 MHz globally
- 698–806 MHz in Region 2[2] and nine countries in Region 3
- 790–862 MHz in Regions 1 and 3
- 2.3–2.4 GHz globally
- 3.4–3.6 GHz in a large number of countries in Regions 1 and 3.

Prior to the WRC-07, the previous WRC (World Administrative Radio Conference [WARC] in 1992 and WRC-2000 in 2000) made the following global spectrum identifications for IMT-2000:

- 806/862–960 MHz
- 1.710–1.885 GHz
- 1.885–2.025 GHz
- 2.11–2.20 GHz
- 2.50–2.69 GHz.

In CEPT, it has been decided that harmonized frequency arrangements at European level will be developed for two of the bands identified in WRC-07, namely, 790–862 MHz and 3.4–3.6 GHz. Thus, IMT will not be deployed in Europe on the globally identified frequency bands, at least not in the near future. Frequency arrangements for the 790–862 MHz band are completed in ECC PT1, and a frequency-division duplexing (FDD) arrangement of 2 x 30 MHz with reverse-duplex direction is proposed as the preferred solution. It is based on 5 MHz blocks with a 1 MHz separation at the 790 MHz boundary and 11 MHz duplex gap. A time-division duplexing (TDD) solution is also provided that is primarily meant for administrations that do not wish to use the preferred harmonized frequency arrangement or do not have the full band available. It consists of 13 blocks of 5 MHz with a 7 MHz guard band at the 790 MHz boundary. Studies of the 3.4–3.6 GHz band are ongoing in both CEPT ECC PT1 and ITU-R WP 5D.

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2 The ITU divides the world into three regions that are roughly defined as Region 1: Europe, Africa, and the Middle East; Region 2: the Americas and the Pacific Islands; and Region 3: Asia and Oceania.

5.2 Standardization activities

Standardization activities related to CRSs are currently carried out mainly at the IEEE and the European Telecommunications Standards Institute (ETSI). Pre-cognitive systems that have CR features have been standardized in the past, including the 5GHz radio local area network (RLAN) with dynamic frequency selection (DFS) and ultra wide band (UWB) devices with a detect and avoid (DAA) mechanism. A 5GHz RLAN uses DFS to search for a different free channel as soon as it detects that the wanted channel is occupied by, e.g., radar signals. DAA in UWB systems detects the presence of signals from other radio systems, such as fixed broadband wireless access and mobile services, and reduces the transmitted power of the UWB device down to a level at which it does not cause interference to the indoor reception of these systems (ECC 2008).

Here we note that the evolution of mobile communication systems in the 3GPP will be an influental path in the introduction of cognitive radio features into real world systems. Many of the features currently being standardized to the 3GPP systems have elements similar to CRS. This document, however, has not fucused in the 3GPP systems.

5.2.1 European Telecommunications Standards Institute

The main standardization body in Europe is ETSI, which produces globally applicable standards for Information and Communications Technologies (ICT), including fixed, mobile, radio, converged, broadcast, and Internet technologies. ETSI is recognized by the EU as a European Standards Organization. ETSI produces, e.g., harmonized European standards to support EU legislation for the free movement of goods within the single market.

The main body in ETSI for CRSs is the Technical Committee Reconfigurable Radio systems (TC RRS), see (ETSI 2011). The main responsibility of ETSI RRS is to carry out standardization activities related to reconfigurable radio systems including SDR and CR. The work focuses on functional architectures for SDR, CR and resource optimization, SDR-based handsets and radio base stations, and the role of RRS in the domains of public safety and defense. The work in RRS is conducted in four WGs, and the following technical reports (TR) have been published:

- WG1 – System aspects

    - TR 102 803 Potential regulatory aspects of Cognitive Radio and Software Defined Radio systems

- WG2 – Radio equipment architecture
    - TR 102 680 SDR Reference Architecture for Mobile Device
    - TR 102 681 Radio Base Station (RBS) Software Defined Radio (SDR) status, implementations and costs aspects, including future possibilities
- WG3 – Functional architecture and cognitive pilot channel
    - TR 102 682 Functional Architecture (FA) for the Management and Control of Reconfigurable Radio Systems
    - TR 102 683 Cognitive Pilot Channel (CPC)
- WG4 – Public safety
    - TR 102 745 User Requirements for Public Safety
    - TR 102 838 Summary of feasibility studies and potential standardization topics.

With its extended mandate, Technical Specifications (TS) can now be produced for the items identified in the study phase. ETSI is now addressing the use cases for CR and the White Space in the UHF band (460–790 MHz).

The ETSI Specialist Task Force 386 (ETSI STF 386) has been established to study “methods, parameters and test procedures for cognitive interference mitigation techniques for PMSE devices”, see (ETSI 2009) The PMSE market (e.g., wireless microphones, in-ear monitors, audio links for media productions) needs access to new spectrum resources to satisfy future demand. The purpose of STF 386 is to achieve co-existence of high audio quality PMSE devices, often using a 100% transmitter duty cycle emission profile with victim radio services (e.g., broadcast services and future land mobile services). The first results of these studies are ready (ETSI 2010; ETSI 2011)'.

5.2.2 IEEE

The IEEE DySPAN Standards Committee aims to develop standards related to *dynamic spectrum access networks*. The focus is on improved use of spectrum. New techniques and methods of dynamic spectrum access require management of interference and coordination of wireless technologies, and they include network management and information sharing. The work is divided into six WGs.

The IEEE 1900.1 Working Group on Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management has published the standard IEEE 1900.1.

The IEEE 1900.2 Working Group on Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence Between Radio Systems has published the standard IEEE 1900.2.

The IEEE 1900.3 Working Group on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules has been disbanded.

The IEEE 1900.4 Working Group on Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks published the standard IEEE 1900.4 "IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks" in 2009. Since April 2009, the 1900.4 Working Group has worked on two projects:

- 1900.4a: Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks – Amendment: Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands
- 1900.4.1: Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks.

The IEEE 1900.5 Working Group on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications is active.

The IEEE 1900.6 Working Group on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems has published two white papers:

- Sensing Techniques for Cognitive Radio – State of the art and trends
- Review of Contemporary Spectrum Sensing Technologies.

An ad hoc on White Space Radio was created to consider the interest in, and the feasibility and necessity of developing a standard defining radio interface (MAC and PHY layers) for white space communication systems on March 8, 2010.

The IEEE 802.22 is the first CR WRAN standard for TV white spaces in the USA. In the IEEE 802.22, the base station (BS) needs to know the locations of all the elements. Satellite-based geolocation capability is needed in the devices. The BS has access to a database that includes information on existing broadcasting systems. Spectrum sensing is required for detecting analogue TV, digital TV, and PMSE signals. Sensing requirements include sensing of receiver sensitivity, channel detection time, probability of detection, and probability of false alarms.

The IEEE 802.19 is the Wireless Coexistence Technical Advisory Group (TAG) within the IEEE 802 LAN/MAN Standards Committee. The TAG deals with coexistence between unlicensed wireless networks. Many of the IEEE 802 wireless standards use unlicensed spectrum and hence need to address the issue of coexistence. Other IEEE activities include IEEE 802.11y, IEEE 802.11h, IEEE 802.11p, IEEE 802.15.3 (UWB), and IEEE 802.16h.

5.3 Research forums

CR is a hot topic in telecommunications research today. Research into CRSs is carried out on a large scale globally. A large number of publications are appearing continually. The creation of intellectual property rights (IPR) is also progressing well. Here, we have summarized European research activities, including EU-funded research projects and cooperation forums.

5.3.1 European research projects

The EU funds research projects related to CRSs. In the Seventh Framework Programme (FP7), several calls for proposals have dealt with CR topics. As an example, from FP7 ICT Call 1, Call 4, and Call 5 under the “Network of the Future” Objective 1.1, approximately 90 projects have been launched since the beginning of the programme (EC 2011). The projects under this objective are organized in three clusters: Converged and Optical Networks (CaON), Radio Access and Spectrum (RAS), and Future Internet Technologies (FI). In 2008, 46 projects resulting from the FP7 ICT Call 1 have been started in these three areas corresponding to 200 million € of EU funding in research. In January 2009, 24 projects from FP7 ICT Call 4 were started in the RAS and CaON areas, representing more than 110 million € of EU investment. In response to FP7 ICT Call 5, 21 new projects have been started in 2010 mainly related to the Future Internet corresponding to 80 million € of EU funding. Many of the projects deal with cognitive radio related topics. Examples of CRS-related projects from the FP7 include ARAGORN, C2POWER, COGEU, E3, EUWB, FARAMIR, OneFIT, ORACLE, PHYDYAS, ROCKET, SACRA, SENDORA, SPORT VIEWS, QOSMOS, QUASAR, and others. As a summary, large investments are currently being made in the development of cognitive radio techniques and demonstrations of their capabilities in EU funded research project in the FP7.

5.3.2 COST actions

The European Cooperation in the field of Scientific and Technical Research (COST) is a European network with a mission to strengthen Europe in scientific and technical research. COST supports coordination costs of research networks called Actions. Two COST Actions, COST Action IC0902 and IC0905, have been established to coordinate research into CRSs.

COST Action IC0902: Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks

The objective of COST Action IC0902 is to integrate the cognitive concept across all layers of communication systems, resulting in the definition of a European platform for CRs and networks (COST 2011a). The duration is 12/2009–12/2013. The Action is organized in five WGs:

- WG1 Definition of cognitive algorithms for adaptation and configuration of a single link according to the status of external environment.
- WG2 Definition of cooperation-based cognitive algorithms, that take advantage of information exchange at a local level.
- WG3 Definition of network-wide mechanisms for enabling the cognitive approach.
- WG4 Definition of mechanisms for intersystem coexistence and cooperation.
- WG5 Definition of a cross-layer cognitive engine.

Four special interest groups (SIG) have been established to bring together experts from different WGs on common research issues on the topics of information representation languages, learning and artificial intelligence, mobility management for cognitive wireless networks, and positioning. The COGNAC project members have participated in this COST Action by attending the meetings and giving presentations.

COST Action IC0905: Techno-Economic Regulatory Framework for Radio Spectrum Access for Cognitive Radio/Software Defined Radio (TERRA)

The objective of COST Action IC0905 is to establish a multi-disciplinary European forum focusing on coordinating techno-economic studies for the development of a harmonized European regulatory framework to facilitate the advancement and broad commercial deployment of CR/SDR systems (COST 2011b). The duration is 05/2010–05/2014. Action is organized in four WGs:

- WG1 CR/SDR deployment scenarios
- WG2 CR/SDR co-existence studies
- WG3 CR/SDR economic analysis
- WG4 Impact assessment of CR/SDR.

The COGNAC project members have participated in this COST Action by attending the meetings and giving presentations and participating in the core group of the management committee and vice-chairing of WG2.

5.3.3 Other forums

There are also numerous other forums related to CRSs:

- Worldwide Universities Network Initiative Cognitive Communications (WUN CogCom)
- Wireless Innovation Forum (WinF) (Version 2.0 of SDR Forum)
- Wireless World Research Forum (WWRF)
- White Spaces Coalition
- Object Management Group (OMG)
- Open Mobile Alliance (OMA)
- Femto Forum

- LTE (Long Term Evolution) Forum
- WiMAX Forum
- Telemanagement Forum (TM Forum)
- eMobility.

6. Future directions

In this chapter, we depict the predicted future directions of cognitive and opportunistic networks in terms of a roadmap and items to be studied. Our presented roadmap includes four paths along which the development of CRSs is advancing:

Path 1: Optimizing the use of spectrum
Path 2: Network optimization
Path 3: Resource management
Path 4: Mobile cloud computing.

6.1 Roadmap

6.1.1 Path 1. Optimizing the use of spectrum

Description

Spectrum usage optimization or dynamic spectrum access (DSA) is the first path of CR. Figure 10 shows an example of a cognitive cycle when spectrum use is of concern. The overall aim is to make more efficient use of spectrum to accommodate the growing demand for future wireless services. Flexible wideband usage of the spectrum is needed to support the transfer to data-oriented services, which requires increasing transmission capacity. On the other hand, the energy efficiency of mobile devices can be enhanced by limiting the transmission time, i.e., by using a frequency band that is as wide as possible.

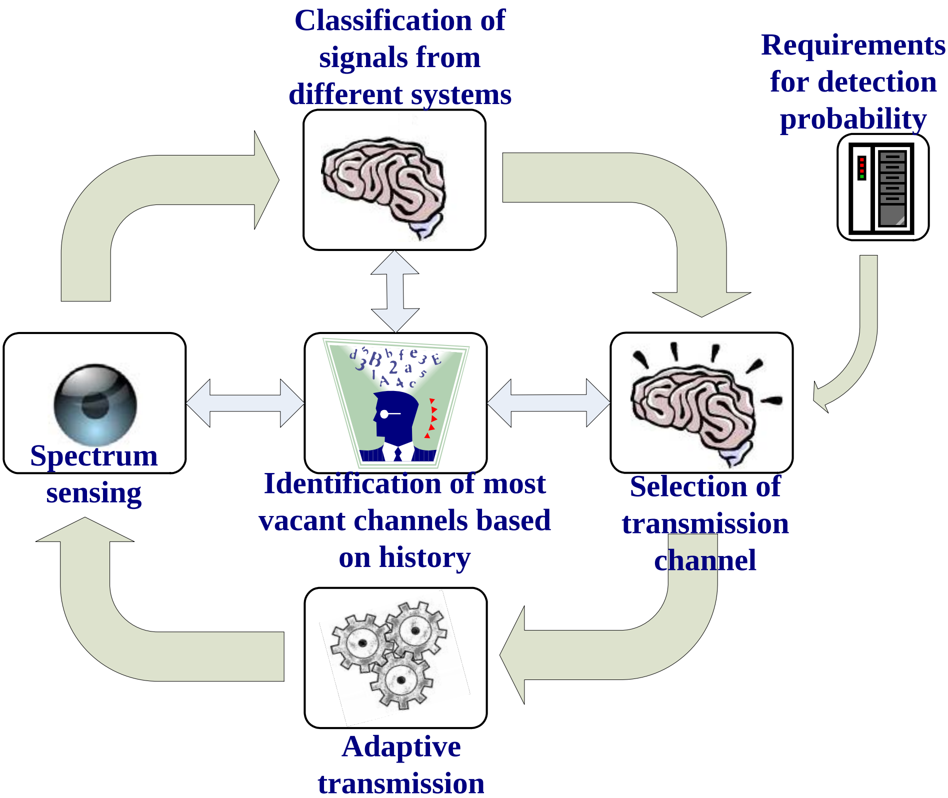

Figure 10. Cognitive cycle for optimizing spectrum use.

With regard to spectrum use, cognitive wireless networks can consist of PUs and SUs. PUs are licensed users of specific frequency bands who own the licensed bands exclusively at any time. SUs use the frequency bands of PUs opportunistically whenever the PUs in the area are not operating or the interference caused by them is tolerated by PUs in their proximity. In this case, unlicensed bands are regarded as special frequency bands that have no PUs.

CR techniques can also be used to optimize spectrum use inside the network to make more efficient use of the spectrum that already belongs to the system. In this case, the CR techniques are used to improve system performance instead of sharing spectrum with other systems.

CR technologies can facilitate secondary markets in spectrum use, implemented by voluntary agreements between licensees and third parties. For instance, a licensee and third party could sign an agreement allowing secondary spectrum uses made possible only by the deployment of CR technologies. Ultimately, CR devices could be developed that “negotiate” with a licensee’s system and only use spectrum if an agreement is reached between a device and the system. In this case, spectrum sensing by the user terminals is not required. Instead, the network operators need negotiation methods for managing the spectrum. They also need to be aware of the overall spectrum allocation and policy.

Research issues

Many of the research issues related to spectrum usage optimization have been addressed in the COGNAC project. Two clearly separate cases need to be addressed: DSA operation in licensed bands and in unlicensed bands. In the former case, the observations and identification of the primary system (cellular network, broadcaster, etc.) are the key issue. The issue of spectrum sensing is therefore the most important research topic. Spectrum sensing also needs to be performed with sufficient reliability to convince the regulators. Four issues, in particular, were addressed in COGNAC, though they need more attention:

- Spectrum sensing should be coupled with database-based solutions.
- The cooperative sensing needs to be surveyed and tested.
- The selection of suitable sensing method to a specific use scenario needs to be defined and demonstrated.
- Actual spectrum efficiency enhancement provided by CR systems should be clearly demonstrated.

In addition to sensing, all the aspects shown in Figure 10 are important to DSA. The classification of signals and traffic patterns in different channels helps the sensing process and supports the learning process. The selection of a transmission channel should be made based on the requirements of the requesting user as well as the characteristics of the channel, e.g., which channel offers sufficiently long idle periods. Adaptive transmission methods, including power control methods that react to the detected changes in the environment, as well as the given a priori information about the PUs in the area, also need to be researched. In the latter case, spectrum users need to organize their operation autonomously. Methods leading to fair and efficient resource use are required and, e.g., game theoretical approaches have been used to find the limits. The opening of the spectrum also brings the risk of malicious users accessing the spectrum and misusing it. Methods to prevent misuse therefore need to be developed.

The current frequency regulation aims to guarantee that systems can operate free from harmful interference. To accomplish this, the operation of different systems in the same bands, following the secondary/primary usage paradigm, requires careful coexistence studies. The coexistence of different systems in the same bands could be eased by more flexible frequency allocation/reuse of methods that exploit CR techniques. Current spectrum owners and operators need to be convinced that secondary spectrum use is viable and will not hinder their business. Key issues to do this include reliable demonstrations of spectrum-sensing methods, comprehensive coexistence studies, and pilot systems.

Beneficiaries and use cases

More efficient and flexible use of spectrum brings many new possibilities in terms of opening the market to new players and new advanced applications. An example of this step for licensed bands is the potential use of white spaces on TV bands. In TV whate space usage, the actual spectrum sensing is not required. Instead, access to available frequency slots is best implemented based on spectrum allocation information from databases or similar sources.

Network infrastructure providers benefit from easier adoption and approval of the new technology to operate in different frequency ranges. New systems that could use these spectrum reuse tools include new mobile communication systems such as future releases of IMT-Advanced, especially in the femtocell-type solutions in which the operation as an SU of the spectrum may become easier due to the close ranges with the base stations (e.g., eNodeBs) and peers. An example of this is the operator deploying femtocells on the same band as its macrocells to provide alternative access methods for users. Another emerging possibility is to use unlicensed bands for cellular access in short ranges.

Beneficiaries of the new technology would be:

- Network operators: possibilities to provide better coverage and data rates for users and thus make a bigger profit; end-user level QoS may also become a reality.
- Spectrum owners: potential revenue by allowing secondary spectrum users (operators) at some frequencies/time instants; a mechanism for managing spectrum leasing dynamically is needed however.

- Operators with reserved spectrum slots may be able to sell or hire the unused spectrum locally and/or temporally, e.g., by some type of auctioning mechanism.
- Spectrum regulators: higher spectrum occupancy to accommodate the growing amounts of wireless traffic.

Another field that could use DSA in the near future is public safety communications and military users. In these cases, the definite need for more bandwidth is motivating the adoption of novel solutions. In addition, the application of wireless technology often takes place in areas in which wireless infrastructure does not exist or has been partly or totally destroyed (natural disasters, war zones, etc…). In this case, beneficiaries of the technology are military and public safety organizations that can deploy their networks more easily in any geographical area.

6.1.2 Path 2. Network optimization

Description

Autonomous network optimization becomes more important as the number of base stations and access points of systems and overlapping networks increases. The driving force behind the explosion in access networking technologies is the fact that the increasing demand for bandwidth can only be satisfied (with spectrum efficiency) by providing wireless access via smaller cells, e.g., femtocells. The resource usage optimization of the resulting heterogeneous networks that partly operate in the same frequency bands must be performed dynamically by the systems themselves. As a result, the self-organizing autonomous networking paradigm will be advanced.

Networks will be able to support adaptation to different environments, using several different radio interfaces. The intelligent selection of a radio interface or other available channels will be made cognitively in order to select the best way to exchange data between the transmitter and the receiver. Devices will be able to perform vertical handovers and form self-organized networks. This will lead to better access to networks for users. Optimization will also lead to savings in resource use (e.g., energy) and network maintenance.

As experience of operation in a heterogeneous environment is gained, it will become feasible to include aspects of, e.g., database-based machine learning features into the systems, allowing them to make predictions and pre-adaptations to their behavior to match future network conditions. Systems will be able to learn from the past, predict the future, and make adaptations accordingly. For example, devices will be able to make use of past information to reduce the dependency on current measurements using, e.g., location information.

Research issues

The current network-operator-centric paradigm of controlling the network operations from one or more selected locations in a centralized manner will be replaced by autonomous processes within the systems controlling the most complicated and dynamic aspects of the networks. The challenges include:

- Handling application/user-related priorities in a very dynamic situation
- Managing the network routing (and proper addressing) in cases in which parts of the networks are mobile and even detached from the fixed backbone; delay-tolerant networking may be one example of requirements
- Selection of communication techniques (e.g., access interface) based on application requirements, the interference environment, and platform constraints
- Cooperation should be designed as part of the control functions in the handsets, and it is not necessarily clear whether device manufacturers see this type of function as necessary.

Beneficiaries and use cases

For operators, the incentive to invest in cognitive technologies is the promised ability to support more customers/data traffic with the invested networking HW technology. From the operators' point of view, networks and services will be easier to deploy with the discussed techniques. Predictive systems should provide even more efficient use of the network and radio resources for the benefit of network operators and service providers.

The autonomous management of some of the basic network functions will ease the burden on network operators and, in fact, may be one of the enabling technologies in future unconventional network structures in which network control, by design, is brought closer to the users (e.g., femtocell and femto nets).

This will lead to the birth of self-organizing and self-healing networks using cognitive techniques.

The most dramatic benefit should become available to users who are able to enjoy fluent (even seamless) network connections despite their mobility. Dynamic management of priorities in complex environments can also enhance the fairness experienced by users (i.e., those who pay more are always able to receive better service). This naturally also benefits the network operators in the form of higher revenue and satisfied customers.

In cooperative scenarios, user terminals use some of their resources for the common good in the network and thus, in some cases, do not actually benefit at all in the short run. In situations in which network conditions are especially hard, network-wide cooperation may result in more reliable connections etc. seen by users. Device manufacturers will take support for heterogeneous network access to the device level.

6.1.3 Path 3: Resource management

Description

The PU/SU concept can be generalized by introducing flexible access rights to all network resources on a local scale, not only spectrum. Nodes of a network, e.g., wireless devices, take their resources to the network. Resources such as memory and processing power are included in the shared resources. The applications and interfaces of the wireless terminals are designed to make flexible use of available resources.

Wireless network resources can be classified into five types: 1) *radio resources,* including time, frequency, space, and power/energy; 2) *built-in resources* such as mass storage, batteries, and processing units, e.g., CPUs; 3) *user interface resources,* which refer to sensors as well as actuators integrated into wireless terminals like speakers, microphones, imaging devices; 4) *social resources,* which are considered part of a resource pool distributed across cooperating entities. Social resources are the individuals behind the wireless devices (e.g., controlling or taking decisions), as well as groups of them, such as in a social network. It is very important to consider these social resources in the overall picture of distributed resources, as individual and group decisions play a key role in the exploitation and management of distributed resources; and 5) *connectivity resources,* which typically include several cellular and short-range air interfaces, can be seen as a fifth resource, as devices nowadays typically have more than one air interface. A large amount and diversity of distributed resources offer great potential for cooperation. Figure 2 has depicted the described resource classification, showing typical examples of these resources in wireless networks.

Users may play a key role by deciding which resources they are willing to share or, in some cases, the cognitive operation is embedded in the system and transparent to the user. In order to encourage nodes to share their resources, nodes need to obtain a clear benefit from this action. Incentive mechanisms in cooperation encourage cooperative behavior on a voluntary basis. For example, incentives can be better or cheaper services for the end-user and even enhance the e-reputation of a cooperative user. A rational entity chooses to cooperate as a result of an incentive mechanism that aims to bring benefits to the cooperating user and eventually all collaborating users.

Full awareness of all local resources, coexisting communication devices, etc. and the ability to optimize communication according to the needs and capabilities of all players in the field open up possibilities: terminals or access points can act as relays, femtocells, local mesh structures, direct communication between terminals, and coordinated multipoint transmit and receive system (several antennas connected).

Research issues

The identification and management of resources in local networking environment(s) must be extended to wireless access. This includes a minimum of the following broad research topics:

- Resource description: Before resources can be shared they need to be defined and described efficiently. Devices have to agree on a common language to describe both the resources and the need for them just to make resource sharing possible.
- Resource discovery: Resource discovery is the process of locating distributed resources on a network. Devices can formulate their needs and publish their resources using resource description protocols. Devices can locate the necessary resources (or services) using resource discovery protocols. In addition, real measurements can be carried out to assess the status of given resources, particularly physical resources.

- Learning: Learning is a crucial part of a cognitive network and makes the operation of CRs more efficient than in the case in which it is only possible to have information available at design time. A cognitive network should be able to learn from the past and present results of its actions and from the actions of PUs in order to improve its future performance.
- Coordination systems must be employed for resource access control in order to share resources efficiently among wireless end-users. Coordination systems allow devices to use other devices' resources or permit pooling and scheduling of resources among those nodes requiring services. Coordination is a great challenge in a mobile wireless network because of its distributed and highly dynamic characteristics.
- A clearing mechanism is needed to permit transactions, generally with an authentication or authorization process. It may also include payment to obtain permission. In several peer-to-peer networks, mutual resource sharing is incorporated into the clearing mechanism. Peers have to contribute their own resources in order to be cleared to use the resources of other peers. The level of the received service improves with increased sharing of the users' own resources. To enable a trust and clearing mechanism for cognitive spectrum use, some kind of authorization may be needed for CR devices. They should be tested carefully to meet tight interference requirements, and only devices proven to work properly would be cleared to coexist with PUs.

It may be challenging to convince people to share resources, for privacy and security reasons. In fact, security, privacy, and trust issues of wireless sharing of a network are big concerns for people. Thus, in some cases the end-user may decide with whom to cooperate and what resources to share. User decisions on what and how to share the resources of their devices are part of the cooperative strategies that need to be devised.

Beneficiaries and use cases

Network operators can use resources more efficiently and support more users with new services. For example, if the network is heavily congested, the user's wireless device senses the congestion in the network and asks if another user is able to tolerate some delay. If this user can tolerate some latency (e.g., because his/her traffic is not delay sensitive), he/she may accept sharing his/her resources to help other users to improve their QoS. It is also possible to borrow resources from other participants in situations in which the user's own resources are not powerful enough for a given task. For example, it may be the case that a given user does not have enough signal strength in his/her cell phone and that the situation of a close-by user is much more favorable, as he/she uses a different service provider.

By sharing all resources cooperatively, even a user with an unfavorable radio channel can obtain the required resource through his/her neighbor device (e.g., air-interface or operator sharing). A simple example of a service provided by a wireless grid is cooperative audio recording in which the stereo sound is produced by combining recordings made by multiple simple devices. Cooperative media downloading is also a possible application scenario for a grid. If several mobile users want to download the same media from a certain source, they can download different parts of the media over a cellular link and then exchange the parts over short-range links, which is a more energy- and spectrum-efficient way than downloading all the data from the source individually. Operators can use resources more efficiently and support more users with new services.

Potential use cases include in-home communications in which local clusters are formed to allow low power transmissions. CR will be used for intelligent home services. Control systems are different, but intelligent systems take care of most of the configurations. There is no need to worry about different radio interfaces or cable connectors.

6.1.4 Path 4: Mobile clouds

Description

Concepts of cloud computing become relevant to wireless subscribers with (momentary) needs for computing and other services. Gradually, all network resources will be able to be managed and shared in a cognitive network. Users have complete freedom to move anywhere and call for their own personal network service using any device they can find in their environment. All relevant resources are included in and managed by the cognitive network. Users can establish ad hoc clusters to improve service quality/availability.

All relevant aspects of the radio systems and their mutual interactions are understood to the point where optimal operation settings to all systems can be found. Processing algorithms and capacity are sufficiently advanced for the adaptation to happen dynamically, even in the smallest of devices and systems.

Cloud computing (Reed 2009) is shifting from large enterprises towards smaller and smaller scale enterprisers. At the same time, the data centers/computing resources are becoming smaller and more local. For example, companies and organizations may want to set up their own private cloud services for security/cost/availability reasons. The services available via these cloud services will also become more customizable.

Mobile clouds define a very generic networking concept ultimately aiming at sharing distributed resources in a wireless network. The type of mobile cloud will strongly depend on the type of resources being shared. In case processing power is resource in question, one could think on the concept of cloud computing. Note that the nodes providing processing power can be within the wireless cloud and also outside that cloud. In the former case the CPU of the wireless devices are connected together through wireless links, whereas in the latter case, external (and typically much powerful) CPUs are also exploited. As mentioned previously, processing power is just one of the possible resources that can be opportunistically shared.

Figure 11 depicts a vision on how future cloud technology will be realized. Mobile clouds are typically independent cooperative arrangements of wireless devices aiming to provide better performance, novel service and to exploit resources more efficiently. However, a much wider approach to mobile clouds is also very promising. Indeed, mobile clouds will be the natural extension of cloud computing platforms towards the users, allowing databases and powerful data processing facilities to be efficiently connected to the users. Note that this is a much more generic, robust and flexible concept than the conventional approach of connecting a wireless device to the cloud-computing platform through a single and vulnerable wireless link. Figure 11 highlights the processing power approach of mobile clouds, where intensive data processing can be carried out inside the mobile cloud, outside of it (by the cloud computing system) and on both clouds as well. Mobile clouds allows also sharing of many other distributed resources available on the wireless devices, such as sensors, actuators, air interfaces, radio resources, apps, etc. It is also very promising to see mobile clouds as termination stages of cloud computing platforms, connecting such a systems to the physical world. This approach has in our view has an enormous potential.

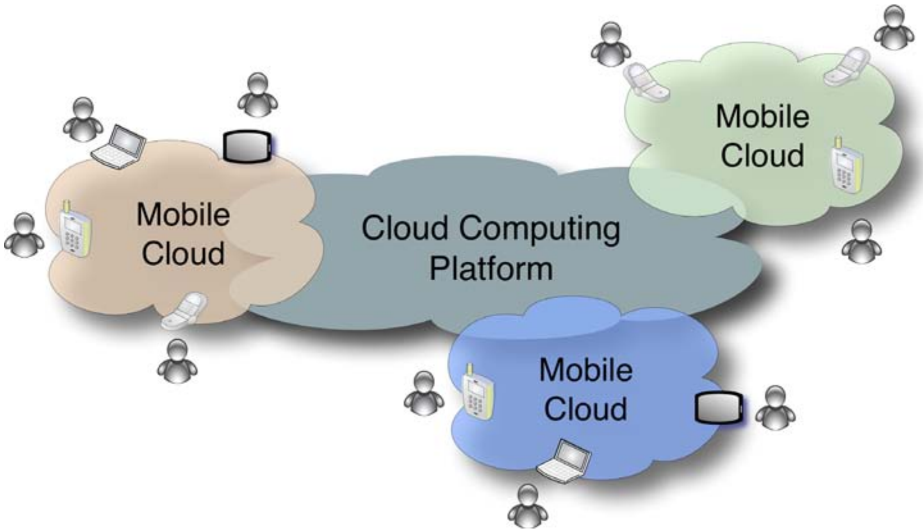

Figure 11. Our vision of future cloud architectures and the key role of mobile clouds.

6.2 Future research items

There has been much progress in recent years in the research of CR systems. Fundamental techniques have been developed for the various phases of the cognitive cycle. There are still many steps to be taken before these techniques can become part of the wireless systems used in everyday life.

In the future, it will be important to showcase the true benefits of CR techniques by analysis, simulations, and, most importantly, real-world demonstrations. For the successful introduction of CR techniques into the spectrum regulatory framework, it will be crucial to demonstrate the capabilities of the new techniques in terms of, e.g., achievable improvements in the spectrum occupancy. Capturing the various benefits of the new techniques will be important in making them appealing to the different stakeholders.

Supporting regulatory and standardization work will remain a crucial task in the future, as spectrum-related aspects of CR techniques require interventions with the regulatory domain. Regulatory and standardization efforts have just been started, and their success is dependent on the developments and support of the research domain. The development of efficient and practically deployable techniques and rules for the coexistence of CRSs with other wireless systems, as well as between the CRSs themselves, will be particularly critical.

In the future, it will be necessary to showcase the real application areas for CR techniques. The use of cognitive principles in different application areas could open up new opportunities that are not foreseen today. Analyses of economic viability will become important. All in all, the Tekes Trial – Cognitive Radio and Network Trial program will have an important role in this development.

Cloud research has become lately a very significant research field around the world. Most of this research, supported widely by industry and academia, focuses on cloud computing. Busines-wise, it is estimated that cloud computing will surpass $100 billion by year 2015. We see that the concept of mobile clouds is highly complementary to that of cloud computing. Indeed, mobile clouds can be also seen as a natural interface to cloud computing. Users carry a mobile device and it is through this device or a cloud of them that users can access to the power of cloud computing.

7. Summary

This report has summarized the main research results from the COGNAC project in the field of cognitive and opportunistic wireless communication networks. CR techniques are promising approaches to ensure efficient use of various resources of wireless communication systems. In terms of spectrum, CRS development is about the development of coexistence techniques to allow different systems to use the same spectrum band in order to maximize the benefits of the spectrum.

The COGNAC project has developed fundamental CR techniques for obtaining knowledge using, e.g., spectrum-sensing techniques, selecting channels using history information, interference management using power and frequency control, cooperation using game theory, and learning using databases. The project has also carried out experimental studies including directional spectrum occupancy measurements and demonstrations of CRSs. The project has participated in the spectrum regulatory framework by providing valuable information on the capabilities and technical approaches of CRSs.

References

Ahuja, S.P. and Myers, J.R. (2006) A survey on wireless grid computing. The Journal of Supercomputing, Vol. 37, July 2006, pp. 3–21.

Biggs, M., Henley, A. and Clarkson, T. (2004) Occupancy Analysis of the 2.4 GHz ISM band. IEE Proc. Commun., Vol. 151, October 2004, pp. 481–488.

CEPT Report 24. (2008) Feasibility of fitting new applications/services into “white spaces” of the digital dividend.

COST (2011a) COST Action IC0902. Cognitive radio and networking for cooperative coexistence of heteregeneous wireless networks. http://newyork.ing.uniroma1.it/IC0902/.

COST (2011b) COST Action IC0905 TERRA. http://www.cost-terra.org/.

EC (2011) European Commission. ICT Research in FP7. The Network of the Future: an essential infrastructure for our society. http://cordis.europa.eu/fp7/ict/future-networks/projects_en.html.

ECC Report 120. (2008) Technical requirements for UWB DAA (Detect and Avoid) devices to ensure the protection of radiolocation services in the bands 3.1–3.4 GHz and 8.5–9 GHz and BWA terminals in the band 3.4–4.2 GHz.

ECC Report 159. (2011) Technical and operational requirements for the operation of cognitive radio systems in the ‘white spaces’ of the frequency band 470–790 MHz.

ETSI TR 102 799. (2010) Operation methods and principles for spectrum access systems for PMSE technologies and the guarantee of a high sound production quality on selected frequencies utilising cognitive interference mitigation techniques.

ETSI TS 102 800. (2011) Protocols for spectrum access and sound quality control systems using cognitive interference mitigation techniques.

ETSI (2009) Terms of reference for Specialist Task Force STF 386. http://portal.etsi.org/STFs/ToR/ToR386v18_ERM17WG3_PMSE_CognRadio.doc.

ETSI (2011) ETSI Reconfigurable Radio Systems. http://www.etsi.org/WebSite/technologies/RRS.aspx.

Farkas, K., Hossmann, T., Ruf, L. and Plattner, B. (2006) Pattern-matching-based link quality prediction in wireless mobile ad hoc networks. In: The Proceedings of the 9th ACM international symposium on Modeling analysis and simulation of wireless and mobile systems, MSWiM ’06, New York, NY, USA, 2006. ACM. Pp. 239–246.

Fitzek, F. and Katz, M. (eds.) (2007) Cognitive Wireless Networks Concepts, Methodologies and Visions: Inspiring the Age of Enlightenment of Wireless Communications. Springer, 2007.

Haykin, S. (2005) Cognitive radio: Brain-empowered wireless communications. IEEE Journal on Selected Areas in Communications, Vol. 25, Feb. 2005, pp. 201–220.

ITU-R Report M. 2072. (2006) World Mobile Telecommunication Market Forecast.

ITU-R Report SM.2152. (2009) Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS).

ITU-R Question 233. (2007a) Measurement of spectrum occupancy.

ITU-R Question 241. (2007b) Cognitive radio systems in the mobile service.

Maldonado, D., Le, B., Hugine, A., Rondeau, T.W. and Bostian, C.W. (2005) Cognitive radio applications to dynamic spectrum allocation: a discussion and an illustrative example. DySPAN 2005. Pp. 597–600.

McKnight, L.W., Sharif, R.M. and van de Wijngaert, L. (2005) Wireless grids: Assessing a new technology for a user perspective. In: Designing Ubiquitous Information Environments: Socio-Technical Issues and Challenges. Springer, 2005. Pp. 169–182.

Nie, N. and Comaniciu, C. (2005) Adaptive channel allocation spectrum etiquette for cognitive radio networks. In: Proceedings of DySPAN 2005, November 2005. Pp. 269–278.

Reed D. (2009) Connecting the Two Ends: Mobile Clouds. Blog in Communications of the ACM, March 2009. http://cacm.acm.org/blogs/blog-cacm/22651-connecting-the-two-ends-mobile-clouds/fulltext.

Rice University WARP – Wireless Open Access Research Platform. (2011) http://warp.rice.edu.

RSPG (2010) RSPG Report on “Cognitive technologies.” RSPG10-306.

SSC (Shared Spectrum Company) (2011). Spectrum Reports. http://www.sharedspectrum.com/papers/spectrum-reports/.

Spaulding A.D. and Hagn, G.H. (1977) On the Definition and Estimation of Spectrum Occupancy. IEEE Transactions on Electromagnetic Compatibility, Vol. 19, Aug. 1977, pp. 269–280.

Takagi, H. and Walke, B.H. (eds.) (2008) Spectrum Requirement Planning in Wireless Communications: Model and Methodology for IMT-Advanced. John Wiley & Sons.

Tonnesen, A. (2004) Implementing and Extending the Optimized Link State Routing Protocol. Master's thesis Department of Informatics, University of Oslo, 2004.

Vanninen, T., Raustia, M., Saarnisaari, H. and Iinatti, J. (2008) Frequency hopping mobile ad hoc and sensor network synchronization. In: Military Communications Conference, 2008. MILCOM 2008. IEEE, Nov. 2008. Pp. 1–7.

Vartiainen, J., Sarvanko, H., Lehtomäki, J., Juntti, M. and Latva-aho, M. (2007) Spectrum Sensing with LAD based Methods. IEEE PIMRC 2007, Athens, Greece.

Wellens, M., Wu, J. and Mähönen, P. (2007) Evaluation of Spectrum Occupancy in Indoor and Outdoor Scenario in the Context of Cognitive Radio. In: Proc. 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2007), Orlando, FL, USA, 2007. Pp. 420–427.

Xilinx Open Source Wiki. (2011) http://xilinx.wikidot.com/.

Appendix A:
COGNAC results from 2008 to 2011

Published papers

General

[1] Matinmikko, M., Mustonen, M., Sarvanko, H., Höyhtyä, M., Hekkala, A., Mämmelä, A., Katz, M. and Kiviranta, M. A Motivating Overview of Cognitive Radio: Foundations, Regulatory Issues and Key Concepts. First IEEE International Workshop on Cognitive Radio and Advanced Spectrum Management (IEEE CogART), 14.02.2008, Aalborg, Denmark.

This paper provides an overview of a CR study with a discussion on enabling techniques for CR, measurements on current spectrum use, forthcoming standardization activities, and some findings from our recent research studies on spectrum sensing, frequency management, and power control. The measurements on current spectrum use have identified that, in general, the overall spectrum occupancy is low. The overall spectrum occupancy does not characterize the actual situation adequately, however, and better measures are needed. The International Telecommunication Union Radiocommunication sector (ITU-R) has started standards activities on CRs, in particular on the measurement of spectrum occupancy and CR systems in the mobile service, indicating that the inclusion of the CR concept into the future regulatory framework is topical.

[2] Matinmikko, M., Höyhtyä, M., Mustonen, M., Sarvanko, H., Chen, T. Katz, M., Mämmelä, A. and Kiviranta, M. Lisää älyä radioverkkoihin. Prosessori Magazine, November 2008. (In Finnish.)

Vaikka tulevaisuuden langattomat tiedonsiirtotekniikat pystyvät lähettämään enemmän bittejä sekunnissa käytettävää taajuuskaistaa kohti, tämä yksin ei riitä. Tarvitaan kokonaan uusia menetelmiä, jotta taajuuskaistojen ja muiden resurssien käyttöä voitaisiin hallita entistä tehokkaammin. Yksi varteenotettavista menetelmistä on älykäs kognitiivinen eli tiedostava radio.

Channel selection

[3] Chen, T., Zhang, H., Katz, M.D. and Zhou, Z. Swarm Intelligence Based Dynamic Control Channel Assignment in CogMesh. IEEE CoCoNet Workshop in conjunction with IEEE ICC08, Beijing, China, 19.–23.05.2008.

In this paper, we address the control channel assignment problem in a CR-based wireless network, namely the CogMesh. Such a network is featured by dynamic spectrum sharing of SUs coexisting with PUs. The opportunistic nature of spectrum utilization among SUs makes a global control channel infeasible. The self-coordination of the network hence becomes a challenging task. Considering the fact that common channels may temporarily exist among a local group of SUs, we propose an adaptive approach that selects local common control channels independently of each SU, according to the qualities of the detected spectrum holes and the choices of its neighbors. To achieve this, a swarm intelligence-based algorithm is used to facilitate the common control channel selection. The idea is to use HELLO messages periodically broadcasted by neighbors as the pheromone to rank the common channels to expedite the channel selection process. The algorithm is completely distributed and therefore scalable. Moreover, it is simple, flexible, adaptive, and well balanced in the exploitation and exploration of the radio resources. The behaviors and performance of the proposed algorithm are verified by simulation.

[4] Höyhtyä, M., Pollin, S. and Mämmelä, A. Performance improvement with predictive channel selection for cognitive radios. IEEE CogART 2008.

The prediction of future availability times of different channels based on history information helps a CR to select the best channels for control and data transmission. Different prediction rules apply to periodic and stochastic ON-OFF patterns. A CR can learn the patterns in different channels over time. We propose a simple classification and learning method to detect the pattern type and to gather the necessary information for intelligent channel selection. Matlab simulations show that the proposed method outperforms opportunistic random channel selection both with stochastic and periodic channel patterns. The number of channel switches needed over time decreases by up to 55%, which also reduces the delay and increases the throughput.

[5] J. Vartiainen, M. Höyhtyä, J. Lehtomäki, and T. Bräysy, Priority Channel Selection Based on Detection History Database. Proc. of CrownCom 2010.

This paper proposes a new database-based, two-stage channel selection method for CRs. The proposed method consists of two stages, namely the database collection and the signal detection parts. The database collects information about channels. When a CR needs to find an unoccupied channel for a transmission, it sends a query to the database. Based on the information collected in the database, the channels that are most likely to be unoccupied at the requesting time are the best candidates when searching for unoccupied channels, and these channels are submitted to the CR. The CR first performs the power level detection. Based on the power level information delivered from the database, full signal detection is performed next to the channel with a low enough power level to ensure that the channel really is unoccupied. As power level detection can be performed much faster than full signal detection, the latter is only performed on the channel that is most likely to be unoccupied based on the power level measurements. This saves both time and computational resources, yet maintains reliable sensing results. It was shown that the method offers benefits over the random channel search, especially when there are many occupied channels. It should be noted that the performance of the proposed method is highly dependent on the validity of the information given by the database.

[6] Höyhtyä, M., Pollin, S. and Mämmelä, A. Classification-based predictive channel selection for cognitive radios. IEEE ICC 2010.

The proposed method classifies traffic patterns of different channels and applies different prediction rules to different types of traffic to find the best channels for secondary use. The method is tested with several different traffic models. The method is shown to improve throughput compared with system operation based on instantaneous information. The classification-based prediction decreases collisions by 60% compared with predictive system operation without classification.

[7] Höyhtyä, M., Vartiainen, J., Sarvanko, H. and Mämmelä, A. Combination of short term and long term database for cognitive radio resource management. 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL) 2010. Invited paper.

We propose a method that uses long-term information on the use of primary channels to select the most auspicious ones to be sensed and exploited by CRs at the requesting time. These channels are investigated in more detail over the short term. Sensing results are stored in the short-term database and used to *predict which channels are best for data transmission. The method makes the operation of CRs more reliable and efficient in terms of delay and throughput, and decreases collisions with PUs.*

Cognitive systems

[8] Zhang, H., Zhou, X. and Chen, T. Cognitive Ultra-wideband Radio for Dynamic Spectrum Accessing Networks. In: Yang Xiao et al ed., Cognitive Radio Networks, CRC Press. ISBN-10: 1420064207, 2008.

This chapter of the book describes the concept and approach of ultra-wideband cognitive radio (CR-UWB), a wireless technique based on UWB transmission that is able to self-adapt to the characteristics of the surrounding wireless communications environment. A novel strategy to exploit the advantages and features of integrating CR with the UWB technology is investigated with the aim of exploring UWB radio as an enabling technology for implementing CR. In particular, it proposes dynamic spectrum accessing and sharing based upon spectrum agility and adaptation flexibility. First, a common architecture supported by CR-UWB, corresponding to heterogeneous networking scenarios, is illustrated. Then, a number of concrete technical methods for the generation of the transmitter-centric, spectrum-agile waveforms are discussed, which take advantage of the adaptive combination of a set of orthogonal UWB pulse waveforms complying with the FCC spectral mask on the transmitter side. Various transmit power control and optimization schemes for improving the system capacity and the bit-error-rate (BER) performance are also derived. Finally, the receiver-centric, spectrum-agile waveform adaptation is analyzed. It is characterized by generating the spectrum-agile UWB waveforms that comply with the receiving interference limit rather than the FCC spectral mask.

[9] Chen, T., Zhang, H., Matinmikko, M. and Katz, M.D. CogMesh: Cognitive Wireless Mesh Networks. WMSN Workshop in conjunction with IEEE GLOBECOM08, New Orleans, USA, 30.11.–4.12.2008.

We introduce the concept of the cognitive wireless mesh network, called CogMesh, in order to meet the future needs of ubiquitous wireless communications. CogMesh is not a concept that simply applies cognitive functionalities to traditional wireless mesh networks. Instead, it aims to enable a uniform service platform by seamlessly integrating heterogeneous wireless networks through the use of advanced cognitive and adaptive technologies under a mesh structure. The *context-based reasoning, policy and role-based control model, and distributed trust and security mechanism are applied to CogMesh to establish a flexible, reliable, scalable, and adaptive wireless network in complex wireless environments. It serves as a model to inspire the design of future wireless networks.*

[10] Chen, T., Zhang, H., Höyhtyä, M., Katz, M. Spectrum Self-coexistence in Cognitive Wireless Access Networks. IEEE GLOBECOM 2009, Honolulu, USA, 30.11.–3.12 2009.

In this paper, we study the spectrum self-coexistence of DSA-based wireless access networks. The objective is to improve spectrum use among densely distributed cells. To achieve this, topology-aware distributed algorithms are proposed for mobile terminal (MT) association and access point (AP) channel selection. The proposed algorithms enable self-coordination of spectrum in the studied networks.

[11] Matinmikko, M., Rauma, T., Mustonen, M., Harjula, I., Sarvanko, H., and Mämmelä, A. Application of fuzzy logic to cognitive radio systems. IEICE Transactions on Communications, Vol. E92-B, December 2009. Pp. 3572–3580.

The paper gives an overview of the way fuzzy logic has been applied to CRSs. The paper proposes a new fuzzy combining scheme for cooperative spectrum to combine the sensing results from several nodes using hard or soft decisions. The new combining scheme provides additional flexibility compared with the existing methods.

Spectrum-sensing methods

[12] Sarvanko, H., Mustonen, M., Hekkala, A., Mämmelä, A., Matinmikko, M. and Katz, M. Performance evaluation of spectrum sensing using Welch's periodogram in cognitive radios. First IEEE International Workshop on Cognitive Radio and Advanced Spectrum Management (IEEE CogART), 14.02.2008, Aalborg, Denmark.

In this paper, we focus on spectrum sensing using Welch's periodogram. In particular, we generalize and apply the theoretical analysis of energy detection to Welch's periodogram. Furthermore, we extend our study to cooperative spectrum sensing. The results indicate that the cooperation between two radios provides the highest cooperation gain.

[13] Matinmikko, M., Sarvanko, H., Mustonen, M. and Mämmelä, A. Performance of Spectrum Sensing Using Welch's Periodogram in Rayleigh Fading Channel. In: Proc. 4th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2009), Hannover, Germany, 22.–24.6.2009.

The paper proposes a new, more realistic performance metric for spectrum sensing, namely the time between failures in detection. The time between failures in detection describes how often the CR misses the detection of the presence of a PU and leads to performance degradation for the PU. The paper also presents a theoretical performance evaluation for Welch's periodogram in Rayleigh fading.

[14] Mustonen, M., Matinmikko, M. and Mämmelä, A. Cooperative Spectrum Sensing Using Quantized Soft Decision Combining. In: Proc. 4th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2009), Hannover, Germany, 22.–24.6.2009.

A method combining cooperative spectrum sensing with quantized soft decision combining is introduced. The sensing information between cooperative radios is shared using two-bit quantized soft decision combining. Simulations are conducted for the proposed method, hard decision combining and non-quantized soft decision combining in an additive white Gaussian noise (AWGN) channel using Welch's periodogram. Hard decision combining is considered with three different decision-making rules, and the obtained simulation results are verified with analytical performance results for Welch's periodogram. The results show substantial improvement in detection probability when sensing information between cooperating nodes is shared using two bits instead of one.

[15] Lehtomäki, J., Vartiainen, J. and Juntti, M. Combined wideband and narrowband signal detection for spectrum sensing. In: Proc. of Wireless Vitae, 2009.

The localization algorithm based on double-thresholding (LAD) is a recent method for detecting and localizing signals without a priori knowledge of the noise power. The LAD method performs best when detecting narrowband (NB) signals. For complete spectrum sensing, it is not enough just to detect the NB signals, as the PU's signal could just as well be a wideband (WB) signal. We propose combining the LAD method with the maximum-minimum eigenvalue (MME) method. The results indicate that the combined method is able to detect *both the NB and WB signals without knowledge of the noise power. The proposed method enables better use of spectrum white spaces in cognitive spectrum use.*

[16] Lehtomäki, J., Salmenkaita, S., Vartiainen, J., Mäkelä, J.-P., Vuohtoniemi, R. and Juntti, M. Measurement studies of a Spectrum Sensing Algorithm based on Double Thresholding. In: Proc. of Wireless Vitae, 2009.

The Welch spectrum estimator may be used for spectrum monitoring and sensing. Conventionally, the detection threshold is set assuming that the noise power is estimated from noise-only samples. The FCME algorithm is a method for making decisions automatically based on the decision variables, without estimation of the noise power a priori. In this paper, we propose the use of the FCME algorithm with the Welch spectrum estimator. The performance is improved significantly compared with the previously used periodogram. In addition, the theoretical analysis of the asymptotic threshold setting for the FCME algorithm with the Welch spectrum estimator is presented. The localization algorithm based on double-thresholding (LAD) with adjacent cluster combining (ACC) uses the FCME algorithm and is suitable for signal detection. Laboratory and field measurement results with the LAC ACC method are included to study the detectability of different signal types, including a real wireless microphone signal.

[17] Suliman, I. and Lehtomäki, J. Optimizing detection parameters for time-slotted cognitive radios. In: Proc. of the IEEE VTC 2009 Spring, Barcelona, Spain, April 2009.

Recently, CR access in time-slotted systems has attracted interest. In these systems, the beginning of the slot is used for detection. If no signal is found to be present, the remainder of the slot can be used for CRs (i.e., SUs). The detection of the occupancy status of the slots is characterized by false alarm probability and detection probability. The detection probability needs to be large enough to protect the PU. If the detection probability is too great, the probability of false alarms increases, reducing the SUs' transmit opportunities. This paper looks at finding the optimum false alarm and detection probabilities. The developed analysis method and results are important for studying the feasibility of opportunistic access in slotted systems.

[18] Suliman, I., Lehtomäki, J., Bräysy, T. and Umebayashi, K. Analysis of cognitive radio networks with imperfect sensing. In: Proc of the PIMRC'09, 2009.

Spectrum-sensing methods are often used for finding free channels to be used by CRs (SUs). Here, a state-diagram-based approach is used to analyze the effects of imperfect spectrum sensing with false alarms and misdetections. The state diagram consists of two tuples such as (1,2), which means that one PU and two SUs are present. We note that the state-dependent transition rates are very important for accurate modeling. This is because, for example, in the state (3,0) (all channels occupied by PUs), collisions happen with increased probability. In this paper, explicit expressions for state-dependent transition rates are presented for the case with three channels. The approach can be generalized and used for a higher number of channels. Primary termination probability is used for evaluating the level of interference to PUs caused by SUs. Secondary success probability is used to find out how often a secondary call starts and terminates successfully. The simulation and analysis results correspond very well.

[19] Vartiainen, J., Lehtomäki, J., Saarnisaari, H. and Juntti, M. Limits of detection for the consecutive mean excision algorithm. In: Proc. of ICASSP2010.

Iterative backward and forward consecutive mean excision (CME/FCME) algorithms are efficient at suppressing and detecting narrowband signals. Being relatively simple computationally, they can be applied to, for example, spectrum sensing in CRs. In this paper, detection performance of the CME algorithms is analyzed using a rectangular signal model approximation. The analysis results provide simple rules to predict whether a signal is detectable. The presented limits of detection can be used, e.g., in CRSs, in which well-defined and predictable performance limits for spectrum sensing are required.

[20] Umebayashi, K., Tsuchiya, H., Kamiya, Y., Suzuki, Y. and Lehtomäki, J. Analysis of weighted cooperative sensing with using signal power estimation. In: Proc. of ICC2010.

Spectrum sensing is one of the key techniques to realize spectrum sharing between the PU, which has priority to use the spectrum, and the SU, which is allowed to use the spectrum without harmful interference being caused to the PU. In this paper, a weighted cooperative sensing (WCS) method is analyzed. In WCS, a global detection at a FC is performed using weighted local soft decisions given by SUs and the usage of the appropriate weight can improve the sensing performance, especially when the SNR of each SU is different. The *weight depends on the noise power and the PU's signal power, and, moreover, multiple antenna elements are used to suppress the effect of Rayleigh fading.*

[21] Khan, Z., Lehtomäki, J., Umebayashi, K. and Vartiainen, J. On the Selection of the Best Detection Performance Sensors for Cognitive Radio Networks. IEEE Signal Processing Letters, Vol. 17, No. 4.04.2010, pp. 359–362.

In cooperative spectrum sensing, information from several CRs is used to detect the PU. To reduce the sensing overhead and total energy consumption, it is recommended to cooperate only with the CRs that have the best detection performance. The problem is that it is not known a priori which of the CRs have the best detection performance however. To this end, methods for selecting the CRs with the best detection performance, based only on hard (binary) local decisions from the CRs, are proposed. Simple counting: select the CRs that report the highest number of PU detections. Partial agreement counting: select the CRs that agree with the FC decision. It is assumed that the FC has a high PU detection probability. Collision detection: select the CRs that are able to detect PUs when the FC failed the detection, i.e., a collision occurred. Simulations are used to evaluate and compare the methods. The results indicate that the proposed CR selection methods are able to offer significant gains in terms of system performance.

[22] Matinmikko, M., Rauma, T., Mustonen, M. and Del Ser, J. Architecture and Approach for Obtaining Spectrum Availability Information. In: Proc. of IEEE VTC Spring 2011, May, Budapest, Hungary, 2011.

This paper presents a novel architecture and approach to obtaining spectrum availability information in future CRSs. There are different techniques for obtaining spectrum availability information, including cognitive pilot channels, databases, spectrum-sensing techniques, and combinations thereof. For spectrum sensing, there are different algorithms and cooperative combining techniques with different characteristics and capabilities in terms of, e.g., performance, complexity, and the requirement for a priori information. This paper presents a unified architecture for selecting methods for obtaining spectrum availability information, taking into account the operational environment and underlying policies. In addition, a novel low-complexity heuristic decision-making method is presented for selecting the spectrum-sensing technique, taking into account different capabilities and requirements while being adaptable to the changing environment.

Cognitive MAC

[23] Ghaboosi, K., Latva-aho, M. and Yang Xiao. A Distributed Multi-channel Cognitive MAC Protocol for IEEE 802.11s Wireless Mesh Networks. In: Proc. of IEEE CrownCom, 15–17 May Singapore, 2008.

A novel distributed frequency agile medium access control (MAC) extension to the IEEE 802.11s amendment for the next generation wireless mesh networks (WMNs) is proposed. The proposed scheme has complete backward compatibility with the legacy IEEE 802.11 and the emerging 802.11s, while it is perfectly capable of multi-channel deployment of available frequency opportunities in order to coordinate concurrent multiple data transmissions. The root concept is to apply the IEEE 802.11s common channel framework (CCF) to attain two important goals: on the one hand, the proposed scheme improves channel use and capacity using the concept of CR and, on the other hand, using the same concept leads to lower access delay due to the smarter decision-making procedures exploited for link layer connection establishment.

[24] Ghaboosi, K., Latva-aho, M. and Yang Xiao. A New Approach on Analysis of IEEE 802.11 DCF in non-saturated Wireless Networks. In: Proc of IEEE VTC'08 Spring, 2008.

Many performance evaluations for the IEEE 802.11 distributed coordination function (DCF) have previously been reported in the literature. Most studies are based on a saturation analysis, and a few models under a finite load condition adopt an M/G/1 queuing system. The use of M/G/1 queuing, however, only considers the first moment of frame service time to derive the probability of the transmission queue being vacant. In this paper, we model the DCF using the Parallel Space-Time Markov Chain (PSTMC), in which frame arrivals are tracked by monitoring the transmission queue during transitions between successive states of the space-time Markov chain. The proposed framework provides the possibility of modeling the contention phase, backoff and post-backoff procedures, and the transmission queue status. The proposed framework is validated by the simulation results.

[25] Ghaboosi, K., Latva-aho, M., Kohno, R. and Pomalaza-Raez. C. eMAC: A Multi-channel Cognitive MAC Protocol for the Next Generation Wireless Networks. In: Proc. of Symposium on Wireless Personal Multimedia Communications, Sendai, Japan, 2009.

In this paper, a medium access control (MAC) protocol, called eMAC, is proposed. Under the proposed scheme, stations maintain double-hop neighborhood (DHN) graphs while exchanging designated eMAC tables to share their knowledge about their neighborhood topology. Using a DHN graph and an adaptive unreachability reporting mechanism, stations are reliably informed about their neighbors' unreachability status. Hence, they avoid establishing link-layer connections with their unreachable neighbors, and, consequently, network resources are not consumed for unsuccessful connection establishment efforts. An adaptive table broadcasting technique to facilitate topology information dissemination in mobile ad hoc networks (MANETs) is also proposed. The performance of the proposed schemes is evaluated and compared with that of earlier schemes through simulations.

[26] Ghaboosi, K., Abdallah, S.A., MacKenzie, A.B., DaSilva, L.A. and Latva-aho, M. A Channel Selection Mechanism based on Incumbent Appearance Expectation for Cognitive Networks. In: Proc. of WCNC'09, 2009.

In this paper, stochastic channel selection in distributed cognitive networks is studied. In particular, a MAC layer load balancing technique for traffic distribution among a set of data channels without centralized control is introduced. The proposed scheme is enabled by a multi-channel binary, exponential backoff mechanism to further facilitate a contention resolution in a multi-channel environment. It is shown through simulations that the proposed MAC layer enhancement outperforms well-known multi-channel MAC protocols both in terms of aggregate, end-to-end throughput and average frame end-to-end delay.

[27] Tuomivaara, H. Distributed TDMA MAC Protocol Design and Implementation for Ad Hoc Networks. In: Proc. of MCC2010.

The design, implementation and evolution of a distributed time division multiple access (TDMA) MAC protocol for wireless ad hoc networks is presented. The target platform for the protocol is the wireless open access platform (WARP), a programmable SDR platform for prototyping wireless algorithms and protocols. The implemented design for the real time system itself is proof that the protocol can work in a real environment. This is backed up by performance evaluation of the implementation.

Interference management

[28] Kiviranta, M., Mämmelä, A., Paaso, H., Höyhtyä, M. and Moilanen, I. Digital signal design and nonlinear distortions in antenna array beamforming. IEEE Wireless Communications and Networking Conference (IEEE WCNC), 2009.

The paper studies the effects of nonlinear elements in beamforming. Nonlinear amplifiers are shown to affect both the level of the main beam as well as the direction of it. In addition, phase noise may distort the signal constellation significantly. As a solution to the problem, careful signal design is needed. Constant envelope modulation is a common method to avoid nonlinear distortions. It is shown, however, that it does not help if the nonlinear amplifier has memory.

[29] Höyhtyä, M., Chen, T. and Mämmelä, A. Interference management in frequency, time, and space domains for cognitive radios. In: Proc. WTS Conference, April 2009.

In order to minimize interference with PUs, CRs should operate multidimensionally over time, frequency, and space. This paper describes methods for power and frequency allocation to achieve the goal. An optimal prediction rule for exponential traffic is developed and applied to different stochastic traffic models. The allowed transmission power of the SU was shown to scale linearly with increasing primary transmission power. The antenna height of the primary transmitter was shown to have a big effect on the allowed power level.

[30] Del Ser, J., Matinmikko, M., Gil-Lopez, S. and Mustonen, M. A Novel Harmony Search based Spectrum Allocation Technique for Cognitive Radio Systems. In: Proc. Seventh International Symposium on Wireless Communication Systems (IEEE ISWCS 2010).

This paper presents the application of the heuristic Harmony Search (HS) algorithm to spectrum channel allocation in CR networks. The proposed algorithm provides a higher degree of diversity in the search process by virtue of its particular improvisation procedure, as opposed to evolutionary computation techniques used so far for this optimization problem. With the focus on minimizing the average Bit Error Rate (BER) over the existing links in the CR network, this manuscript poses and describes the centralized and distributed implementations of the proposed HS allocation procedure in detail. On the one hand, the simulation results verify that our approach achieves near-optimum spectral channel *assignments at very low computational complexity. On the other hand, HS is shown to outperform genetically inspired allocation algorithms in simulated scenarios.*

[31] Matinmikko, M., Mustonen, M., Höyhtyä, M., Rauma, T., Sarvanko, H. and Mämmelä, A. Distributed and Directional Spectrum Occupancy Measurements in the 2.4 GHz ISM Band. In: Proc. IEEE ISWCS 2010.

This paper presents distributed and directional spectrum occupancy measurements in the 2.4 GHz ISM (Industrial, Scientific, and Medical) band. Spectrum occupancy measurements can be used to assess how efficiently the spectrum bands are used today. Future CRSs can improve spectrum occupancy by filling the gaps in the prevailing spectrum by opportunistically using unoccupied channels. Most of the spectrum occupancy measurements in the literature have been conducted using a single measurement device with an omnidirectional antenna presenting an average of the overall situation. To characterize the influence of the spatial dimension on the spectrum occupancy in a given area, we introduce the directional spectrum occupancy metric. Directional spectrum occupancy is defined as the fraction of time that the received power in a channel exceeds a threshold in a given measurement direction. We have used two separately located measurement devices with directional antennas to measure the directional spectrum occupancy in an office area with a heavy traffic load. The results indicate that the spectrum occupancy is heavily dependent on the measurement location and direction. The influence of the spatial dimension is therefore crucial to the development of future CRSs.

[32] Xianfu Chen, Zhifeng Zhao, Honggang Zhang and Tao Chen. Reinforcement Learning Enhanced Iterative Power Allocation in Stochastic Cognitive Wireless Mesh Networks. Springer Wireless Personal Communications Journal, special issue on "Cognitive Radio Networks and Communications," April–June 2010.

As the scarce spectrum resource is becoming over-crowded, cognitive wireless mesh networks have great flexibility to improve spectrum use by opportunistically accessing the licensed frequency bands. One of the critical challenges of realizing such a network is the allocation of transmit powers and frequency resources adaptively among SUs of the licensed frequency bands while maintaining the quality-of-service (QoS) requirement of the PUs. In this paper, we consider the power control problem in the context of cognitive wireless mesh net-

works formed by a number of clusters under the total transmit power constraint of each SU as well as the mean-squared error (MSE) constraint by PUs. The problem is modeled as a non-cooperative game. A distributed iterative power allocation algorithm is designed to reach the Nash equilibrium (NE) between the coexisting interfered links. It offers an opportunity for SUs to negotiate the best use of power and frequency with each other. Furthermore, it discusses how to negotiate the transmission power level and spectrum usage among the SUs adaptively according to the changing networking environment. We present an intelligent policy based on reinforcement learning to acquire the stochastic behavior of PUs. Based on the learning approach, the SUs can adapt to the dynamics of the interference environment state and reach new NEs quickly through partially cooperative information sharing via a common control channel. Theoretical analysis and numerical results both show the effectiveness of the intelligent policy.

[33] Xianfu Chen, Zhifeng Zhao, Honggang Zhang and Tao Chen. Distributed Iterative Power Allocation in Cognitive Wireless Mesh Networks. In: International Conference on Wireless Communications & Signal Processing 2009 (WCSP'09), Nanjing, China.

This paper is a conference paper that includes part of the work that is presented in the journal paper [32].

[34] Umebayashi, K., Kamiya, Y., Suzuki, Y. and Lehtomäki, J. Transmit power selection by cooperative sensing in cognitive radio networks. In: Proc. of IEEE WCNC'09, 2009.

In conventional spectrum sharing, the SU senses the spectrum and makes a binary decision: the spectrum is either available or not depending on the distance between the PU and the SU. To ensure interference-free transmission for PUs, every PU is surrounded by guard bands in which transmission is forbidden. In this paper, a novel cooperative sensing method based on cooperative multi-hypothesis testing is proposed. Instead of just making a binary decision, we employ a new approach in which the allowable maximum transmit power is found, with the constraint on the miss detection probability, which guarantees PU performance. The proposed approach also allows secondary transmission in the guard band of the conventional approach, provided that the transmit power is sufficiently small. This enables more effective spectrum usage. In addition, if the

SU is located far enough from the PUs, the proposed approach can provide higher transmit power for the SU.

[35] Matinmikko, M., Mustonen, M., Höyhtyä, M., Rauma, T., Sarvanko, H. and Mämmelä, A. Cooperative Spectrum Occupancy Measurements in the 2.4 GHz ISM Band. 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL) 2010.

This paper presents cooperative spectrum occupancy measurements in the 2.4 GHz ISM band. Spectrum occupancy describes the efficiency of spectrum use in terms of the proportion of time that the bands are occupied. In this paper, spectrum occupancy is measured from two measurement devices with several directional antennas. The spectrum occupancy information obtained from the different antennas and measurement devices is combined using techniques known from the cooperative spectrum-sensing research for future CRSs. We introduce a new metric, the cooperative spectrum occupancy, to characterize the resulting spectrum occupancy that is obtained by combining the occupancy measurements from the antennas with different combining techniques, such as AND, OR, and majority combining rules. As the transmission power levels on the ISM band are too low to allow efficient frequency reuse, the resulting spectrum occupancies are heavily dependent on the measurement location. Instead of averaging out the influence of the spatial dimension, the new metric can give more insights into the actual spectrum occupancy in a given area, taking into account the spatial dimension.

Cooperation

[36] Khan, Z., Latva-aho, M. and Grace, D. Modeling cooperation and coordination in opportunistic spectrum access as a turn-taking dilemma. In: Proc. of WOCN09, 2009.

This paper presents several fundamental concepts of game theory and shows how they relate to the game formulation of a small cluster of opportunistic wireless nodes in CR networks. It has been shown that in some resource allocation scenarios, it may be an optimal strategy for wireless nodes to endure short-term losses for longer-term gains. In such scenarios, the maximum total payoff may not be achieved by simultaneous mutual cooperation but by taking turns defecting. The paper presents a novel idea of modeling cooperation and coordination for *opportunistic spectrum access as a turn-taking Prisoner's dilemma. The simulation results show that for the proposed resource allocation, the game turn-taking strategies outperform traditional tit-for-tat, and grim-trigger strategies.*

[37] Khan, Z., Lehtomäki, J., Latva-aho, M. and DaSilva, L. On Selfish and Altruistic Coalition Formation in Cognitive Radio Networks. In: Proc. of CrownCom2010.

A sensing-throughput tradeoff problem for distributed CR networks is formulated as a coalition formation game. The formation of coalitions enables the CRs to increase their achievable throughput, under the detection probability constraint, while taking into account the overhead caused by combining sensing reports. In the proposed game, CRs form coalitions either to increase their individual gains (selfish coalition formation) or to maximize the overall gains of the group (altruistic coalition formation). The altruistic coalition formation solution yields significant gains in terms of reduced average false alarm probability and increased average throughput per CR compared with the selfish and non-cooperative solutions. Given a target detection probability for a coalition, an SNR-dependent target detection probability is proposed for individual CRs in a coalition, and its impact on the average throughput per CR is analyzed. The impact of the cost of distributed cooperative sensing on the cooperative strategies of CRs is also analyzed.

[38] Khan, Z., Glisic, S., Da Silva, L. and Lehtomäki, J. Modeling of the Dynamic Coalition Formation Games for Cooperative Spectrum Sharing in an Interference Channel. Accepted for publication in IEEE Transactions on Computational Intelligence in AI and Games, 2010.

The dynamic coalition formation game for the spectrum sharing problem in an interference channel is analyzed. The strategic decision for any link consists of an allocation of power across the available bandwidth to maximize the individual data rate. Coalitions are formed if some rational demands of wireless links are satisfied, with coalition participants agreeing to share (allocate power over) bandwidth W according to certain ratios. A key question addressed by this paper is one of how to coordinate distributed wireless links with partial channel knowledge to form coalitions to maximize their data rates while also taking into account the overhead in the message exchange needed for coalition formation. The proposed model is dynamic in the sense that distributed transmitter-receiver pairs, with partial channel knowledge, reach stable coalition structures (CSs) *through a time-evolving sequence of steps. Using simulation, it is shown that coalition formation yields significant gains in terms of average rates per link for different network sizes. We also show average maximum coalition sizes for different distances between transmitters and their own receivers. Finally, we analyze the mean and variance in time for the game to reach stable coalition structures.*

[39] Khan, Z., Lehtomäki, J., Godreanu, M., Latva-aho, M. and DaSilva, L. Throughput-efficient Dynamic Coalition Formation in Distributed Cognitive Radio Networks. Accepted for publication in the EURASIP Journal on Wireless Communications and Networking, 2010.

The proposed coalition formation enables the CRs to increase their achievable throughput, under the detection probability constraint, while also taking into account the overhead in sensing reports combining. It has been shown that the proposed coalition formation solutions yield significant gains in terms of reduced average false alarm probability and increased average throughput per CR compared with the non-cooperative solutions. It has also been shown that when the cost in terms of overhead in the combining sensing report is taken into account, the performance of the grand coalition degrades significantly, as the number of CRs increases. The impact of the distance between the PU transmitter and the distributed CR network on cooperative strategies of the distributed CRs is evaluated.

[40] Lehtomäki, J., Vartiainen, J., Khan, Z. and Bräysy, T. Selection of Cognitive Radios for Cooperative Sensing. In: Proc. of CogArt'10**.**

Cooperative spectrum sensing for CR networks has been widely studied to increase the reliability of PU detection. A large number of cooperating CRs typically leads to an increase in the overhead of the sensing reporting and in energy consumption. One recent line of research has examined sensor selection techniques in which a subset of the CRs is selected to perform cooperative spectrum sensing in order to reduce the overhead and save network energy. The selection of such a subset is challenging, as, for example, the sensing performances of the CRs are not known a priori. We present a literature review of CR selection techniques for hard decision cooperative sensing and perform a novel analysis for a simple counting (SC) CR selection method.

[41] Khan, Z., Lehtomäki, J., DaSilva, L.A. and Latva-aho, M. Analysis of Autonomous Opportunistic Spectrum Access Strategies for Cognitive Radios: Benefits of Adaptive Strategies. Submitted to DySPAN 2011.

We investigate autonomous opportunistic spectrum access (OSA) strategies for a distributed CR network in which two or more distributed CRs sense the channels sequentially in some sensing order until they find a free channel to transmit on, if one exists. First, we evaluate the performance of a traditional OSA strategy in terms of the probability of success (the probability that a given CR finds a channel free), the mean time of success (if successful, the mean time to find a channel), and the throughput achievable by a CR. We find that the performance of the traditional OSA strategy is limited by the collisions between the distributed uncoordinated CRs. To reduce the likelihood of collisions between the distributed CRs, we propose adaptive OSA strategies. We show that when the number of CRs is less than or equal to the number of potential channels, the proposed adaptive OSA strategies enable the CRs to arrive on collision-free channel sensing orders. We also show that a g-persistent strategy, in which a CR maintains information regarding past successes (and failures) of accessing the channel, converges quickly to collision-free sensing orders. We compare such a strategy against a randomized one after every collision strategy in which a new channel sensing order is randomly selected whenever a CR experiences a collision. Moreover, the implementation of a g-persistent strategy is not complex, as it only requires two binary flags to maintain state information at an individual CR.

Distributed resources

[42] Sarvanko, H., Höyhtyä, M., Katz, M. and Fitzek, F. Distributed resources in wireless networks: Discovery and cooperative uses. In: Proc. of ERCIM eMobility Workshop.

This paper gives an overview of distributed resources in wireless networks, focusing on cooperative resource use and resource discovery. We defined a framework for distributed resources and resource sharing in wireless networks by generalizing and combining an environmentally aware CR area and resource discovery area. A novel classification of different resource discovery methods is provided, motivating the use of cooperation in wireless networks as well as foreseeing future developments in this area. The paper also gives a broad view of cognition in wireless networks, considering awareness and intelligent use of all the available resources in a wireless environment.

Regulatory and standards contributions

- Nokia Corporation, Nokia Siemens Networks, and VTT: ITU-R WP5A/279 Proposal for a revised structure and revisions of a working document towards a preliminary draft new report on “Cognitive Radio Systems in the Land Mobile Service,” 3rd ITU-R WP5A meeting, Geneva, Switzerland, 18.–27.5.2009.
  - *The contribution proposes a revised structure for the report.*
- Nokia Corporation, Nokia Siemens Networks, and VTT: ITU-R WP5A/281 Text proposals for a working document towards a preliminary draft new report on “Cognitive Radio Systems in the Land Mobile Service,” 3rd ITU-R WP5A meeting, Geneva, Switzerland, 18.–27.5.2009.
  - *Complete restructuring of the report based on the revised structure. Text proposals, e.g., to add a white space definition and cognitive cycle.*
- Nokia Corporation, Nokia Siemens Networks GmbH & Co. KG, and VTT (responsible): ITU-R WP5A/368 Text proposal and revisions for Section 6.4 of a working document towards a preliminary draft new report on “Cognitive Radio Systems in the Land Mobile Service,” 4th ITU-R WP5A meeting, Geneva, Switzerland, 23.11.–2.12.2009.
  - *Text added on spectrum sensing and its challenges, databases, techniques for decision-making, adjustment, and learning.*
- Nokia Corporation, Nokia Siemens Networks GmbH & Co. KG, and VTT (responsible): ITU-R WP5A/369 Editorial update proposals for Section 5 of a working document towards a preliminary draft new report on “Cognitive Radio Systems in the Land Mobile Service,” 4th ITU-R WP5A meeting, Geneva, Switzerland, 23.11.–2.12.2009.
  - *Editorial updates to delete duplicated or misplaced information and make the text clearer and more concise.*
- Nokia Corporation, Nokia Siemens Networks GmbH & Co. KG, and VTT: ITU-R WP5A/370 Text proposal and revisions for Section 5.2 and Section 6.1 of a working document towards a preliminary draft new report on “Cognitive Radio Systems in the Land Mobile Service,” 4th ITU-R WP5A meeting, Geneva, Switzerland, 23.11.–2.12.2009.

- *Text added on the capabilities of CRS, coexistence, and sharing.*

- Nokia Siemens Networks, Nokia Corporation, and VTT: Text proposal and revisions for sections 6.1, 6.2, 6.3, and chapter 8 of a working document towards a preliminary draft new report on "Cognitive Radio Systems in the Land Mobile Service," 5th ITU-R WP5A meeting, Geneva, Switzerland, 10.–19.5.2010.
  - *Contribution on deployment scenarios, potential applications, operational techniques (e.g. CPC and centralized decision making) and the impact of CRS to spectrum management.*
- Nokia Corporation, Nokia Siemens Networks, and VTT: Text proposals and revisions for chapter 5 and section 6.3 of a working document towards a preliminary draft new report on "Cognitive Radio Systems in the Land Mobile Service," 5th ITU-R WP5A meeting, Geneva, Switzerland, 10.–19.5.2010.
  - *Contribution on general description of cognitive radio systems and operational techniques (e.g. cognitive control channel and distributed decision making).*
- Nokia Corporation, Nokia Siemens Networks, and VTT: Text proposal and revisions for section 6.2 and chapter 7 of a working document towards a preliminary draft new report on "Cognitive Radio Systems in the Land Mobile Service," 5th ITU-R WP5A meeting, Geneva, Switzerland, 10.–19.5.2010.
  - *Contribution on potential applications of CRS and coexistence and sharing.*
- Nokia Siemens Networks GmbH & Co. KG., Nokia Corporation & VTT, "Revisions of a working document towards a preliminary draft new report on cognitive radio systems in the land mobile service", 6th ITU-R WP5A meeting, Geneva, Switzerland, 8.–17.11.2010.
  - *Overall revision of the working document.*
- Nokia Siemens Networks GmbH & Co. KG., Nokia Corporation & VTT, "Modification proposals for section 7 of a working document towards a preliminary draft new report on cognitive radio systems in the land mobile service", 6th ITU-R WP5A meeting, Geneva, Switzerland, 8.–17.11.2010.
  - *Contribution on coexistence and sharing.*
- Nokia Siemens Networks GmbH & Co. KG., Nokia Corporation & VTT, "Modification proposals for sections 6.3 and 6.4 of a working document to-

wards a preliminary draft new report on cognitive radio systems in the land mobile service", 6th ITU-R WP5A meeting, Geneva, Switzerland, 8.–17.11.2010.

- *Contribution on potential applications (e.g. cognitive mesh networks) and operational techniques (e.g. cognitive control channels and databases).*

Other

- A half-day tutorial: Challenges of cognitive radios in the physical layer. Mämmelä, A. and Matinmikko, M. Third International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2008), Singapore, 15.–17.05.2008.
- Timo Bräysy participated in a panel discussion on "Community Wireless Networks" in the LANMAN'08 conference in Cluj, Romania, 3.–6.09.2008.
- Timo Bräysy participated in a panel discussion on "Cognitive Wireless Networks" in WPMC'08 conference in Saariselkä, Finland 8.–11.09.2008.
- Kaveh Ghaboosi was on research exchanges in the US: 16.6.–25.8.2008 at Virginia Tech and 25.8.–6.9.2008 at Rice University.
- A full-day research seminar on the themes of several TEKES GIGA projects of CWC and VTT was held on 4.12.2008. The following COGNAC-related presentations were scheduled:
    - Marcos Katz, VTT, "COGNAC project overview"
    - Timo Bräysy, CWC, "Management Framework for Cognitive Networks"
    - Kaveh Ghaboosi, CWC, "Intelligent Stochastic Channel Selection & Contention Resolution in Cognitive Ad Hoc Networks"
    - Marja Matinmikko, VTT, "Challenges of Spectrum Sensing in Cognitive Radios"
    - Marko Höyhtyä/Tao Chen, VTT, "Control Issues in Cognitive Networks"
    - Miia Mustonen, VTT, "Process and Requirements for IMT-Advanced".
- Seminar presentations 2009:
    - Marja Matinmikko, Cognitive and opportunistic communication networks (COGNAC). GIGA Results Promotion, Helsinki 20.10.2009.

    - Marja Matinmikko, Kognitiivinen radio tutkimuksen näkökulmasta. Radiotaajuuspäivä, Viestintävirasto, Helsinki, 29.10.2009.
    - Marcos Katz, From Cognitive Radio to Cognitive Networks: New Paradigms for Future Wireless Networks, NRC Workshop, Helsinki 25.11.2009.
    - Marja Matinmikko, From Cognitive Networks back to Cognitive Radio: Focus on Spectrum, NRC Workshop, Helsinki 25.11.2009.
- Participation in the 3rd (18.–27.5.2009), 4th (23.11.–2.12.2009), 5th (10.–19.5.2010) and 6th (8.–17.11.2010) ITU-R WP5A meetings in Geneva, Switzerland. Focus on the development of report "Cognitive Radio Systems in the Land Mobile Service".
- Contributions in the eMobility white paper "Cognitive radio systems," published in November 2009.
- Three invention reports regarding CRSs.
    - Rauma T. and Matinmikko, M. Method and Arrangement for Adaptive Signal Detection. August 2009.
    - Rauma, T. and Matinmikko, M. Arrangement for Model-based Learning in Cognitive Radio Systems. June 2010.
    - Höyhtyä, M., Vartiainen, J. and Sarvanko, H. Combination of short term and long term database for cognitive radio resource management.
- Two patent applications based on the invention reports
    - Rauma, T. and Matinmikko M. Method and Arrangement for Adaptive Signal Detection.
    - Höyhtyä, M., Vartiainen, J. and Sarvanko, H. Method and device for selecting one or more resources for use from among a set of resources.
- Mr. Kaveh Ghaboosi publicly defended his doctoral thesis on October 29, 2009. The thesis titled "Intelligent Medium Access Control for the Future Wireless Networks" was partially based on his research work performed in the COGNAC project.

- Timo Bräysy and Marja Matinmikko participated in the TEKES GIGA Programme thematic group AR1 (Wireless Access) roadmap work by providing input for several topics that can be considered essential to CRs and networks.
- International cooperation with professors Luiz DaSilva and Allen MacKenzie from Virginia Tech continued during 2009. A short course on “Resource management for dynamic spectrum access” was held in Oulu/CWC in spring 2009. Two Ph.D. students from Virginia Tech also stayed in Oulu/CWC for about a month as visiting researchers.
- Visiting researcher Gian Paolo Perrucci from Aalborg University visited VTT for two months in June–July 2008. His research topic was energy measurements for cooperative and cognitive wireless mobile networks.
- Two researchers, Laszlo Blazovics and Csaba Varga, from Budapest University of Technology and Economics visited VTT in November-December 2009. Their research topics were cooperation in disruptive channels and social networking.
- Visiting researcher Javier Del Ser from Robotiker (TECNALIA), Spain, visited VTT for three months in March–May 2010. Javier Del Ser’s research topic was application of harmony search to channel allocation in CR systems.
- Zaheer Khan visited Prof. Luiz DaSilva in Trinity College, Dublin, Ireland.
- Samir Perlaza, a PhD student of Prof. Debbah from Supelec, France, visited CWC in August 2010 for three weeks. He collaborated with CWC researchers on the subject of interference management in the femtocell networking environment.
- Marja Matinmikko gave an invited keynote speech “Cognitive radio systems: technical challenges and ongoing regulatory activities” at the MOBILIGHT 2010 conference in Barcelona in May 2010 (arranged by Javier Del Ser).
- Marja Matinmikko has participated in COST Action TERRA meetings 7.5.2010, 30.–31.8.2010, and 19.–21.1.2011.

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Title

Towards Cognitive Radio Systems
Main Findings from the COGNAC project

Abstract

Cognitive radio systems have recently emerged as potential enablers of more efficient use of various resources in future wireless communication systems. Cognitive radio systems can obtain knowledge of their operational environment and internal state, adapt their operations to optimize performance, and learn from the results. This report presents the main results of the COGNAC project in the field of cognitive and opportunistic wireless communication networks. It identifies fundamental techniques for cognitive and opportunistic networks, summarizes the research activities carried out in the COGNAC project, and provides insight into future research directions.

Theoretical studies have covered various aspects of cognitive radio techniques, e.g., spectrum-sensing techniques for obtaining information about current spectrum use, dynamic channel access for adapting operations, interference management using power and frequency control, cooperation among devices using game theory, and learning using stored history data. Experimental studies were conducted in the form of spectrum occupancy measurements and the implementation of a cognitive radio test bed. Contributions were made to spectrum regulatory bodies to pave the way for the introduction of cognitive radio techniques into the spectrum regulatory framework. Finally, a roadmap for cognitive radio systems was developed.

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