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COGNITIVE MANAGEMENT FRAMEWORKS AND SPECTRUM MANAGEMENT STRATEGIES EXPLOITING COGNITIVE RADIO PARADIGM

By

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To my beloved parents

for their unconditional love and support.

Ai miei cari genitori

per il loro affetto e supporto incondizionato.

Abstract

Cognitive Radio (CR) paradigm represents an innovative solution to mitigate the spectrum scarcity problem by enabling Dynamic Spectrum Access (DSA), defined in order to conciliate the existing conflicts between the ever-increasing spectrum demand growth and the currently inefficient spectrum utilization. The basic idea of DSA is to provide proper solutions that allow sharing radio spectrum among several radio communication systems with sake of optimizing the overall spectrum utilization. This dissertation addresses the problem of modelling cognitive management frameworks that provide innovative strategies for spectrum management suitable to different scenarios and use cases in the context of DSA/CR Networks (CRNs).

The first solution presented in this dissertation initially addresses the development of a framework that provides spectrum management strategies for Opportunistic Networks (ONs) defined as extended infrastructures created temporarily to serve specific regions following the policies dictated by the operator. The development of systems based on the CR paradigm to support the ONs is considered a key aspect to allow autonomous decisions and reconfiguration ability mechanisms because of the temporarily nature of these networks and the highly dynamic nature of the radio environment. Then, in order to expand the design of cognitive management frameworks providing spectrum management solutions that have applicability in a number of different scenarios and use cases, a cognitive management framework that exploits the Partially Observable Markov Decision Process (POMDP) concept is proposed to combine the CR capabilities of radio environment awareness with a statistical characterization of the system dynamic. Finally, the framework based on POMDPs is further extended with new functionalities able to characterize the environment dynamic through long-term predictions carried out exploiting the so-called belief vector. These frameworks as a whole aim at demonstrating that a reliable characterization of the radio environment that combines awareness of its surrounding with a statistical evaluation of the system dynamics is able to guarantee an efficient utilization of the available spectrum resources.

From a methodological point of view, the development and assessment of the proposed cognitive management frameworks and the corresponding spectrum management solutions involve analytical studies, system-level simulations and a real-time platform implementation.

Acknowledgments

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I am deeply thankful to my parents, my five brothers and sisters, my brothers and sisters in law and to all my nieces and nephews for always being there for me, supporting me despite the distance that separated us. Their unconditional love and support has been a constant source of strength and motivation to always continue on. I am also grateful to all my friends from my home town, my school, the University where I studied and those I met during these unforgivable years in Barcelona. All of them have encouraged me in some small way.

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Contents

List of Figures

List of Tables

Acronyms

3GPP	3rd Generation Partnership Project
ADC	Analog to Digital Converter
AP	Access Point
ARQ	Automatic Repeat reQuest
BCMF	Base-line Cognitive Management Framework
BS	Base Station
BST	Base Station Transceiver
C4MS	Control Channel for the Cooperation of the Cognitive Management System
CA	Context Awareness
CCM	Configuration Control Module
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CMON	Cognitive systems for Managing the Opportunistic Network
CR	Cognitive Radio
CRC	Cyclic Redundancy Check
CRN	Cognitive Radio Network
CSCI	Cognitive management Systems for Coordinating the Infrastructure
CSI	Channel State Information
D2D	Device-To-Device
DAC	Digital to Analog Converter

DBPSK Differential Binary Phase Shift Keying

DFS Dynamic Frequency Selection

DH Digital Home

DSA Dynamic Spectrum Access

DSM Dynamic Spectrum Management

DSONPM Dynamic, Self-Organising Network Planning and Management

DSP Digital Signal Processor

ECMF Evolved Cognitive Management Framework

ETSI European Telecommunications Standards Institute

FA Functional Architecture

FCMF Final Cognitive Management Framework

FFT Fast Fourier Transform

FI Future Internet

FPGA Field-Programmable Gate Array

GMSK Gaussian Minimum Shift Keying

GRC GNU Radio Companion

GSM Global System for Mobile Communications

ICIC Inter-Cell Interference Coordination

IEEE Institute of Electrical and Electronics Engineers

IMT International Mobile Telecommunications

ISM Industrial, Scientific and Medical

ITU International Telecommunication Union

JRRM Joint Radio Resources Management

KD Knowledge Database

KM Knowledge Manager

LBT Listen Before Talk

LTE Long-Term Evolution

MIH Media-Independent Handover

MSC Message Sequence Chart

ON Opportunistic Network

OSA Opportunistic Spectrum Access

OSDM Observation Strategy Decision Making

POMDP Partially Observable Markov Decision Process

QoE Quality of Experience

QoS Quality of Service

RAN Radio Access Network

RAT Radio Access Technology

RF Radio Frequency

RRS Reconfigurable Radio System

SCC Standards Coordinating Committee

SDR Software Defined Radio

SOI Spectrum Opportunity Index

SpHO Spectrum HandOver

SSDM Spectrum Selection Decision Making

SWIG Simplified Wrapper and Interface Generator

TBS Television Broadcast Service

TPC Transmit Power Control

UE User Equipment

UHF Ultra High Frequency

UMTS Universal Mobile Telecommunications System

USRP Universal Software Radio Peripheral

UWB Ultra Wide Band

WiMAX Worldwide Interoperability for Microwave Access

WIR Wireless Innovation Forum

WLAN Wireless Local Area Network

WRAN Wireless Regional Area Network

WS White Space

WSD White Space Device

Chapter 1

Introduction

1.1 Background

The licensed static spectrum allocation policy, in use since the early days of radio communications, has been proven to effectively control interference among the radio communication systems. However, the overwhelming proliferation of new operators, innovative services and wireless technologies during the last years has resulted, under this static regulatory regime, in the exhaustion of spectrum bands with commercially attractive radio propagation characteristics. The vast majority of spectrum regarded as usable has already been assigned, then hindering commercial rollout of new emerging services. This situation produced the common belief about depletion of usable radio frequencies that was certainly strengthened by the overly crowded frequency allocation charts of many countries. Notwithstanding, some preliminary field measurements of spectrum usage revealed that most of the allocated spectrum was vastly underutilized [1], with temporal and geographical variations in the use of the assigned spectrum ranging from 15% to 85% [2].

More recent spectrum measurement campaigns carried out all over the world have confirmed the underutilization of the spectrum, then indicating that the spectrum scarcity problem actually results from the static and inflexible spectrum management policies rather than the physical depletion of usable radio frequencies. For instance, in [3] authors illustrate a spectral occupancy measurement campaign conducted in the frequency range between 806 MHz and 2750 MHz in urban Auckland, New Zealand. While in [4] a detailed analysis from 20 MHz to 3 GHz spectrum band and at different locations in Guangdong (province of China) has been performed. Several spectrum measurement campaigns covering wide frequency ranges have been carried out in USA [5]-[9] in different locations and scenarios in order to determine the degree to which allocated spectrum bands are used in real wireless communication systems. Moreover, in [10] authors provide an extensive measurement campaign conducted in Germany, comparing indoor and outdoor measurement results also in the band from 20 MHz to 3 GHz.

All these studies have confirmed that the static spectrum allocation policy was once appropriate and then, this outdated scheme has become obsolete. Therefore, new spectrum management paradigms are required for a more efficient exploitation of the precious radio resources. This situation has motivated the emergence of flexible spectrum access policies aimed at overcoming the drawbacks and shortcomings of the currently inefficient static allocation policies.

In this context, the so-called Cognitive Radio (CR) represents an innovative way to detect and use the precious wireless spectrum resources. CR was originally defined as a context-aware intelligent radio capable of autonomous reconfiguration by learning from and adapting to the surrounding [11]. In particular, it interacts with the environment following the cognition cycle defined in [11] that allows CRs continually observing their Radio Frequency (RF) environment, orienting themselves, creating a plan, deciding and then acting. In addition, learning may be pursued in the background.

CR paradigm is considered a key solution to mitigate the spectrum scarcity problem by enabling Dynamic Spectrum Access (DSA), defined in order to conciliate the existing conflicts between the ever-increasing spectrum demand growth and the currently inefficient spectrum utilization [12]. DSA stands for the opposite of the static spectrum management policy and covers any innovative solution meant to share spectrum among several radio systems with sake of increasing the overall spectrum utilization. The basic idea of the DSA is to allow the so-called secondary users accessing in an opportunistic and non-interfering way some licensed bands temporarily unoccupied by the licensed (or primary) users. Secondary terminals monitor the spectrum in order to identify time and frequency gaps left unused by primary users, perform transmissions and vacate the channel as soon as primary users return. Secondary transmissions are allowed following this operating principle as long as they do not result in harmful interference to primary radios. The temporarily unused portions of spectrum are called spectrum White Spaces (WSs) that may exist in time, frequency, and space domains. The basic concept of the CR paradigm introduced in [11] has been reconsidered in the literature by many subsequent papers, each trying to redefine it in particular scenarios. In the specific DSA context, the following definition given in [12] is the most cited one:

"*Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency and modulation strategy) in real-time, with two primary objectives in mind: highly reliable communications whenever and wherever needed; efficient utilization of the radio spectrum.*"

According to this definition, the tasks of the CR cycle should be characterized in the context of DSA in order to enable the following capabilities [12]:

- Radio-scene analysis, which consists in estimating interference conditions of the radio environment and identifying the set of available spectrum holes or WSs.

- Channel identification, which consists in estimating the Channel State Information (CSI) and predicting the channel capacity.

- Transmit-power control and Spectrum management, which adjusts transmission parameters based on a feedback received from previous tasks.

A detailed description of the cognitive cycle and its characterization to the DSA context will be given in Chapter 2.

With the advent of the CR paradigm as a key enabler of DSA, many papers proclaimed the need of Cognitive Radio Networks (CRNs), which allow a wireless communication system based on the cognitive cycle to observe the environment, act, and learn in order to optimize its performance. For instance, in [14] a CRN is defined as a wireless network with the capabilities of radio environment awareness, autonomous decision making, adaptive reconfiguration of its infrastructure and intelligent learning from experience of a continuously changing environment to solve the challenges of efficient spectrum management and high quality end-to-end performance.

Hence, a CRN needs the ability to be aware of certain information, such as the available spectrum, the operation mode of the wireless network, the transmitted waveform, the network protocol, the geographical information, the type of services, the user needs and the security policy. Furthermore, a CRN must analyse the achieved information and make the decision to optimize the end-to-end performance of the wireless network. Based on the optimized decision, a CRN must finally reconfigure its network parameters when necessary.

Moreover, CRNs deal with challenges in terms of coexistence with primary users and different Quality of Service (QoS) requirements associated with the various cognitive communications. According to [15], in a network that guarantees the cognitive capabilities the following issues have to be considered:

- Interference avoidance: to operate while controlling the amount of interference perceived by primary networks.

- QoS awareness: to enable QoS-aware communications in dynamic and heterogeneous spectrum environments.

- Seamless communication: to provide seamless communications regardless of the activity of primary users.

Several papers have illustrated the expected benefits of developing cognitive management functional architectures, which support CRNs to exploit the mentioned cognitive radio capabilities for efficient spectrum management and high quality end-to-end performance [14], [16], [17]. These studies have motivated the development of advanced cognitive management tools in many specific scenarios and presented in several papers. For instance, in [17] a cognitive management framework is illustrated to carry out an autonomous optimization of resource usage in next-generation home networks. The proposed framework is able to autonomously improve the performance of network nodes in a dynamic environment according to the aims, the restrictions and the policy regulations formulated by network stakeholders. In [19], a cognitive management tool is considered to dynamically select and adapt the most appropriate technology in a multi-Radio Access Technology (RAT) context. The proposed system acquires useful knowledge through an advanced learning scheme based on Bayesian statistics in order to exploit the acquired knowledge to select the optimal device configuration. In [20], cognitive management tools are used to improve efficiency of medical applications and a novel cognitive architecture defined as Co-health is proposed to exploit available knowledge and previous experience to support electronic healthcare, especially in emergency situations.

In [21] authors propose to consider cognitive management systems for provisioning efficient applications in the Future Internet (FI). The main objective of the FI is to provide emerging and new applications through a wide range of Internet-enabled devices. New applications and services need the support of a network capable of handling amplified data traffic volumes [22]. This increasingly demanding of new applications needs technological solutions able to provide the users with radio resources and high-quality services anywhere and anytime. The solution proposed in [21] is based on the Opportunistic Networks (ONs) defined as extended infrastructures, temporarily created in order to serve specific regions providing application needs, which follow the policies dictated by the operator. Because of the temporarily nature of the ONs and the highly dynamic nature of the environment, including traffic and application issues, as well as the need to identify radio resource opportunities, solutions including autonomous decisions and reconfiguration ability mechanisms provided by a cognitive management system are deemed essential. Moreover, in this paper authors claimed that the defined ON-based solutions can prove beneficiary in different scenarios of the FI.

Furthermore, the shown usefulness of cognitive capabilities supported by cognitive management architectures has motivated also the initiation of different research projects (e.g., [23]-[25]) and standardization activities (e.g., [26], [27]).

1.2 Motivations, Objectives and Contributions

During the last years, the concept of DSA enabled by CR has gained popularity as the most promising solution to achieve high efficiency in spectrum usage. As explained in the previous section a key role for solving the challenges of efficient radio resource use is played by the CRNs that allow the exploitation of the cognitive cycle. Moreover, the implementation of cognitive management systems supporting CRNs has been proposed as a powerful option to improve their performance and push forward their massive deployment and commercialization. Although the benefits of CR and DSA supported by cognitive management architectures have been discussed through different studies (e.g., [27]-[30]), many aspects are still topic under investigation. For instance, spectrum sensing strategies to identify spectrum opportunities, coordination of opportunistic spectrum access among different users, spectrum selection strategies that guarantee interference-free and high quality services, are still topic requiring satisfactory solutions.

In this context, the main objective of this Ph.D. dissertation is to design and implement cognitive management frameworks that provide innovative strategies for spectrum management that exploit the CR capabilities. The solutions proposed in this dissertation initially address the development of a framework that provides spectrum management strategies for ONs. Then, in order to expand the design of cognitive management frameworks based on the cognitive cycle and provide spectrum management solutions that have applicability in a number of different scenarios and use cases, a cognitive management framework that exploits the Partially Observable Markov Decision Process (POMDP) concept [32] is presented in order to combine the observations carried out during the CR cycle with a statistical characterization of the system dynamic. Finally, the framework based on POMDPs is further extended with new functionalities able to characterize the environment dynamic through long-term predictions carried out exploiting the so-called belief vector. These frameworks as a whole aim at demonstrating that a reliable characterization of the radio environment that combines awareness of its surrounding with a statistical evaluation of the system dynamics can guarantee an efficient utilization of the available spectrum resources.

From a methodological point of view, the development and assessment of the proposed cognitive management frameworks and the corresponding spectrum management solutions combine analytical studies, system-level simulations and a testbed implementation. With all the above considerations, the main contributions of this Ph.D. can be summarized as follows:

1. **Conception, design and development of a cognitive management framework for spectrum management based on the POMDP concept**. The developed framework embraces aspects related to the cognitive cycle that includes observation, analysis, decision and action for an efficient spectrum management, which can be exploited for different scenarios and use cases. The spectrum management solutions designed and implemented in this framework are based on the use of POMDPs that combine actual observations of the radio-environment with its statistical evaluation. Through this framework it will be demonstrated how the use of the POMDPs in the strategies for spectrum management is decisive to reduce the number of observations performed during the CR cycle optimizing, as it will be widely explained, the costs in terms of signalling overhead.

2. **Conception, design and development of a cognitive management framework for spectrum management based on the Belief-vector concept.** The belief vector represents a powerful tool to develop a statistical characterization of certain processes. Then, the solution based on the POMDPs has been extended towards the cognitive management framework presented in this contribution that relies on a long-term characterization of the dynamic of the radio environment through the exploitation of the belief vector concept. In details, this framework is designed and implemented to propose innovative strategies making use of the belief vector concept to

characterize and predict the environment dynamics in terms of the traffic generation patterns and the interference behaviour in the radio electrical spectrum. It will be illustrated how this framework is able to guarantee solutions for spectrum management that achieve satisfactory performance through a smart characterization of the scenario dynamicity.

3. **Design and Implementation of a simulator to assess the cognitive management frameworks based on the cognitive cycle.** The developed simulator has been specifically designed and implemented with the aim of providing an off-line model to assess the spectrum management strategies based on the cognitive cycle firstly in a simplified radio environment. Hence, the cognitive management framework providing solutions based on the POMDP has been implemented and assessed in the simulator achieving promising performance results. Then, the simulator has been extended in order to implement also the cognitive management framework that provides spectrum management strategies based on the belief vector obtaining its expected benefits in the performance results. The satisfactory results achieved through the off-line simulator led to the performance study of the solution that exploits the belief vector concept also in the real-time environment provided by the testbed previously mentioned and presented in the next contribution.

4. **Design and Implementation of a real-time testbed to evaluate in a realistic environment the performance of the proposed cognitive management frameworks**. Real-time emulators enable to carry out realistic scenarios to test algorithms, policies, protocols, services and applications under realistic conditions, thus constituting a powerful tool for assessing not only the QoS but also the Quality of Experience (QoE) of the end-user that could not be obtained through off-line simulations. Guided by this motivation, an evolutionary real-time testbed has been envisaged, implemented and validated to evaluate in a real environment the spectrum management strategies proposed in this dissertation.

    a. **Baseline tesbed for solutions in ONs.** This baseline testbed has been developed for demonstrating and validating the cognitive management framework for spectrum management in ONs. It is based on reconfigurable devices that can transmit/receive in different frequencies dynamically configured. This allows establishing and monitoring ON radio links, and reconfiguring them based on the actual changes in the current spectrum conditions. Hence, through the testbed the proposed framework and the corresponding spectrum management strategies have been assessed in a real-time environment.

    b. **Extended tesbed for solutions based on the belief-vector.** Motivated by the satisfactory results achieved through the off-line simulations, the baseline version of the testbed has been extended to accurately assess the performance of the cognitive management framework based on the belief-vector concept also in a more realistic platform considered essential towards the implementation of the proposed spectrum management strategies in a real system.

1.2.1 List of Publications

The contributions of the thesis illustrated in Section 1.2 have been published or submitted for several publications. In the following a list of papers associated with this thesis work is presented.

Journals (submitted for revision)

J1. J. Pérez-Romero, A. Raschellà, O. Sallent, A. Umbert, “A Belief-based Decision Making Framework for Spectrum Selection in Cognitive Radio Networks” submitted for consideration of publication in IEEE Transactions on Vehicular Technology.

Conferences

C1. A. Raschellà, J.Pérez-Romero, O. Sallent, A. Umbert, “Evaluation of a Belief-based Decision Making in a Real-time Platform for Cognitive Radio Networks”, 9th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM 2014), Oulu, Finland, 02 - 04 June 2014.

C2. J. Pérez-Romero, A. Raschellà, O. Sallent, A. Umbert, “Enhanced Cognitive Radio Operation through Belief-based Decision Making”, 20th European Wireless Conference (EW 2014), Barcelona, Spain, 14 - 16 May 2014.

C3. A. Raschellà, J. Pérez-Romero, O. Sallent, A. Umbert , “On the impact of the Observation Strategy in a POMDP-based framework for Spectrum Selection”, 24th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2013), London, United Kingdom, 08 - 11 September 2013.

C4. A. Raschellà, J.Pérez-Romero, O. Sallent, A. Umbert, “On the use of POMDP for Spectrum Selection in Cognitive Radio Networks”, 8th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM 2013), Washington DC USA, 08 - 10 July 2013.

C5. J. Pérez-Romero, A. Raschellà, O. Sallent, A. Umbert, “Multi-band Spectrum Selection Framework based on Partial Observation”, 14th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2103), Madrid, Spain, 4 - 7 June 2013.

C6. A.Raschellà, A.Umbert, J.Pérez-Romero, O.Sallent, “A Testbed Platform to Demonstrate Spectrum Selection in Opportunistic Networks”, 6th Joint IFIP Wireless and Mobile Networking Conference (WMNC 2013), Dubai, United Arab Emirates, 23 - 25 April 2013.

C7. A.Raschellà, A.Umbert, J.Pérez-Romero, O.Sallent, "On Demonstrating Spectrum Selection Functionality for Opportunistic Networks", 2nd International Conference on Mobile Services, Resources, and Users (MOBILITY 2012), Venice, Italy, 21 -26 October 2012.

1.2.2 Relation to Research Projects

The work carried out during the doctoral research period has been supported by the following research projects funded by both Spanish and European Union entities:

- ARCO: "Opportunistic and Cognitive Radio Access," original title in Spanish: "Acceso Radio Cognitivo y Oportunista", funded by the Spanish Research Council (MICINN) in the framework of Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica 2008-2011, Ref. TEC2010-15198.

- OneFIT: "Opportunistic Networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet", funded by the European Union in the Seventh Framework Programme (FP7).

- NEWCOM#: "Network of Excellence in Wireless COMmunications" funded by Call 1 of the Seventh Framework Program (FP7).

1.3 Thesis Outline

This Ph. D. thesis is structured in four core chapters, followed by a concluding chapter. The organization of this dissertation is illustrated in Figure 1.1.

Chapter 2 includes an overall overview of the CR and the ONs. The topics discussed in this chapter are the key concepts towards the implementation of the cognitive management frameworks proposed in this dissertation. The chapter includes: a general description of the CR paradigm including the cognitive cycle; the basic DSA concepts with particular emphasis on the different existing models and on the exploitation of the CR cycle to enable such models; a typical example of CRN and the corresponding functionalities that a cognitive management system should provide to enable DSA; the general concepts of ONs including the scenarios where can be implemented and the explanation of the different tasks involved from their creation to their termination.

Chapter 3 presents the cognitive management frameworks and the Functional Architectures (FAs) proposed to implement the frameworks together with the corresponding spectrum management strategies developed in this thesis. Specifically, in the second section of the chapter the framework developed for ONs, and called Base-line Cognitive Management Framework (BCMF), is presented. In details, particular emphasis will be given to the following modules of the FA implemented for spectrum management in ONs: a dynamic spectrum management module providing a strategy that enables to find radio spectrum opportunities; a cognitive management system module, which provide solutions for decision-making spectrum selection. While this framework has been developed for the specific case of ONs, the ones based on the cognitive cycle can be considered for a wider set of use cases and scenarios.

In particular, the third section of the chapter presents the cognitive management framework and the FA together with the corresponding spectrum management strategies based on the POMDPs, and called Evolved Cognitive Management Framework (ECMF). This solutions are implemented in a decision-making module in charge of selecting the most appropriate radio spectrum when needed, and in a knowledge management module responsible of computing and storing statistical information of the radio environment; finally, a context awareness module in charge of performing measurements of different parameters that characterize the radio environment is decisive for the implementation of this solutions.

Finally, the framework based on the POMDPs has been extended with new functionalities towards the solution based on the belief vector concept, called Final Cognitive Management Framework (FCMF) and presented in the fourth section of the chapter together with the FA and the corresponding spectrum management strategies. In details, the new functionalities allow exploiting the impact of the scenario dynamicity in terms of interference and traffic generation patterns on the performance results. Moreover, in this chapter the belief vector concept is widely explained and further details on his behaviour are provided in Appendix A.

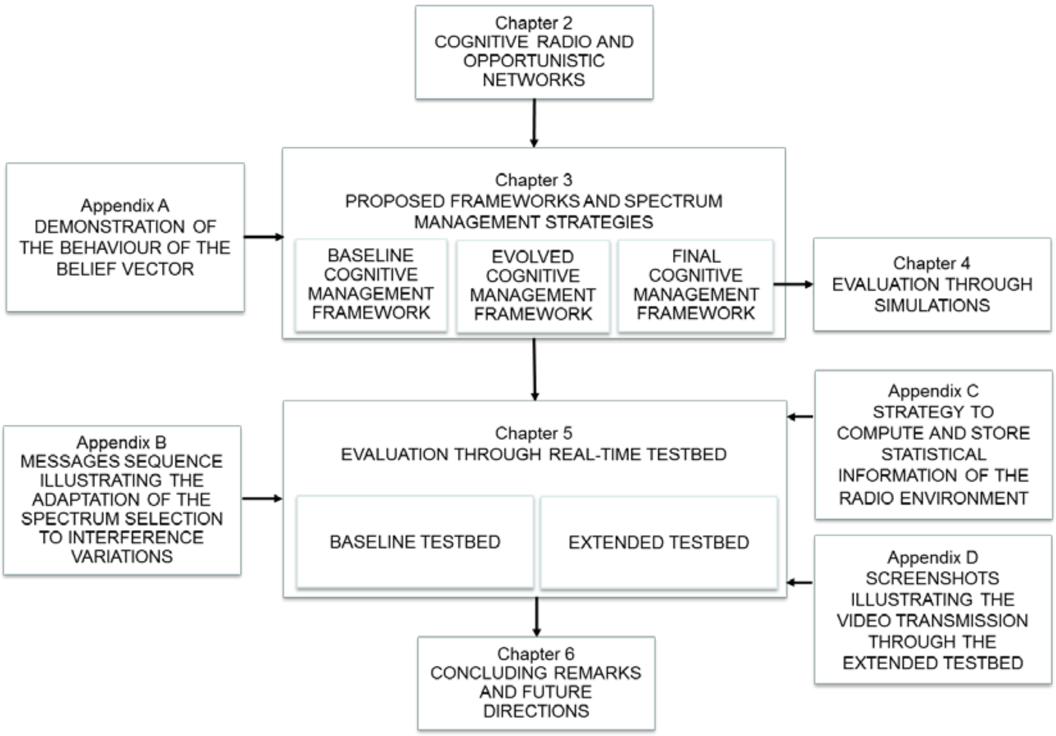


Figure 1.1: Outline of the Ph.D. Dissertation

Chapter 4 provides all the details of the design and the implementation of the off-line simulator envisaged to assess the frameworks based on the cognitive cycle. In particular, firstly the details of the scenario developed in the simulator for the implementation of the proposed frameworks and for the evaluation of the corresponding spectrum management strategies are given. Then, the performance results of these solutions provided, respectively, by the ECMF and the FCMF are widely illustrated in the rest of the chapter.

Chapter 5 gives a comprehensive description of the testbed, providing details of hardware, software and its capabilities. In details, in the second section of the chapter the implementation of the individual node that will compose both versions of the testbed, the baseline version and the extended one, is presented. While in the third section of the chapter the design of the baseline testbed architecture for the implementation of the BCMF together with the spectrum management strategies provided for ONs, and the corresponding emulation results are widely analysed. An example of how the baseline testbed works in an ON in case of real-time scenario characterized by interference variations with the help of some screenshots is provided in Appendix B.

Finally, in the fourth section of the chapter the extended testbed architecture for the implementation of the FCMF together with the spectrum management strategies based on the belief vector concept, and the corresponding emulation results are illustrated. The strategy implemented in the extended testbed that enables to compute and to store the statistical information of the radio environment is explained in Appendix C. Moreover, in the fourth section of the chapter an example that demonstrates the practicability of the belief-based approach for a realistic entertainment application in a Digital Home (DH) scenario is provided. Further details of this experiment are given in Appendix D with the help of some screenshots.

Finally, Chapter 6 summarizes the main conclusions derived from the work carried out in this thesis and it suggests possible directions for future works.

Chapter 2

Cognitive Radio and Opportunistic Networks

2.1 Introduction

DSA based on the CR principles is considered a key solution to increase the efficiency of spectrum use in radio communication systems. For this purpose, the definition of a CRN supported by specific management tools that exploit the CR capabilities has been considered essential in the literature. Furthermore, the development of cognitive management systems has been taken into consideration in many specific scenarios such as in the case of ONs exploitation for FI applications. In that context, this chapter provides a general overview of the CR paradigm and of the ONs. In particular, in Section 2.2 the introduction of the CR and a detailed description of the CR cycle are given; while, Section 2.3 presents the basic concepts of the DSA and how it is enabled by the CR; moreover, in this section a typical example of CRN with the corresponding functionalities, which enables DSA, is provided. In Section 2.4 the general concepts of the ONs are given with particular emphasis on the scenarios where they can be implemented and the explanation of the different tasks involved from their realization to their termination. Finally, Section 2.5 provides the summary of this chapter.

2.2 Cognitive Radio Paradigm

The CR concept was introduced by J. Mitola III as a smart, context-sensitive radio that can be programmed and configured dynamically under varying environmental conditions [11]. The operations of the CR systems are typically assumed to follow the cognitive cycle illustrated in Figure 2.1 in order to interact with the environment. Any CR system following this cycle gathers observations from the outside world through different types of sensors, orients itself, creates a plan of possible courses of actions, decides and then acts. During this cycle, the CR system also learns from the outcomes of its decisions and sensory inputs from the outside world. Clearly this original definition of CR is very general, applicable to a vast number of scenarios; in details, in the original study of J. Mitola III the observations were focused on the following inputs: *(i)* radio spectrum; *(ii)* images from cameras; *(iii)* speech recognition and; *(iv)* geo-location. Hence, general CR is an adaptive, self-organizing architecture for holistic resource management in wireless networks capable of adjusting its own behaviour through learning.

A CR system can observe a number of different aspects of its environment. The most commonly mentioned example is the radio environmental information achieved by some kind of spectrum sensor. Usually, a spectrum sensor would measure features such as either the sensed power in a range of frequencies, or the presence of signals transmitted through particular technologies or digital modulation schemes. This spectrum sensor could also be implemented either on an individual CR system by a hardware component, or it could be based on cooperation between several CR systems in the neighbourhood. The observations could also be done through explicit communication amongst different radios such as transmitters that send control information on the used frequencies.

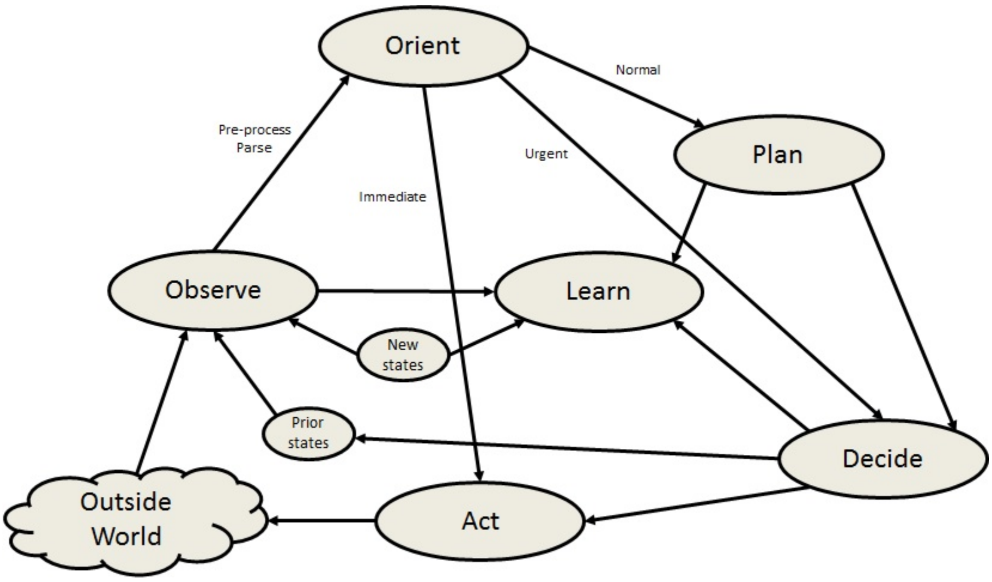


Figure 2.1: Cognitive Cycle

The orientation stage involves the processing of the information achieved from the different sensors, and the integration with any prior knowledge for updating the estimated state of the system and its environment. Depending on the diversity of the sensing information and available prior knowledge, numerous different state estimation and learning mechanisms can be used in the orientation state. For instance, further processing of information achieved by spectrum sensors can be gathered with location information to make logical conclusions whether certain transmitters are active or not. Depending on the change in state, the CR shifts either to the planning state, or, in case urgent reaction is needed, to the decision one. After reaching the decision making state, the CR should potentially act according to the decisions made. Actions here would usually relate to change in any of the tuneable parameters across the entire protocol stack, including selection of protocols to be used, and actual links or end-to-end connections established to other nodes. During the learning state the CR updates the different models that have been constructed on the environment, on the properties of other radios, and on the dynamics of its own state.

CR paradigm relies frequently, but not necessarily, on the use of the Software Defined Radio (SDR) technology, which is a multi-band radio supporting multiple air interfaces and protocols. It is reconfigurable through software running on a Digital Signal Processor (DSP), Field-Programmable Gate Array (FPGA), or general purpose microprocessor [33]. Hence, CR systems, usually built upon a SDR platform, are context-aware intelligent radio capable of autonomous reconfiguration by learning from and adapting to the surrounding communication environment [34]. They are capable of sensing their Radio Frequency (RF) environment, learning about their radio resources, user and application requirements, and adapting their behaviour accordingly. The idea behind SDR is to define all radio functionalities in software rather than in dedicated hardware, in order to reuse one platform for many different radio standards, to achieve the CR activities.

Through the SDR the following main characteristics of the CR defined in [12], [16] can be exploited: cognitive capability, i.e. the ability to capture information from the radio environment, and reconfigurability, which enables the transmitter parameters to be dynamically programmed and modified according to the radio environment. In fact, SDR is capable of sensing spectrum occupancy and opportunistically adapting transmission parameters to utilize empty frequency bands without causing harmful interference to primary networks. Moreover, through SDR, a CR system is able to reconfigure several parameters such as the operating frequency (to take profit of spectrum holes detected on different frequency bands), modulation and/or channel coding (to adapt to the application requirements and the instantaneous channel quality conditions), transmission power (to control interference), and communication technology (to adapt to specific communication needs). Based on the characteristics of the detected spectrum holes, these parameters can be reconfigured so that the CR is switched to a different spectrum band; transmitter and receiver parameters are reconfigured and the appropriate communication protocols and modulation schemes are used.

2.3 Dynamic Spectrum Access to exploit Cognitive Radio Paradigm

Spectrum underutilization has motivated different activities and initiatives in the regulatory, economic and research communities in looking for better spectrum management policies [35]. DSA solutions have been proposed to provide procedures or schemes to achieve flexible spectrum access approaches aimed at overcoming the disadvantages and shortcoming of the currently inefficient static allocation policies. The key enabler of the DSA concept is the CR that provides functionalities such as the possibility to use the spectrum in an opportunistic way observing the outside world.

2.3.1 Dynamic Spectrum Access Models

Several DSA models have been defined to optimize the spectrum usage depending on the specificities of the radio environment as shown in Figure 2.2. From the figure the following classification can be defined:

- **Dynamic exclusive use model**. It basically keeps the structure of the static spectrum allocation policy. Spectrum bands are licensed to operators, technologies and/or services for exclusive use, but some flexibility is introduced to optimize spectrum efficiency. Two different approaches can be distinguished in this model:

  – *Spectrum property rights* [36]. It enables licensed users to sell and lease some portions of its licensed spectrum and to select the technology to be employed as well as the service to be given in that band. Hence, in this context, economy and market would play a more important role in driving the most profitable use of spectrum under this scheme. It is worth highlighting that even though licensed users can sell or lease the spectrum for economic profit, this spectrum sharing is not mandated by the regulatory organism.

  – *Dynamic spectrum allocation* [37], [38]. It aims at managing the spectrum used by a converged radio system and sharing it between participating Radio Access Networks (RANs) over space and time to optimize overall spectrum efficiency. A bandwidth reservation will result in unused spectrum for long periods of time and along large geographical areas. Hence, spectrum efficiency can be improved by exploiting the spatial and temporal traffic variations of different services. The underlying idea of DSA methods is to enable two or more networks of a converged radio system to share an overall block of spectrum such that spectrum allocations can adapt to either temporal or spatial variations in demand on the networks. However, such strategies allocate, at a given time and region, a portion of the spectrum to a RAN for its exclusive use. Furthermore, such an allocation varies at a much faster scale than the current policy (e.g., traffic demands usually exhibit a periodic daily pattern). This approach received great attention within the research community.

- **Open sharing model** [39]. Also defined as spectrum commons, it considers open sharing amongst peer users as the basis for managing a spectral region in a similar way as wireless services operating in the unlicensed Industrial, Scientific and Medical (ISM) band. Spectrum commons proponents declare that wireless transmissions can be regulated by baseline rules enabling users to coordinate their utilization, avoiding interference-producing collisions, and preventing congestion.

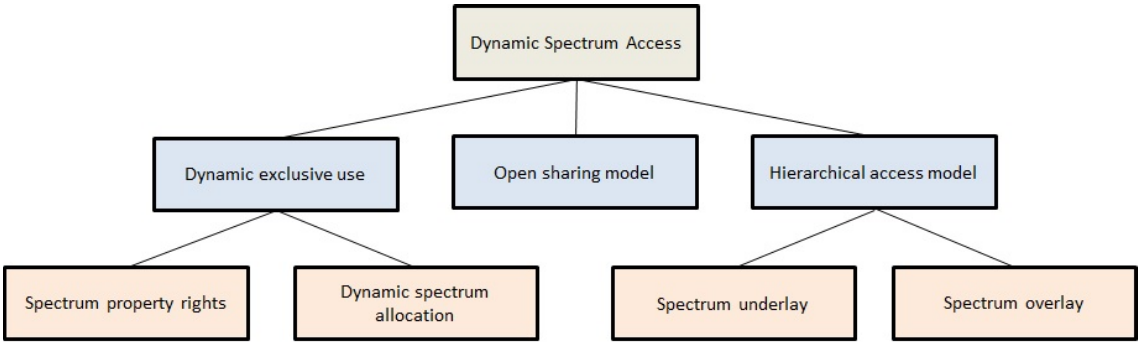


Figure 2.2: Classification of the Dynamic Spectrum Access Models

- **Hierarchical access model**. It is a hybrid model of the above two and built upon a hierarchical access structure that distinguishes between primary or licensed users, and secondary or license-exempt users. The basic idea is to open licensed spectrum to secondary users limiting the interference perceived by primary ones. Two approaches to spectrum sharing between primary and secondary users have been considered:

  – *Spectrum underlay*. It enables to overlap transmissions from secondary users but imposes severe constraints on their transmission power so that they operate below the noise floor of primary users. Therefore, secondary transmissions have to spread over a wide frequency band, which can be achieved by means of technologies such as Code Division Multiple Access (CDMA) or Ultra Wide Band (UWB). This approach enables secondary users to potentially obtain short-range high data-rates with extremely low transmission power. Another advantage is that the activity of primary users does not need to be tracked by secondary ones. The most important problem in this approach is that the low transmission power still limits the applicability of spectrum underlays to short-range applications [40].

  – *Spectrum overlay*. It is not necessarily characterized by severe restrictions on the transmission power of secondary users, but rather on when and where they may transmit. The basic idea of this approach is to define spatial and temporal spectrum gaps not occupied by primary users, referred to as spectrum holes or white spaces, and place secondary transmissions within these spaces. Hence, the purpose of this scheme is to define and exploit local and instantaneous spectrum availability in a nonintrusive and opportunistic way. This approach is also defined as Opportunistic Spectrum Access (OSA) [42].

2.3.2 Cognitive Radio as an enabler of Dynamic Spectrum Access

The CR technology in the context of DSA enables the users to: (1) determine which portion of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (*spectrum sensing*); (2) select the best available channel (*spectrum decision*); (3) coordinate access to this channel with other users (*spectrum sharing*); (4) get free the channel when a licensed user is detected (*spectrum mobility*). Focusing on these functions, the result is the simplified version of the full cognitive cycle and it is shown in Figure 2.3 [43]. The states defined in the cycle can be characterized as:

1. *Spectrum sensing.* A CR user can only allocate an unused portion of the spectrum. Therefore, the CR user should monitor the available spectrum bands, capture their information, and then detect the spectrum holes.

2. *Spectrum decision.* Based on the spectrum availability, CR users can allocate a channel. This allocation not only depends on spectrum availability, but it is also determined based on internal (and possibly external) policies.

3. *Spectrum sharing.* Since there may be multiple CR users trying to access the spectrum, CR network access should be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.

4. *Spectrum mobility.* If the specific portion of the spectrum in use is required by a primary user, or if the Quality of Service (QoS) of the spectrum worsens, the communication needs to be continued in another vacant portion of the spectrum.

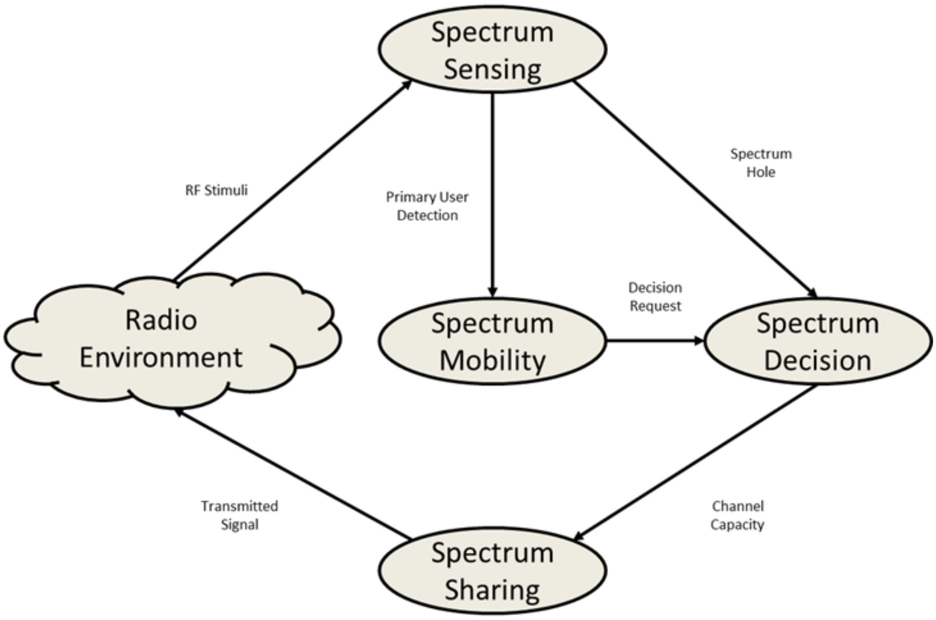


Figure 2.3: Specialization of the cognitive cycle to the DSA case

However, compared to the full cognitive cycle, the loop missed a few important components. For instance, one is the learning module, which prevents mistakes from previous iterations from being made on future ones. Several schemes have been proposed to classify the functions required in the context of the described CR and the DSA cycle. For instance, according to [1], the main functions are categorized into:

1. *Spectrum opportunity identification.* It is responsible for accurately identifying and intelligently tracking idle frequency bands that are dynamic in both time and space. Hence, this function is equivalent to the *spectrum sensing* function previously described.

2. *Spectrum opportunity exploitation.* It takes input from the *spectrum opportunity identification* function and it decides whether and how a transmission should be carried out. This function comprises the aforementioned *spectrum decision* and *spectrum sharing* ones.

3. *Regulatory policy.* It defines the basic etiquette for secondary users, dictated by a regulatory body, to guarantee compatibility with legacy systems. An example of this DSA policy is Dynamic Frequency Selection (DFS) [2]. DFS allows unlicensed 802.11 communications devices in the 5 GHz band to coexist with legacy radar systems. The policy specifies the sensor detection threshold as well as the timeline for radar sensing, usage, abandoning the channel, and a non-occupancy time after detection. This policy allows limited but minimal harm to legacy radar systems by accounting for the specific form of sensor for detection and prescribing the timeline for channel use and release.

The *spectrum mobility* function is not explicitly considered in the classification criterion proposed in [1], but it could be included within the *spectrum opportunity exploitation* one.

2.3.3 DSA/CR Networks Architecture

Once a radio supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum. Therefore, new functionalities are required in a DSA/CRN (CRN for simplicity from here on) to support this adaptively and to achieve spectrum-aware communication protocols. A typical CRN architecture is illustrated in Figure 2.4 according to the open sharing and hierarchical DSA models described in Section 2.3.1 [43]. For each of these models, the interconnection architecture may be built without a central network entity such as a Base Station (BS) or an access point (*CR ad hoc Access*) or rely on some additional network nodes (*CR Network Access*). Moreover, the figure illustrates how the network allows the access to both unlicensed band and licensed bands according to the open sharing and hierarchical access models, respectively. In case of hierarchical access model, so when licensed bands are considered, the components of the network can be classified in two groups: the first one is defined as *primary network* while there exist different ways to specify the second one, such as *CR network* or *secondary network*. *Primary network* is the legacy network having an exclusive right to a certain spectrum band such as the common cellular and TV broadcast networks; while, *CR network* does not have a license to operate in the desired band.

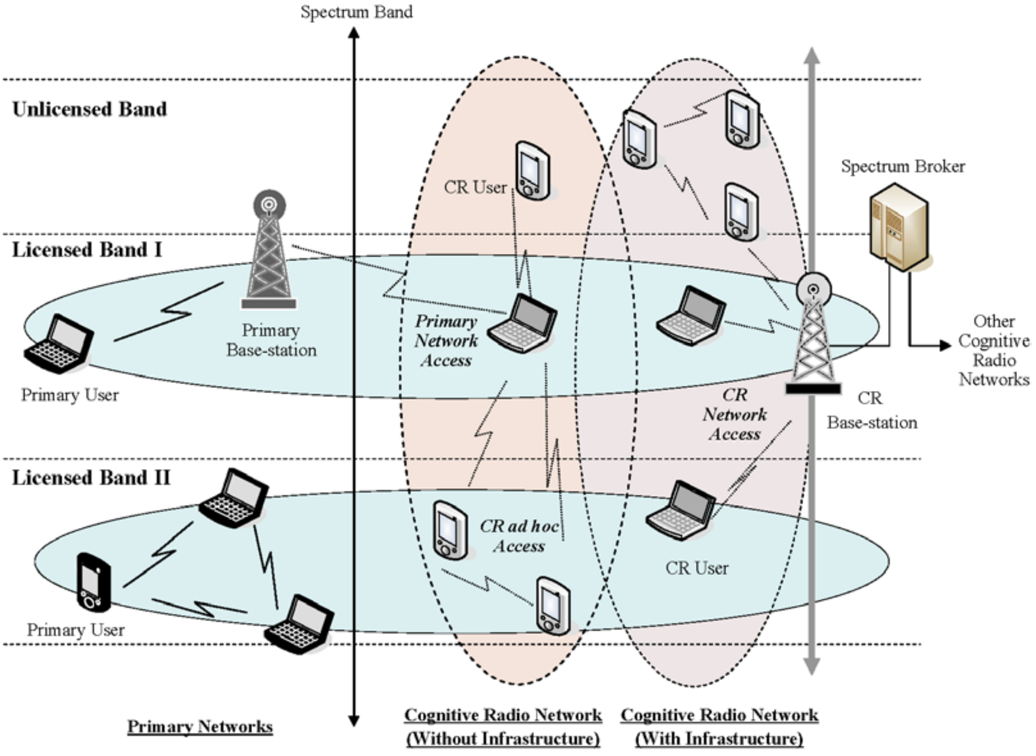


Figure 2.4: CRN architecture for DSA applications [43]

Then, the spectrum access is allowed only in an opportunistic manner. The basic components of primary networks are:

- *Primary user.* It is authorized to use always a particular spectrum band. This use is controlled only by the primary BS and it should not be affected by the operations of other unlicensed users. Primary users do not need any modification or additional functions for coexistence with BSs and CR users.

- *Primary BS.* It is a fixed infrastructure network component which has a spectrum license such as BS Transceiver system (BST) in a cellular system. In principle, the primary BS does not have any CR capability for sharing spectrum with CR users. However, the primary BS may be requested to have both legacy and CR protocols for the primary network access of CR users.

The basic elements of the CR network are defined as follows:

- *CR user.* It does not hold spectrum license and it use detected spectrum holes in an opportunistic way. Hence, additional functionalities are required to share the licensed spectrum band.

- *CR BS.* It is a fixed infrastructure component with CR capabilities. CR BS provides single hop connection to CR users without spectrum access license. Through this connection, a CR user can access other networks.

- *CR spectrum broker.* It is a central network entity that controls the spectrum sharing among different CRNs. Spectrum broker can be connected to each network and can serve as a spectrum information manager to enable coexistence of multiple CRNs [45]-[46].

Since CRNs can operate in both licensed and unlicensed bands, the required functionalities that the cognitive management tools should provide vary according to the characteristic of the spectrum. The following CRNs operations can be distinguished [43]:

- **CRN on licensed band**. In this case there are temporally unused spectrum holes. Therefore, CRNs can be deployed to use these spectrum holes through cognitive communication techniques. This architecture is illustrated in Figure 2.5; it can be observed that the CRN coexists with the primary network at the same location and on the same spectrum band. There exist various challenges for CRNs on licensed band due to the existence of the primary users. Although the main objective of the CRN is to find the best available spectrum, the interference avoidance with primary users is the most important issue in this architecture. In fact, when primary users appear in the spectrum band occupied by CR users, this must release the current spectrum band and select a new available spectrum.

- **CRN on unlicensed band**. Open spectrum policy that began in the ISM band has provoked a wide variety of innovative technologies. Notwithstanding, due to the interference among multiple heterogeneous networks, the spectrum efficiency of the ISM band is worsening. CRNs can be designed for operation on unlicensed bands such that the efficiency is improved in this portion of the spectrum. The CRN on unlicensed band architecture is shown in Figure 2.6. As there are no license holders, all the entities of the network have the same right to access the spectrum bands. Multiple CRNs can coexist in the same area and share the same portion of the spectrum. Therefore, intelligent spectrum sharing algorithms are needed to improve the efficiency of spectrum usage. In this architecture, CR users focus on detecting the transmissions of other CR users; hence, sophisticated spectrum sharing methods among CR users are required. If multiple CRN operators reside in the same unlicensed band, fair spectrum sharing among these networks is also required.

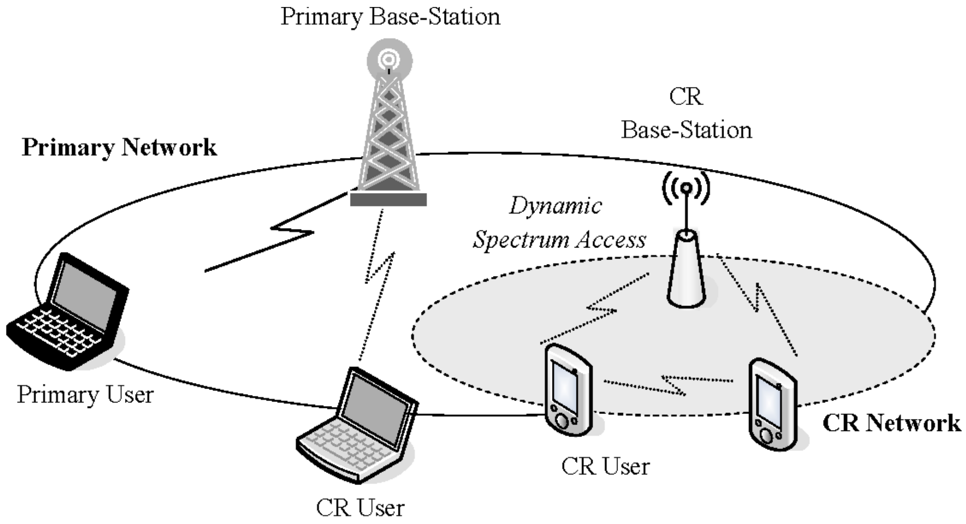


Figure 2.5: CRN on licensed band [43]

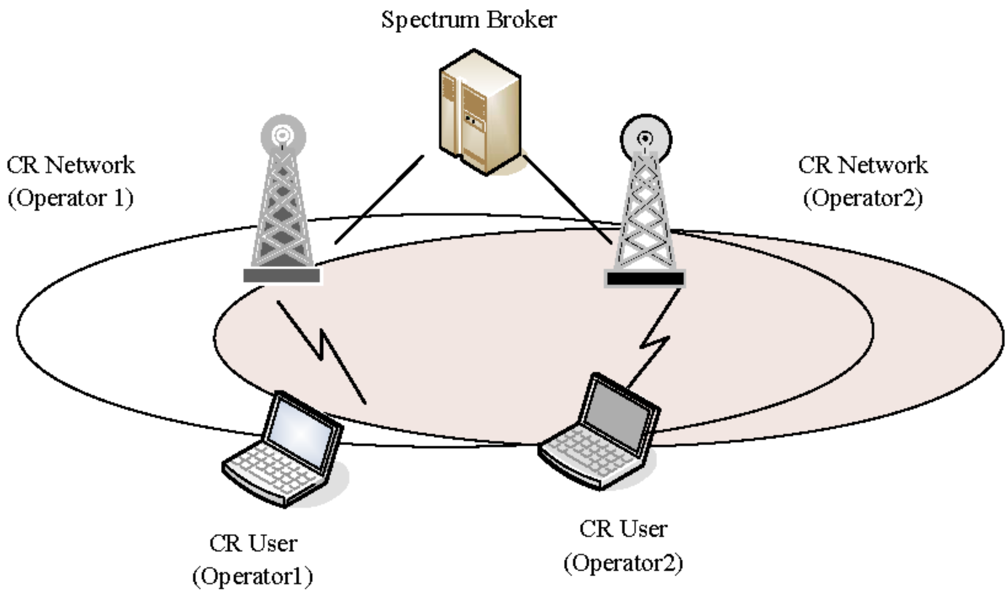


Figure 2.6: CRN on unlicensed band [43]

2.3.4 Standardization Activity

An important feature in the commercial feasibility and deployment of the DSA/CR concept is its standardization. Important standardization organizations are: the Institute of Electrical and Electronics Engineers (IEEE), the International Telecommunication Union (ITU), the Wireless Innovation Forum (WIR), the European Telecommunications Standards Institute (ETSI), and the European association for standardizing information and communication systems (ECMA) [47].

Important standards on DSA/CR environment are: the IEEE 802.22 for Wireless Regional Area Network (WRAN) that use WSs in the TV frequency spectrum; the IEEE P1900 series of standards in the area of dynamic spectrum management [48] developed by the IEEE Standards Coordinating Committee (SCC) 41, previously known as IEEE P1900 Standards Committee. There exist several other standards within IEEE as well, but less known. IEEE 802.22 is the first worldwide standard based on the DSA/CR technology [49], [50]. The development of the IEEE 802.22 WRAN standard is aimed at using CR paradigm to enable sharing of geographically unused spectrum allocated to the Television Broadcast Service (TBS), to bring broadband access to hard-to-reach, low population density areas, typical of rural environments, and it is timely and has the potential for a wide applicability worldwide

The 802.22 project initially identified the North American frequency range of operation between 54 and 862 MHz that was extended between 47 and 910 MHz in order to meet additional international regulatory requirements. Since there is no worldwide uniformity in channelization for TV services, the standard also accommodates the various international TV channel bandwidths of 6, 7, and 8 MHz.

The standard defines the physical (PHY) and MAC layers of a DSA/CR-based air interface [50], [51] for use by license-exempt devices on a non-interfering basis in spectrum allocated to the TV broadcast service. This standard considers the utilization of TV bands for the following reasons: *(i)* the favourable propagation characteristics of the lower frequency bands allocated to the TV service; *(ii)* the consequent larger coverage areas; *(iii)* the considerable amount of available TVWSs.

While IEEE 802.22 focuses on the development of specific mechanisms for the PHY and MAC layers, the IEEE P1900 series concentrate on the development of architectural concepts and specifications for policy-based network management with DSA in a heterogeneous wireless access network, composed of incompatible wireless technologies such as 3rd/4th Generation (3G/4G), WiFi, and Worldwide Interoperability for Microwave Access (WiMAX). The series is composed of six standards that are in detail: IEEE P1900.1 defining terminology and concepts, IEEE P1900.2 providing recommended practice for interference and coexistence analysis, IEEE P1900.3 that gives dependability and evaluation of regulatory compliance, IEEE P1900.4 that defines architectural building blocks, IEEE P1900.5 that provides policy language and policy architectures, IEEE P1900.6 giving spectrum sensing aspects.

Other IEEE standardization activities have been proposed to address coexistence issues amongst various systems or to make amendments to existing standards with the aim of supporting coexistence with license-exempt devices. For instance, several amendments have been made to the PHY and MAC layers of the IEEE 802.11 standard to support channel access and coexistence in TVWSs. Some examples include the introduction of new functionalities such as sensing of other transmitters (IEEE 802.11af, also known as WiFi 2.0), Transmit Power Control (TPC) and DFS (IEEE 802.11h), and some extensions thereof (IEEE 802.11y). Similarly, the IEEE 802.16h amendment develops improved mechanisms to enable coexistence among license-exempt systems based on the IEEE 802.16 standard, and to facilitate the coexistence of such systems with primary users [53].

In addition to the work performed by the IEEE, some other organizations are working on the definition of standards for DSA/CR systems. For instance, ITU Radiocommunication Sector (ITU-R) published two technical reports [55], [56] on the application of SDR to the International Mobile Telecommunications

(IMT) 2000 global standard for 3G mobile communications and other land mobile systems. In September 2009 the WIR initiated a test and measurement project in order to develop a set of use cases, test requirements, guidelines and methodologies required for secondary opportunistic access to TVWS. The project addresses critical functions such as spectrum sensing, interference avoidance, database performance and policy conformance. In October 2009 the ETSI Technical Committee for Reconfigurable Radio Systems (RRS) published a series of technical reports [57] summarizing various feasibility studies and examining standardization needs and opportunities. In December 2009 ECMA released the first DSA/CR standard for personal/portable devices operating in TVWS [57], [59]. The standard specifies the PHY and MAC layers of a DSA/CR system with flexible network formation, mechanisms for protection of primary users, adaptation to different regulatory requirements, and support for real-time multimedia traffic.

Despite the number of initiatives and activities carried out so far, standardization of DSA/CR systems constitutes an exciting challenge still requiring much more effort. Different countries may have several spectrum regulations. While this appears to be reasonable as a result of different social and economic environments, this situation complicates the standardization of DSA/CR systems and the development of worldwide standards. Moreover, there exists a variety of organizations working independently on different standards. Furthermore, the evolving trend towards converged heterogeneous wireless access networks poses unique challenges. Although some consolidation is required in this area, the fact is that regulation, standardization and evolution towards heterogeneity is ongoing and the final impact remains unknown. How these aspects can be harmonized constitutes a big question yet to be answered in the foreseeable future.

2.4 Opportunistic Networks

2.4.1 Basic Concepts and State of the Art

ONs, which are defined as temporary, operator-governed, coordinated extension of existing infrastructures, have been proposed as an innovative approach for exploiting CR paradigm in the FI [21]. ONs can include user terminals and infrastructure elements like a BS and they are dynamically created through RAN operator in places and at the time they are needed to deliver multimedia flows to mobile users, in a most efficient way. ONs exist temporarily because they are considered only for the time needed to support a certain application requested in particular locations and times. Due to the highly dynamic nature of the environment, including traffic and application issues, as well as the potential complexity of the infrastructure, the exploitation of CR concepts such as self-organizing and learning mechanisms is essential for the definition of the ONs. Self-organizing enables a system to identify opportunities for improving its performance and adapting its operation without the need of human intervention. Learning mechanisms are important to increase the reliability of decision making.

At the lower layers, the RAN operator designates the spectrum that will be used for the communication of the ONs nodes and the selected bands will be temporarily licensed during the multimedia flows transmissions. In ONs the routes are computed at each hop while a packet is forwarded; therefore, each node receiving a message for an eventual destination, exploits local knowledge to decide the best next hop to reach the packet destination. When a forwarding opportunity is not available the node can save the message and wait for future contact opportunities with other devices to send the information. Realization and management of ONs are concepts of high interest deeply investigated in various research projects (e.g., [24]) and scientific articles (e.g. [60]-[67]).

Focusing on the literature, for instance in [60] different solutions are provided to manage problems at the network, transport and application layers, which is in charge of carrying and forwarding the data in an ON. Moreover, an overall overview of several hybrid networks with the aim to exploit infrastructureless segments to increase the efficiency of the infrastructure-based network in a dynamic manner is illustrated in [61]. Furthermore, literature is rich with respect to optimization algorithms and strategies which are relevant to the design and reconfiguration of networks [62]-[64].

In some particular situation the network operator could no longer provide the resources to the ONs; in these cases the termination of the network can be forced. In general, the aim of the operators is to preserve application provision until either the network resources are exhausted, or all applications are reassigned to another network. The basis for solving this kind of problem is also under investigation; for instance, in [65]-[67] authors propose various works in the area of equipment management for driving the users to the most appropriate network that satisfy the applications requirements through cognitive techniques.

2.4.2 Opportunistic Network Scenarios

ONs have been proposed to provide efficient solutions for a wide range of possible scenarios [68]. All these scenarios consider the use of the spectrum under both type of regulatory bands defined in the previous section: licensed and unlicensed bands. Some examples of the scenarios identified in [68] are briefly illustrated and shown from Figure 2.7 to Figure 2.9.

- **Opportunistic coverage extension.** It describes a situation in which a device cannot connect to the operator’s infrastructure, due to lack of coverage or a mismatch in the radio access technologies. The proposed solution includes an additional connected user that, by creating an opportunistic network, establishes a link between the initial device and the infrastructure, and acts as a data relay for this link.

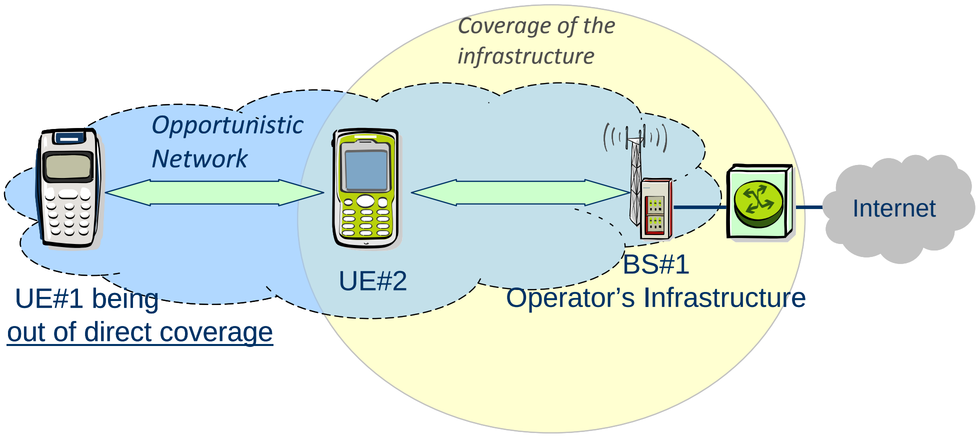


Figure 2.7: Opportunistic coverage extension scenario

- **Opportunistic capacity extension.** It depicts a situation in which a device cannot access the operator infrastructure due to the congestion of the available resources at the serving access node. The solution proposes the redirection of the access route through an ON that avoids the congested network segment.

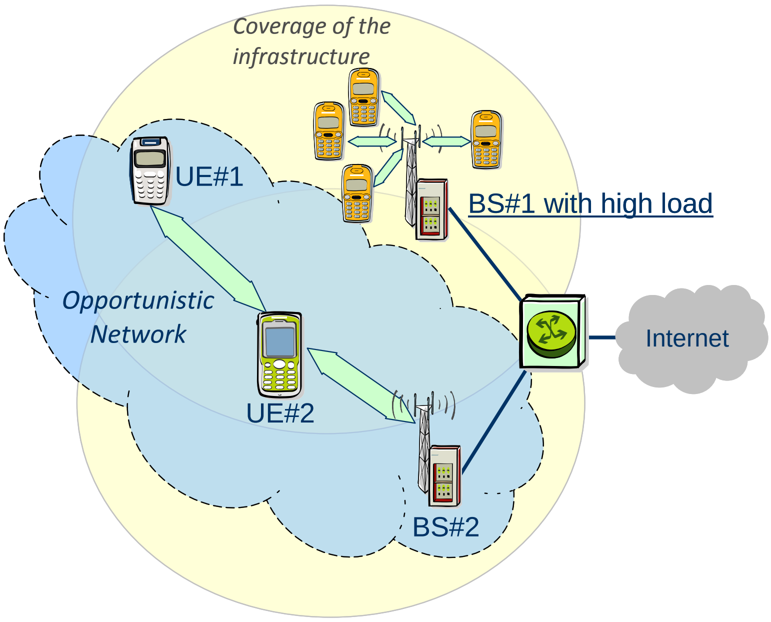


Figure 2.8: Opportunistic capacity extension scenario

- **Infrastructure supported opportunistic ad-hoc networking.** It considers the creation of a localised, infrastructureless ON among several devices for a specific purpose such as peer-to-peer communications, home networking, and location-based service. This scenario foresees the ON creation and benefits from the local traffic offloading, as well as on new opportunities for service providing.

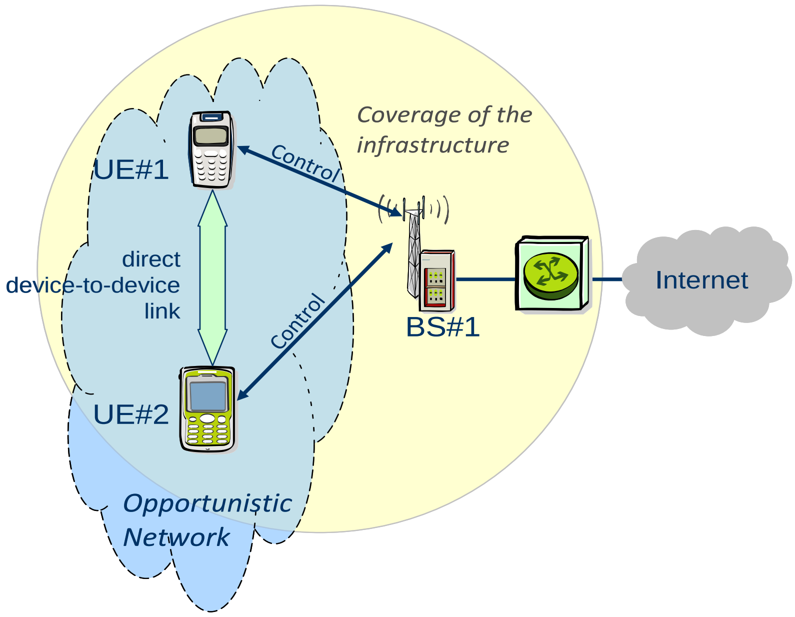


Figure 2.9: Infrastructure supported opportunistic ad-hoc networking scenario

2.4.3 Opportunistic Network Life Cycle

Considering the operator-governed feature and the dynamic nature of this kind of networks, an ON life cycle has been defined in [69] and it is made up of the following phases: (1) Suitability determination, (2) Creation, (3) Maintenance and (4) Termination. Next a detailed description of the main management stages in the ON life cycle is provided and illustrated in Figure 2.10 [69].

1) **Suitability determination**. Depending on the observed radio environment and some defined criteria, this stage is in charge to establish the time and the place where it is suitable the creation of an ON. The valuation of the suitability is based on the result of a deep feasibility analysis of the radio environment in order to keep moderate complexity. The suitability determination analysis will be carried out through a trigger (see Figure 2.10). This functionality will need the inputs from the context awareness of the radio environment to detect dynamically when the criterion for the creation of an ON is found. After the activation of the trigger, the following functionalities are defined:

    a) *Identification of potential nodes*. With this functionality which nodes can be included in the ON are defined; therefore, discovery procedures will be introduced to identify candidate nodes with particular associated characteristics (capabilities, location, etc.).

    b) *Identification of potential radio paths*. Once the nodes are identified, it is important to define also the appropriate routes across the nodes included in the ON. Moreover, mechanisms which lead to the identification of spectrum opportunities, guarantying that the resulting interference conditions are acceptable, are needed.

c) *Assessment of potential gains*. Once the potential nodes and radio paths are selected, specific metrics to quantify the gain that can be obtained by the ON are performed.

2) **Creation.** This is the logical phase deriving by the suitability stage. In particular, the suitability stage provides different configurations for an ON, whose feasibility and potential gains have been already valuated. Then, the creation stage will carry out a detailed analysis that will need additional context awareness and/or more accurate estimations related to different aspects of the radio environment. Hence, the same functionalities as for the suitability determination stage are identified, although the specific algorithmic solutions are envisaged to be different. The creation stage will take the decision on whether to define an ON or not. In positive case, all the necessary procedures and associated signalling will be triggered in this stage.

3) **Maintenance and Termination**. The ON will be dynamic and temporary in nature during all its operational life-time. Capabilities for the reconfiguration of the ON will provide the adaptability needed for radio environment changes. Therefore, during these stages the following activities are defined:

   a) *Monitoring*. It will achieve all the information which can affect decision-making processes around the ON. Relevant changes are modifications in terms of nodes, spectrum, finalization of an application, changes in the gains achieved with the ON, etc. The finalization of an application causes termination decision and the corresponding signalling is triggered in order to get free the resources used by the ON.

   b) *Reconfiguration decisions*. This activity will be in charge of the modifications at the ON configuration to obtain its most efficient operation. Reconfiguration decisions will be supported by other functionalities such as discovery procedures for the identification of new nodes, identification of new spectrum opportunities, etc. This activity will be performed considering the procedures and associated signalling specified in the system.

   c) *Handover to infrastructure decisions*. When a termination decision is taken (e.g., if the achieved gains are inadequate, or if the desired QoS is degraded) but at the same time, there is some services that are expected to survive ON termination, handover decisions will be needed to manage these services (e.g., selecting new infrastructure nodes, modifying QoS settings, etc.).

The ON definition needs optimum decisions to be realized for its configuration, in terms of the selection of the nodes that can participate, the spectrum for their communication and the applied routing schemes. Therefore, innovative strategies and mechanisms must be defined to carry out the functionalities of the ON life cycle illustrated above. Different strategies, which will be illustrated next in this section, with the aim to support suitability determination, creation, maintenance and termination of ONs can be found in the literature. The solutions proposed in this dissertation concern the spectrum management during ON creation and ON maintenance.

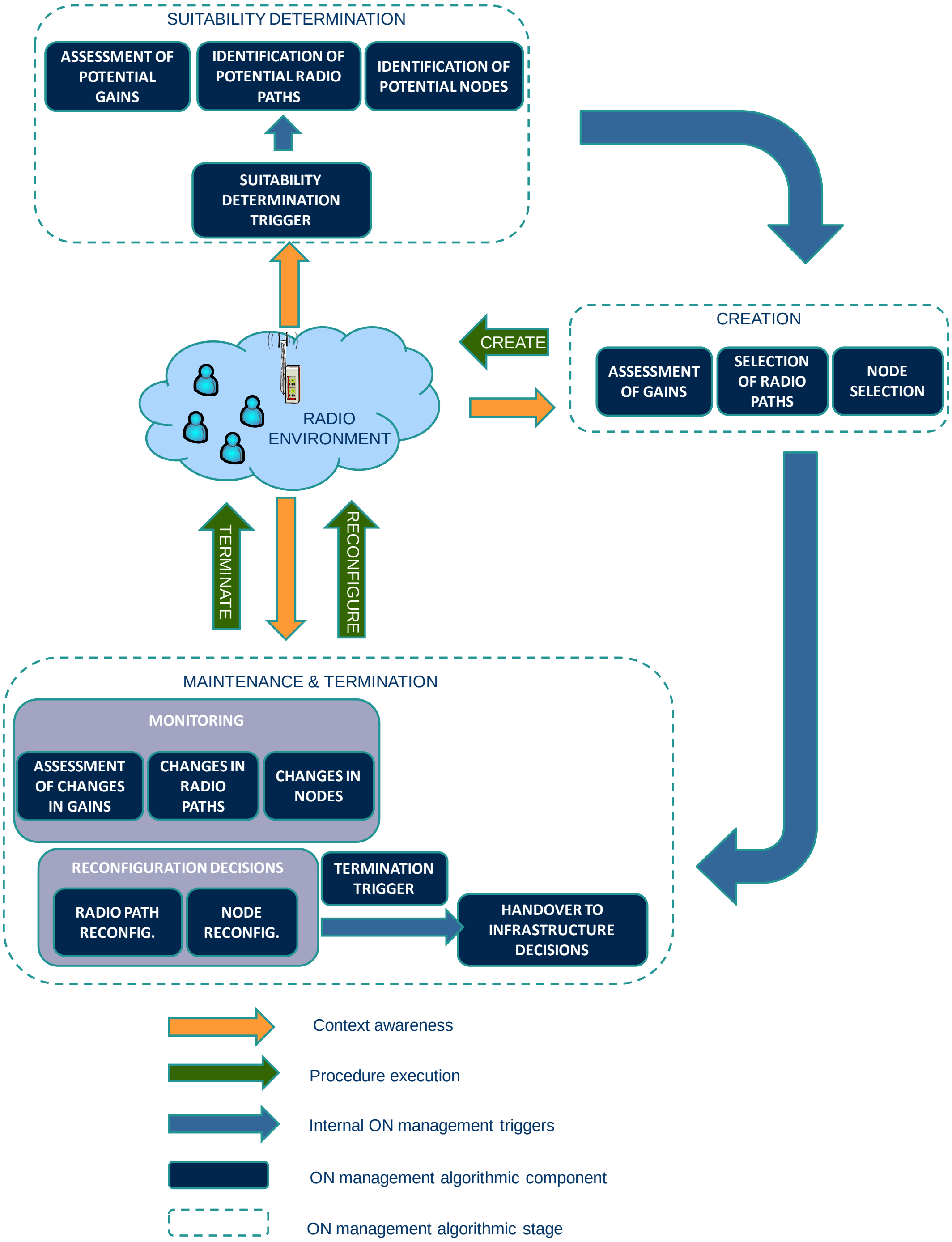


Figure 2.10: Life cycle of the ON and management stages

Before to examine in depth the development of the ON spectrum management solutions proposed in this dissertation, which will be provided in the next chapter, a brief revision of the state-of-the-art for the other functionalities of the ON life cycle is given in the following:

- **Discovery procedure.** This task is part of the suitability determination. In [70]-[72] the main discovery IEEE and 3rd Generation Partnership Project (3GPP) mobility procedures are illustrated. Such mechanisms will be the basis of discovery procedures in ONs environments. In particular, through these documents, node-to-node discovery mechanisms of nodes that could belong to ONs can be realized.

- **Candidate node identification.** Also this task is part of the suitability determination. During this phase algorithms for the determination of the nodes that are candidate to be introduced in the ON and privacy/security issues must be defined. For instance, in [73], [74] authors propose different privacy models adapted to content-based ONs.

- **Handling interference scenarios.** This area involves the suitability determination management task. The main objective of this phase is to avoid interfering with primary users. Extensive simulation scenarios, including various combinations of macro/micro/pico structures, to realize interference studies have been carried out. Further studies have been made to characterize the default requirements; they are related to Inter-Cell Interference Coordination (ICIC) illustrated in 3GPP specifications [75]. Therefore, these results will be used for examination of interference scenarios and to decide the suitability of the ON. Moreover, coexistence of ON and infrastructure utilizing licensed bands must be analysed.

- **Routing schemes.** This task is part of the ON creation. In [50], [51] and [76], different strategies are proposed regarding routing schemes. Moreover, the ECODE project [52] defines routing systems for cognitive radio networking.

- **Network design.** Also this task involves the ON creation. In literature some optimization algorithms can be found, like in [52] important for the design and the reconfiguration of networks. The computational effort associated with the optimal solution of the problem has led to the design of heuristic algorithms.

- **QoS control.** This area is part of the ON maintenance task. For instance, in [77], [78] considered QoS metrics are the delay in delivering the different messages as well as the message delivery ratio, measured during different considered routing. The provision of QoS mechanisms is identified also as a research challenge in [43] through the development of spectrum mobility mechanisms ensuring that the secondary communication can be continued whenever the primary user appears. In a similar context, in [79] an intercell spectrum sharing for infrastructure-based CRNs, which includes QoS monitoring mechanisms in the secondary transmissions to detect QoS degradations and decide on spectrum reallocations, was proposed also as a solution suitable for ON.

- **Handling of forced terminations.** There may be situations in which the network operator may no longer maintain the assignment of resources to the ON. In such cases there can be the forced termination of the network. The issue is to preserve application provision until either the network resources are exhausted, or all applications are reassigned to another network. The basis for solving this problem is again 3GPP as well as various works in the area of equipment management through legacy or cognitive techniques [65], [66] and [80]. These mechanisms acquire process and exploit context, profiles, policies and knowledge. Then, they reach distributed and autonomous decisions on the best network to be connected.

2.5 Summary

This chapter has presented the general concepts related to CR paradigm, DSA and ON that represent an essential baseline towards the description of the cognitive management frameworks and the spectrum management solutions proposed in this dissertation and illustrated in the following chapters. In details, a general overview of the CR concept and the definition of its cycle have been described. Then, how CR enables DSA and the general CR/DSA Network has been illustrated highlighting the most important functionalities to be implemented. Finally, a general overview of the ON, considered as a powerful tool that exploits the CR capabilities in the context of the FI has been illustrated. Moreover, different scenarios where the ON can be proposed and its life cycle from its creation to its termination, together with the functionalities defined for each phase have been explained as well.

Chapter 3

Proposed Cognitive Management Frameworks and Spectrum Management Strategies

3.1 Introduction

Spectrum management solutions are responsible of proper utilization of the radio resources and they are decisive to allow spectrum sharing among different radio systems guaranteeing QoS requirements for different service classes and without causing any interference. In this respect, the objective of this chapter is to describe the cognitive management frameworks and the spectrum management solutions that exploit CR networking proposed in this dissertation. The Functional Architectures (FAs) of the proposed cognitive management frameworks are based on the one defined in [81] by the European Telecommunications Standardization Institute (ETSI) for Reconfigurable Radio Systems (RRSs). Moreover, all the solutions illustrated in this chapter involve a set of j=1,..., L links each one intended to support data transmission between a pair of terminals and/or infrastructure nodes. The generic radio link j is characterized by a required bit rate $R_{req,j}$, while the potential spectrum to be assigned to the different radio links is organized in a set of i=1,..., M spectrum blocks.

The first framework described in Section 3.2 is the Base-line Cognitive Management Framework (BCMF) whose FA is a particularization of the one introduced in [82], for the management of ONs from their creation to their termination. In details, the FA of the BCMF includes cognitive management modules that provide solutions specifically for spectrum management in ONs, which has been divided in two different steps: *(i)* the spectrum opportunity identification that is in charge of finding out the set i of possible spectrum blocks available for the set j of links; *(ii)* the spectrum selection that, based on the results of the previous step, is responsible to decide the most adequate spectrum block for the communication.

While the second framework defined in this dissertation, which is illustrated in Section 3.3, is the Evolved Cognitive Management Framework (ECMF) whose FA includes all the cognitive management modules that provide strategies for an efficient spectrum selection based on the CR cycle paradigm described in Section 2.2. Moreover, in this version of the framework Partially Observable Markov Decision Processes (POMDPs) are considered as decision-making strategy in order to combine the observations that characterize the CR cycle with a statistical characterization of the system dynamics through a first definition of the belief vector concept, which will be better assessed in the third framework proposed in this dissertation.

In fact, the FA of the ECMF has been extended with new functionalities that have led to the definition of the third framework illustrated in Section 3.4 that is the Final Cognitive Management Framework (FCMF). The new functionalities enable to exploit the belief vector, which was introduced in the ECMF, as a long-term means to characterize and predict the environment dynamics in terms of the traffic generation patterns and the interference behaviour in the radio electrical spectrum. Finally, Section 3.5 provides the summary of this chapter.

3.2 Base-line Cognitive Management Framework for Opportunistic Networks

As it was mentioned, the FA of the first framework proposed in this dissertation is based on the one considered in [82], which extends the ETSI’s approach defined in [81], basically by adding two new cognitive management entities, to achieve close cooperation between the infrastructure and the ONs. These entities are the Cognitive management Systems for Coordinating the Infrastructure (CSCI) and the Cognitive systems for Managing the Opportunistic Network (CMON). The BCMF envisaged in this dissertation aims at implementing in a real-time environment the entities of the FA described in [82] that allow spectrum management during the ON creation and the ON maintenance stages. Hence, in Section 3.2.1 a comprehensive description of the FA introduced in [82] is provided; while, in Section 3.2.2 the proposed framework and the corresponding strategies for spectrum opportunity identification and spectrum selection are illustrated.

3.2.1 Opportunistic Network Functional Architecture

Figure 3.1 provides a high level representation of the main functional blocks of the FA defined in [82]. Besides the CSCI and CMON entities, some further features need to be added to the existing RRS FA building blocks and/or existing Radio Access Technologies (RATs), for the support of ONs with regard to UE discovery, link establishment, relay function and associated security. The blocks defined in the FA illustrated in Figure 3.1 and their main functions are the following:

- **Cognitive management System for the Coordination of the Infrastructure (CSCI).** It is mainly responsible for the activities before an ON is created. In fact, it is the functional entity in charge of the detection of situations where an ON is useful, which decides on the suitability of an ON and which provides policy and context information from the infrastructure to the ON.

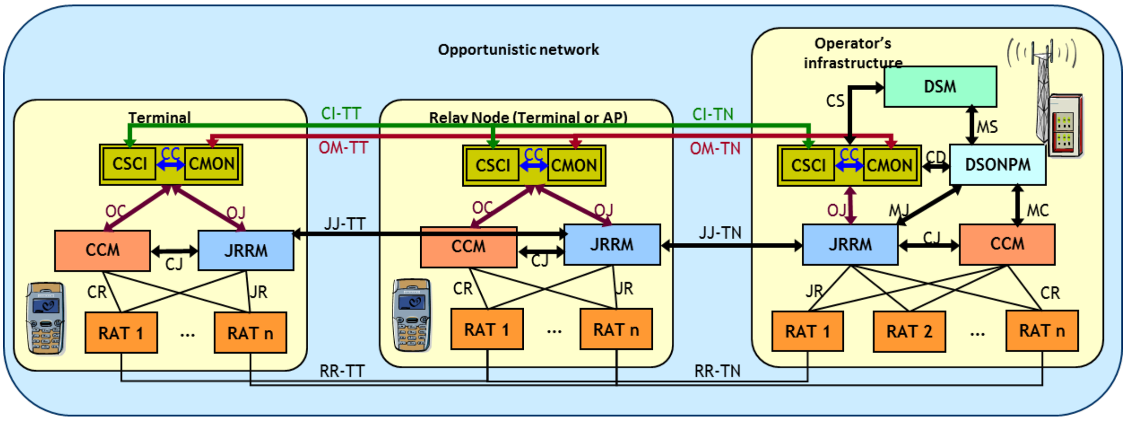


Figure 3.1: FA as an evolution of the ETSI RRS [82]

- **Cognitive Management system for the Opportunistic Network (CMON).** It controls the life cycle of the ON from creation to termination. This includes the execution of the creation procedures to enforce the design obtained from the CSCI, the supervision of the ON during maintenance phase and as well as the termination procedures.
- **Dynamic Spectrum Management (DSM).** It provides mid- and long-term management (e.g. in the order of hours and days) of the spectrum availability conditions and related constraints to guide the spectrum selection decision making.
- **Dynamic, Self-Organising Network Planning and Management (DSONPM).** It provides mid- and long-term decisions upon the configuration and reconfiguration of the network or parts of it.
- **Joint Radio Resources Management (JRRM).** It performs the joint management of the radio resources across different radio access technologies. It selects the best radio access for a given user based on the session's requested QoS, radio conditions, and network conditions.
- **Configuration Control Module (CCM).** It is responsible for executing the reconfiguration of a terminal or a BS, following the directives provided by the JRRM or the DSONPM.

Moreover, the following used interfaces illustrated in Figure 3.1 have been defined:

- **CI-Interface** for the Coordination with the Infrastructure. It is located between different CSCI blocks and it is used by the infrastructure network with a twofold aim: *(i)* to inform infrastructure network elements about the suitability of an ON; *(ii)* to provide context and policy information needed for the creation and maintenance of the ON. By this interface, the network can also receive context information from the terminals to enable the ON suitability determination.
- **OM-Interface** for Opportunistic Management between different CMON blocks. Nodes can negotiate about the creation of an ON through this interface. During the negotiation, node capabilities and user preferences can be exchanged and the QoS capabilities of an ON can be

negotiated. After the negotiation, OM interface is also used for the exchange of ON-creation, ON-maintenance and ON-termination messages.

- **CC-Interface.** It connects CSCI in a node with the CMON in the same node and it is used e.g. to send a trigger for the creation of an ON from the CSCI to the CMON as well to provide information about the resources which can be used by the ON.

- **CS-Interface.** It connects both CSCI and CMON entities with the DSM and it is used by CSCI and CMON to obtain information on spectrum usage and spectrum policies from the DSM. This spectrum related information can be used for the suitability determination of ONs as well as for the decision making on which spectrum shall be used in an ON.

- **MS-Interface.** It connects DSONPM and DSM and it is used by the DSONPM to achieve information on spectrum usage and spectrum policies from the DSM. It enables DSONPM to obtain information about the available spectrum for different RATs, unoccupied spectrum bands and spectrum opportunities.

- **OJ-Interface.** It connects JRRM with both, CSCI and CMON entities and it is used to trigger the JRRM for the establishment and release of radio links during the creation, maintenance and termination of an ON. Further on, context information e.g. on available access networks or on link performance can also be exchanged via this interface.

- **OC-Interface.** It connects CCM with both, CSCI and CMON entities and may be used to obtain additional information about the current device configuration which cannot be provided by the JRRM. However, it is assumed that for the normal ON management procedures, the CCM is not involved because the CMON uses the OJ interface to trigger link setup or release procedures.

- **CR-Interface.** It connects CCM and the underlying RAT to control the reconfiguration of the radio access in a terminal or BS by the CCM.

- **JR-Interface.** It connects JRRM and RAT to report information on resource status such as cell load or link measurements towards the JRRM.

- **CJ-Interface.** It connects CCM and JRRM and it is used by the JRRM to instruct the CCM on reconfigurations.

- **MJ-Interface.** It connects DSONPM and JRRM to provide status information like cell load and other Key Performance Indicators (KPIs) from the JRRM towards the DSONPM.

- **MC-Interface.** It connects DSONPM and CCM and it is used by the DSONPM to instruct the CCM on reconfigurations.

- **JJ-Interface.** It connects different JRRM instances for the exchange of JRRM related information between different nodes.

- **RR-Interface.** It connects different RATs. This can e.g. be the interface used by a GSM, UMTS, LTE, WLAN or other protocol stack in the terminal towards a protocol stack of the same RAT in another terminal or in the network infrastructure.

More detailed descriptions of CSCI and CMON functionalities are illustrated in Figure 3.2 and Figure 3.3, respectively, in the network infrastructure side and in the terminal one [82].

The CSCI is the functional entity in charge of the ON suitability determination phase which allows determining whether or not right conditions are in place for creating an ON. Then, the CSCI delegates the creation, the maintenance and the termination of the ON to the associated CMON functional entity. As it can be observed from Figure 3.2 and Figure 3.3, the CSCI is located in both, the operator infrastructure side (where it is defined as CSCI-N) and the terminal side (where it is defined as CSCI-T). The suitability determination is typically a centralized process with the decision making located in the infrastructure; notwithstanding, in some cases it can be located inside a device. Hence, the decision making in the CSCI can be based on both, infrastructure information provided by functional entities in the network and user/device information given by functional entities from a selected set of devices. The CSCI-N involves Context Awareness (CA), operator policy derivation and profile management which give the input to the decision-making mechanism that establishes the time and the place where it is suitable an ON creation.

The CSCI-T involves CA, operator policy acquisition and profile management which provide the input to the decision-making mechanism as well. In details, the CA functional entity of the CSCI-N involves the monitoring of the status of the infrastructure network, in order to achieve information from the radio environment and to evaluate the necessity to create an ON. This information includes capabilities, status, location, mobility level and supported applications of the candidate nodes. Also the CA functional entity in the CSCI-T is used in order to acquire information for the status of the nodes, which then will be used as input to the decision-making mechanism.

The operator policy derivation and management in the infrastructure side designates high level rules to be followed. These rules are imposed by operators/regulators and involve reconfiguration strategies with the aim to maximize the QoS levels and to minimize the cost factors. In the terminal side, the operator policy derivation and management is replaced by the policy acquisition which is responsible for acquiring the necessary policies defined in the CSCI-N by the operators.

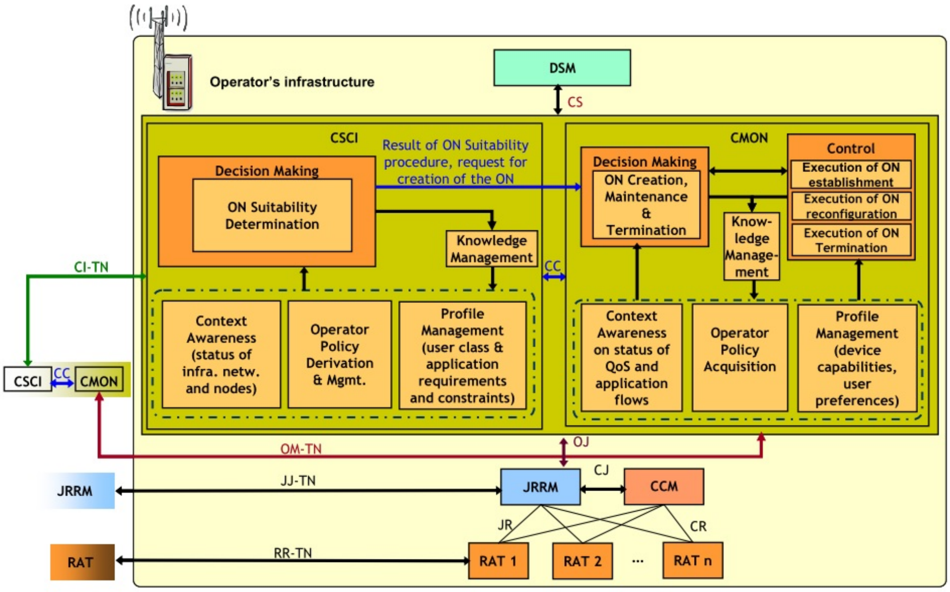


Figure 3.2: CSCI and CMON functionalities Infrastructure side [82]

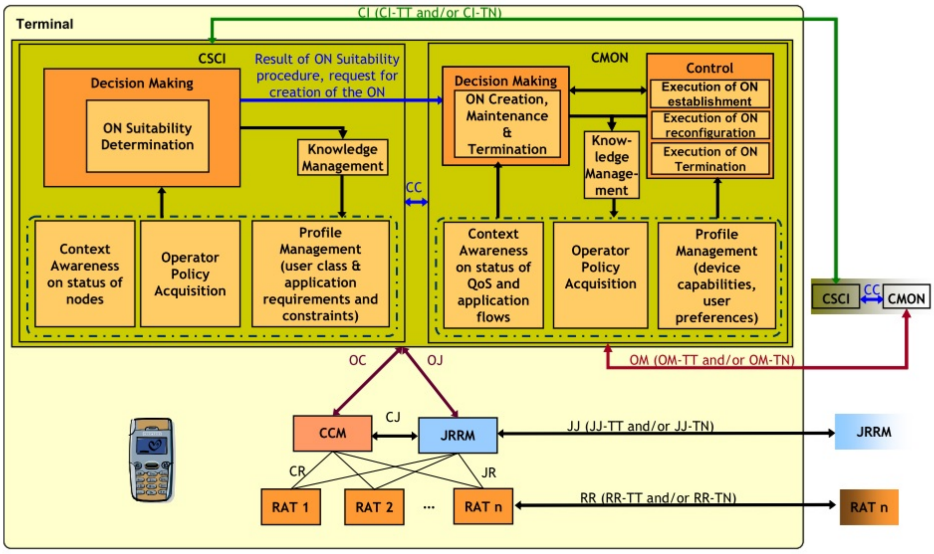


Figure 3.3: CSCI and CMON functionalities Terminal side [82]

The profile management functional entity in the CSCI-N includes preferences, requirements and constraints of user classes and applications which are required for the decision making. In the CSCI-T the profile management functionalities are also included in order to provide details on the user class and application requirements and constraints to the terminals as well.

In case that the conditions and the potential gains by the operation of the ON are satisfied, the result of the ON suitability determination phase achieved by the CSCI entity will be communicated to the CMON one which will manage the creation of the ON. In both entity, CSCI-N and CSCI-T, the ON suitability determination process relies on the Knowledge Management functional entity which connects the decision making with the other ones in order to make better decisions in the future, according to the learned results.

As it has been mentioned, the CMON entity is in charge of ON creation, maintenance and termination according to the information received by the CSCI one. Moreover, the CMON is responsible for the coordination of the nodes in the ON. The CMON is also located in both, the operator infrastructure and the terminal side. Typically, the CMON in the operator infrastructure (defined as CMON-N) involves CA, policy acquisition and profile management which provide the input for the decision making mechanism. In the terminal side, the CMON (defined as CMON-T) provides functionality for the CA, the policy acquisition as defined by the operator and the profile management as well.

The CA functional entity of the CMON-N provides constant feedback of the ON’s experienced QoS to trigger reconfiguration or termination procedures in case of either a detriment of QoS, or the loss of the resources. In details, the CA entity achieves from the radio environment the following information: measurements from radio link layers, geo-location coordinates from device built-in positioning functions, QoS parameters, ON-related device capabilities and context information from specific monitoring mechanisms. While, in the CMON-T the CA provides the status of QoS and application flows to the decision-making mechanism.

The policy acquisition functional entity in both cases, infrastructure and terminal sides, obtains and manages the policies which have been defined by the operator. Policies are used as input during the decision making mechanism for selecting the most appropriate configuration, based on the user profile.

The profile management functional entity involves the device capabilities and user preferences such as: the set of potential configurations (e.g., RATs that the device is capable of operating with); the set of applications/services that can be used; the sets of QoS levels associated with the use of an application/service; the ON-related user preferences associated with the use of an application/service at a particular quality level.

Hence, the decision-making functionality is responsible to handle effectively the ON creation, maintenance and termination according to the input from the CA, policy acquisition and profile management functional entities. According to the derived decision, the control entity illustrated in Figure 3.2 and Figure 3.3 deals with issues such as the execution of ON establishment, reconfiguration and termination.

In details, after the establishment of the ON this entity controls whether to proceed with an ON reconfiguration as defined in the maintenance phase or initiate the handover functionality and release the resources in case of termination. In case of reconfiguration the CCM component will be triggered to control over terminal reconfiguration capabilities. Via the JRRM entity, the CMON will control over communication protocol stacks in the terminals and infrastructure nodes by managing radio layers operation (e.g., radio link setup, radio link configuration) and network layer operation (e.g., route management internal to ON and to/from infrastructure). The contextual and performance parameters collected by the CMON during the life cycle of an ON are used for learning and improving its management functions. Equally, these data are sent to the CSCI for improving the governance functions hosted by this entity.

Also in the case of CMON entity the cognition relies on the fact that the Knowledge Management functional entity interacts with the other ones in order to make better decisions in the future, according to the learned results.

3.2.2 Spectrum Management Solutions for Opportunistic Networks

As it was explained in Section 2.4.3, innovative strategies are needed to carry out the functionalities of the ON life cycle; in that context, this chapter focuses on the spectrum management that is involved in all its stages. During the suitability determination, which is the result of a rough feasibility analysis in order to keep complexity moderate, there is the need to introduce mechanisms leading to the identification of spectrum opportunities ensuring that the resulting interference conditions in the possible future ON will result acceptable. The suitability stage will provide one or several possible configurations for an ON, whose feasibility and potential gains have been roughly estimated. Then, during the creation a detailed analysis (thus probably requiring additional CA and/or more accurate estimations related to several aspects of the radio environment) will be conducted and the spectrum to be assigned will be decided.

The identification of spectrum opportunities during the suitability phase for the creation of an ON can be measured with many different criteria. Some bands may be strictly restricted of such use e.g. based on policies or the node capabilities. There are also characteristics that may make some spectrum band more suitable for the creation of an ON than others. These characteristics may be related e.g. to the other services existing on the frequency band. The selection of the frequency band for the creation of an ON from a set of bands is illustrated in Figure 3.4 [68].

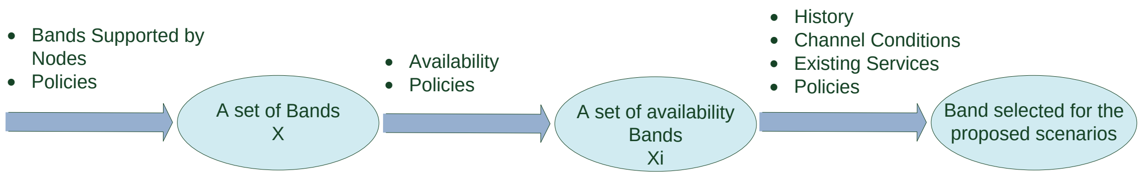


Figure 3.4: Selection of the spectrum band for the creation of an ON

From the figure it can be observed a first set of bands **X** consisting of all possible bands that can be used for creating an ON. From this set another one (i.e. $\mathbf{X_i}$ in the figure) can be obtained after different restrictions depending on the availability of the bands due to: *(i)* policies which determine the allowed frequency bands; *(ii)* bands that nodes are not able to utilize. The method used for checking the availability of the spectrum that lead to the creation of the subset $\mathbf{X_i}$, is mandated by the policies on the different bands. From the subset $\mathbf{X_i}$, the spectrum band for the creation of the ON is selected. This selection is affected by factors such as channel idle time prediction based on history information, policies and channel conditions.

Channel prediction is done by using channel occupancy information from the past time periods. This history information can be obtained e.g. from local database and gathered by sensing nodes that sense the spectrum. The period over which the history information is gathered may vary significantly e.g. over one week or a couple of seconds [69]. This activity can be considered as a form of learning which gives an approximation of the length of the idle time in the vacant channel. This approximation can be used as a criterion for selecting the most suitable spectrum band for the creation of an ON. Longer the idle period, less channel changes need to be performed during the lifetime of an ON. Channel changes introduce additional delay and control signalling at the ON and may result to a decreased QoS experience of the user or even a break in the delivered service in case a new spectrum band is not immediately available.

Spectrum opportunity identification and spectrum selection functionalities should be executed taking as input the frequency bands (i.e. $\mathbf{X_i}$ in Figure 3.4) that are available for establishing communication amongst the ON nodes. Hence, spectrum opportunity identification is crucial to creation and management of ONs and it is one of the key issues in order to achieve communications among the users without causing any interference.

In particular, spectrum opportunity identification functionality can be considered as part of the stage in which the ON achieves the necessary awareness level on its environment to make the appropriate decisions. Such decisions enable to identify the available spectrum bands and associated features that will allow evaluating the necessary elements for the spectrum selection.

Spectrum opportunity identification and spectrum selection functionalities have been a topic of research in different studies. For instance, [83]-[84] proposed energy detection as a means to identify spectrum opportunities; while, in [2] authors focused their attention on a hierarchical dynamic spectrum access model to open licensed spectrum to secondary users while limiting the interference perceived by primary users. In particular, basic components of this work include spectrum opportunity identification, spectrum opportunity exploitation, and regulatory policy. The works in [85]-[89] present different algorithms and protocols for finding and sharing spectrum opportunities in CRNs.

The most relevant contribution of this thesis regarding spectrum management in ON is the design and the implementation of a framework based on the FA illustrated in Section 3.2.1 providing new solutions for spectrum opportunity identification and spectrum selection and their validation in a real-time platform that will be widely illustrated in Chapter 5. This platform is built based on reconfigurable devices able to operate in different frequencies dynamically configured. It allows establishing and monitoring ON radio links, and reconfiguring them based on the changes in the current spectrum conditions. In this way, the real-time platform provides a practical insight for testing different algorithms in real environments, going beyond the purely theoretical analyses based on models and/or simulations.

The spectrum selection solutions can be implemented either in a centralised manner, in which decisions are made by the infrastructure node, or following a decentralised approach, in which decisions are made by the terminals. In this dissertation a fully centralized architecture is considered; therefore, ON management features are attributed to the infrastructure side. Moreover, the spectrum management solutions proposed in this dissertation involve only the creation and maintenance stages of the ON life cycle. In fact, it is assumed that the decision to create an ON among different devices has been previously made in the ON suitability phase, and the set of available bands $\mathbf{X_i}$ have been then selected. Hence, Figure 3.5 focuses on the elements of the FA defined in [82] and implemented for the BCMF developed in this dissertation. These elements include the DSM that executes the spectrum opportunity identification and the CMON-N, which takes as input the result of the spectrum opportunity identification and carries out the spectrum selection in case of ON creation and ON maintenance in the infrastructure side.

Focusing now on the spectrum management, the spectrum opportunity identification solution proposed in this dissertation for ONs and implemented in the DSM executes two different procedures in case of both cases, ON creation and ON maintenance: the measurement procedure and the spectrum block formation.

In the measurement procedure, the total set of bands $\mathbf{X_i}$ is subdivided into N smaller portions of equal band Δf. The measurement policy performs an energy detection sensing (during a period of time Δt) for each Δf portion until measuring the total band, starting from frequency *F_min_band* to *F_max_band*. This measurement is repeated *Num_Meas* times. Then, based on the multiple measurements carried out, the Spectrum Opportunity Index (SOI) is obtained for each portion, defined as the fraction of measurements in which this portion has been detected as available. The power threshold to decide if a portion is free is set based on [90]. In details, this threshold is set as the measured noise plus a margin defined to reduce the probability of false alarm; further details on the computation of the threshold are given in Chapter 5.

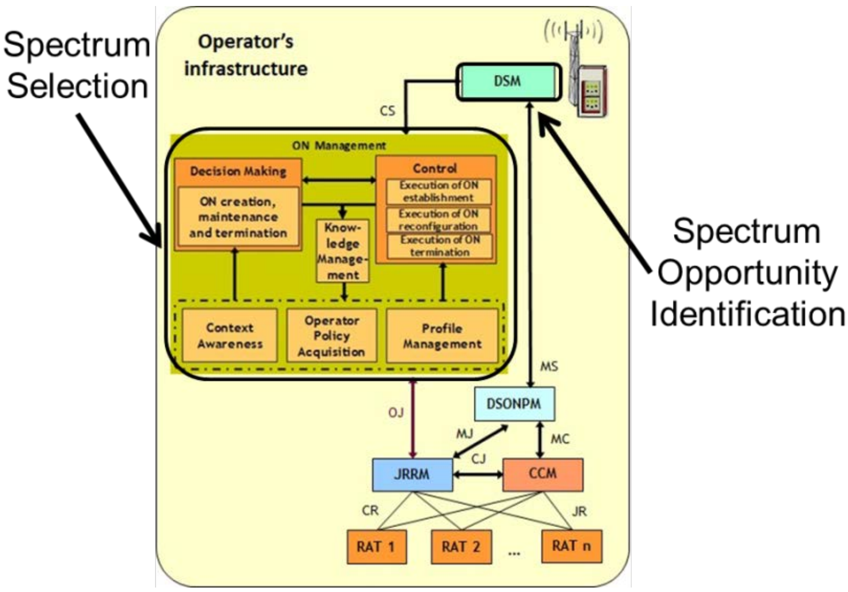


Figure 3.5: FA of the proposed BCMF

In the spectrum block formation procedure, the consecutive spectrum blocks with SOI above a certain threshold are grouped in blocks. Each block is constituted by a number of portions included between the minimum value P_{min} and the maximum one P_{max}. For each block, the procedure returns the 2-tuple $i_k=\{f_k,BW_k\}$ where f_k is the central frequency of the i-th block and BW_k is its bandwidth.

The spectrum selection solution proposed for ONs in this dissertation and implemented in the CMON-N uses as input the set of available spectrum blocks i resulting from the spectrum opportunity identification, together with the characteristics of each block in terms of available bit rate based on radio considerations of both ON creation and ON maintenance cases. The output of this solution will be a list of spectrum assignments to each of the existing ON radio links. Furthermore, this strategy makes use of the fittingness factor concept as a metric between 0 and 1 in order to capture how suitable a specific spectrum block is for a specific radio link [92]. In particular, the strategy relies on the estimation of the fittingness factor for each link and for each available spectrum block based on information statistics for the different channels stored in the Knowledge Management. Starting from the formulation defined in [93], the fittingness factor definition considered in this spectrum selection strategy is given by:

$$f_{j,i} = \frac{1-e^{-\frac{\Gamma \cdot U_{j,i}}{(\xi-1)^{1/\xi}\left(R_{j,i}/R_{req,j}\right)}}}{\lambda} \tag{3.1}$$

where $R_{req,j}$ is the bit rate requested for the activation of link j provided by the JRRM block, $R_{j,i}$ denotes the achievable bit rate by the j-th link in the i-th spectrum block provided by the DSM; Γ and ξ are shaping parameters with the aim to capture different degrees of elasticity with respect to the bit rate requirements; $U_{j,i}$ is the following utility function [94] that relates the achievable and the required bit rates:

$$U_{j,i} = \frac{(\xi-1)\cdot\left(R_{j,i}/R_{req,j}\right)^{\xi}}{1+(\xi-1)\cdot\left(R_{j,i}/R_{req,j}\right)^{\xi}} \tag{3.2}$$

while λ is a normalization factor given by:

$$\lambda = 1-e^{-\frac{\Gamma}{(\xi-1)^{1/\xi}+(\xi-1)^{(1-\xi)/\xi}}} \tag{3.3}$$

The proposed formulation of the fittingness factor increases with the available bit rate $R_{j,i}$ up to the maximum $R_{req,j}$ value and then it starts to smoothly decrease reflecting that it becomes less efficient from a system perspective to have an available bit rate much higher than the required one. In Figure 3.5 different entities composing the CMON-N can be observed; in details, each entity involved in the spectrum selection strategy and its specific role in the execution of this solution are explained in the follow:

- **Control.** It triggers the ON creation to the Decision Making and, after that whether to proceed with an ON reconfiguration decided during the maintenance phase.

- **Context Awareness (CA).** It provides feedback of the QoS experienced by the nodes of the ON to trigger reconfiguration or termination procedures in case of either a detriment of QoS, or the loss of the resources.

- **Knowledge Management.** It stores in a knowledge database the channel occupancy information from past time periods.

- **Decision Making.** It implements the spectrum selection strategy that, considering the set i of spectrum blocks as the result of the spectrum opportunity identification, selects at time t the spectrum block that can guarantee to the link j during its activation the highest fittingness factor in accordance with the statistic information stored in the Knowledge Management. In details, the Decision Making selects the spectrum block $SB_j(t) \in i$ characterized by f_j central frequency and BW_j bandwidth that from time t can guarantee to the link j the following highest fittingness factor:

$$SB_j(t) = \arg\max(f_{j,i}(t)) \tag{3.4}$$

Hence, the proposed spectrum selection solution reassures the assignment of the most suitable spectrum block in terms of requested bit rate among the available ones, resulting from the spectrum opportunity identification strategy, and by exploiting the information stored in the Knowledge Management.

3.3 Evolved Cognitive Management Framework based on POMDPs

The ECMF proposed in this dissertation exploits the DSA/CR cycle paradigm including *observation*, *analysis*, *decision* and *action* in order to perform efficient decision making strategies for spectrum selection in CRNs.

The observation of the radio environment and the analysis of such observations will lead to acquire knowledge about the state of the potential spectrum blocks that can be selected (e.g. the amount of measured interference, their occupation, etc.) as well as their dynamic behaviour (e.g. how the interference changes with time). Observations of the radio environment involve making measurements at several nodes of a CRN. Then, these measurements need to be reported to the node in charge of the decision making. This is usually done through signalling procedures supported by cognitive control channels [81], [95]. As a result, the observation stage can be very costly in terms of practical requirements such as signalling overhead, battery consumption, etc. Consequently, decision making strategies able to efficiently operate with the minimum amount of measurements would be of high interest.

In this respect, in the framework proposed in this section, POMDPs have been considered as decision making strategy since they allow achieving an optimized performance by combining observations at specific periods of time with a statistical characterization of the system dynamics through the belief vector whose elements represent the statistical characterization of the processes. Different decision making criteria for spectrum selection that can be found in the literature rely on databases that record historical information about the occupation in the different channels [96], [97]. This type of information can be used to build predictive models on spectrum availability like in [97]. In [99] an adaptive spectrum decision framework is presented taking into account different type of applications while in [100] a radio resource management method using both long and short term history information is analysed. In [101] the use of reinforcement learning for the detection of spectral resources in a multi-band CR scenario was investigated.

The idea to exploit POMDPs as decision making tool has been considered in several research works. For instance, in [102], [103] opportunistic spectrum access approaches to channels that can be either busy or idle are proposed, assuming a single unlicensed user. While, in [104] the problem was studied to a multi-user scenario through a collaborative approach in which users need to exchange information about their belief vectors at each time slot to generate consistent actions.

The main contributions of this framework respect to the state of the art can be summarized as follows: *(i)* the proposed framework, as a difference from previous works such as [102], [103], does not rely only on binary (i.e., idle/occupied) measurements of the different spectrum blocks but it considers a generalization in which the temporal variation of each spectrum block is able to capture different degrees of interference; *(ii)* the proposed framework inherently considers heterogeneity of the requirements for the different users accessing the spectrum, so that not all the channels are equally appropriate for all the users depending on application needs; *(iii)* the proposed framework captures the multi-user perspective in a centralized way hence having a single decision making point. This allows avoiding the inter-terminal information exchange that would be required in other collaborative decentralized approaches such as [104], where all the terminals need to have knowledge about the state of each other to ensure consistency between the actions taken by each one, which would involve large amounts of signalling; *(iv)* the considered candidate spectrum blocks can belong to different bands allowing different degrees of spectrum sharing with other systems (e.g. non-licensed ISM bands, licensed bands allowing primary/secondary spectrum sharing such as TVWS bands, licensed bands with exclusive use such as those belonging to the mobile network operator in charge of the CRN, etc.). Correspondingly, the channels in each spectrum band can be subject to very different interference conditions.

The strategy considered in this section consists in performing an efficient allocation of the *i*-th spectrum block to the *j*-th radio link by properly matching the bit rate requirements with the achievable bit rate in each spectrum block. This will be conducted by the execution of the spectrum selection decision making, which will take a so-called *action*, corresponding to the allocation of a spectrum block to a radio link, anytime that a data transmission session is initiated on this radio link. The action made for the *j*-th link at time *t* is denoted as $a_j(t) \in \{1,..., M\}$ and corresponds to the selected spectrum block among those currently available.

The considered interference model denotes as $I_{j,i}(t)=I_{max,j,i} \cdot \sigma_i(t)$ the interference spectral density measured by the receiver of the *j*-th link in the *i*-th spectrum block at a given time due to other external transmitters (i.e. outside the control of the decision making entity). In order to capture that interfering sources may exhibit time-varying characteristics, $\sigma_i(t)$ is a spectrum block-specific term between 0 and 1 (i.e. $\sigma_i(t)=0$ when no interference exists and $\sigma_i(t)=1$ when the interference reaches its maximum value $I_{max,j,i}$). For modelling purposes, it is considered that the set of possible values of $\sigma_i(t)$ is translated into a discrete set of interference states $S^{(i)}(t) \in \{0,1,..., K\}$ where state $S^{(i)}(t)=k$ corresponds to $\sigma_{k-1}<\sigma_i(t)<\sigma_k$ for $k>0$ and to $\sigma_i(t)=\sigma_0=0$ for $k=0$. Note also that $\sigma_K=1$. The system state at time *t* is then given by the M-column vector $S(t)=[S^{(i)}(t)]$. Moreover, assuming that the state of each spectrum block remains the same for a time step of duration Δt, the interference evolution for the *i*-th block is modelled as a discrete-time Markov process with the state transition probability from state *k* to *k'* given by:

$$p_{k,k'}^{(i)} = \Pr\left[S^{(i)}\left(t+\Delta t\right) = k' \middle| S^{(i)}\left(t\right) = k \right] \tag{3.5}$$

It is assumed that the state of the *i*-th spectrum block $S^{(i)}(t)$ evolves independently from the other blocks, and that the state evolution is independent from the assignments made by the spectrum selection strategy. The execution of the spectrum selection decision-making strategy proposed in this framework results into actions corresponding to the allocation of spectrum blocks to the different radio links. The action made for link *j* at time *t* is denoted as $a_j(t) \in \{1,..., M\}$ and corresponds to the selected spectrum block among those currently available (i.e. not allocated to other links). It is assumed that an action is taken for a given link at any time that a data transmission session is initiated on this radio link. As a consequence of the different actions and resulting spectrum block assignments, each radio link with a data session in course (i.e., an active link) will obtain a reward that measures the obtained performance depending on the interference state of the spectrum block at each time. Then, let denote $r^{(i)}_{j,S^{(i)}(t)}$ the reward that the *j*-th link gets at time *t* when using its allocated spectrum block *i* and the interference state is $S^{(i)}(t)$.

The reward is defined as a metric between 0 and 1 capturing how suitable the *i*-th spectrum block is for the *j*-th radio link/application, depending on the bit rate that can be achieved in this block with respect to the bit rate required by the application $R_{req,j}$. Several possible definitions of the reward metric as a function of the bit rate may exist such as sigmoid functions, linear functions or fittingness factor. The reward function considered in this framework is based on the fittingness factor defined in Section 3.2.2. Hence, the definition of the reward can be formulated starting from equation (3.1) and taking into account also the state *k* as follows:

$$r^{(i)}_{j,k} = \frac{1 - e^{-\frac{\Gamma \cdot U_{j,i,k}}{(\xi-1)^{1/\xi}\left(R_{j,i,k}/R_{req,j}\right)}}}{\lambda} \qquad (3.6)$$

where it can be observed that in this case the parameter $R_{j,i,k}$, and consequently $U_{j,i,k}$, depend also on the state *k*.

The total system reward $T_R(t)$ is then given by the sum of rewards of all the active links at time *t*. As a general target, the spectrum selection decision making should follow the optimal policy that maximizes the performance in terms of the expected long-term total system reward $T_R(t)$ accumulated over a certain time horizon tending to infinity. For this purpose, the decision making entity would ideally need to know the actual interference state of all the spectrum blocks at time *t*. However, this would impact in terms of increasing signalling overheads and battery consumption to perform all the required *observations* and report them to the decision-making entity. To overcome this issue, this framework proposes to make the *decisions* based on a statistical characterization of the interference state of the different spectrum blocks rather than on actual exhaustive observations. In the proposed solution, observations about the interference state of the spectrum blocks are carried out only at specific time instants defined according to a certain observation strategy. In this case, due to the partial knowledge that the decision making process has about the actual interference state of the spectrum blocks, the spectrum selection process can be modelled as a POMDP and the statistical characterization of the spectrum blocks at time *t* is given in terms of the belief vector $\Upsilon(t)=[b^{(i)}_k(t)]$ where component $b^{(i)}_k(t)$ is the probability that the *i*-th block will be in state $S^{(i)}(t)=k$ at time *t*.

In a POMDP the complexity associated to finding the optimal policy that maximizes the expected long-term system reward can be prohibitive, mainly because the number of states $(K+1)^M$ grows exponentially with the number of spectrum blocks. Consequently, in this framework the so-called myopic policy that maximizes the immediate system reward $T_R(t+\Delta t)$ is proposed for the *analysis* phase. It is worth mentioning that myopic policies have been found in some works to be optimal under certain conditions [105]. More specifically, considering that the spectrum block selection is made at time t for just one link j and among the set of available blocks, the selection will not impact on the immediate reward of any other link and the myopic spectrum selection policy becomes:

$$a_j(t) = \arg \max_{\substack{i \in \{1,\ldots,M\} \\ i \text{ available}}} E\left[T_R(t+\Delta t)\right] = \arg \max_{\substack{i \in \{1,\ldots,M\} \\ i \text{ available}}} E\left[r^{(i)}_{j,S^{(i)}(t+\Delta t)}\right] \quad (3.7)$$

The expected reward $E\left[r^{(i)}_{j,S^{(i)}(t+\Delta t)}\right]$ is computed using the belief vector values at time t and the state transition probabilities that the spectrum block i is in state k at time t and jumps to state k' in the next period $t+\Delta t$. Then, the decision policy is formulated as:

$$a_j(t) = \arg \max_{\substack{i \in \{1,\ldots,M\} \\ i \text{ available}}} \sum_{k=0}^{K} b^{(i)}_{k}(t) \sum_{k'=0}^{K} p^{(i)}_{k,k'} \cdot r^{(i)}_{j,k'} \quad (3.8)$$

The FA envisaged to implement the ECMF, which is based on the ETSI's one [83], is illustrated in Figure 3.6; specifically, it provides the spectrum selection policy considered in this section and it is characterized by the following entities:

- **Knowledge Management.** It includes the Knowledge Database (KD) and the Knowledge Manager (KM). The KD stores the information about the state transition probabilities $p^{(i)}_{k,k'}$, the reward values $r^{(i)}_{j,k}$ and belief vectors $b^{(i)}_{k}$. While the KM is in charge of updating the belief vector values $b^{(i)}_{k}(t)$ with time resolution Δt in accordance with the discrete-time Markov process that models the interference state in each spectrum block. To perform this update, the knowledge about the real interference of the spectrum blocks obtained through observations performed at certain time instants can be exploited to obtain a more accurate estimation of the probability that the i-th block will be in state k at a later time. More precisely, let define as $o^{(i)}(t)$ the observation made at time t in the spectrum block i. This observation is needed to provide the actual interference state of the spectrum block, that is $o^{(i)}(t)=k$. Using the available observations $o^{(i)}(t)$, the values of $b_k^{(i)}(t)$ are updated for all the spectrum blocks every Δt as follows:

$$b^{(i)}_{k'(t+\Delta t)} = \begin{cases} p^{(i)}_{k,k'} & \text{if } (o^{(i)}(t)=k) \\ \sum_{n=0}^{K} p^{(i)}_{n,k'} \cdot b^{(i)}_{n(t)} & \text{otherwise} \end{cases} \tag{3.9}$$

The first condition in (3.9**)** corresponds to the spectrum blocks for which an observation is performed at time t providing the actual interference state of the spectrum block (i.e. $o^{(i)}(t)=k$). Then, the probability $b_{k'}^{(i)}(t+\Delta t)$ that spectrum block i will be in state k' in the next time period $t+\Delta t$ is simply given by the state transition probability $p^{(i)}_{k,k'}$. In turn, the second condition in (3.9**)** corresponds to those spectrum blocks for which no observation has been performed at time t. In this case, the actual interference state is not known and thus the value $b_{k'}^{(i)}(t+\Delta t)$ is computed probabilistically from the belief values $b_n^{(i)}(t)$ and the state transition probabilities to state k'. According to the above, an observation strategy is required in the Decision Making entity to determine the time instants in which the observations of the different spectrum blocks must be triggered.

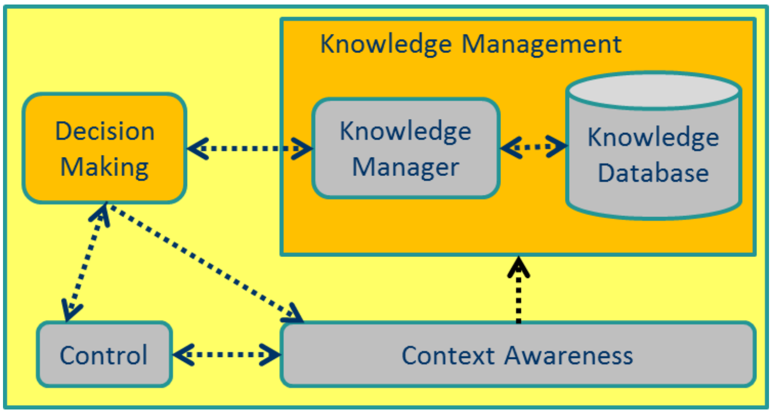


Figure 3.6: FA of the proposed ECMF

- **Decision Making.** It is in charge of selecting the most appropriate spectrum block each time that a new session is established in a certain radio link following the decision policy (3.8). Furthermore, in the framework illustrated in this section the observation strategy implemented in the Decision Making triggers the execution of the observations with a certain time period defined as T_{obs} for all the spectrum blocks. In order to assess the performance of the proposed POMDP-based approach, the following reference strategies have been also implemented in the Decision Making:

- ✓ **Full Observation spectrum selection strategy (FO)**. This strategy performs an observation of the actual interference state $S^{(i)}(t)$ for all the available spectrum blocks (i.e. those that are not allocated to any link) whenever a new link establishment is required. Then, the spectrum block that provides the highest reward is allocated, that is:

$$a_j(t) = \arg \max_{\substack{i \in \{1,\ldots,M\} \\ i \text{ available}}} r^{(i)}_{j,S^{(i)}(t)} \tag{3.10}$$

- ✓ **Steady state probabilities-based spectrum selection strategy (PR)**. This strategy makes the decisions based on the steady state probabilities $\pi_k^{(i)}$ that simply measure the probability that the spectrum block i will be in state k. Hence, the decision policy is then formulated in a similar way as for the POMDP-based strategy in (3.8) but with the static values of $\pi_k^{(i)}$ instead of the dynamic values of the belief vector, that is:

$$a_j(t) = \arg \max_{\substack{i \in \{1,\ldots,M\} \\ i \text{ available}}} \sum_{k=0}^{K} \pi_k^{(i)} \sum_{k'=0}^{K} p^{(i)}_{k,k'} \cdot r^{(i)}_{j,k'} \tag{3.11}$$

- **Context Awareness (CA).** It is in charge of performing the observations $o^{(i)}(t)$ through measurements of the interference states k of the set i of spectrum blocks triggered by the Decision Making entity every T_{obs}; then, the CA provides to the KM the knowledge about the real interference of the spectrum blocks achieved through the execution of the observations. Measurements are also needed for acquiring the statistics of the state transition probabilities and of the rewards stored in the KD. The values of $p^{(i)}_{k,k'}$ and $r^{(i)}_{j,k}$ can be obtained based on some initial acquisition mechanisms including measurements of the different links and spectrum blocks. The details on how to perform this acquisition as well as the capability to update the stored values whenever relevant changes are detected are out of the scope of this framework. The dynamic acquisition of unknown transition probabilities will be defined in the final version of this framework illustrated in Section 3.4.

- **Control.** It handles message exchange between the terminals and the Decision Making to support the establishment/release of radio links. Moreover, this entity can exchange the necessary signalling messages with any node that requests to the CA measurements of the radio environment.

a) POMDP Observation Strategy

Next the impact of the observation strategy implemented in the Decision Making entity to determine the time instants in which the observations of the different spectrum blocks are realized is examined. In fact, if measurements are made very often, this will turn into a more accurate knowledge of the actual system state that will impact on making better decisions thus resulting in better performance. On the contrary, this will increase the cost in terms of sensing requirements and signalling overheads to report the measurement results. Hence, a trade-off arises between performance and measurement cost. To account for the above trade-offs, the following POMDP-based observation strategies have been also proposed, implemented and assessed in the Decision Making entity:

- **Periodic Observation strategy.** This strategy supports the POMDP-based decision making of equation (3.8) by means of observations triggered periodically every T_{obs} for all the spectrum blocks that are not allocated to any link.

- **Adaptive Observation strategy.** This strategy supports the POMDP-based decision making of equation (3.8) by means of observations whose periodicity is adaptively varied depending on the dynamics of each spectrum block. In particular, assuming that the last observation made for the *i*-th spectrum block at time *t* indicated that the real interference state was *k*, the next observation will be triggered by the Decision Making entity at time $t+T_{obs}(i,k)$. The period $T_{obs}(i,k)$ is computed based on the expected duration of the *k*-th interference state obtained from the transition probabilities for the *i*-th spectrum block:

$$T_{obs}(i,k) = \tau \frac{\Delta t}{1 - p_{k,k}^{(i)}} \tag{3.12}$$

  where τ is a coefficient to be selected ($0 < \tau \leq 1$).

Moreover, in both approaches, measurements are triggered by the Decision Making entity for non-used spectrum blocks, while allocated blocks will be measured at the time when they are released if the time elapsed since the last observation is higher than $T_{obs}(i,k)$.

3.4 Final Cognitive Management Framework based on Belief-vector

The ECMF based on the POMDPs has been extended towards the FCMF in order to exploit the belief vector as a long-term means to characterize and predict the environment dynamics. Therefore, key elements to achieve a smart characterization of the scenario dynamicity have been included in this version of the framework.

In the ECMF illustrated in Section 3.3 the observation strategies based on partial observations implemented in the Decision Making entity allow triggering an observation at time t (i.e., $o^{(i)}(t)$) that gives the interference state k used to update the belief vector of the spectrum blocks through a prediction made only for the next time step $t+\Delta t$. While, in the proposed FCMF the use of the belief vector in the spectrum selection decision making strategy is exploited in order to carry out a long-term prediction of the interference dynamic of the spectrum blocks. In fact, as long as the belief vector predicts with sufficient accuracy the existing conditions at the decision making time, smart and proper decisions can be made with minimum requirements in terms of observations. Moreover, further observation strategies have been considered associated to the dynamicity of the scenario besides the POMDPs. In particular, such strategies determine the instants when measurements on the radio environment need to be performed. Hence, in the FCMF the prediction of the environment will enable to choose the most appropriate observation strategy and the associated spectrum selection decision-making criterion broadening the concept of partial observations considered in the ECMF, and then balancing the trade-off between performance and measurement requirements.

Firstly, it will be described how the POMDP-based decision making strategy of equation (3.8) is extended in order to exploit the belief vectors of the spectrum blocks for long-term predictions; then, it will be illustrated the introduction of the new entities in the FA introduced in Section 3.3 that enable to smartly characterize the scenario dynamicity in the FCMF and how they interact with the existing modules of the FA defined to implement the ECMF.

The main contributions of this solution respect to the framework proposed in Section 3.3 are the following: *(i)* the FCMF exploits the belief vector concept for long-term prediction of the environment dynamics in terms of traffic generation patterns and interference states durations. Furthermore, it does not consider only the POMDPs but it takes into consideration different observation strategies to determine the instants when measurements on the radio environment need to be performed assessing the trade-off existing between performance and observation requirements of the cognitive cycle; *(ii)* the ECMF proposed in Section 3.3 relies only on simulation studies. While in the FCMF, after a previous simulation analysis with the aim to assess the effectiveness of the new definition of the spectrum selection policy, the framework has been designed, developed and evaluated also by means of a real-time testbed; *(iii)* the FCMF allows acquiring dynamically all the transition probabilities stored in the KD by means of real-time measurements of the spectrum blocks interferences.

The interference model and its time evolution is the same as the one defined in the ECMF. Considering the state transition probability given for the i-th spectrum block from state k to k' given by equation (3.5), the state transition probability matrix for the i-th spectrum block is:

$$\mathbf{P^{(i)}} = \begin{bmatrix} p_{0,0}^{(i)} & p_{0,1}^{(i)} & \cdots & p_{0,K}^{(i)} \\ p_{1,0}^{(i)} & p_{1,1}^{(i)} & & p_{1,K}^{(i)} \\ \vdots & & \ddots & \vdots \\ p_{K,0}^{(i)} & p_{K,1}^{(i)} & \cdots & p_{K,K}^{(i)} \end{bmatrix} \quad (3.13)$$

Moreover, let define $\boldsymbol{\pi}^{(\mathbf{i})} = \left[\pi_0^{(i)} \quad \pi_1^{(i)} \quad \cdots \quad \pi_K^{(i)}\right]^{\mathbf{T}}$, where superscript T denotes transpose operation, as the steady state probability vector whose k-th component is the probability that the i-th spectrum block is in the k-th interference state. Each radio link with a data session in course will obtain the reward defined in equation (3.6) that measures the obtained performance for the j-th link depending on the interference state k of the allocated spectrum block i at each time t. Using vector notation, the reward is $\mathbf{r_j^{(i)}} = \left[r_{j,0}^{(i)} \quad r_{j,1}^{(i)} \quad \cdots \quad r_{j,K}^{(i)}\right]^{\mathbf{T}}$. Considering equation (3.6), the average reward experienced on the j-th link and i-th spectrum block along a session starting to transmit data at time t+1 and ending after a certain duration D_j time steps, can be defined as:

$$r_{SESSION,j}^{(i)} = \frac{1}{D_j}\sum_{n=1}^{D_j} r_{j,S^{(i)}(t+n)}^{(i)} \quad (3.14)$$

Therefore, the spectrum selection policy proposed in equation (3.7) and executed at time t for the j-th radio link is redefined here to target the maximization of the expected reward that the session will experience along its overall duration:

$$a_j(t) = \arg \max_{\substack{i\in\{1,\dots,M\} \\ i \text{ available}}} E\left[r_{SESSION,j}^{(i)}\right] = \arg \max_{\substack{i\in\{1,\dots,M\} \\ i \text{ available}}} E\left[\frac{1}{D_j}\sum_{n=1}^{D_j} r_{j,S^{(i)}(t+n)}^{(i)}\right] \quad (3.15)$$

To be able to estimate the interference state of the different spectrum blocks at future time instants t+n, measurements (observations) carried out at specific time instants in the past, together with the statistical characterization of the interference dynamics in each spectrum block will be exploited. In particular, given the observation on the i-th spectrum block $o^{(i)}(t-m^{(i)})$ conducted at time step $t-m^{(i)}$ that provides the value of the interference state of the i-th spectrum block measured at time step $t-m^{(i)}$, i.e. $o^{(i)}(t-m^{(i)})=S^{(i)}(t-m^{(i)})$, equation (3.15) can be reformulated in order to exploit knowledge from the observations in the past as:

$$a_j(t) = \arg \max_{\substack{i\in\{1,\dots,M\} \\ i \text{ available}}} \Phi_j^{(i)}(t) \tag{3.16}$$

where $\Phi_j^{(i)}(t)$ is the spectrum block-dependent decision function to be maximized, given by:

$$\Phi_j^{(i)}(t) = \frac{1}{\overline{D_j}} \sum_{n=1}^{\overline{D_j}} E\left[r_{j,S^{(i)}(t+n)}^{(i)} \middle| o^{(i)}\left(t-m^{(i)}\right) = S^{(i)}\left(t-m^{(i)}\right) \right] \tag{3.17}$$

Notice that, given that the session duration D_j will usually be random and unknown at the decision making time t, it has been characterized statistically in (3.17) in terms of its average value $\overline{D_j}$. In (3.17), the estimation of the expected reward achieved in the i-th spectrum block at future time instants $t+n$ based on the past observation at $t-m^{(i)}$ will rely on the statistical characterization of the interference dynamics given by the belief values defined in the vector version as $\mathbf{b}^{(\mathbf{i})}(t) = \left[b_0^{(i)}(t) \quad b_1^{(i)}(t) \quad \cdots \quad b_K^{(i)}(t) \right]^{\mathbf{T}}$. If the last observation was taken at time step $t-m^{(i)}$, the component $b_k^{(i)}(t)$ is defined as:

$$b_k^{(i)}(t) = \Pr\left[S^{(i)}(t) = k \middle| o^{(i)}\left(t-m^{(i)}\right) = S^{(i)}\left(t-m^{(i)}\right) \right] \tag{3.18}$$

Then, the expected reward obtained in the i-th spectrum block at time $t+n$ can be expressed in terms of the belief vector as:

$$E\left[r^{(i)}_{j,S^{(i)}(t+n)} \middle| o^{(i)}\left(t-m^{(i)}\right)=S^{(i)}\left(t-m^{(i)}\right)\right]=\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t+n\right)\mathbf{r}^{(\mathbf{i})}_{\mathbf{j}} \quad (3.19)$$

By making use of (3.17) the estimation of the average reward achieved in the *i*-th spectrum block along the session duration of the *j*-th radio link given by the decision function (3.16) can be expressed in terms of the belief vector as:

$$\Phi^{(i)}_j\left(t\right)=\frac{1}{\overline{D_j}}\sum_{n=1}^{\overline{D_j}}\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t+n\right)\mathbf{r}^{(\mathbf{i})}_{\mathbf{j}} \quad (3.20)$$

Notice that in equations (3.16) and (3.20) the new version of the decision policy exploits the belief vectors of the spectrum blocks for all the session duration of the *j*-th link. Moreover, the decision function $\Phi^{(i)}_j\left(t\right)$ will be particularized for different observation strategies going beyond the consideration of the only concept of partial observations exploited in the first version of the framework.

Figure 3.7 illustrates the extended FA of the FCMF related with the belief-based spectrum selection problem considered in this section to implement the decision-making criterion given by (3.16) and (3.20).

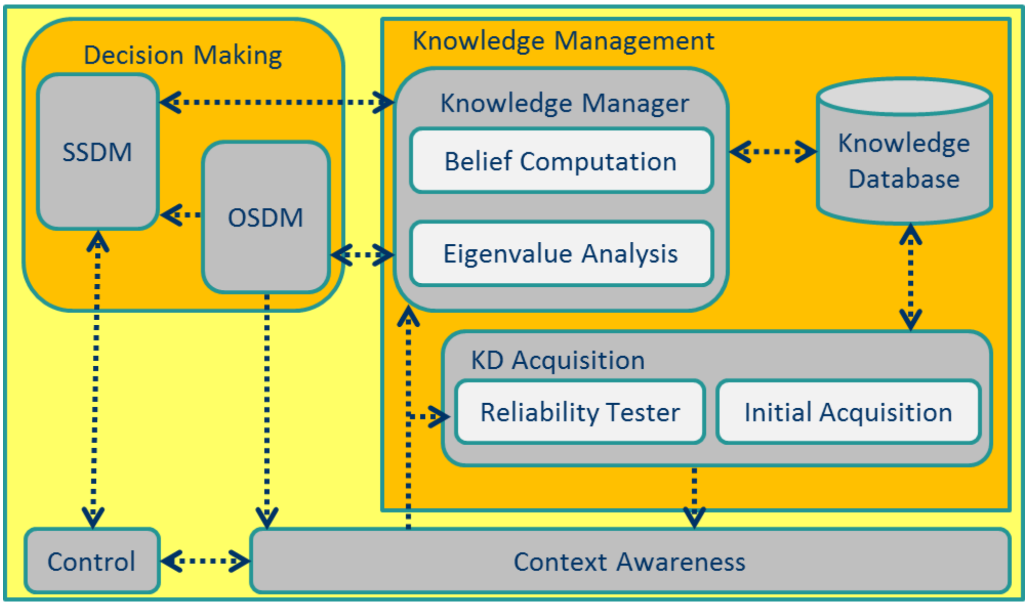


Figure 3.7: Extended FA of the proposed FCMF

From Figure 3.7 it can be noticed that the Decision Making entity is now split into two main decision processes: the Spectrum Selection Decision Making (SSDM), which is responsible for deciding the spectrum to be assigned to each link and implements the decision making criterion given by (3.16) and (3.20), and the Observation Strategy Decision Making (OSDM), which is in charge to select the observation strategy that particularizes (3.20), then that specifies the time instants when measurements have to be carried out in each spectrum block. While the KM is now spit into the following entities: the Belief Computation that updates the belief vectors of the spectrum blocks through observations performed at certain time instants, and the Eigenvalue Analysis, which as it will be widely explained throughout this section, characterizes the impact of the scenario dynamicity through the eigenvalue concept in terms of interference on the belief vector updating. Finally, the knowledge management is strengthened by the inclusion of the KD Acquisition entity that triggers the collection of measurements to fill the KD and to verify the correctness of the stored information to deal with changes in the stationary conditions of the environment. The entities of the FA are illustrated in depth in the following.

i. Knowledge Management entity

This entity collects, processes and stores the necessary information from the environment to drive the decision-making process. Therefore, it is based on the characterization of the spectrum blocks in terms of their interference states and associated rewards. It includes the following entities:

- **Knowledge Database**. This entity stores information about the operational environment; in particular, it stores: (1) the state transition probability matrix $\mathbf{P}^{(\mathbf{i})}$ for the different spectrum blocks; (2) the steady state probability $\boldsymbol{\pi}^{(\mathbf{i})}$ for the different spectrum blocks; (3) the vectors $\mathbf{r}_{\mathbf{j}}^{(\mathbf{i})}$ with the values of the reward that the different radio links can obtain in each spectrum block for each interference state; (4) the last observation $o^{(i)}(t-m^{(i)})=S^{(i)}(t-m^{(i)})$ of the actual interference state of the i-th spectrum block that was measured at time step $t-m^{(i)}$.

- **Knowledge Manager**. It processes the statistics and measurements contained in the KD to extract the relevant information that will support the decision making process. It consists of the following modules:

  ✓ **Belief Computation.** This module basically keeps the functionality implemented in the first version of the KM of updating the belief vector values for each spectrum block and providing the result to the Decision Making entity each time that a new spectrum selection has to be made. In this case, the computation of the belief vector of the i-th spectrum block at a certain time instant t is done recursively starting from the last observation of the actual interference state that was taken at time step $t-m^{(i)}$. In details, considering that $o^{(i)}(t-m^{(i)})=S^{(i)}(t-m^{(i)})$ the components of the belief vector at time $t-m^{(i)}$ are given by:

$$b_k^{(i)}\left(t-m^{(i)}\right)=\begin{cases}1 & \text{if} \quad k=S^{(i)}\left(t-m^{(i)}\right)\\ 0 & \text{otherwise}\end{cases} \tag{3.21}$$

This is expressed in vector notation as:

$$\mathbf{b}^{(\mathbf{i})}\left(t-m^{(i)}\right)=\mathbf{x}\left(S^{(i)}\left(t-m^{(i)}\right)\right) \tag{3.22}$$

where $\mathbf{x}(k)$ is defined as a column vector of K+1 components numbered from 0 to K that has all of them equal to 0 except the k-th component that is equal to 1. Then, the belief vector at a time instant t > $t-m^{(i)}$ can be obtained from the belief vector at the previous time step t-1 making use of the state transition probability matrix as:

$$\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t\right)=\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t-1\right)\cdot\mathbf{P}^{(\mathbf{i})} \tag{3.23}$$

By recursively applying (3.22) for the last $m^{(i)}$ time steps and by making use of (3.21) the belief vector at time t as a function of the last observation is given by:

$$\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t\right)=\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t-m^{(i)}\right)\left[\mathbf{P}^{(\mathbf{i})}\right]^{m^{(i)}}=\mathbf{x}^{\mathbf{T}}\left(S^{(i)}\left(t-m^{(i)}\right)\right)\left[\mathbf{P}^{(\mathbf{i})}\right]^{m^{(i)}} \tag{3.24}$$

To compute the decision function (3.20) at time t the belief vector needs to be extrapolated to future time instants t+n. This can be done easily from (3.22) leading to:

$$\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t+n\right)=\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t\right)\left[\mathbf{P}^{(\mathbf{i})}\right]^{n} \tag{3.25}$$

- ✓ **Eigenvalue Analysis.** The introduction of this block is decisive for the long term prediction of the belief vector. In fact, the accuracy of the prediction of the future interference state in the i-th spectrum block at time $t+n$, given by the belief will depend on the total time elapsed since the last measurement on this spectrum block, i.e. $n+m^{(i)}$ time steps, as well as on the dynamism and randomness exhibited by the interference conditions affecting the i-th spectrum block. Clearly, in highly random environments where the interference level changes very often in a low predictable way, if $n+m^{(i)}$ is large, it can be expected that the accuracy of $\mathbf{b}^{(i)T}(t+n)$ will be low and, given that the belief is driving the decision making process in (3.20), the spectrum selection may take wrong decisions (e.g., assign the i-th spectrum block to a radio link expecting that the interference observed in the future will be low while the reality could be that a high interference level will be observed). On the contrary, for rather static environments where interference level remains stable for long periods of time or varies according to highly predictable patterns, the accuracy of the belief will be high even though $n+m^{(i)}$ is large. Therefore, the Eigenvalue Analysis module will be in charge of characterizing the degree of predictability associated to the dynamism exhibited by the radio environment. This characterization will be used to ensure, by means of a smart observation strategy, that the elapsed time $n+m^{(i)}$ is adequate enough to make accurate decisions based on (3.20). For this purpose, the outcome of this module will be a metric reflecting the degree of predictability of the scenario to be used when deciding the appropriate observation strategy. As explained in the following, this metric results from the analysis of the eigenvalues of the state transition probability matrices. To characterize the impact of the scenario dynamicity on the belief vector computation, let start by analysing the belief vector evolution depending on the time $m^{(i)}$ elapsed since the last observation of a certain spectrum block. In that respect, it can be easily proved that, if $m^{(i)}$ tends to infinity, meaning that there are no observations in this spectrum block, the belief vector tends to the steady state probability vector, that is:

$$\lim_{m^{(i)}\to\infty} \mathbf{b}^{(\mathbf{i})\mathrm{T}}(t) = \lim_{m^{(i)}\to\infty} \left[\mathbf{b}^{(\mathbf{i})\mathbf{T}}\left(t - m^{(i)}\right)\left[\mathbf{P}^{(\mathbf{i})}\right]^{m^{(i)}} \right] = \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \tag{3.26}$$

The proof of (3.26) is a straightforward application of a well-known property of ergodic discrete time Markov processes [106]. It states that, for a Markov process with state transition probability matrix $\mathbf{P}^{(\mathbf{i})}$, steady state probability vector $\boldsymbol{\pi}^{(\mathbf{i})}$ and any vector $\mathbf{y}$ representing an initial state probability distribution, the following relationship holds:

$$\lim_{n\to\infty} \mathbf{y}^{\mathbf{T}} \left[\mathbf{P}^{(\mathbf{i})}\right]^{n} = \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \tag{3.27}$$

Then, (3.26) is obtained simply by considering $\mathbf{y} = \mathbf{b}^{(i)}(t-m^{(i)})$. From (3.27) condition (3.26) can also be expressed in terms of the future evolution of the belief vector as:

$$\lim_{n\to\infty}\mathbf{b}^{(\mathbf{i})\mathrm{T}}(t+n) = \lim_{n\to\infty}\left[\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t)\left[\mathbf{P}^{(\mathbf{i})}\right]^{n}\right] = \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \tag{3.28}$$

The convergence speed of $\mathbf{b}^{(i)T}(t)$ towards the steady-state reflected in (3.26) and (3.28) will be associated with the interference dynamics in the *i*-th SB captured in the state transition matrix $\mathbf{P}^{(i)}$. If interference varies slowly it is more likely to have at time $t+n$ similar conditions as those existing at time t (i.e. $\mathbf{b}^{(i)T}(t)$ will be more similar to $\mathbf{b}^{(i)T}(t+n)$) than if interference varies quickly. To capture this effect based on the properties of $\mathbf{P}^{(i)}$ the following theorem can be employed:

Theorem 1: The absolute value of the second highest eigenvalue of matrix $\mathbf{P}^{(i)}$ *denoted as* $\left|\lambda_1^{(i)}\right|$ *drives the convergence of the belief vector* $\mathbf{b}^{(i)T}(t)$ *towards the steady state. The lowest the value of* $\left|\lambda_1^{(i)}\right|$ *the faster will be the convergence.*

Moreover, to estimate the time needed for reaching convergence, the following corollary is defined:

Corollary 1: The convergence time of the belief vector $\mathbf{b}^{(i)T}(t)$ *towards the steady state can be roughly estimated as* $-1/\ln\left|\lambda_1^{(i)}\right|$.

The theorem and the corollary are demonstrated in Appendix A. Based on the theorem and on the corollary, the Eigenvalue Analysis entity will evaluate the values of $\left|\lambda_1^{(i)}\right|$ for the different spectrum blocks making use of the state transition matrices stored in the KD and will take them as representative values of the degree of predictability associated to the dynamism exhibited by the radio environment. Then, these values will be used by the Decision Making entity to select the observation strategy to be used.

- **Knowledge Database Acquisition**. The KD acquisition entity is responsible of filling the KD contents with the statistics illustrated before. This entity involves the following two main functionalities:

  - ✓ **Initial Acquisition.** This corresponds to the measurement acquisition process to fill the KD with the values of the state transition probability matrices $\mathbf{P}^{(i)}$ for the different spectrum blocks, the steady state probabilities $\boldsymbol{\pi}^{(i)}$ and the reward vectors $\mathbf{r}_{\mathbf{j}}^{(\mathbf{i})}$ that will be used during the system operation. These values will be computed by measuring the durations of the interference states in the different spectrum blocks and the associated rewards in the different radio links, in order to get multiple time samples of each parameter to be acquired (e.g. the values of the state transition probabilities, steady state probabilities, etc.). The details on the estimation of each parameter will be provided in Chapter 5.

- ✓ **Reliability Tester (Stationarity Analysis)**. Once the acquisition phase has been completed, the resulting values of the above parameters will be kept in the KD and they will be assumed to be valid as long as the stationary conditions of the environment do not change significantly with respect to the existing conditions at the time when statistics were taken. In case of non-stationary environments, in which the statistical behaviour of the interference in the different spectrum blocks may change after some time, the system needs to implement mechanisms to detect these relevant changes and trigger again the KD acquisition process so that statistics are properly updated. The details on this procedure are, however, out of the scope of this dissertation. As a reference, the hypothesis testing mechanism proposed in [107] to detect this type of changes could be easily adapted to work in the proposed framework.

ii. Decision Making entity

The Decision Making entity involves SSDM and OSDM entities that are illustrated in the following.

- **Observation Strategy Decision Making (OSDM)**. The observation strategy specifies the time instants when the actual interference state in each spectrum block is measured. Then, the OSDM functionality is in charge of selecting the observation strategy to be applied in each spectrum block. The observation strategy should make sure that the time $m^{(i)}$ elapsed between the last observation and the spectrum selection decision-making time t is adequate enough to compute the belief vector $\mathbf{b}^{(i)\mathbf{T}}(t+n)$ and make accurate decisions based on (3.20). As explained in the previous section this will be related with the interference dynamics in each spectrum block. Therefore, the OSDM functionality will make use of the eigenvalues $\left|\lambda_1^{(i)}\right|$ associated to each spectrum block provided by the Eigenvalue Analysis function. In addition, the estimation of the belief vector $\mathbf{b}^{(i)\mathbf{T}}(t+n)$ at the future time instants $t+n$ depends also on the application duration D_j, which will establish the maximum time horizon n over which the belief vector needs to be estimated. To take this into account, the OSDM will also make use of the traffic characterization in terms of the average session duration for all the links $\overline{D}$ and the average session generation rate ρ (sessions/time step). Then, in this framework the decision making criterion has been implemented to select one of the following observation strategies:

- ✓ **Instantaneous Measurements (IM) strategy.** This strategy consists in performing instantaneous measurements of the interference states in all the spectrum blocks at the time t when a new session has to be established, i.e. at the time when the spectrum selection decision making is executed. In this specific case, the belief vector in (3.24) will always be computed with $m^{(i)}=0$ and therefore it will capture the exact interference state at the decision making time *t*. Then, the belief vector at *t* will be given by:

$$\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t) = \mathbf{x}^{\mathbf{T}}\left(S^{(i)}(t)\right) \tag{3.29}$$

- ✓ **Periodic Measurements (PM) strategy.** This strategy consists in performing periodic measurements of the *i*-th spectrum block with observation period $T_{obs}^{(i)}$. In this way, the elapsed time $m^{(i)}$ between the last observation of the *i*-th spectrum block and the decision making time *t* will always be upper bounded by $m^{(i)} \le T_{obs}^{(i)}$. Then, in order to make sure that the measurement obtained $m^{(i)}$ time steps ago is sufficiently representative of the interference state at time *t*, it can be sufficient to ensure that the belief vector has not reached convergence during the time between two consecutive observations. According to the abovementioned corollary this can be achieved if the observation period fulfils the following condition:

$$T_{obs}^{(i)} < \frac{1}{-\ln\left|\lambda_1^{(i)}\right|} \tag{3.30}$$

  Also in this case like for the observation strategies defined in Section a), it will be assumed that only the spectrum blocks that are not allocated to any link will be measured, since they are the only spectrum blocks that can be considered in the decision making process. In turn, when a spectrum block is released, it will also be measured in case that the time since the last observation exceeds $T_{obs}^{(i)}$.

- ✓ **Steady-state (StS) strategy.** This is the simple case in which no actual observations are performed. In this case, $m^{(i)} \to \infty$ so from (3.26) the values of the belief vector will be equal to the steady-state probabilities $\boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}}$.

The rationality of the observation strategies proposed in the Decision Making entity will be assessed in chapters 4 and 5, and it is due to the following considerations:

- ✓ In low predictable environments (i.e. $\left|\lambda_1^{(i)}\right| < \lambda_{THR}$ where λ_{THR} is a threshold to be set), the convergence of the belief vector towards the steady state probabilities will be very fast, so measurements made at a given time will no longer be a valid indication of the actual interference state after a short time. In this case, two extreme approaches are considered for the observation strategy depending on the actual needs of the decision making:

  1. If the decision making needs to accurately track the actual variability of the environment

(e.g. this would be the case when decisions need to look only for a very short term period after the decision is made, like when applications generate sessions with a very short duration $\overline{D}$ in comparison with the duration $-1/\ln\left|\lambda_1^{(i)}\right|$ to reach the steady-state), the observation strategy would need to ensure that the time $m^{(i)}$ between the last measurement and the decision making time is as close to 0 as possible, so IM strategy that executes measurements just at the time when the decision is made (i.e. each time that a session is generated) is a good option.

2. If the decision making needs to have a longer term perspective (i.e. when the session duration $\overline{D}$ is larger than the time $-1/\ln\left|\lambda_1^{(i)}\right|$ needed to reach the steady-state), the steady-state probabilities already provide a good indication of the dynamic behaviour of the interference, so measurements would not actually be needed. Then, the StS strategy is the most preferable option.

✓ In environments with high predictability (i.e. $\left|\lambda_1^{(i)}\right| \geq \lambda_{THR}$), the convergence of the belief vector towards the steady state can be slower. This means that the observations made at a certain time can be representative of the actual behaviour over a longer time horizon (i.e. over a longer time $m^{(i)}$). Also in this case the following extreme approaches are taken into account:

1. For session durations $\overline{D}$ shorter than the time $-1/\ln\left|\lambda_1^{(i)}\right|$ needed to reach the steady state, it will be worth to use previous measurements (either through IM or PM strategies) because they can be representative of the spectrum block state along the session duration. In this case, the choice between IM and PM is related to the session arrival rate ρ that reflects the rate at which the spectrum selection decision making is triggered. In particular, if the session arrival rate is high in comparison with the observation period $T_{obs}^{(i)}$ of PM (i.e. $\rho > 1/T_{obs}^{(i)}$) this strategy becomes a good option because each observation made will be applicable for multiple spectrum selection decision making processes associated to the new sessions generated between two consecutive observations. In this way, this can substantially reduce the signalling and battery consumption associated to the measurement procedures in comparison to IM that would make measurements for every new generated session. On the contrary, if the session arrival rate is low (i.e. $\rho < 1/T_{obs}^{(i)}$) meaning that the spectrum selection decision making will be mainly inactive between two consecutive observation periods, IM becomes a better option, because it only makes the measurements at the time when they are needed.

2. In the case of long session durations (i.e. larger than the time needed to achieve the steady state $\overline{D} > -1/\ln\left|\lambda_1^{(i)}\right|$) the average reward achieved along the session duration will be

mainly driven by the steady-state behaviour of the spectrum block instead of the actual measurements at session initiation, so in this case the simpler StS strategy becomes a good choice.

Figure 3.8 summarizes the decision making criterion implemented in the OSDM entity to choose the observation strategy that better fits the radio environment conditions. From the figure it can be observed that:

- ✓ IM strategy is selected either in case of low predictability and short sessions, or in case of high predictability, short sessions and low session rate.
- ✓ StS strategy is selected either in case of low predictability and long sessions, or in case of high predictability and long sessions.
- ✓ PM strategy is selected in case of high predictability, short sessions and high session rate.

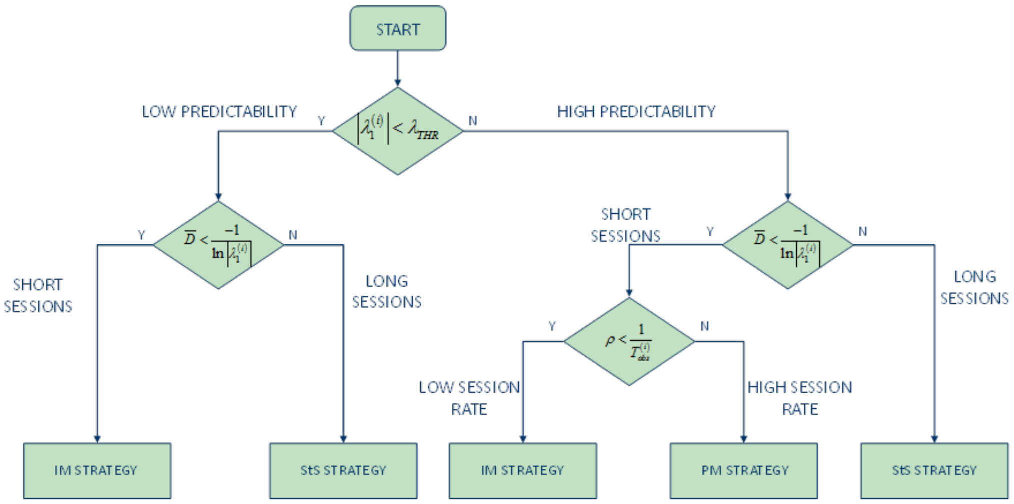


Figure 3.8: Decision making criterion for the selection of the observation strategy

- **Spectrum Selection Decision Making (SSDM)**. It will be in charge of executing the Spectrum Selection decision making each time that a new session is established in a certain radio link. For that purpose, it will implement the decision making criterion given by (3.16) based on the general decision function (3.20). This general decision function can be particularized for each of the observation strategy selected by the OSDM as follows:
  - ✓ **IM strategy.** In this case, the belief vector at the decision-making time t is given by (3.29). Then, by considering (3.29) and the estimation of the future belief vector given by (3.25) in the general decision making function (3.20) it yields:

$$\Phi_j^{(i)}(t) = \frac{1}{\overline{D_j}} \mathbf{x}^{\mathbf{T}} \left(S^{(i)}(t)\right) \left(\sum_{n=1}^{\overline{D_j}} \left[\mathbf{P}^{(\mathbf{i})}\right]^n \right) \mathbf{r}_{\mathbf{j}}^{(\mathbf{i})} \tag{3.31}$$

- ✓ **PM strategy.** In this case, the general decision making function (3.20) can be computed from the belief vector $\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t)$ at the decision-making time t given by (3.24) and its future evolution given by (3.25), yielding:

$$\Phi_j^{(i)}(t) = \frac{1}{\overline{D_j}} \mathbf{b}^{(\mathbf{i})\mathbf{T}}(t) \left(\sum_{n=1}^{\overline{D_j}} \left[\mathbf{P}^{(\mathbf{i})}\right]^n \right) \mathbf{r}_{\mathbf{j}}^{(\mathbf{i})} \tag{3.32}$$

- ✓ **StS strategy.** In this case $m^{(i)} \to \infty$, so from (3.26) the belief vector yields $\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t) \to \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}}$. Then, by using (3.25) and (3.26), the general decision making function (3.20) becomes:

$$\begin{aligned} \Phi_j^{(i)}(t) &= \lim_{m^{(i)} \to \infty} \frac{1}{\overline{D_j}} \mathbf{b}^{(\mathbf{i})\mathbf{T}}(t) \left(\sum_{n=1}^{\overline{D_j}} \left[\mathbf{P}^{(\mathbf{i})}\right]^n \right) \mathbf{r}_{\mathbf{j}}^{(\mathbf{i})} = \\ &= \frac{1}{\overline{D_j}} \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \left(\sum_{n=1}^{\overline{D_j}} \left[\mathbf{P}^{(\mathbf{i})}\right]^n \right) \mathbf{r}_{\mathbf{j}}^{(\mathbf{i})} = \frac{1}{\overline{D_j}} \left(\sum_{n=1}^{\overline{D_j}} \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \left[\mathbf{P}^{(\mathbf{i})}\right]^n \right) \mathbf{r}_{\mathbf{j}}^{(\mathbf{i})} = \\ &= \frac{1}{\overline{D_j}} \sum_{n=1}^{\overline{D_j}} \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \mathbf{r}_{\mathbf{j}}^{(\mathbf{i})} = \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \mathbf{r}_{\mathbf{j}}^{(\mathbf{i})} \end{aligned} \tag{3.33}$$

The Belief Computation entity in the KM will provide the decision making with the values of the belief vector $\mathbf{b}^{(\mathbf{i})\mathbf{T}}$(t), the state transition probability matrices $\mathbf{P}^{(\mathbf{i})}$ and the reward vector $\mathbf{r}_{\mathbf{j}}^{(\mathbf{i})}$ so that the abovementioned decision making functions (3.31) to (3.33) can be computed in accordance with the observation strategy.

iii. Context Awareness entity

This entity keeps the functionality implemented in the first version of the framework. Hence, it is in charge of acquiring the required measurements to support the operation of the Knowledge Management entity. Specifically, it will provide the different observations $o^{(i)}(t) = S^{(i)}(t)$ that will be used by the KM and will be stored in the KD. Measurements in the extended version will be triggered by the OSDM functionality in accordance to the observation strategy or by the KD Acquisition functionality (e.g. at initial acquisition or after detecting a change in the stationary conditions in order to fill the contents of the KD). Measurements will be delivered to the KM and/or the KD Acquisition that will process them to obtain the KD statistics.

Measurements done by the CA can be carried out at either the centralized entity or at other nodes of the different links. In this case, the CA will rely on the Control entity to communicate with these nodes and retrieve the measurements.

iv. Control entity

Also the control entity keeps its previous functionality providing the signalling means to support the communication between the cognitive management entity and the different nodes of the network. Hence, in the context of the spectrum selection process considered in this framework two main functions are envisaged for this control entity:

- Whenever a new session has to be established in a given radio link, the control entity will trigger the decision making requesting the allocation of a spectrum block and will inform the involved nodes about the result of this allocation.
- Whenever the CA needs to collect a measurement at a certain node of the network, the control entity will exchange the necessary signalling messages with this node in order to request and retrieve the measurement.

The signalling exchange relies on a cognitive control channel that allows the transmission of different information elements and the realization of diverse operations within a cognitive radio system. Details on the specific implementation and signalling exchange can be found in [81] and [95].

3.5 Summary

This chapter has presented the cognitive management frameworks and the strategies proposed in this dissertation to support spectrum management exploiting CR networking. The first cognitive management framework (i.e., the BCMF) has been considered as a baseline for deriving spectrum management solutions. In details, the considered FA represents a centralized architecture, which enables the formulation of strategies for spectrum management, particularly for creation and maintenance stages of the ON life cycle. The FA of the BCMF is composed of a DSM designed for spectrum opportunity identification and a CMON-N implemented for spectrum selection. Moreover, the CMON-N is made of a decision making process associated to creation, maintenance and termination stages that achieves the information on spectrum opportunity identification from the DSM. Furthermore, in the module are implemented a control mechanism, which executes the decisions taken, the Knowledge Management module that allows exploiting the cognitive features and the CA, which provides the necessary inputs about the radio environment conditions to the decision-making strategies.

Inspired on this first framework, the second framework proposed in this dissertation (i.e., the ECMF) has been based on the CR cycle paradigm with the aim to perform efficient decision-making strategies for spectrum selection in CRNs. The POMDPs have been proposed as decision-making strategy in order to exploit partial observations at specific periods of time with a statistical characterization of the system dynamics through a first definition of the belief vector concept.

The second framework has been further expanded, and a third framework (i.e., the FCMF) has been defined to exploit the belief vector as a long-term means to characterize and predict the environment dynamics. Moreover, different observation strategies have been implemented each one selected appropriately to balance the trade-off between performance and measurement requirements. The FAs of the ECMF and the FCMF are both based on: *(i)* a Knowledge Management module that includes a KD, which stores the information about the statistics of the radio environment and a KM that is in charge of updating such information; *(ii)* a Decision Making that selects the most appropriate spectrum block each time that a new session is established in a certain radio link; *(iii)* a CA, which performs observations through measurements of the interference states triggered by the Decision Making; *(iv)* a Control module that manages message exchange between the terminals and the cognitive management frameworks to support the establishment/release of radio links. Although the main modules of these solutions are the same, essential new functionalities with the aim to characterize the radio environment dynamic have been developed in the FA of the FCMF.

Chapter 4

Evaluation through Simulations

4.1 Introduction

To validate the effectiveness of the spectrum management strategies based on the CR cycle proposed in Section 3.3 and Section 3.4, the corresponding cognitive management frameworks have been implemented through a Matlab-based simulator. The simulator represents the first step towards the assessment of the proposed solutions, which have also been analysed through emulation platforms that enable real-time evaluations, as it will be described in Chapter 5.

In this chapter the main principles of the simulator and the performance study of the spectrum management strategies are presented. In particular, in Section 4.2 details on the evaluation scenario are provided; while, in Section 4.3 the Key Performance Indicators (KPIs) considered in order to assess the performance of the proposed strategies are presented. In Section 4.4 the results of the performance assessing the POMDP-based strategy implemented in the ECMF and described in Section 3.3 are illustrated. Then, in Section 4.5 performance results are presented in order to assess the belief-based decision-making approach implemented in the FCMF proposed in Section 3.4 depending on several traffic generation patterns and particularised to the different observation strategies that can be selected in the Observation Strategy Decision Making (OSDM) entity. Finally, concluding remarks are given in Section 4.6.

4.2 Evaluation Scenario

The considered scenario assumes that a set j of radio links are controlled by the centralized management entity that resides at the infrastructure side in charge of deciding the spectrum block belonging to the set i to be used by each radio link. Some illustrative use cases where this system model can be applicable are: *(i)* a Digital Home (DH) scenario in which different devices need to communicate; *(ii)* a set of cognitive small cells deployed in a cellular network that make use of additional spectrum to increase the network capacity; *(iii)* an opportunistic Device-To-Device (D2D) radio link created to extend the coverage of certain cellular terminals that are outside the coverage area of the cellular infrastructure. In the context of this dissertation a realistic DH environment has been implemented in the simulator to evaluate the effectiveness of the proposed strategies.

A set of i = 5 spectrum blocks has been considered. Blocks B1 and B5 belong to the ISM band at 2.4 GHz with bandwidth 20 MHz. Spectrum blocks B2, B3 and B4 belong to the WSs in the TV band operated at frequencies 400, 800 and 600 MHz, respectively. Their bandwidths are 16, 24 and 16 MHz, respectively. Three different interference states are considered for the five spectrum blocks.

A set of j = 3 links is considered in the evaluation. The j-th link is supposed to generate sessions whose duration is exponentially distributed with average D_j which is varied in the different simulations.

The time between the end of a session and the beginning of the next one is also exponentially distributed with average T_{inter} also varied in different simulations. The simulator takes as input different parameters that characterize the scenario such as the duration of the interference states of the spectrum blocks, the bit rate requirements, the T_{obs} parameter in case of partial observations and the overall duration of the simulation. The bit rate requirement considered throughout this chapter reflects possible DH entertainment applications; in details, for the link 1 it is $R_{req,1}$=200 Mb/s, while for links 2 and 3 it is $R_{req,2}$= $R_{req,3}$=100 Mb/s. The simulated DH scenario consists in an indoor environment in a single floor of dimensions 16.8m x 30.4m organised in six different rooms.

The propagation losses between any two positions are computed using the following model [108], [109]:

$$L(dB) = L_0 + 20\log f\left(MHz\right) + 10\alpha\log d\left(m\right) + N_w L_w \tag{4.1}$$

where L_0=-27.55 dB is the free space loss, α is the propagation coefficient with the distance between transmitter and receiver d expressed in meters, f is the frequency used for the communication, N_w is the number of traversed walls between transmitter and receiver, and L_w is the attenuation of one wall dependent on the material and width. In this scenario walls are considered made out of bricks with a width of 15cm, while the ceiling height is around 3.5m. Based on measurements, the estimated values of the propagation model in this scenario resulted to be α=2.6 and L_W=5.1 dB [108].

The considered relationship between the bit rate experienced by the j-th link in the i-th spectrum block and the interference conditions is given by:

$$R_{j,i} = BW_i \log_2\left(1+\frac{\frac{P_j}{L_{j,i}}}{\left(N_0 + I_{\max j,i}\sigma_i\right)BW_i}\right) \quad (4.2)$$

where BW_i is the total bandwidth of the *i*-th spectrum block, P_j is the transmit power in link *j* and $L_{j,i}$ are the propagation losses associated to link *j* when using the *i*-th spectrum block according to equation (4.1). N_o is the background noise spectral density and the term $I_{max,j,i}\cdot\sigma_i$ is the interference spectrum density when using the *i*-th spectrum block depending on its interference state, as described in Section 3.3. Simulations take into account N_o=-164 dBm/Hz. All the simulation parameters related to the links to evaluate $R_{j,i}$ are summarized in Table 4.1.

Table 4.1: Characteristics of the Links

	Parameter	**Value**
Link 1	Transmission Power	20 dBm
	Distance	10 m
	N_w	1
Link 2, 3	Transmission Power	20 dBm
	Distance	20 m
	N_w	3

The interference that affects the five spectrum blocks implemented in the simulator are defined as follows:

- For the spectrum block B1 that belongs to the ISM band, the interference comes from an external interferer located at 20m, traversing 2 walls and with average transmit power of 20 dBm in interference state 1 and 10 dBm in interference state 2.

- For the spectrum blocks B2, B3 and B4 that belong to the white spaces in the TV band, the interference causes a reduction in the signal-to-noise ratio of 10 dB in interference state 1 and a reduction of 40 dB in interference state 2. These reductions are associated to different densities of White Space Devices (WSDs) located in the surroundings of the building.

- For the spectrum block B5 that also belongs to the ISM band, the interference comes from another external interferer located at 10m, traversing 1 wall and with average transmit power of 20 dBm in interference state 1 and 10 dBm in interference state 2.

With all the above and considering the bit rates requested for the links, Table 4.2 presents the rewards $r_{j,k}^{(i)}$ obtained through equation (3.6) with parameters Γ=1 and ξ=5, for each link in the different spectrum blocks and interference states.

Table 4.2: Bit Rates and Reward Values of the Links in the Different Spectrum Blocks

Link	Spectrum Block	State $S^{(i)}$=0		State $S^{(i)}$=1		State $S^{(i)}$=2	
		$R_{j,i,0}$ (Mb/s)	$r_{j,0}^{(i)}$	$R_{j,i,1}$ (Mb/s)	$r_{j,1}^{(i)}$	$R_{j,i,2}$ (Mb/s)	$r_{j,2}^{(i)}$
1	B1	264	0.92	150	0.85	87	0.21
	B2	297	0.86	246	0.95	87	0.21
	B3	365	0.74	308	0.84	73	0.11
	B4	281	0.89	228	0.98	70	0.10
	B5	264	0.92	69	0.09	20	0.00
2,3	B1	145	0.87	40	0.16	8	0.00
	B2	204	0.68	151	0.85	12	0.00
	B3	263	0.55	184	0.68	6	0.00
	B4	185	0.73	132	0.92	6	0.00
	B5	145	0.87	4	0.00	0.45	0.00

4.3 Key Performance Indicators

In order to assess the performance of the proposed strategies, appropriate Key Performance Indicators (KPIs) are considered in the Matlab-based simulator. Firstly, a parameter that represents the satisfaction of using a selected link for a particular application is taken into account. Moreover, as it was mentioned in Chapter 3, a metric that captures how appropriate a spectrum block is for a radio link is considered in order to assess the spectrum management solutions proposed in this dissertation, because not all the spectrum blocks are equally suitable for all the users depending on the application needs. Finally, since the spectrum selection strategies implemented in the ECMF and in the FCMF have been proposed with the aim to reduce practical requirements such as signalling overhead and battery consumption, a parameter representing the amount of observations of the radio environment executed during the use of the proposed solutions is an essential key parameter. Motivated by these considerations, the following KPIs are taken into account to evaluate the spectrum selection strategies proposed, respectively, in Section 3.3 and Section 3.4:

- Average satisfaction probability: It is the fraction of time that the established sessions in the links achieve a bit rate higher or equal than the requirement $R_{req,j}$. The result is the average for all the links along the total simulation time.

- Average system reward: It is the reward obtained by the active links depending on their allocated spectrum blocks and corresponding interference state computed through equation (3.6) and averaged along the total simulation time T_{SIM}. Furthermore, the result is averaged for all the L links.

- Average system session reward: It is the reward experienced during each session by the active links depending on their allocated spectrum blocks and corresponding interference state computed through equations (3.6) and (3.14), averaged along the total simulation time T_{SIM} and for all the L links.

- Observation rate: It is the average number of observations per second that are performed to determine the interference state of the different spectrum blocks.

4.4 Performance results of the POMDP-based framework

The objective of this section is to assess the usefulness of the POMDP-based solution proposed in Section 3.3 in the scenario illustrated in Section 4.2. In the simulator the FA of the ECMF described in FA of the proposed ECMF has been implemented and it includes: the Knowledge Management entity that stores the information about the radio environment and update the belief vector values; the Decision Making, which selects the most appropriate spectrum block each time that a new session is established in a certain radio link following the decision strategies defined in equations (3.8), (3.10) and (3.11). Moreover, it triggers the execution of the observations with the time period T_{obs} for all the spectrum blocks; the Context Awareness that measures every T_{obs} the interference states implemented in the simulator; the Control that simulates the message exchange for the establishment and the release of radio links.

The simulation results illustrated in this section aim at analysing the effectiveness of the proposed POMDP-based approach implemented in the ECMF compared to the references policies illustrated in Section 3.3 (i.e., the Full Observation spectrum selection strategy, FO and the Steady state probabilities-based spectrum selection strategy, PR). Moreover, a random selection policy as a further baseline reference is considered in the evaluation of the proposed strategy. Furthermore, this analysis aims at assessing the impact of the time period selected to execute the observations (i.e. T_{obs} parameter) and defined in the Decision Making entity.

Performance results have been obtained with the simulator operating in time steps of Δt = 1s during one week. The average durations of the three states for each spectrum block are presented in Table 4.3. Considering these durations the values of the state transition probabilities for each link $p_{k,k'}^{(i)}$ have been computed and stored in the KD. Then, during the strategy execution they are used by the KM to update the belief vector values $b_k^{(i)}(t)$ every Δt following equation (3.9), and by the Decision Making to select the *i*-th spectrum block each time that a new session is established in the *j*-th radio link following the decision policy defined in (3.8). For the comparison with the PR strategy also the values of the steady state probabilities $\pi_k^{(i)}$ have been computed considering the average durations of the interference states of the spectrum blocks illustrated in Table 4.3.

Table 4.3: Durations of the Interference States for the different Spectrum Blocks

State	B1	B2	B3	B4	B5
S_i=0	40 min	4 min	4 min	40 min	32 min
S_i=1	12 min	4 min	12 min	4 min	4 min
S_i=2	12 min	40 min	24 min	12 min	4 min

The performance of the different strategies in terms of average reward, satisfaction probability and observation rate is presented in Figure 4.1 as a function of the observation period T_{obs}. Note that as T_{obs} is a key parameter of the POMDP-based spectrum selection strategy, it does not affect the performance of the other ones.

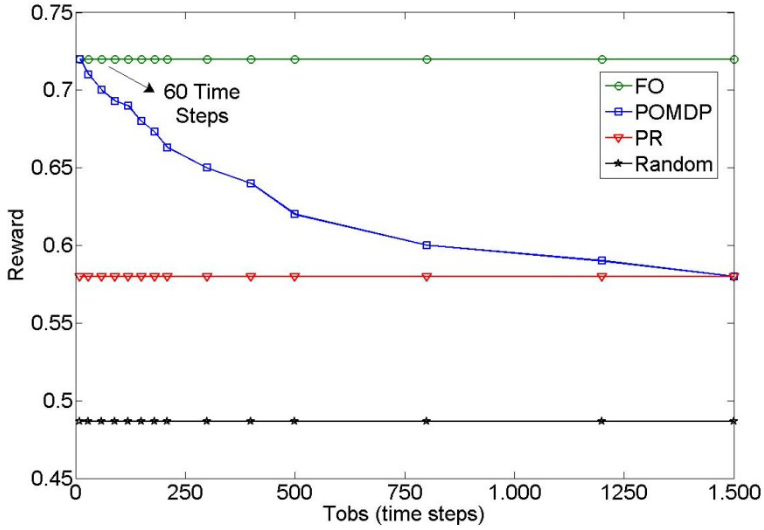
Moreover, the time between the end of a session and the beginning of the next one T_{inter}= 10 time steps is considered in these results. From Figure 4.1 it can be observed that the performance obtained by the POMDP-based solution is a decreasing function of the observation period T_{obs}.

In particular, in Figure 4.1(a) and Figure 4.1(b) it can be noticed that for low values of T_{obs} the average reward and the average satisfaction probabilities are very similar to the ones obtained by the FO strategy that has a perfect knowledge of the different spectrum blocks.

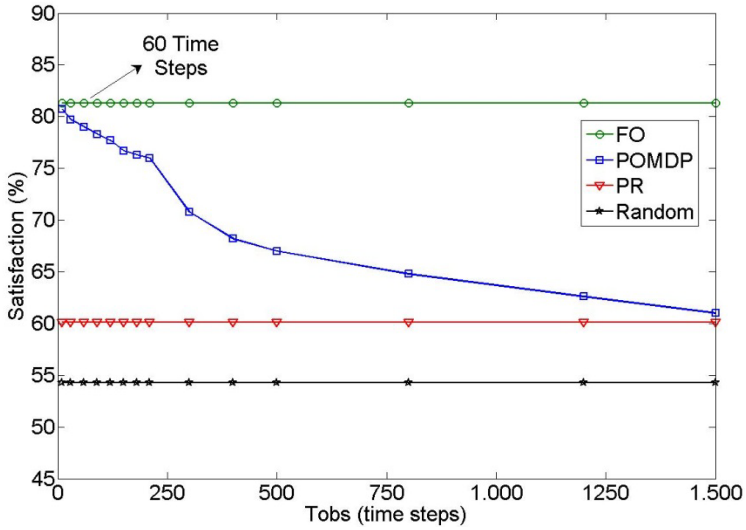
However, this similar performance is achieved by the POMDP with much less requirements in terms of observations, as it can be noticed in Figure 4.1(c) that depicts the observation rate as a function of T_{obs} for both FO and POMDP strategies (remember that PR solution does not require observations of the system during its operation). For instance, when T_{obs} is 60 time steps, POMDP achieves a reduction of around 68% with respect to FO in terms of observation rate, while the performance of the POMDP-based approach in terms of reward and satisfaction probability is only about 3% smaller than the performance achieved by FO. Further reductions in terms of observation rate can be achieved when increasing T_{obs}, as seen in Figure 4.1(c).

Concerning the comparison against the PR strategy, it can be observed in both Figure 4.1(a) and Figure 4.1(b) that for low values of the observation period, the POMDP-based strategy achieves a significant improvement in both the reward and the satisfaction (e.g. for T_{obs}=60 time steps there is an improvement of 32%). Then, for large values of T_{obs} the performance of both PR and POMDP tends to converge to similar values. The reason is that the dynamic update of the belief vector values for the POMDP-based strategy according to equation (3.9) tends to converge towards the steady state probabilities when there are very large periods without any observations as it was explained in equation (3.11).

Finally, focusing now on the comparison against the Random strategy, it can be observed in Figure 4.1(a) and Figure 4.1(b) that POMDP achieves a very significant improvement in terms of both reward and satisfaction probability, in the order of 43% and 46%, respectively, for the case of T_{obs}=60 time steps.



(a)



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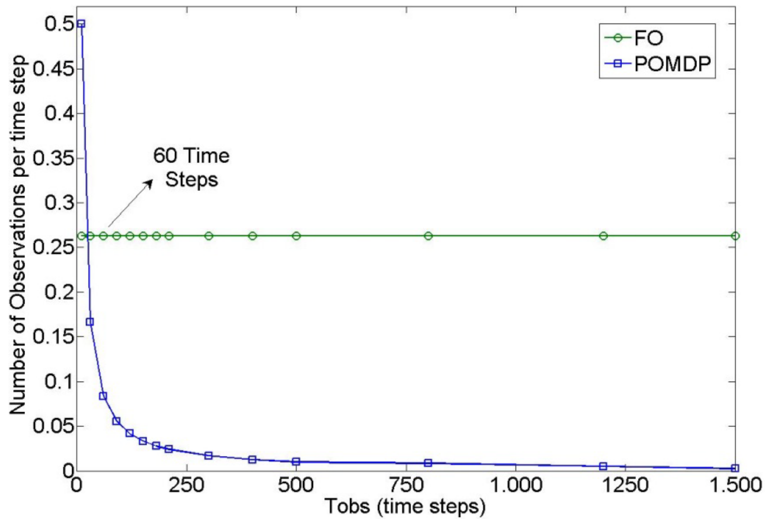
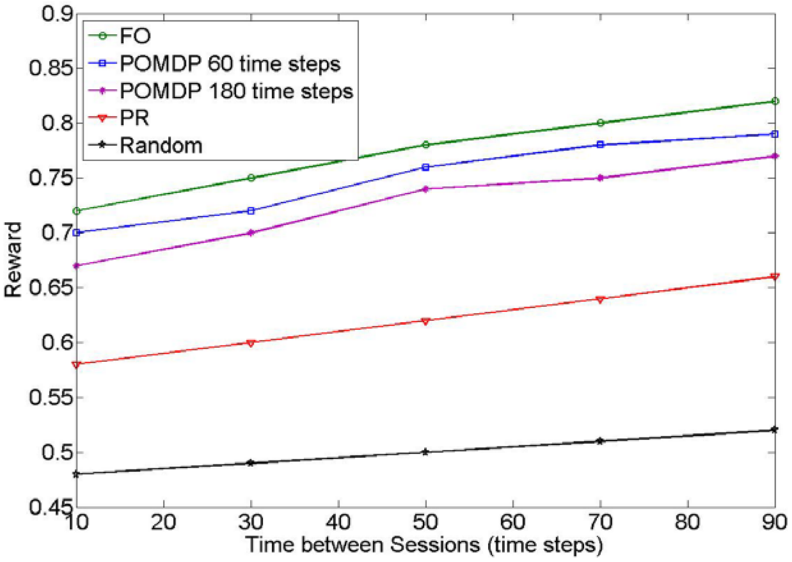


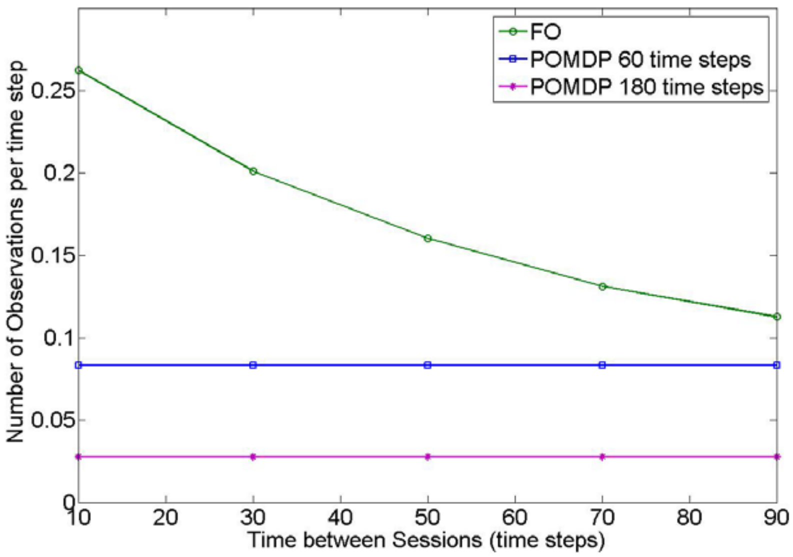
(c)

Figure 4.1: Performance Results as a function of the observation time

To evaluate the impact of varying the time between the end of a session and the beginning of the next one T_{inter}, Figure 4.2 presents the performance in terms of average reward and observation rate for all the considered strategiesas a function of T_{inter}. For the POMDP-based solution, T_{obs}=60 and T_{obs}=180 time steps are considered.



(a)



(b)

Figure 4.2: Performance Results as a function of the time between sessions

It can be observed in Figure 4.2(a) that the reward tends to increase with T_{inter} for all the strategies and that the reward obtained by the POMDP strategy is still very close to the one achieved by FO, while requiring a much lower observation rate as seen in Figure 4.2(b).

Moreover, the POMDP allows still obtaining a significant improvement with respect to PR and Random solutions for both values of T_{obs}.

In summary, the selection of the values of T_{obs} in the Decision Making entity included between 60 and 180 time steps is a good trade-off between performance and observation requirements. In fact, considering these values of T_{obs} the proposed POMDP-based solution allows obtaining similar performance in terms of reward and satisfaction as the full observation scheme that makes decisions based on knowing the real interference state in all the available spectrum blocks, in spite of requiring a much lower measurement rate.

Furthermore, varying the value of T_{inter} the POMDP-based strategy in both cases, with T_{obs}=60 and T_{obs}=180 time steps is still the best option that guarantees the most favourable trade-off between performance and measurement requirements.

4.4.1 Analysis of the Impact of the Observation Strategy

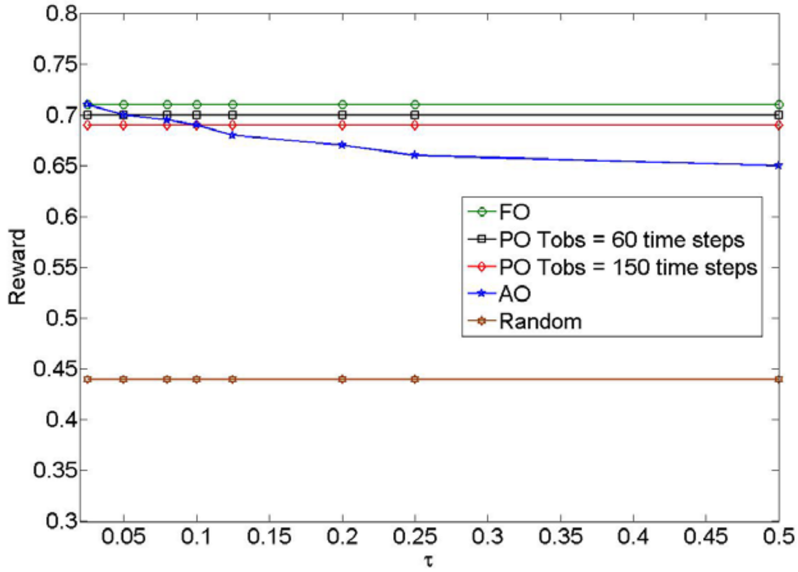
To evaluate the impact on the obtained performance of the observation strategy implemented in the Decision Making entity, this section makes a comparison between the Periodic Observation strategy (PO) and Adaptive Observation strategy (AO) introduced in Section 3.3. Also in this study performance results has been obtained with the simulator operating in time steps of Δt=1s during one week. While the average durations of the three states for each spectrum block are presented in Table 4.4. These durations have been considered to update the values of $p_{k,k'}^{(i)}$ stored in the KD.

Table 4.4: Durations of the Interference States for the different Spectrum Blocks

State	B1	B2	B3	B4	B5
S_i=0	10 min	10 min	4 min	30 min	10 min
S_i=1	50 min	10 min	90 min	50 min	50 min
S_i=2	10 min	80 min	4 min	10 min	50 min

Since the main objective of this section is the study of the impact of the observation strategy, only the POMDP-based approach and the FO policy are considered in the evaluation of the performance results. While, as an additional baseline reference the random solution is still considered to highlight the importance in terms of performance of implementing strategies for spectrum selection in the Decision Making entity.

The performance of the different solutions in terms of average reward, satisfaction probability and observation rate is presented in Figure 4.3 as a function of the parameter τ of the AO strategy. In case of PO approach T_{obs}=60 and T_{obs}=150 time steps have been considered. From Figure 4.3(a) and Figure 4.3(b) it can be observed that all the strategies achieve a very significant improvement of around 60% in terms of reward and satisfaction probability with respect to the random spectrum selection solution. Besides, the reward and satisfaction achieved by both POMDP-based approaches PO and AO is very similar to the FO-based solution, particularly for low values of τ roughly up to 0.1.



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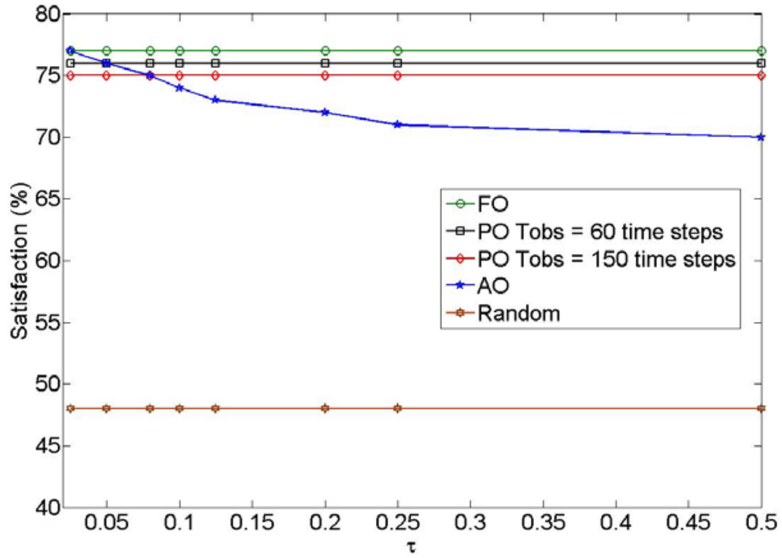

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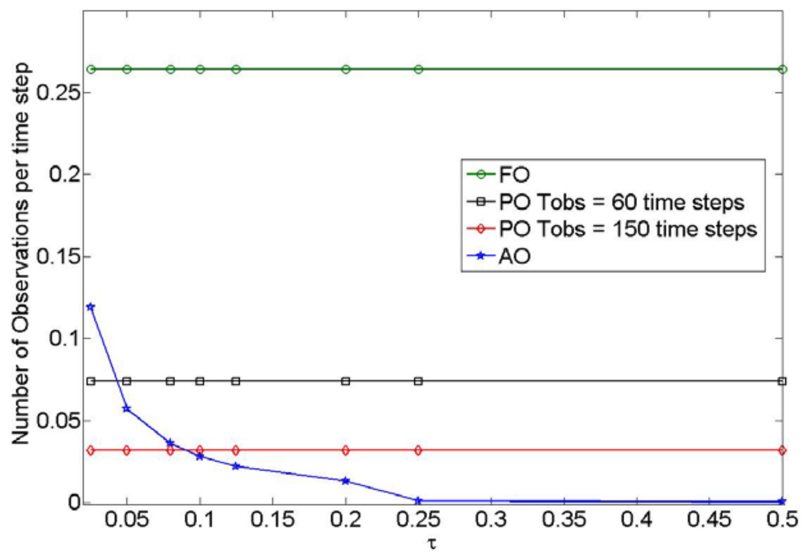


(c)

Figure 4.3: Performance Results as a function of the coefficient τ

However, as seen in Figure 4.3(c), this is achieved with a very significant reduction in the observation rate with respect to FO. For instance, when τ is 0.1 with AO the observation rate is reduced in 89% with respect to FO, while for PO the reduction is 72% and 88% for the cases T_{obs}=60 and T_{obs}=150 time steps, respectively. In turn, the reward and satisfaction achieved with AO and τ=0.1 is only 3% less than with FO, while the reduction with PO is between 1.5% and 3% depending on T_{obs}. Then, AO strategy with setting τ=0.1 is a good trade-off among the considered fixed T_{obs} period values of PO strategy. Moreover, increasing factor τ tends to degrade the performance of AO because of the longer time between observations.

To further gain insight in the capability of the AO strategy to adapt to interference dynamics, the impact of varying the average durations of the interference states for each spectrum block has been analysed.

Hence, the durations of Table 4.4 have been multiplied by a factor varied between 0.5 and 3. Figure 4.4 presents the corresponding performance in terms of observation rate for the different strategies, considering τ = 0.1 for the AO one.

From the figure it can be observed that the observation rate requirements for AO are significantly reduced when the state durations are longer, which leads to further improvements in comparison with FO and PO.

For instance, when the durations are multiplied by a factor 3, AO strategy allows a reduction in the observation rate of 75% with respect to PO with T_{obs}=150 time steps and of 89% with T_{obs}=60 time steps. This reduction is achieved without having a significant impact in terms of neither reward nor satisfaction. Specifically, the obtained values for all the considered strategies range from 0.68 to 0.70 in the case of the reward, and from 72% to 76% in the case of the satisfaction.

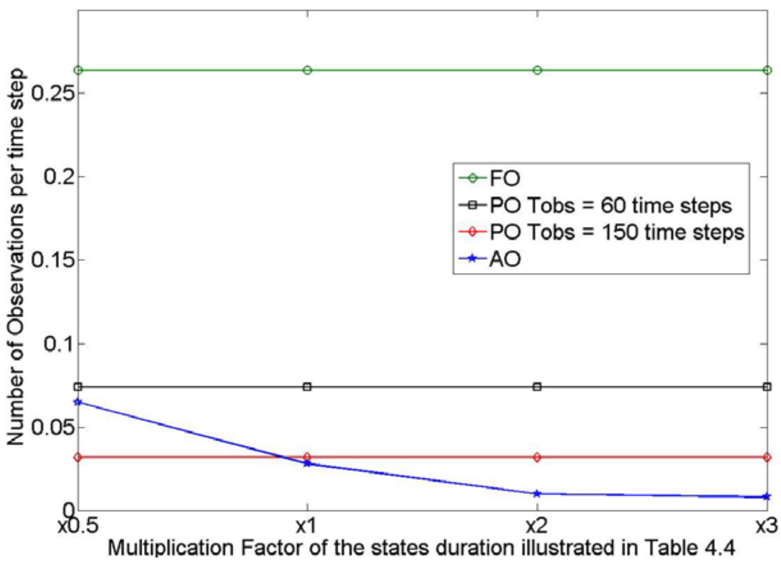


Figure 4.4: Performance Results as a function of the average duration of the spectrum blocks states

In summary, an adaptive observation strategy able to modify the observation rate requirements in accordance with the observed interference dynamics allows further reduction in the observation rate with respect to a periodical approach.

4.5 Performance results of the Belief-based framework

Once assessed the usefulness of the POMDP-based solution, in this section performance evaluation of the belief-based one implemented in the FCMF proposal introduced in Section 3.4 is analysed. The objective of this section is to assess the observation strategies under different environment conditions in terms of the traffic generation patterns. In details, simulation results aim at demonstrating that a proper characterization of the traffic in terms of the average session duration for all the links D and the average session generation rate ρ will drive the OSDM in the Decision Making entity to select the observation strategy that better balance the trade-off between achievable performance and measurement requirements.

Hence, the simulator has been extended in order to consider also new entities of the extended FA of the FCMF described in Figure 3.7, such as: the Belief Computation module that updates the belief vectors of the spectrum blocks following the new observation strategies implemented in the Decision Making; the Eigenvalue Analysis module implemented to determine the predictability of the interference conditions that characterize the different spectrum blocks. Notice that in this case the KD Acquisition entity has not been implemented in the simulator; in fact, the values of the parameters stored in the KD are supposed to be obtained after an initial acquisition mechanism that is out of the scope of this chapter and that will be presented in Chapter 5.

Since the objective of this study is to assess the observation strategies depending only on the traffic generation patterns, the interference conditions of the five spectrum blocks do not change during the simulation campaign. In details, the average durations of the states for each spectrum block are presented in Table 4.5. Furthermore, the corresponding second highest eigenvalues, which drive the convergence of the belief vector of the transition probability matrices, are 0.994 for B1, B2 and B3, 0.991 for B4 and 0.993 for B5; moreover, λ_{THR} is assumed to be 0.95. Therefore, the considered eigenvalues reflect the high predictability defined in Figure 3.8.

The durations defined in Table 4.5 have been considered to compute and store in the KD the state transition probability matrix $\mathbf{P}^{(i)}$ and the steady state probability $\boldsymbol{\pi}^{(i)}$ for the different spectrum blocks. While, for each link the session durations and the session generation rates of the data transmissions are varied in the different simulations and they are exponentially distributed with averages, respectively, $\overline{D_j}$ (time steps) and ρ_j (sessions/time step). Finally, different values of T_{obs} for PM strategy and simulation time T_{SIM}=10000 time steps have been taken into account.

Table 4.5: Durations of the Interference States for the different Spectrum Blocks in case of high predictably

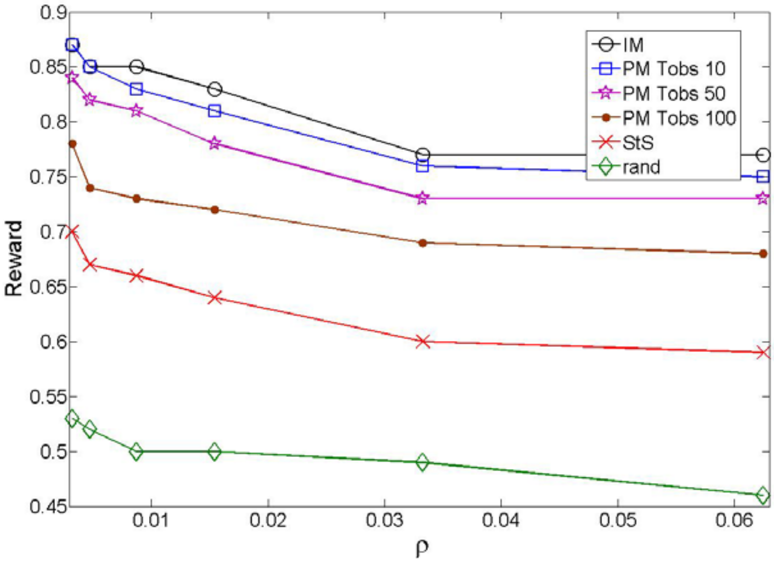
State	B1	B2	B3	B4	B5
S_i=0	480 steps	120 steps	480 steps	240 steps	360 steps
S_i=1	120 steps	120 steps	120 steps	120 steps	160 steps
S_i=2	120 steps	480 steps	160 steps	60 steps	60 steps

The performance of the different strategies as a function of the session rates ρ is presented in Figure 4.5 in terms of average system session reward, satisfaction probability for the different links and observation rate. Also in this study the random strategy is considered as additional baseline reference. $\overline{D_j}$ = 15 time steps and T_{obs}=10, 50 and 100 time steps in case of PM strategy, in order to fulfil condition (3.30), are considered in these results. While, $\overline{D_j}$ and ρ are the same for all the links. Firstly it can be observed how all the proposed strategies allow achieving a clear improvement in terms of both reward and satisfaction probability with respect to the random selection of the spectrum block.

The IM strategy, which makes decisions based on the most recent information at the decision making time, achieves the best performance in terms of reward and satisfaction probability. However, it can be observed in Figure 4.5(c) that the observation rate increases linearly with the session generation rate, because each time a new session arrives it requires performing observations on all the available spectrum blocks.

Regarding StS strategy, from the perspective of observation rate it would be the best strategy because it does not require observations at all. However, its performance in terms of reward/satisfaction is highly degraded with respect to IM in the considered scenario (reward reductions of around 35% can be observed in Figure 4.5(a) because decisions are made without considering the real interference state of the spectrum blocks.

Concerning PM strategy, the figure reflects that the proper setting of the observation period T_{obs} should result from the trade-off between reward and observation rate, even if its value fulfils condition (3.30). In fact, low values such as T_{obs}=10 time steps lead to a large reward at the expense of an increase in the observation rate, as seen in Figure 4.5(a) and Figure 4.5(c), respectively. In turn, when increasing the value of T_{obs} the observation rate can be substantially reduced. However, this is at the expense of degrading the reward, because the time elapsed between the measurements and the decision making time increases with T_{obs} and thus the belief becomes less accurate. Taking as a reference the reward degradation with respect to IM, values of T_{obs} between 50 and 100 time steps achieve a good trade-off between reward/observation rate in this scenario, because the reward reduction with respect to IM is around 10%, while a very significant reduction in terms of observation rate is achieved, particularly for large session generation rates ρ.



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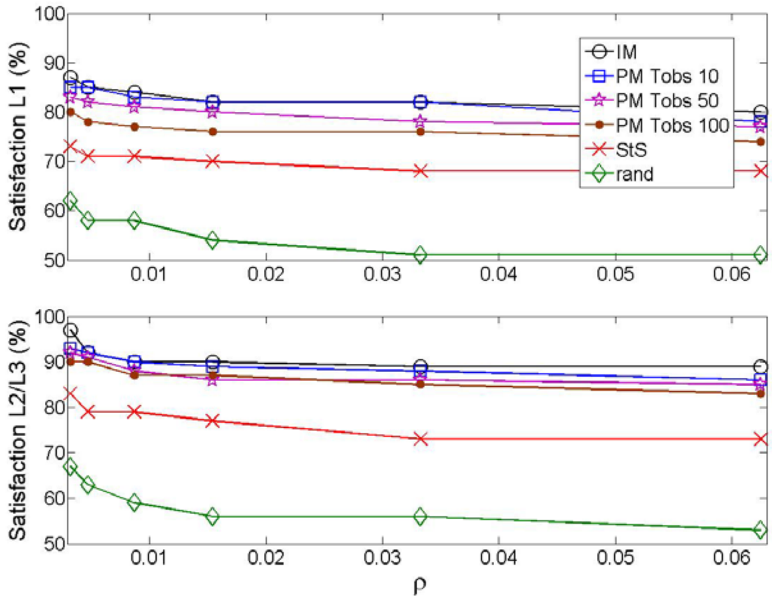

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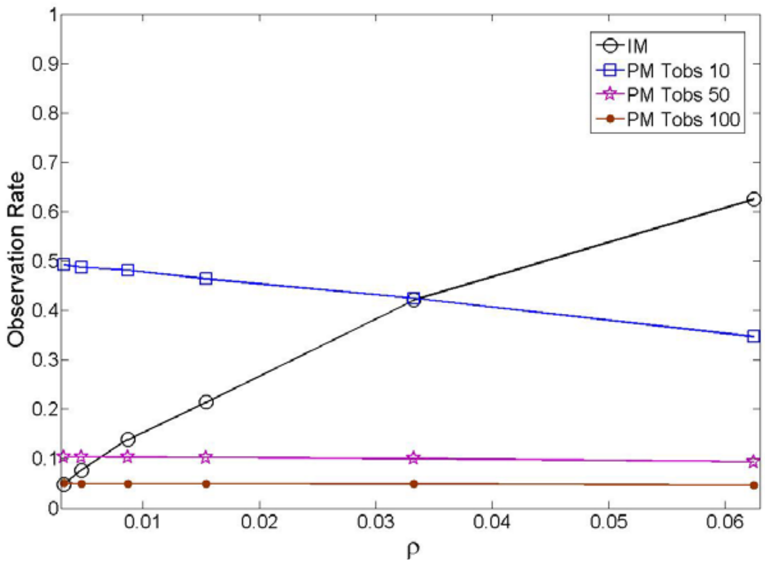


(c)

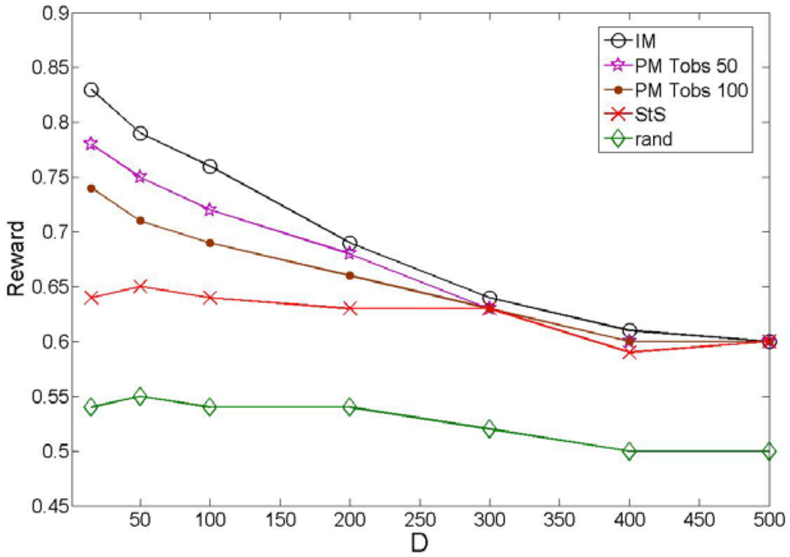
Figure 4.5: Performance Results as a function of the session generation rate

It is also worth mentioning that, while the observation rate in IM increases linearly with the session generation rate ρ (see Figure 4.5(c)), in the case of PM it decreases slightly with ρ. This slight decrease, particularly noticeable in Figure 4.5(c) for the case T_{obs}=10 time steps, is due to the fact that observations in PM are only carried out in the spectrum blocks that are not allocated to any link, so observation rate decreases when increasing the spectrum block occupation (i.e. when increasing ρ). Figure 4.6 presents the performance comparison between the different strategies as a function of the average session duration $\overline{D_j}$. In this case T_{obs}=50 and 100 time steps are considered. The time between the end of a session and the beginning of the next one T_{inter} is exponentially distributed with average 50 time steps. From the figures it can be noticed how, for short session durations the comparison between the different techniques leads to similar conclusions as those obtained in Figure 4.5.

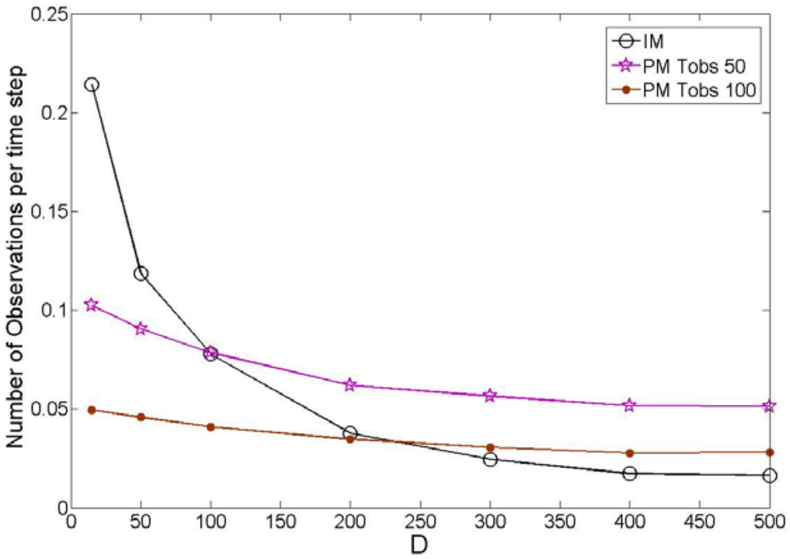
However, for long session durations it is observed that IM, PM and StS techniques tend to converge towards similar values of the reward. The reason is that, when a spectrum block is allocated to a link for a long time, the link will tend to experience the steady-state conditions in this spectrum block. Therefore, the reward estimation based on the steady-state probabilities made by the StS at the decision-making time becomes a good estimate of the actual performance that will be achieved. Correspondingly, for long session durations, StS becomes the most adequate strategy because it is capable of properly estimating the performance without requiring any observations.

In summary, based on the obtained results it can be concluded that the traffic generation pattern plays a key role when the OSDM has to select the most adequate observation strategy in the belief-based decision making approach. On the one hand, for long session durations, the approach selected by the OSDM would be the decision making based on steady-state conditions because it allows properly estimating the performance without requiring dynamic observations of the environment. On the contrary, for shorter session durations the choice between IM and PM is related to the session arrival rate ρ that reflects the rate at which the spectrum selection functionality is triggered. In particular, a belief-based decision making with periodic observations would be the selected approach by the OSDM for large session generation rates ρ as long as the observation period is properly set, because it allows achieving good performance in terms of reward while significantly reducing the observation rate requirements. In details, in the considered scenario, a proper setting of the observation period included between 50 and 100 time steps allows the periodic approach performing better than IM for session generation rates ρ approximately above $1/T_{obs}$, while for lower session generation rates the OSDM would select the IM approach that is more convenient than the PM one.

Motivated by the obtained results, a detailed assessment of the FCMF including also low predictable conditions and the KD acquisition entity will be performed in an actual environment by a real-time testbed in the next chapter.



(a)



(b)

Figure 4.6: Performance Results as a function of the session durations

4.6 Summary

This chapter has presented the simulation-based performance results of the spectrum management strategies based on the CR cycle proposed in this dissertation. The main conclusions that can be drawn from this performance assessment are summarized as follows.

The assessment of the use of partial observations in the Decision Making entity has revealed that the POMDP-based strategy implemented in the ECMF enables the achievement of similar performance in terms of reward and satisfaction as the full observation approach making decisions based on accurate knowledge about the actual interference state in all the available spectrum blocks. Nevertheless, through the combination of partial observations of the system at specific time instants and the statistical information stored in the Knowledge Database, it has been shown that the ECMF approach requires a much lower measurement rate compared to the full observation scheme. In addition, it achieves a significant performance gain in terms of reward with respect to a random spectrum selection and to a strategy that makes decisions based on static knowledge of the spectrum block statistics.

Regarding the impact of the observation strategy implemented in the Decision Making entity, it has been obtained that the POMDP-based solution characterized by an adaptive observation strategy is able to modify the observation rate requirements in accordance with the observed interference dynamics, thus allowing a further reduction in the observation rate with respect to a periodical approach.

The analysis of the belief-based policy proposed in the FCMF has revealed that the characterization of the traffic in terms of the average session duration and the average session generation rate allows the OSDM entity selecting the observation strategy that better balances the trade-off between achievable performance and measurement requirements. In details, the simulation results have shown that, for long session durations a steady state-based strategy that does not require dynamic observations becomes the best approach to be selected. In turn, for short session durations the use of periodic measurements achieves a good trade-off between reward and observation rate for large session generation rates, while for low session generation rates the use of instantaneous measurements made at the decision making time is the option that would be selected by the OSDM.

Chapter 5

Evaluation through Real-Time Testbed

5.1 Introduction

This chapter presents the real-time testbed developed to implement and evaluate the spectrum management solutions proposed in this dissertation. In details, the first version of the testbed consists of wireless software-defined nodes that provide a hardware platform supported by software for emulating spectrum management strategies in ONs. Then, the testbed has been extended in order to evaluate the proposed belief-based spectrum selection strategy.

The chapter is organized as follows. Section 5.2 presents the implementation of the individual node with details about hardware and software components. Moreover, the implementation and validation of the functionalities provided by each node are described. Section 5.3 illustrates the architecture of the first version of the platform for the implementation of the BCMF and the emulation results assessing the proposed solutions for spectrum opportunity identification and spectrum selection in ONs. In turn, Section 5.4 describes the architecture of the extended version of the platform for the implementation of the FCMF and the emulation results that assess the proposed belief-based spectrum selection strategy. Finally, concluding remarks are given in Section 5.5.

5.2 Individual Node

Each individual node is implemented through Universal Software Radio Peripheral (USRP) version 1 integrated boards [110] controlled by a Personal Computer (PC) running Linux Operating System (OS) where GNU radio [111] software for properly configuring the transmission and reception parameters of the USRP modules is implemented. The Linux OS was selected for the implementation of the testbed for its capability to guarantee appropriate levels of real-time management while guaranteeing a high degree of flexibility, and for its interprocess communication methods considered in order to exploit the auto reconfigurability functionality of the hardware.

5.2.1 Hardware Component

USRP incorporates Analog to Digital and Digital to Analog Converters (ADC/DAC), a Radio Frequency (RF) front end, a Field Programmable Gate Array (FPGA) and a USB 2.0 interface to connect to the PC. A typical setup of the USRP board is illustrated in Figure 5.1 and it consists of one motherboard that supports up to four daughterboards, where up to 2 receivers and up to 2 transmitters can be plugged in. RF front ends are implemented on the daughterboards.

In details, the motherboard contains 4 high-speed 12-bit ADCs and 4 high-speed 14-bit DACs. All the ADCs and DACs are connected to the FPGA that performs high bandwidth math procedures such as filtering, interpolation and decimation. The DACs clock frequency is 128 Msample/s, while ADCs work at 64 Msample/s to digitize the received signal. The USB 2.0 controller sends the digital signal samples to the PC in 16-bit I and 16-bit Q complex data format (4 bytes per complex sample); since the maximum USB data rate is 32 MB/s, 8 Msample/s is the maximum sample rate manageable by the USB controller. Consequently, the FPGA has to perform filtering and digital down-conversion (decimation) to adapt the incoming data rate to the USB 2.0 and PC computing capabilities. The maximum RF bandwidth that can be handled is thus 8 MHz. There exits different kinds of daughterboards that allows a very high USRP reconfigurability. A complete list of daughterboards that can be used with the USRP motherboard can be found in [110]; while, in the testbed proposed in this dissertation Transceivers *XCVR2450* working in the frequency ranges 2.4 - 2.5 GHz and 4.9 - 5.9 GHz have been used.

Notice that the first range includes specifically the 13 sub-bands around the 2.4 ISM band (2.412 GHz to 2.472 GHz in 5 MHz steps), used by WiFi applications (i.e. IEEE 802.11b, 802.11g and 802.11n standards). The bands from 5.170 GHz to 5.320 GHz and from 5.500 GHz to 5.825 GHz are also used by WiFi applications (i.e. IEEE 802.11a standard). The bandwidth of each WiFi channel is 20 MHz and the mentioned ranges are illustrated in Figure 5.2.

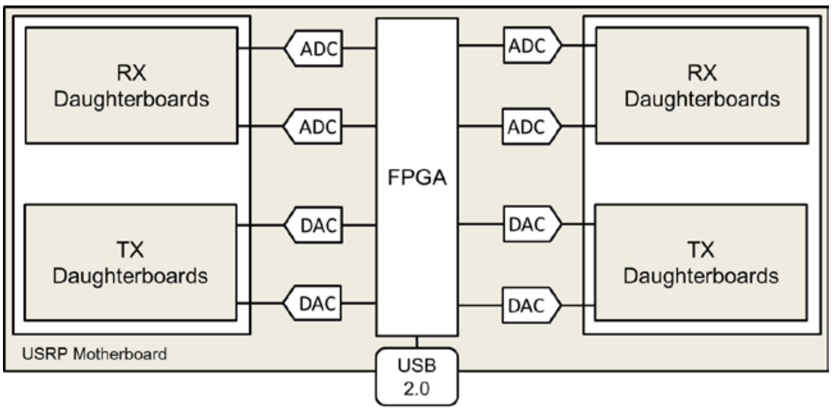


Figure 5.1: USRP Motherboard

Channel Number	Channel GHz
1	2.412
2	2.417
3	2.422
4	2.427
5	2.432
6	2.437
7	2.442
8	2.447
9	2.452
10	2.457
11	2.462
12	2.467
13	2.472

Channel Number	Channel GHz
34	5.170
36	5.180
38	5.190
40	5.200
42	5.210
44	5.220
46	5.230
48	5.240
52	5.260
56	5.280
60	5.300
64	5.320
100	5.500

104	5.520
108	5.540
112	5.560
116	5.580
120	5.600
124	5.620
128	5.640
132	5.660
136	5.680
140	5.700
149	5.745
153	5.765
157	5.785
161	5.805
165	5.825

2.4GHz – has 3 non-overlapping channels separated by 20MHz.

5GHz – has 24 non-overlapping channels separated by 20MHz.

Figure 5.2: ISM Channels

5.2.2 Software Component

GNU radio software is a free and open source toolkit that provides a library of signal processing blocks like modulators, demodulators, filters, etc., for building SDRs. It is an empowering tool that enables to explore new ways of using the electromagnetic spectrum growing into a widely used cross-platform package that supports SDRs.

In GNU radio, the programmer builds a SDR by creating a graph where the vertices are signal processing blocks and the edges represent the data flow between them. All the signal processing blocks are written in C++; these blocks process streams of data from their input port to their output one. The input and output ports of a signal process block are variable; hence, a block can have multiple outputs and multiple inputs. Python programming language is used to create a network or graphs and glue the signal processing blocks together.

The Simplified Wrapper and Interface Generator (SWIG) is an open source package used by GNU radio as glue such that the C++ classes can be used from Python. SWIG has the ability to convert the C++ classes into Python compatible ones. As a result, the whole GNU radio framework is capable of putting together and exploiting the benefits of both C++ and Python. The input and output ports of a signal process block are variable; hence, a block can have multiple outputs and multiple inputs.

There is also a graphical environment available to create a custom radio called GNU Radio Companion (GRC) [111], which allows connecting graphically the signal processing blocks. Figure 5.3 illustrates an example of screenshot of the GRC.

GNU radio has been used to implement all the processes carried out at the different entities of the proposed cognitive management frameworks described in Section 3.2 and Section 3.3. Moreover, GNU radio has been considered to enable the data and control communication between USRP transceivers.

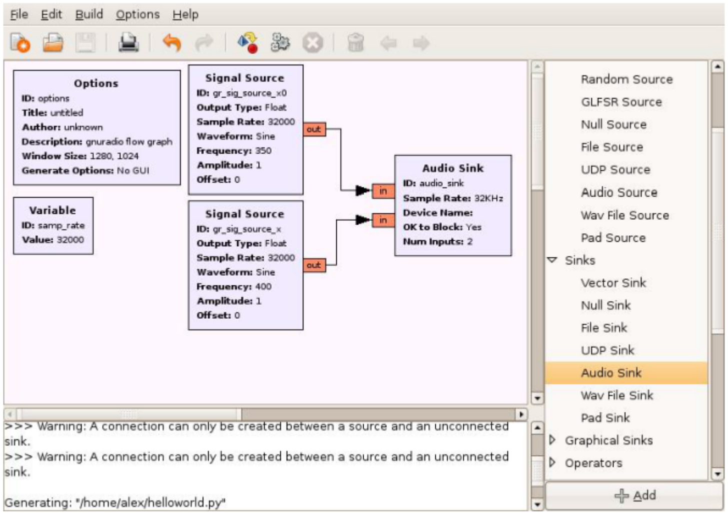


Figure 5.3: GNU Radio Companion screenshot

5.2.3 Individual Node Set-up

Figure 5.4 illustrates a general scheme of two USRP nodes acting as transmitter and receiver, respectively, reflecting the transmission and reception processes and the connection of the PCs running GNU radio software to the hardware platforms. Each individual node can act as either transmitter or receiver in the testbed and it provides spectrum sensing and data transmission functionalities.

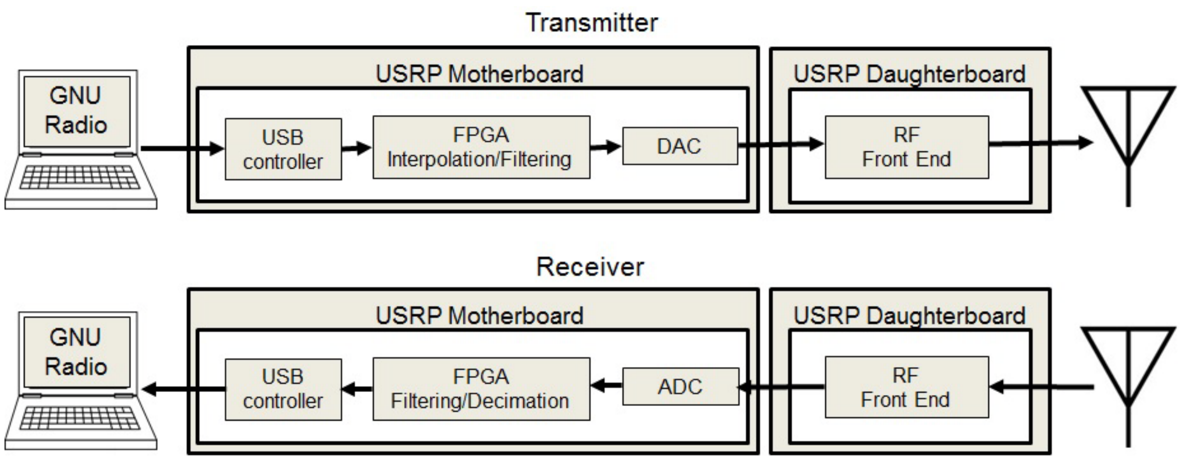


Figure 5.4: Transmitter/Receiver nodes implemented through USRP and GNU radio

Regarding the spectrum sensing functionality, it is exploited by the following functional entities: *(i)* the DSM implemented in the node that represents the infrastructure during the measurement procedure of the spectrum opportunity identification solution illustrated in Section 3.2.2; *(ii)* the CA implemented in the node that represents the cognitive management entity in order to provide the observations in the belief-based spectrum selection solution proposed in Section 3.4.

The script *usrp_spectrum_sense.py* has been considered for the design of the spectrum sensing functionality implemented in the individual node of the testbed; it can be found in the toolkit provided by GNU radio software. This script has been used as a basic code for implementing a wideband spectrum analyser; in details, the script has been extended in order to properly sense the spectrum bands considered in the strategies explained in the next sections. As it was mentioned, the USRP cannot examine more than 8 MHz of RF spectrum due to the USB 2.0 limitations. Notwithstanding, USRP RF front end can be tuned in suitable steps in order to scan across a RF spectrum wider than 8 MHz.

The script receives several input parameters from the user such as: the lowest frequency of the band to be sensed *f_min*; the highest frequency of the band to be sensed *f_max*; how long the spectrum sensing functionality is executed in the entire frequency range whose bandwidth is *f_max-f_min*; the decimation factor that adapts the incoming data rate to the USB 2.0 and PC computing capabilities; the Fast Fourier Transform (FFT) size parameter that is the number of samples considered to perform the magnitude analysis of the sensed signal. In particular, the selection of this parameter allows dividing the entire frequency range to be sensed into smaller spectrum blocks. The output of this script provides the signal energy detected in each sample during the execution of the spectrum sensing functionality.

Regarding the data transmission functionality, it allows sending either, signalling messages among nodes, or user data between a pair of terminals. The data transmission functionality has been implemented through the GNU radio's *benchmark_tx.py* and *benchmark_rx.py* scripts. In details, the file *benchmark_tx.py* is the transmitter code that generates packets whose size is specified by the user; while, the file *benchmark_rx.py* is the receiver code, which listens for incoming packets and it checks for errors in each received one through the Cyclic Redundancy Check (CRC) error-detecting code. These scripts take the following input parameters from the users: a modulation scheme between the Gaussian Minimum Shift Keying (GMSK) and the Differential Binary Phase Shift Keying (DBPSK); the data transmission bit rate; the packet size; the central frequency of the spectrum block for the data transmission.

The main problem found in these scripts is that the implementation uses only one way data flow; therefore, the transmitter cannot receive ACK (positive acknowledge) or NACK (negative acknowledge) messages useful to allow retransmissions of either lost or erroneous packets. Hence, these scripts have been modified by adding a stop and wait error-control method that uses acknowledgement messages in order to monitor the performance of the data transmission. Stop and wait is the simplest kind of Automatic Repeat reQuest (ARQ) method [113].

In an ARQ scheme a number of parity-check bits are generated for each block of information, and then transmitted together with the information. At the receiver side, the parity checking is performed on the received data. If the parity checking is successful, the received block is assumed to be error-free, delivered to higher layers, and the receiver notifies that the block has been successfully received sending an ACK. If there is a parity failure, errors are detected in the received data, and the transmitter is requested sending a NACK in order to retransmit the same block of information. The stop and wait scheme implemented in the testbed enables the following procedures illustrated in time line order:

- *benchmark_rx.py* takes the input parameter and then, it listens to the selected spectrum block waiting for data reception;
- *benchmark_tx.py* takes the input parameter and then, it sends the *i*-th packet to *benchmark_rx.py*;
- *benchmark_rx.py* checks for a possible error in the received packet through the CRC and it sends the corresponding acknowledgement message to *benchmark_tx.py*;
- *benchmark_tx.py* waits for the *i*-th ACK or NACK message from *benchmark_rx.py* during a certain time (defined as timeout);
- if the *i*-th ACK is received before the timeout is expired then, *benchmark_tx.py* sends the next packet to *benchmark_rx.py*;
- if the *i*-th NACK is received or the *i*-th ACK is not received before the timeout is expired, *benchmark_tx.py* retransmits the *i*-th packet to *benchmark_rx.py*.

5.2.4 Individual Node Validation

The validation of the ability of the spectrum sensing functionality implemented in each individual node has been considered an essential step forward towards the development of the testbed platforms illustrated in the next sections. Hence, in order to perform this validation, the spectrum opportunity identification for ONs presented in Section 3.2.2 has been firstly implemented and assessed in an individual node. The objective of this section is then to demonstrate that the spectrum sensing capability of the individual node is able to properly capture the actual conditions of the spectrum band in the scenario under test, where a number of WiFi Access Points (APs) exists.

a) Configuration

The scenario considered in this study is the indoor office illustrated in Figure 5.5 located within the Campus Nord of Universitat Politècnica de Catalunya (UPC) in Barcelona. The environment where the node operates includes the presence of two WiFi APs (i.e. AP1 and AP2 in the figure) that occupy ISM channels at, respectively, 2.412 GHz and 2.432 GHz. The individual node where the spectrum opportunity identification strategy has been implemented is located in room R1.

The measurement procedure of the strategy considered the ISM band from *F_min_band*=2.4 GHz to *F_max_band*=2.5 GHz that has been subdivided in 1000 portions of Δf=100 kHz. The spectrum sensing functionality was executed for each portion during Δt=100 ms. The threshold to detect that a portion is available is set using the following procedure in accordance to [90]: *(i)* to provide an estimate of the thermal noise, the USRP antenna was replaced with a matched load (i.e., a 50 ohm resistor) and a measurement was performed in the band from 2.4 GHz to 2.5 GHz; *(ii)* the Cumulative Distribution Function (CDF) of the thermal noise was calculated for all the 100 kHz portions; *(iii)* a threshold between thermal noise and signal energy was selected considering a false alarm probability equal to 1%.

The minimum and the maximum numbers of spectrum portions of a block P_{min} and P_{max} illustrated in Section 3.2.2 in this example have been set, respectively, to 30 and 300 portions.

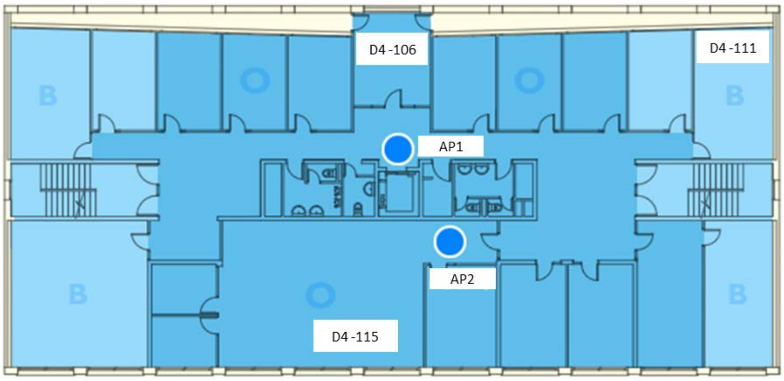


Figure 5.5: Considered scenario for validating the spectrum sensing capability of the individual node

b) Key Performance Indicators

In order to validate the spectrum sensing capability of the individual node, the following KPIs are considered:

- Spectrum Opportunity Index (SOI): as it was mentioned in Section 3.2.2, it is defined as the fraction of measurements in which a given spectrum portion has been detected as available. This KPI is considered essential to demonstrate that the measurement procedure of the spectrum opportunity identification strategy implemented in the individual node is able to capture the actual condition of the spectrum band.

- Identified spectrum blocks: it is the output of the strategy that presents a list with the different spectrum blocks sensed as free of interference, represented by the central frequency and the bandwidth of each one. This KPI validates the capability of the spectrum block formation procedure in the individual node in accordance with the SOI measured in each spectrum portion and the P_{min} and P_{max} values.

c) Obtained Results

Under the configuration presented above, Figure 5.6 illustrates the obtained SOI for all the 1000 portions of 100 kHz averaged during a 10 minutes period. It can be observed that: *(i)* the spectrum portions in the ISM channels occupied by AP1 and AP2 at 2.412 GHz and 2.432 GHz, have a SOI equal to 0%; *(ii)* there are three groups of consecutive 100 kHz blocks with a high opportunistic index value (i.e. greater than 80%).

As a result, the spectrum blocks provided as output by the spectrum opportunity identification strategy are those indicated in Table 5.1, considering that the minimum and the maximum numbers of portions of a block have been set, respectively, to P_{min}=30 and P_{max}=300. Correspondingly, the available set of portions between 2442 to 2500 MHz with a total of 58 MHz has been split into 2 blocks of 29 MHz (i.e., each one of 290 blocks). Hence, it can be concluded that the measurement procedure of the spectrum opportunity identification strategy validates the capability of the individual node to detect the spectrum portions free of the interference caused by the APs whose configuration is known. Moreover, it was assessed how the spectrum block formation procedure of the spectrum opportunity identification strategy is able to define available spectrum blocks guaranteeing the conditions dictated by P_{min} and P_{max}. This validation has motivated the development of the testbed platforms that will be illustrated in the next sections ensuring their capability of perceiving correctly the actual condition of the spectrum band under study.

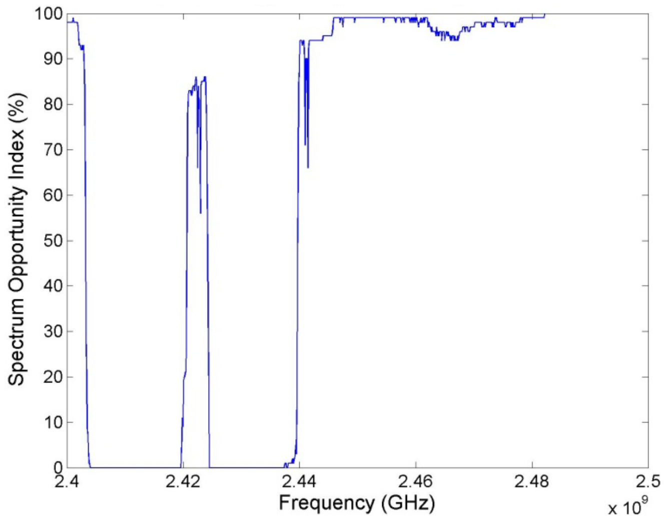


Figure 5.6: Measured Spectrum Opportunity Index

Table 5.1: Spectrum blocks obtained as a result of the spectrum opportunity identification strategy

Index	Central Frequency (MHz)	Bandwidth (MHz)
1	2401.500	3
2	2422.000	4
3	2456.500	29
4	2485.500	29

5.3 Baseline Testbed

5.3.1 Testbed Architecture

The objective of this testbed is to provide a real-time platform that allows implementing the BCMF and evaluating the spectrum management solutions for ONs illustrated in Section 3.2.2. For that purpose, a scenario is considered where two devices need to communicate through an ON link controlled by the infrastructure that includes the BCMF. Hence, spectrum opportunity identification and spectrum selection functionalities reside in the infrastructure node. Figure 5.7 illustrates the developed testbed.

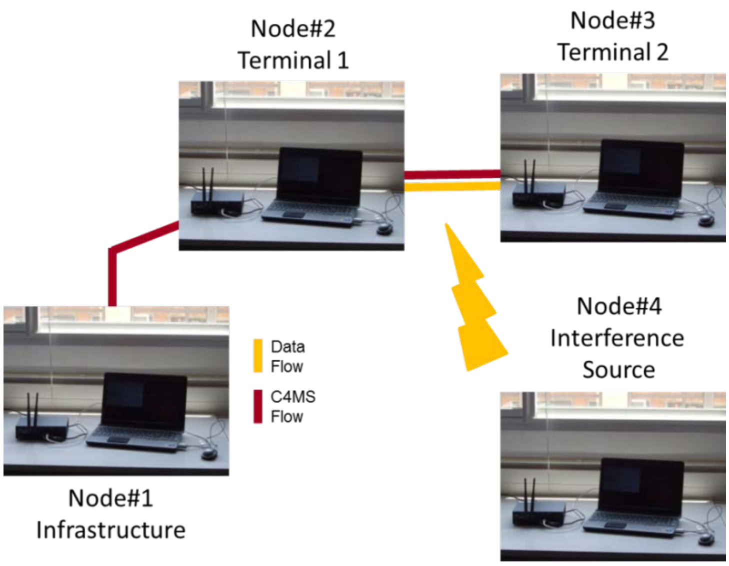


Figure 5.7: Testbed Architecture for Spectrum opportunity Identification and Spectrum Selection in ONs

Node#1 represents the infrastructure side where the DSM for spectrum opportunity identification and all the functionalities of the CMON-N for spectrum selection in case of ON creation and ON maintenance are implemented. In turn, Node#2 and Node#3 are the terminals exchanging data through the ON link. Node#2 is programmed to monitor periodically the performance achieved in the selected spectrum channel and sent to Node#1.

In order to illustrate how the BCMF is able to detect and react to time-varying interference conditions over the different spectrum channels during the ON maintenance, a controlled interference source is also included. It is implemented as Node#4, whose operating frequency at each time can be defined as part of the testbed configuration set-up. Moreover, the periods in which the interference source is active or inactive are also controlled following specific patterns whose statistic can also be configured. A single RAT is considered and, therefore, the JRRM module in ETSI RRS functional architecture is omitted in the implemented testbed.

It can be observed from Figure 5.7 that the signalling flow is implemented through the Control Channel for the Cooperation of the Cognitive Management System (C4MS) protocol, which uses the implementation option based on IEEE 802.21 “Media-Independent Handover (MIH) Services” [114]. C4MS constitutes a key element for the operations of the ONs life cycle because it enables the delivery of guidance/assistance information among the nodes of ONs and providing means for their management.

5.3.2 Evaluation of Spectrum Selection

The purpose of this section is to evaluate the performance of the spectrum selection strategy based on the fittingness factor concept proposed in Section 3.2.2 and implemented in the testbed. For benchmarking purposes, a random spectrum selection scheme is considered.

a) Configuration

In the scenario illustrated in Figure 5.7, the two terminals forming the ON (i.e., Node#2 and Node#3) need a spectrum block to transmit data in the ON link under the infrastructure (i.e., Node#1) control. The allocated spectrum block is selected by the Decision Making implemented in the Node#1 following equation (3.4) among the blocks resulting from the spectrum opportunity identification executed in the ISM 2.4 GHz band. Once the spectrum is assigned, Node#2 is the data transmitter and Node#3 the receiver. Since the main objective of this section is to assess the spectrum selection strategy, it is supposed that the spectrum opportunity identification has been executed considering $P_{min}=P_{max}=50$ and its result is represented by the spectrum blocks illustrated in Table 5.2.

Table 5.2: Result of the spectrum opportunity identification strategy

Index	Central Frequency (MHz)	Bandwidth (MHz)
1	2472	5
2	2484	5

Moreover, the external interference (i.e., Node#4) is configured to operate on the specific spectrum block centred at 2.472 GHz. The activity of this external interference is automatically adjusted following the transmission patterns indicated in Table 5.3, considering 4 different experiments whose duration is 10 minutes each. The spectrum block centred at frequency 2.484 GHz is available during the overall experiment, although it is subject to some spurious uncontrolled interference existing in the environment. Statistics obtained in this spectrum block indicate that it is free of interference during 99.92% of the time. These activities are supposed to be known and stored in the Knowledge Management.

The ON link is configured to generate sessions with a certain average duration and an inactivity time between them, shown in Table 5.3 as well. The requested bit rate for the link is 512 kb/s with GMSK modulation; while, the available bit rate is 512 kb/s when the spectrum blocks are free of interference and 0 kb/s otherwise.

Consequently, the fittingness factor achieved by the link using the spectrum block centred at 2.472 GHz ranges between 0 (when the interference is active) and 1 (when the spectrum block is free of interference and the available bit rate equals the requested one); while, the fittingness factor obtained using the spectrum block centred at 2.484 GHz is able to reach its maximum value during all the experiments.

Table 5.3: Activity patterns of the external interference and the ON link

Experiment	Average inactivity time interferer	Average activity time interferer	Average inactivity time ON link	Average session duration ON link
1	300s	300s	30s	60s
2	300s	60s	30s	60s
3	60s	300s	30s	60s
4	300s	300s	90s	120s

b) Key Performance Indicators

In order to assess the performance of the proposed spectrum selection strategy, two KPIs are taken into account. In this case the stop and wait error-control method provided by the data transmission functionality implemented in the individual node is exploited to evaluate the spectrum selection strategy. Hence, in this study the following KPIs are considered:

- Efficiency in the data transmission: it is defined as the ratio between successfully transmitted data packets in the ON link and total number of transmitted data packets including retransmissions. This KPI is periodically computed by Node#2.

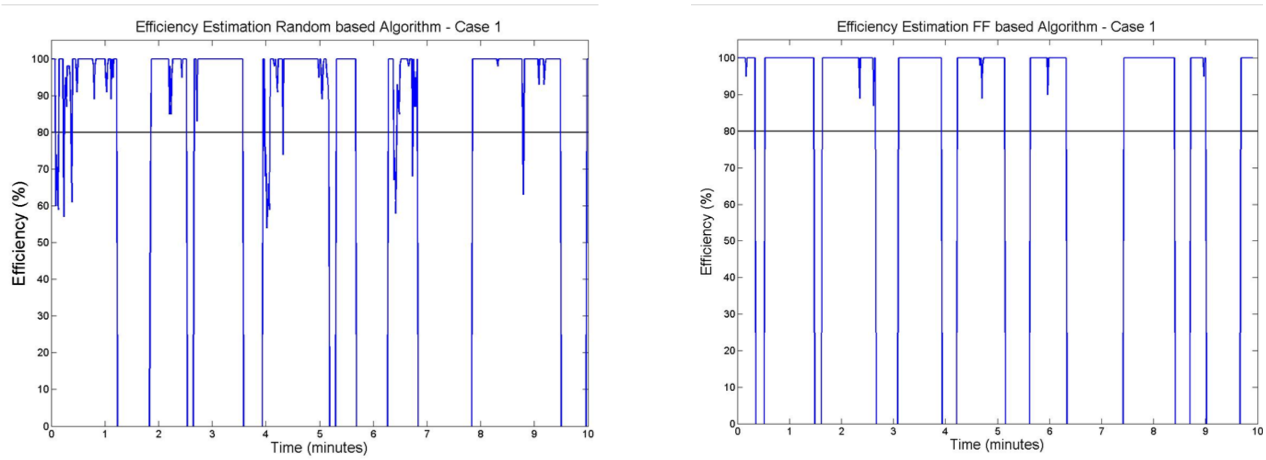
- Spectrum HO rate (SpHO): it is defined as the ratio of spectrum handovers per unit of time that have occurred during the experiment in the ON link. The spectrum handover procedure is executed whenever the efficiency falls below 80%.

c) Obtained Results

Four experiments characterized by different durations of the interference activity on the spectrum block centred at 2.472 GHz, and average link activity are considered in this study. Results compare the behaviour of the proposed spectrum selection strategy based on the fittingness factor against a random spectrum selection. For that purpose, each experiment has been carried out two times, one per strategy.

Figure 5.8 plots the results of experiment 1 in terms of efficiency observed by the ON link. Notice that only the periods in which a session in the ON link has been established are plot. The results for the execution of the random strategy are plot in Figure 5.8(a) and the results for the fittingness factor-based strategy are plot in Figure 5.8(b). Notice that, although the statistical pattern is the same for the two executions, the actual durations of each session are different due to the randomness in the session generation. In this experiment, the interferer in one of the spectrum blocks is active 50% of the time, with an average duration much longer than the session duration of the ON link.

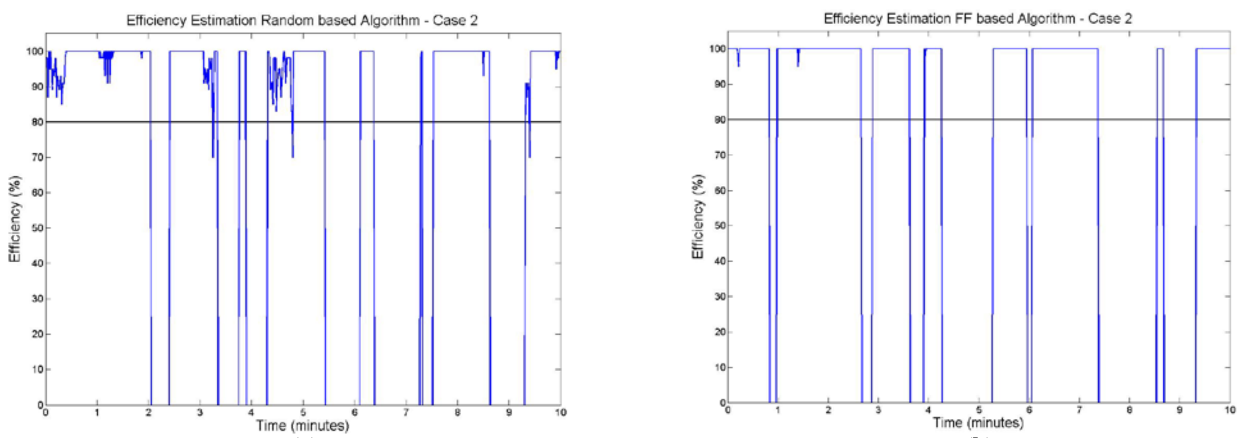
Correspondingly, in the random spectrum selection (see Figure 5.8(a)) spectrum handovers need to be carried out soon after if the allocation has been performed in this block during the ON maintenance phase in case the interference arises in the allocated block. This can be observed in the figure because the efficiency falls below the limit of 80%. The resulting spectrum handover rate observed during the whole execution for the different experiments with the random strategy is indicated in Table 5.4. On the contrary, with the fittingness factor based spectrum selection strategy the efficiency is kept at a high level during the whole execution and correspondingly no spectrum handovers are required.



(a) (b)

Figure 5.8: Spectrum Selection Results of experiment 1 - (a) Random, (b) Fittingness factor-based

Figure 5.9 plots the results corresponding to experiment 2. In this case, the duration of the interferer activity is much lower (17% of the time with an average duration of 60s).

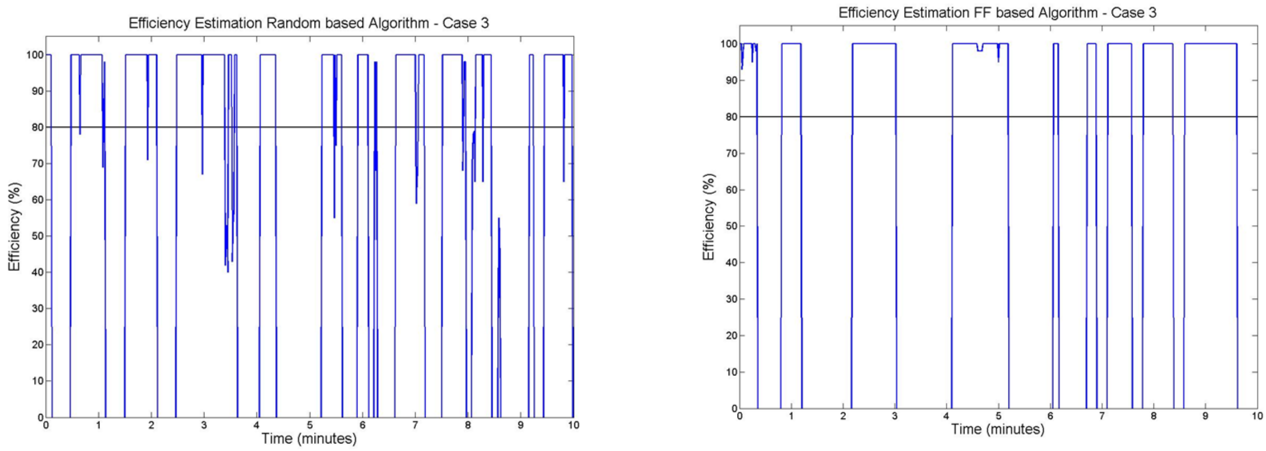


(a) (b)

Figure 5.9: Spectrum Selection Results of experiment 2 - (a) Random, (b) Fittingness factor-based

As it can be noticed in Figure 5.9(a) and Table 5.4, the resulting SpHO rate for the random case is more reduced than with experiment 1. In any case, the fittingness factor achieves a better efficiency (see Figure 5.9(b)).

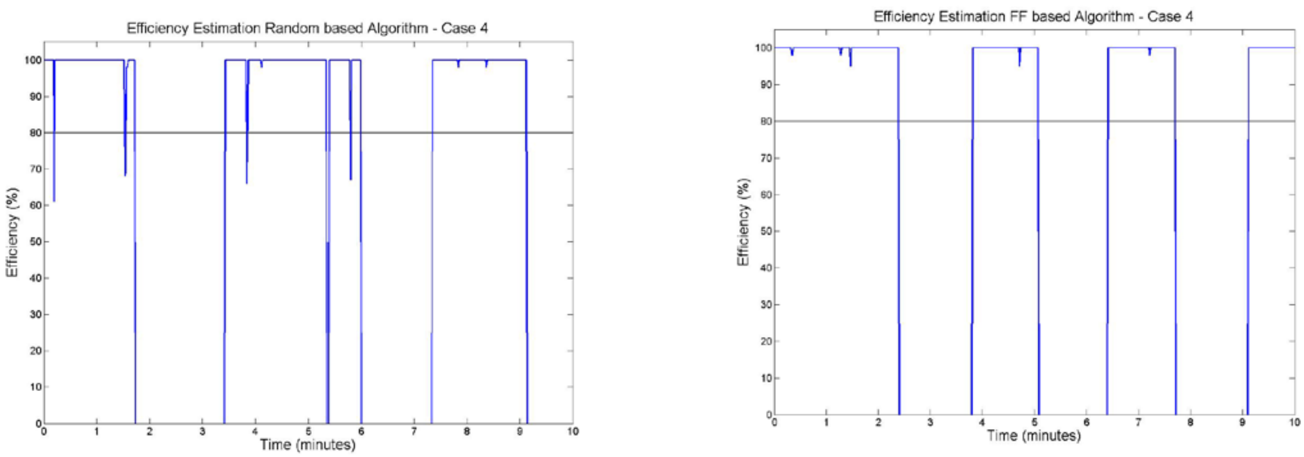
In experiment 3, the activity factor of the interference is 83%, so it is most of the time interfered. As a result, it can be observed in Figure 5.10(a) that the random selection strategy is able to keep a good degree of efficiency by executing a high number of spectrum handovers, resulting in the largest SpHO rate among all the experiments, as seen in Table 5.4. Again, the fittingness factor spectrum selection provides the best performance.



(a) **(b)**

Figure 5.10: Spectrum Selection Results of experiment 3 - (a) Random, (b) Fittingness factor-based

Finally, experiment 4 illustrated in Figure 5.11 considers that the interferer has the same activity pattern as in experiment 1 (50% of activity) but with much longer session durations in the ON link.



(a) **(b)**

Figure 5.11: Spectrum Selection Results of experiment 4 - (a) Random, (b) Fittingness factor-based

In this case, the SpHO for the random selection case is more reduced than with experiment 1 as shown in Table 5.4. The reason is that, once a SpHO is executed during the ON link session, if the new allocation is done over the spectrum block with less interference, it is possible to keep it until the end of the session. In any case, fittingness factor based spectrum selection is able to provide again a much better performance.

Table 5.4 : Spectrum Handover rate for the random selection

Experiment	SpHO rate (HO/min)
1	2.2
2	0.5
3	2.8
4	0.6

5.3.3 Demonstration of Opportunistic Network Management

The aim of this section is to illustrate how the result of the spectrum opportunity identification strategy is used to perform the spectrum selection functionality in a scenario where the interference conditions vary during the ON management phase and, therefore, can affect the performance of the selected spectrum. Furthermore, the demonstration highlights the signaling means implemented in the platform, which support the different ON stages. To this end, in the scenario illustrated in Figure 5.7 the terminals (i.e., Node#2 and Node#3) will constitute an ON to exchange data through the ON link.

The first step of this demonstration is the ON creation, which includes the execution of the spectrum opportunity identification and the spectrum selection strategies by the Node#1. Once the ON has been created, the transmission of data between Node#2 and Node#3 starts on the spectrum block assigned by Node#1. At this stage, the ON is in maintenance mode and the Node#2 starts to monitor the radio link. If the node perceives degradation in the data transmission, it triggers the ON reconfiguration in order to achieve a cleaner spectrum block.

The signalling messages flow exchanged among the nodes implemented in the baseline testbed follows the procedures for the ON creation and ON reconfiguration of the Message Sequence Chart (MSC) based on the MIH defined in [114]. The procedure for the ON creation implemented in the testbed is illustrated in Figure 5.12.

The steps of the procedure that lead to the creation of the ON are the following:

1. The first step towards the ON Creation (ONC) is the ON Negotiation (ONN) that allows achieving the information used for the configuration of the radio link. Hence, the message *MIH_C4MS_ONN.request* defined to start the negotiation is sent from Node#2 to Node#1 to obtain a valid configuration of the radio link. The message indicates the terminals involved (i.e., Node#2 and Node#3) and the QoS requirements that the link is expected to support, in terms of required bit rate.

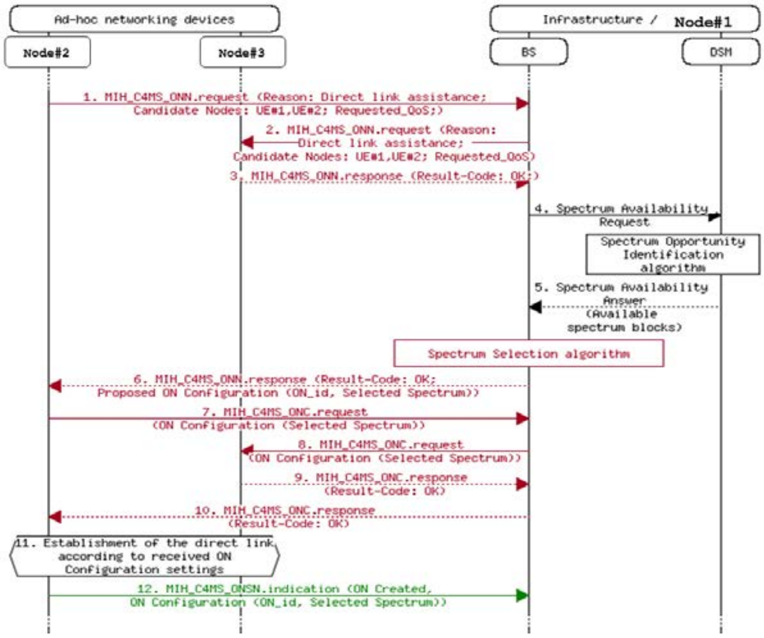


Figure 5.12: Implemented message exchange for the ON creation

2. Node#1 sends a *MIH_C4MS_ONN.request* to Node#3 informing it about the intention to establish a direct radio link with Node#2 and allowing it to join the negotiation process for the derivation of the radio link configuration.

3. Node#3 replies to Node#1 with a *MIH_C4MS_ONN.response* message, notifying its acceptance for the establishment of the link.

4. The CMON-N entity in the BS inquires the DSM entity to determine spectrum availability for the link. Therefore, the spectrum opportunity identification strategy is executed.

5. DSM reply provides the CMON-N entity in the BS the available spectrum blocks, and the spectrum selection strategy is executed to decide the spectrum block to be allocated to the link.

6. The proposed ON configuration with the selected spectrum is transferred to Node#2 by issuing a *MIH_C4MS_ONN.response* message.

7. Then the ONC can be started. Hence, Node#2 sends the message *MIH_C4MS_ONC.request* defined to start the creation to Node#1 with the final ON configuration.

8. Node#1 sends another *MIH_C4MS_ONC.request* towards Node#3 with the final ON configuration.

9. Node#3 replies with a *MIH_C4MS_ONC.response* message with a successful result-code indicating that the terminal is ready to establish the link.

10. Node#1 concludes the ON creation procedure by sending a *MIH_C4MS_ONC.response* message to

Node#2.

11. The link establishment takes place at this point.

12. Finally, the creation of the ON is notified to Node#1 from Node#2 by sending a *MIH_C4MS_ONSN.indication* message.

Similarly, Figure 5.13 describes the MSC of an ON reconfiguration process that can take place during the ON maintenance phase. The description of the different steps is as follows:

1. Node#2 detects that the radio link is not performing as expected. In the evaluation of the performance results, this will be due to interference generated by Node#4 in the spectrum currently in use in the radio link connecting Node#2 and Node#3.

2. As in the creation phase, it is considered that ON operational policies dictate that the direct link establishment can be assisted by the infrastructure so that a *MIH_C4MS_ONN.request* is sent from Node#2 to the infrastructure. This message will indicate the reason (low link quality level), the ON identifier and the required QoS in terms of bit rate.

3. Also as in the creation phase, CMON-N entity in the BS may need to refresh spectrum availability information and determine to send an inquiry to the DSM entity, triggering the spectrum opportunity identification.

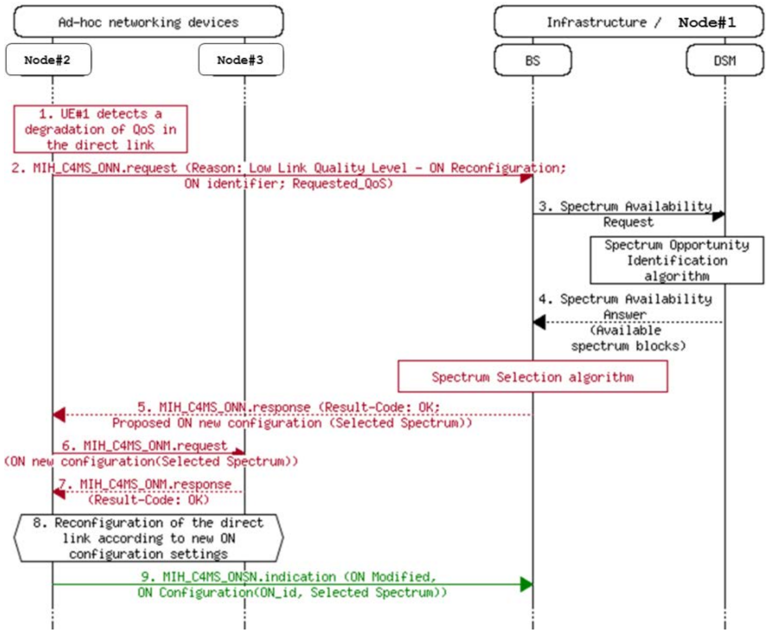


Figure 5.13: Implemented message exchange for the ON reconfiguration

4. DSM reply provides the CMON-N entity in the BS with the available spectrum blocks at this time. Based on this information, the selection of new spectrum blocks to carry out the transmission will be performed.

5. The new proposed ON configuration in terms of selected spectrum is transferred to Node#2 by issuing a *MIH_C4MS_ONN.response* message.

6. Node#2 sends a *MIH_C4MS_ONM.request* message (ON-Modification) towards Node#3 with the new ON configuration.

7. Node#3 replies with a *MIH_C4MS_ONM.response* message where a successful result-code is reported to indicate that the terminal is ready to reconfigure the link with the proposed settings.

8. The link is reconfigured at this step.

9. Finally, the modification of the ON is notified to the infrastructure from Node#2 by sending a *MIH_C4MS_ONSN.indication* message.

Notice that, from the spectrum management perspective, the spectrum opportunity identification strategies used in the ON creation and ON maintenance stages are the same. Similarly, the spectrum selection strategy considered in case of ON creation and ON maintenance stages is also the same, but, as a difference from the ON creation stage, in the ON maintenance case the trigger of the strategy occurs whenever some changes are identified in the environment such as bad channel quality experienced by an active link or a link release while there are other active links. In these two cases, the spectrum selection solution makes decisions on spectrum mobility to modify the current spectrum block allocated to an active link.

During the execution of the demonstration, the nodes follow the procedures illustrated in the MSCs of Figure 5.12 and Figure 5.13 for, respectively, ON creation and ON reconfiguration. In details, for the ON creation the allocated spectrum block will be decided by the infrastructure (i.e. Node#1) during the ONN procedure based on the spectrum opportunity identification executed by Node#1 in the ISM 2.4 GHz band. The spectrum opportunity identification procedure is the same explained in Section 5.2.4, but now performing the spectrum sensing functionality during few milliseconds for each portion, averaging the measurements during a period of 10s and with P_{min}=P_{max}=50.

Firstly, Node#2 has sent the *MIH_C4MS_ONN.request* message to Node#1 to start the negotiation for the creation of ON indicating the requested bit rate. After receiving the *MIH_C4MS_ONN.request* message from Node#2 and contacting Node#3 to confirm its availability to create the ON, Node#1 executes the spectrum opportunity identification strategy. Table 5.5 illustrates the result of the spectrum opportunity identification at this stage.

Table 5.5: Spectrum opportunity identification result

Index	Central Frequency (MHz)	Bandwidth (MHz)
1	2422	5
2	2427	5
3	2432	5
4	2437	5
5	2442	5
6	2447	5
7	2452	5

Since the aim of this experiment is to show the adaptation of the spectrum selection strategy to the interference variations to illustrate an example of ON management, the value of the fittingness factor guaranteed by all the spectrum blocks for the bit rate requested in the link are supposed to be the same.

In this particular experiment Node#1 chooses the spectrum block #6 centred at 2.447 GHz for the operation of the ON between Node#2 and Node#3. This information is communicated to Node#2 in the *MIH_C4MS_ONN.response* message.

This triggers the *MIH_C4MS_ONC.request* message to finalise the ON creation. After that the ON has been created, the transmission of data between Node#2 and Node#3 starts on this specific spectrum block. The characteristics of the data transmission for the communication between terminals are given in Table 5.6.

During the ON maintenance phase, Node#2 through the stop and wait error-control periodically monitors the efficiency in the data transmission as the ratio between successfully transmitted data packets and total number of transmitted data packets including retransmissions. This is computed based on the received acknowledgements for each packet.

Table 5.6: Experiment Assumptions

Parameter	Value
Modulation	GMSK
Data Rate	256 kbps
Packet Size	1500 byte
Minimum Efficiency threshold	80%
Experiment Time	25 minutes

In order to illustrate the capabilities of the BCMF to react to time-varying interference conditions and to adapt the selected spectrum block to provide good QoS for the ON communication, the interference source in the testbed platform (i.e., Node#4) is configured to transmit at different frequencies during the experiment as illustrated in Figure 5.14. In this particular realization, after roughly 8 minutes running the testbed, Node#4 starts transmitting on the same frequency band used for ON data transmission (i.e. the spectrum block #6 centred at 2.447 GHz).

As a result, degradation in the communication is observed, as seen in Figure 5.15 that depicts the evolution of the efficiency in the ON link communication together with the central frequencies of the spectrum blocks assigned to the ON. When the efficiency is below the threshold of 80%, Node#2 triggers the ONM procedure illustrated in Figure 5.13, requesting for a new spectrum block where data communication can be continued with improved QoS. Node#2 sends a *MIH_C4MS_ONN.request* message to the infrastructure starting the ON reconfiguration procedure.

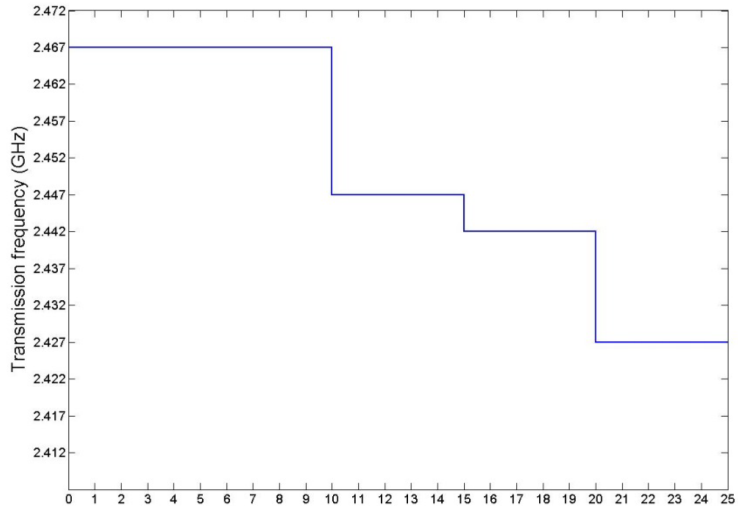


Figure 5.14: Transmission frequencies configured in Node#4

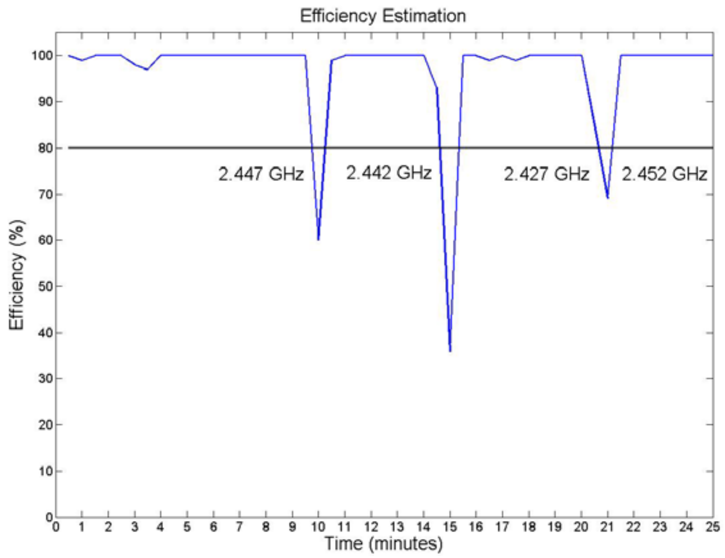


Figure 5.15: Efficiency in the data transmission through the ON. The frequencies assigned to the ON are indicated in the figure

After executing again the spectrum opportunity identification strategy, the spectrum selection functionality decides that ON will continue operation through the spectrum block centred at 2.442 GHz. This is notified to Node#2 in the *MIH_C4MS_ONN.response* message. After receiving this response, Node#2 sends the *MIH_C4MS_ONM.request* to Node#3 to reconfigure the link in the new spectrum block. Then, the transmission between the terminals continues, reaching again high efficiency levels. The same process is illustrated twice during the rest of the demonstration time.

For a better understanding of the process some screenshots of the different PCs controlling the nodes of the testbed are presented in Appendix B reflecting some instants of the demonstration illustrated in this section, related to the MSCs of the ON creation and ON maintenance procedures described, respectively, in Figure 5.12 and Figure 5.13.

5.4 Extended Testbed

5.4.1 Testbed Architecture

The testbed illustrated in Section 5.3.1 has been extended in order to implement the FCMF described in Section 3.4 and to assess in real-time the belief-based spectrum selection policy proposed in this dissertation. In particular, motivated by the simulation results illustrated in Section 4.5, the KD acquisition entity is also considered in the testbed and the simulation analysis is extended in the real-time environment provided by the platform considering different interference conditions.

The extended version of the testbed consists of six reconfigurable individual nodes to implement two terminals communicating through the radio link, the central node where the cognitive management processes are executed, and three nodes representing interference sources. Figure 5.16 depicts the scenario that has been implemented using the abovementioned six reconfigurable nodes, while Figure 5.17 presents the extended version of the implemented testbed.

Node#1 is the centralized entity where the extended FA of the FCMF of Figure 3.7 has been implemented. Node#2 and Node#3 are the terminals that need to establish a radio link for supporting a data communication under the control of Node#1 that will decide the spectrum to be used by this radio link. The control messages are sent among the nodes through Ethernet cables. Moreover, Nodes #4, #5 and #6 are external interference sources transmitting in certain spectrum blocks.

Node#1 includes the decision making, the knowledge management and the CA functionalities. Specifically, the CA entity performs measurements by means of the spectrum sensing functionality implemented in the USRPs for each spectrum block during a sensing time Δt_m. Then, based on the detected energy, the CA identifies the interference states of each spectrum block. These measurements are triggered either by the KD Acquisition entity during the measurement acquisition phase in order to fill the KD, or by the decision making in accordance to an observation strategy selected among the IM, PM and StS by the OSDM. By properly processing the measurements of the interference states, the KD Acquisition derives samples of the durations of each state.

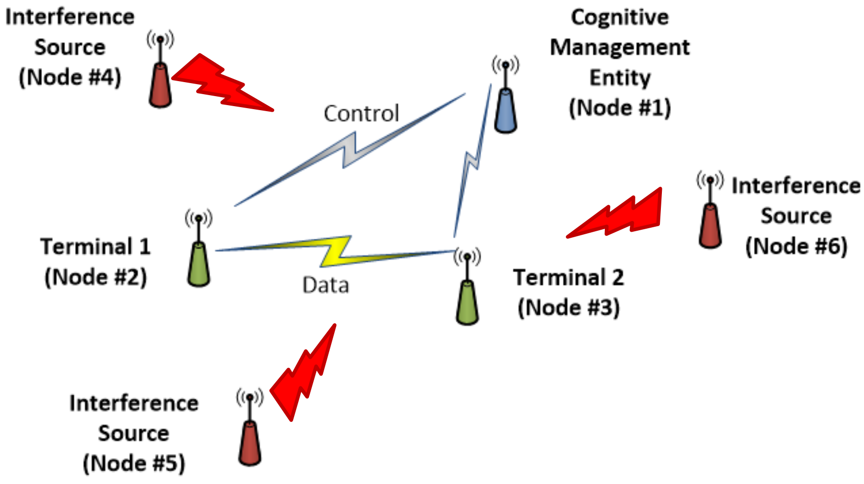


Figure 5.16: Scenario Implemented through the Extended Testbed

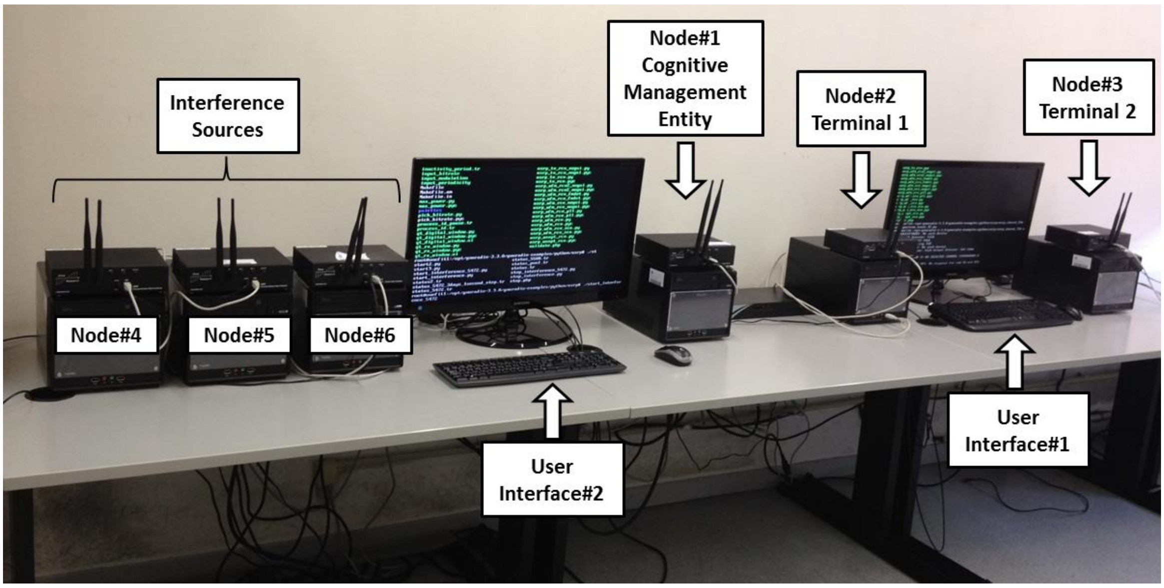


Figure 5.17: Testbed Architecture for the belief-based spectrum selection

From these durations, the KD Acquisition estimates the values of state transition probabilities and steady state probabilities to be stored in the KD. The estimation of each parameter will be done as the average of a sufficient number of sample that ensures convergence under some reasonable limits, as explained in Appendix C. In particular, the considered convergence condition in this dissertation is that the size of the 95% confidence interval of every measured parameter is below a fraction η of the measured average value. The convergence criterion defined in Appendix C is used with η=0.2%.

The KM is in charge of providing the OSDM with the dynamism information of the radio environment characterized by the eigenvalues calculated for all state transition probabilities stored in the KD. Moreover, each time that a new session is established in a radio link the KM provides the data function parameters to the SSDM that selects the most appropriate spectrum block following equation (3.16) particularized for the observation strategy decided in the OSDM entity.

Node#2 is programmed to compute periodically the system session reward in order to measure the achieved performance depending on the experienced bit rate in the allocated spectrum block.

Moreover, the USRP-based interference sources implemented in Nodes #4, #5 and #6 are transmitting in specific spectrum blocks following random patterns whose statistics can be controlled at the testbed configuration. As seen in Figure 5.17, two screens connected to two switches are the user interfaces that allow running and controlling the testbed operation. Specifically, the User Interface#1 allows configuring the parameters of the cognitive management entity and the communicating terminals, while the User Interface#2 allows the configuration of the interference sources.

In each emulation run, the testbed produces a number of performance statistics that are stored in files so that they can be post-processed later on. In particular, statistics related to the performance obtained in the communication through the radio link between Terminal 1 and Terminal 2 are stored in Node#2, while the statistics related to the cognitive management entity are stored in Node#1.

5.4.2 Evaluation of Spectrum Selection and Observation Strategies

a) Configuration

The emulation assumptions and scenario parameters that have been considered to evaluate the performance achieved by the belief-based solution implemented in the FCMF and making use of the testbed described in Section 5.4.1 are described in the following. A set of M= 3 spectrum blocks are taken into account. The bandwidth is 200 kHz for all the spectrum blocks and the central frequencies are 5472, 5490, 5508 MHz. Two different interference states are considered for the spectrum blocks: $S^{(i)}$=0 when no interference exists and $S^{(i)}$=1 when the interference corresponds to its maximum value.

The average durations of the interferences states for each spectrum block and the corresponding values of $\lambda_1^{(i)}$ are presented in Table 5.7, considering that the testbed operates in time steps of 10 seconds. As indicated in the table, two different sets of parameters are considered reflecting two degrees of predictability in the interference. The case denoted as HP corresponds to High Predictability while the case denoted as LP corresponds to Low Predictability.

Table 5.7: Characterization of the interference states

	Spectrum Block	State $S^{(i)}$=0 (time steps)	State $S^{(i)}$=1 (time steps)	$\lambda_1^{(i)}$
LP	#1	24	6	0.792
	#2	3	24	0.625
	#3	24	8	0.833
HP	#1	480	120	0.990
	#2	60	480	0.981
	#3	480	160	0.992

L=1 radio link is considered to transfer the data flow between Node#2 and Node#3 of the testbed (see Figure 5.16) with bit rate requirement R_{req}= 512 kbps. During the data transmission sessions Node#2 computes the system session reward value $r^{(i)}_{s^{(i)}(t)}$ in the selected *i*-th spectrum block following equation (3.14). Different values of the average link session duration $\overline{D_j} = \overline{D}$ and average session rate ρ are considered as indicated in Table 5.8. Specifically, 5 different scenarios are considered by combining the LP and HP possibilities of interference dynamism with different values of session duration and session generation rate. This allows demonstrating the effect of the observation and decision making strategies under different situations in terms of interference dynamics and traffic patterns.

For the PM strategy, the observation period $T^{(i)}_{obs}$ has been selected to fulfil condition (3.30) for all the spectrum blocks. Specifically, for the scenarios with HP $T^{(i)}_{obs}$ is set to 50 time steps and for the scenarios with LP $T^{(i)}_{obs}$ is set to 2 time steps.

Table 5.8: Characterization of the Scenarios

Scenario	$\overline{D_j} = \overline{D}$ (time steps)	ρ (sessions/time step)	Predictability
1	1	0.5	LP
2	15	0.063	
3	15	0.013	HP
4	15	0.063	
5	500	$1.8 \cdot 10^{-3}$	

b) Key Performance Indicators

In order to assess the performance of the proposed observation strategies, appropriate KPIs are also defined for the belief-based policy for the performance study in the real-time environment provided by the testbed. In particular:

- Average system session reward: it is the reward experienced by each data transmission session depending on the interference state of the allocated spectrum block averaged along the total emulation time.
- Average throughput: it is the bit rate in kb/s achieved in the radio link averaged along the total emulation time.
- Observation rate: it is the average number of observations per time step that are performed to determine the interference state of the different spectrum blocks during the system operation. This KPI is only applicable to IM and PM policies, while StS strategy does not require observations.

c) *Obtained Results*

This section compares the performance obtained in a real-time environment by each of the observation strategies and associated spectrum selection decision-making criteria considered in Section 3.4, namely IM, PM and StS. For that purpose, the different scenarios considered in Table 5.8 are evaluated during a total emulation time T_{em}= 3600 steps (i.e. 10 hours) starting from the time when the KD statistics have been acquired under the considered convergence criterion.

Figure 5.18 to Figure 5.22 present the time evolution of the average system reward for the different strategies in all the scenarios. As a baseline reference the random strategy in which the spectrum block is randomly selected among the available ones at the time that each session is established is also included in the comparison.

Table 5.9 summarizes the average reward, throughput and observation rate for the different strategies along the whole emulation time. Moreover, the last column of Table 5.9 indicates the strategy that will be selected by the proposed OSDM approach in each of the considered scenarios assuming λ_{THR}= 0.95.

Firstly it can be observed from the figures and Table 5.9 that the proposed strategies in all the scenarios allow achieving a clear improvement in terms of both reward and throughput with respect to the random selection of the spectrum block. Focusing on scenario 1, characterized by LP of the interference together with very short sessions, the results illustrated in Figure 5.18 highlight that the best performance is achieved by IM strategy, which would be the one selected by OSDM in this scenario.

In fact, instantaneous measurements allow obtaining an improvement of around 9% and 19% with respect to PM and StS solutions, respectively. In turn, in scenario 2 the interference dynamics is the same as in scenario 1, but in this case longer sessions are considered. Correspondingly, the interference will exhibit variations along the session duration, meaning that in this case the performance is not very sensitive to the actual interference state at the time when a session is started.

Instead, steady-state probabilities are already good representatives in most of the cases of the actual interference conditions that will be experienced along each session. As a result, it can be observed in Figure 5.19 and Table 5.9 that in this scenario there are very small differences in the reward performance obtained by IM, PM and StS, while StS does not require carrying out observations and consequently it becomes the best choice to be made by OSDM.

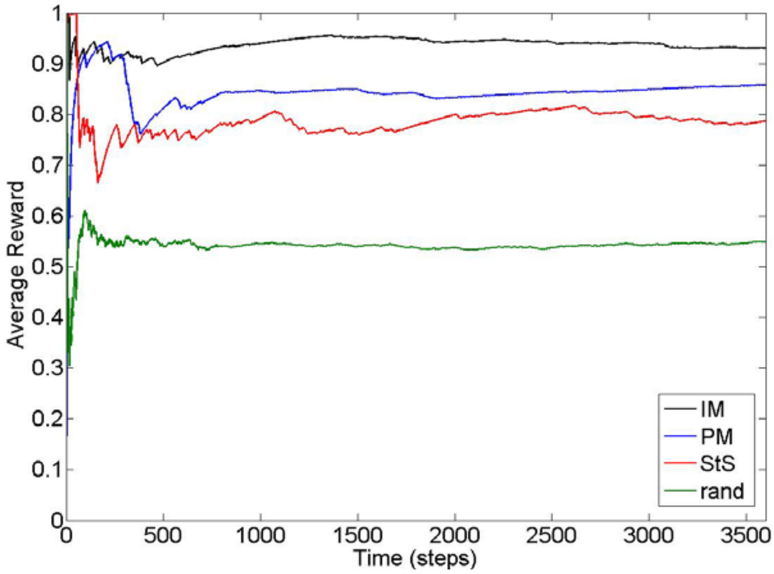


Figure 5.18: Average system reward Scenario 1 emulated by the Extended Testbed

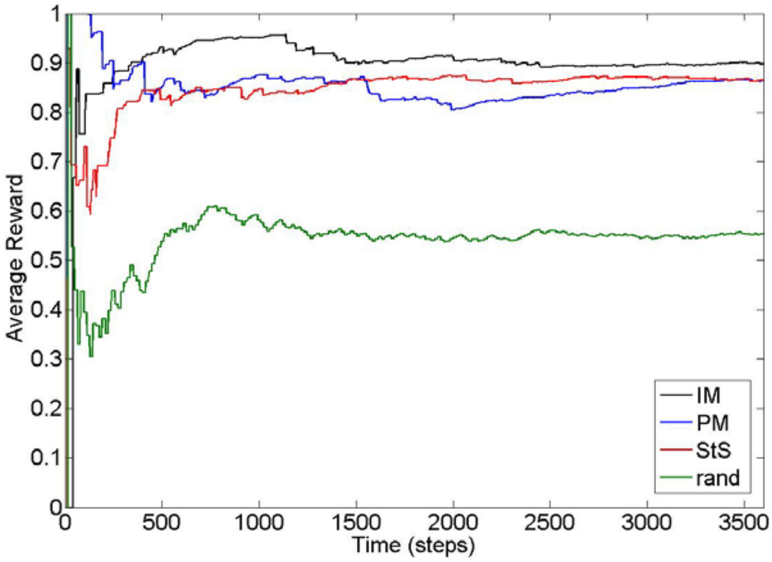


Figure 5.19: Average system reward Scenario 2 emulated by the Extended Testbed

Scenario 3 is characterized by HP in the interference; moreover, session duration is much shorter than the interference dynamics (i.e., $\overline{D} < -1/\ln\left|\lambda_1^{(i)}\right|$) and session generation rate is low, meaning that in this case the IM approach is the one selected by OSDM. Results in Figure 5.20 and Table 5.9 reveal that this is a good option since it allows achieving the highest reward with very reduced requirements in terms of observation rate.

On the contrary, scenario 4 corresponds to the same interference dynamics and session duration as in scenario 3 but with higher session generation rate.

As a result, IM suffers an increase in the observation rate that is almost 5 times higher than with scenario 3. Then, in scenario 4, PM strategy becomes a better option since it allows achieving a similar reward as IM but with much less observation requirements, as seen in Table 5.9 and Figure 5.21. In turn, it achieves an improvement in around 15% with respect to StS. Correspondingly, the selection made by OSDM in this scenario is PM.

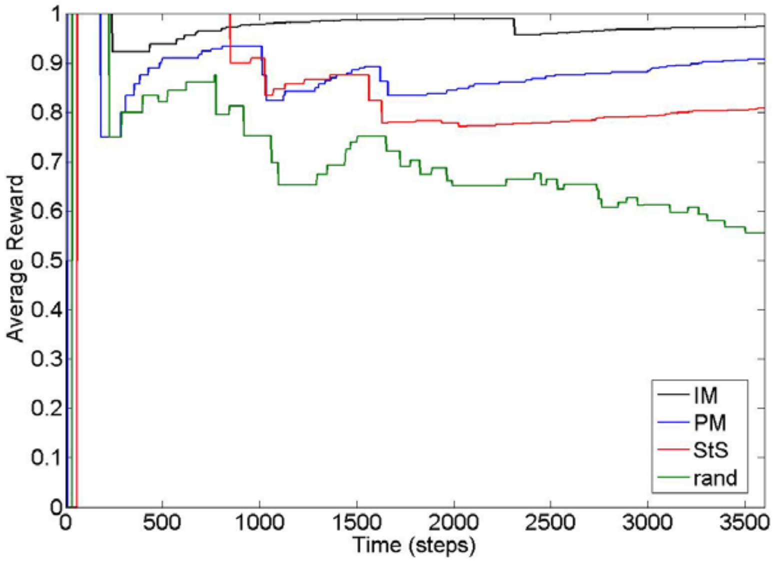


Figure 5.20: Average system reward Scenario 3 emulated by the Extended Testbed

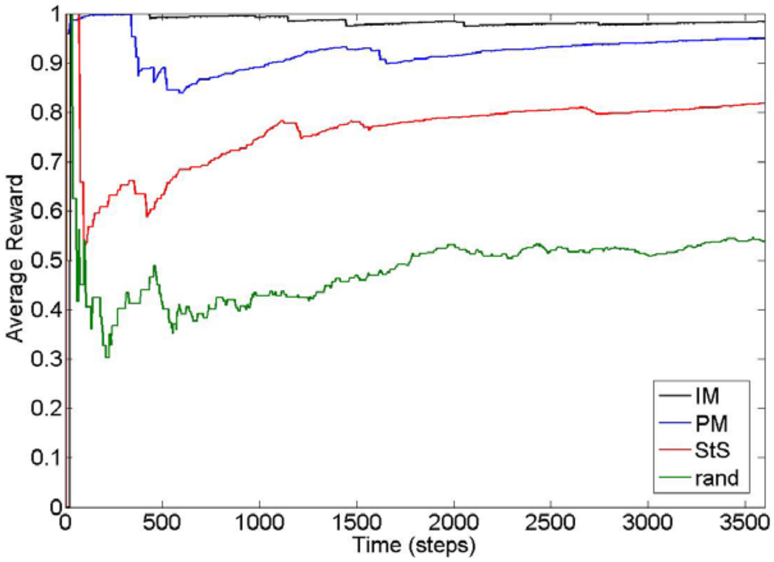


Figure 5.21: Average system reward Scenario 4 emulated by the Extended Testbed

Finally, scenario 5 is characterized by the same interference dynamics as scenarios 3 and 4 but now the session duration is much longer, so that in this case OSDM selects StS as the most appropriate strategy. Results in Table 5.9 and Figure 5.22 reveal that this becomes the best option because it provides a very similar reward performance as IM and PM but without requiring observations.

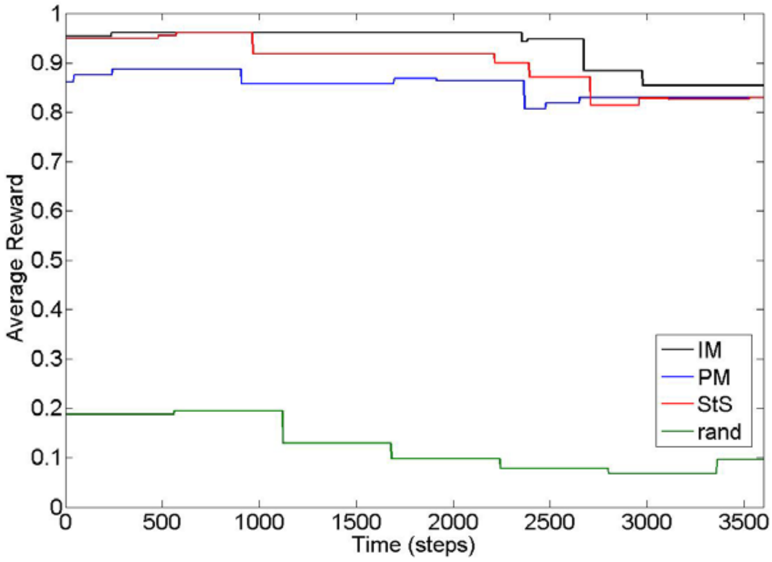


Figure 5.22: Average system reward Scenario 5 emulated by the Extended Testbed

Table 5.9: Average performance Results in terms of reward, throughput (kb/s) and observation rate (observations/time step)

Scenario	KPI	IM	PM	StS	random	Selected Strategy by OSDM
1	Reward	0.94	0.86	0.79	0.55	IM
	Throughput	477	425	403	281	
	Observation rate	1.5	1.1	0.0	0.0	
2	Reward	0.89	0.87	0.86	0.55	StS
	Throughput	452	443	432	284	
	Observation rate	0.19	1.1	0.0	0.0	
3	Reward	0.97	0.91	0.79	0.55	IM
	Throughput	491	465	406	274	
	Observation rate	0.04	0.06	0.0	0.0	
4	Reward	0.98	0.95	0.82	0.54	PM
	Throughput	502	486	413	305	
	Observation rate	0.19	0.06	0.0	0.0	
5	Reward	0.85	0.83	0.83	0.09	StS
	Throughput	441	388	409	47	
	Observation rate	0.01	0.07	0.0	0.0	

In order to complement the analysis, while the previous results have focused on the performance achieved after the proper convergence of the KD statistics in the KD initial acquisition functionality, the operation of this functionality is studied. Specifically, Figure 5.23 depicts the initial acquisition process for one of the parameters stored in the KD, namely the state transition probability $p_{0,0}^{(1)}$ for spectrum block #1 with the configuration LP. To compute it, the CA entity performs on spectrum block #1 a measurement once per time step during a sensing time Δt_m=2s.

Then, based on the energy detected it sends the interference state to the KD acquisition entity where the different samples of $p_{0,0}^{(1)}$ are computed. Figure 5.23 presents the evolution of the sample average $\overline{p_{0,0}^{(1)}}$ and the 95% confidence interval bounds $\overline{p_{0,0,\min}^{(1)}}$ and $\overline{p_{0,0,\max}^{(1)}}$ as a function of the number of samples N. It can be observed in the figure how the confidence interval gets narrower when increasing the number of samples.

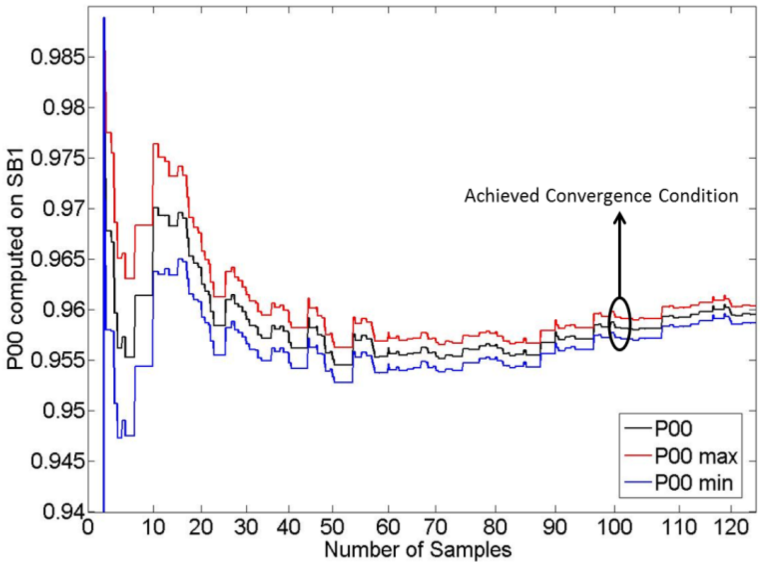


Figure 5.23: Evolution of the initial acquisition process for parameter $p_{0,0}^{(1)}$ in terms of the sample average $\overline{p_{0,0}^{(1)}}$ and the 95% confidence interval bounds $\overline{p_{0,0,\min}^{(1)}}$ and $\overline{p_{0,0,\max}^{(1)}}$

Then, considering the convergence condition with parameter η=0.2% it is shown in the figure that the convergence is achieved after N=100 samples. Then, the sample average $\overline{p_{0,0}^{(1)}}$ existing at this point of time is the one stored in the KD.

5.4.3 Demonstration of Cognitive Network Management on Applications

The aim of this section is to illustrate the practicability of the proposed belief-based spectrum selection policy for an application in a realistic Digital Home (DH) scenario. The future DH is expected to consist of different kind of devices such as equipment with communication capabilities (e.g., desktop PCs and laptops), consumer electronics (e.g., TV sets with wireless interfaces, digital media servers, game consoles, home security and automation systems), more traditional appliances equipped with communication interfaces to allow, for example, remote control and monitoring (e.g., washing machines and fridges). On the other hand, the provisioning of wireless management applications in the DH needs an efficient exploitation of all possible sources of available spectrum resources, such as license-exempt ISM bands and Ultra High Frequency (UHF) bands (i.e., TVWSs) through e.g., the ECMA-392 radio networking standard [59] and also the exploitation of licensed spectrum (e.g., spectrum licensed to a mobile network operator providing management services in the DH) as a mechanism for enhancing QoS provision to some DH connections.

In the context of this section, the emulation of a DH scenario where an entertainment application is provided has been implemented through the extended version of the testbed. For this evaluation the scenario of Figure 5.16 representing a general configuration of the six individual nodes, which compose the extended version of the testbed, can be particularized to emulate the specific entertainment DH scenario illustrated in Figure 5. 24.

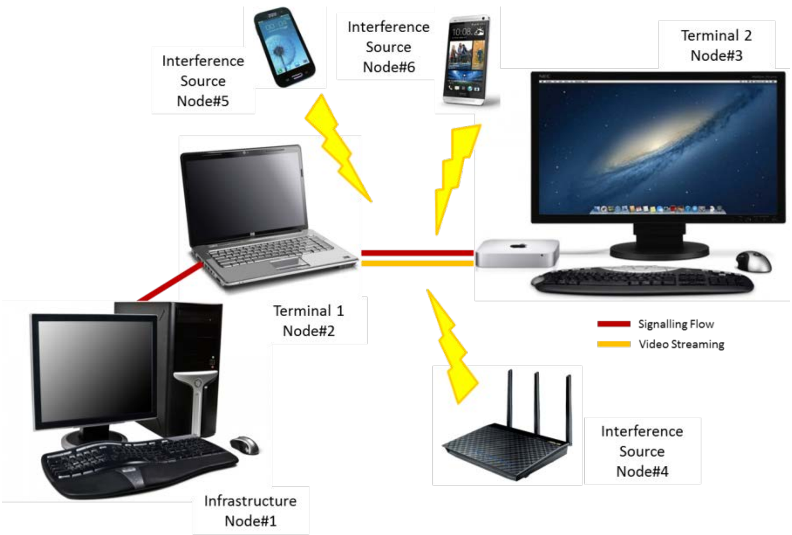


Figure 5.24: Emulated Digital Home scenario

In details, Node#1 emulates the infrastructure that includes the decision making, the knowledge management and the CA functionalities. Node#2 and Node#3 emulate two PCs that need a spectrum block selected by Node#1 for the transmission of a streaming video. After the selection of the spectrum block, the video is transmitted by Node#2 where it is stored to Node#3 that is connected to a large screen where the video will be displayed. Moreover, Nodes #4, #5 and #6 are possible external interference sources transmitting in the spectrum blocks considered for this evaluation.

a) Configuration

The spectrum blocks and the interference states considered to assess the practicability of the proposed belief-based spectrum selection strategy are the same taken into account in Section 5.4.2. While the average durations of the interference states for each spectrum block and the corresponding values of $\lambda_1^{(i)}$ considered for this evaluation are illustrated in Table 5.10. A radio link is considered to transfer the streaming video, whose duration $\overline{D}$ is of around 20 minutes, from Node#2 to Node#3 with bit rate requirement R_{req} = 1 Mbps. Node#2 implements a packet segmentation that allows dividing the video into Ethernet frames whose size can be selected during the configuration set-up of the testbed. Notice that considering λ_{THR}= 0.95 this scenario is characterized by high predictability condition (i.e., $\left|\lambda_1^{(i)}\right| \geq \lambda_{THR}$) and short sessions (i.e., $\overline{D} < -1/\ln\left|\lambda_1^{(i)}\right|$); moreover, the session generation rate is low (during this evaluation only one data transmission session is carried out). With all the above, the IM strategy is the approach considered in the OSDM for the spectrum selection executed by the SSDM at the decision making time for the streaming video transmission (see Figure 3.8).

Table 5.10: Characterization of the interference states

Spectrum Block	State $S^{(i)}$=0 (time steps)	State $S^{(i)}$=1 (time steps)	$\lambda_1^{(i)}$
#1	600	200	0.993
#2	170	650	0.993
#3	600	400	0.996

b) Key Performance Indicators

In order to demonstrate the practicability of the belief-based spectrum selection strategy proposed in this dissertation in a realistic DH scenario, the following appropriate KPIs are considered:

- Interference behaviour of the spectrum blocks: it illustrates the temporal evolution of the interference states that characterizes each spectrum block. This KPI is considered to show how the belief-based approach allows a streaming video transmission in a spectrum block free of interference.
- Received Ethernet frames: it is the total number of frames received by Node#3 during the streaming video transmission that includes the number of frames received correctly, the number of frames received erroneously and the number of frames lost during the transmission.

c) *Obtained Results*

The aim of this section is to assess the practicability of the belief-based approach proposed in this dissertation for the realistic entertainment application provided in a DH scenario illustrated in Figure 5.24. Considering the configuration previously described, in the infrastructure node the IM strategy is executed at the decision-making time; moreover, a random strategy as a baseline reference for performance comparison is also included. For that purpose, the streaming video transmission has been carried out twice, one per strategy at different times.

Figure 5.25 illustrates the temporal evolution of the interference states that characterize each spectrum block during 15 hours (i.e., $S^{(i)}=0$ when no interference exists and $S^{(i)}=1$ when the interference reaches its maximum value); moreover, in the figure it is shown the time instant at which Node#2 requires a spectrum block for the video transmission and then, at which the SSDM selects a spectrum block for each strategy (i.e., the IM and the random). In details, from the figure it can be observed that after 120 minutes the SSDM selects for the video transmission the first spectrum block executing the decision making criterion given by (3.16) and based on the decision function (3.20) that is particularized to equation (3.31) for the IM selection strategy. Notice that this selection guarantees a video transmission free of the interference during its duration of around 20 minutes. While after roughly 720 minutes the SSDM selects the second spectrum block for the video transmission following the random strategy; in this case the selected block is affected by the interference at the decision-making time instant. It is worth mentioning that the SSDM would have selected in this case the third spectrum block following the IM strategy and then, ensuring a block free of interference for the streaming video transmission.

The consequent performance results achieved through each observation strategy are illustrated in Figure 5.26 in terms of received Ethernet frames. From the figure it can be observed that in case of IM strategy only the 0.5% of the frame has been received erroneously by Node#3 and the 0.03% of the frames has been lost; although the spectrum block has been free of interference during the overall video transmission, possible spurious uncontrolled interference existing in the realistic scenario can cause the detriment of few frames. While in case of random strategy it can be noticed that the 17% of the frame has been received erroneously by Node#3 and even the 61% of the frames has been lost. For a clearer illustration of the effects caused by error-affected frames and lost frames on the quality of the transmission, some screenshots of the video displayed on the screen connected to Node#3 are presented in Appendix D.

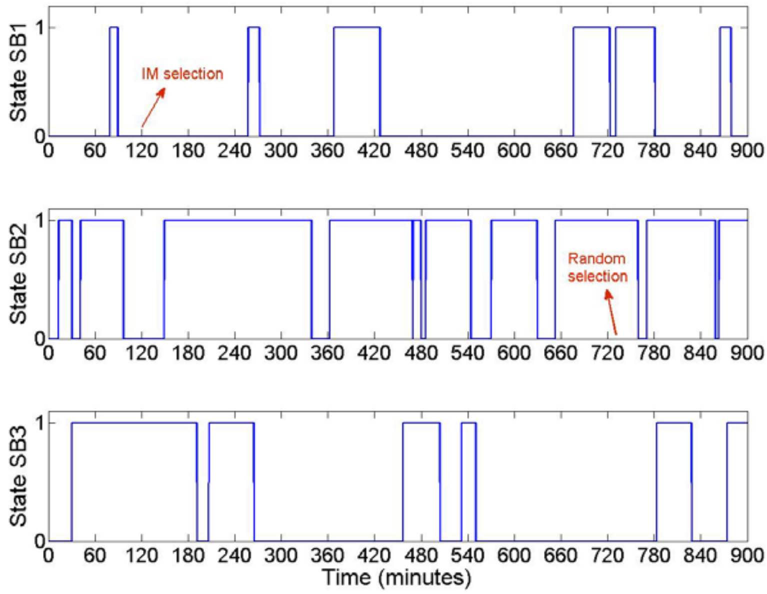


Figure 5.25: Temporal evolution of the interference of the spectrum blocks

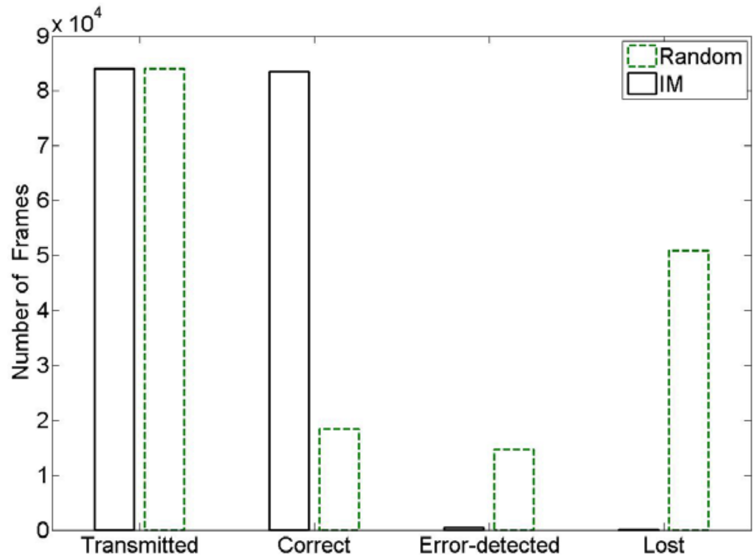


Figure 5.26: Transmitted and received frames

5.5 Summary

This chapter has presented the real-time testbed platform developed to implement and evaluate the spectrum management solutions proposed in this dissertation. In details, the hardware and the software components, and the implementation of the individual node of the platform have been firstly described. Furthermore, the spectrum opportunity identification strategy has been executed in the individual node in order to validate its capability to properly capture the actual conditions of the spectrum band in the scenario under test. Then, the first version of the testbed and the emulation results of the solutions for ONs proposed in this dissertation have been presented. Finally, the extended version of the testbed implemented for the emulation of the proposed belief-based spectrum selection policy and the performance results have been illustrated. In details, the spectrum selection policy has been assessed in the real-time environment provided by the testbed taking into consideration also the low predictably described in Figure 3.8. Moreover, the practicability of the proposed strategy has been illustrated for an entertainment application provided in a realistic DH scenario. The main conclusions achieved through this performance evaluation are summarized as follows.

The execution of the spectrum opportunity identification policy in the individual node has validated its capability to capture the actual conditions of the spectrum band in the scenario under test. In fact, the results have shown that the measurement procedure of the strategy enables the individual node to detect correctly the real interference condition of the spectrum band under study.

A performance comparison of the proposed spectrum selection solution has been carried out against a random selection, revealing that the knowledge about the statistical behaviour of the different spectrum blocks provided by the spectrum selection approach based on the fittingness factor is able to reduce the spectrum handover ratio while keeping the desired efficiency level of the communication.

It has been illustrated that, during the ON management phase, the spectrum selection functionality is able to trigger the necessary ON reconfiguration procedure and associated spectrum handover during the ON maintenance stage to react in front of changes in the interference that arises in the different spectrum blocks. Through this feature, it is possible to keep the on-going communication in the ON link.

Results achieved through the extended version of the testbed have validated the satisfactory performance of the belief-based spectrum selection policy obtained by the simulator also in a real-time environment. In details, it has been observed that: *(i)* IM strategy is suitable for scenarios with low predictability with short session durations or for scenarios with high predictability under low traffic conditions (i.e. short sessions and low session rates); *(ii)* PM strategy is suitable for highly predictable scenarios with traffic characterized by high session rates and short session durations; *(iii)* StS strategy is suitable for scenarios with long session durations.

It has been demonstrated how the knowledge management entity of the FCMF proposed in this dissertation is able to properly extract the relevant knowledge from the radio environment. In this respect, it has been illustrated how the KD acquisition entity allows assessing the degree of predictability of the interference of the different spectrum blocks through the spectrum sensing functionality provided by the USRP.

Finally, it has been illustrated how the belief-based spectrum selection policy can be exploited in a realistic application in a DH scenario, showing that the proposed solution allows the transmission of a high resolution streaming video compared to a random selection strategy.

Chapter 6

Concluding Remarks and Future Directions

Cognitive Radio (CR) paradigm represents an innovative solution to mitigate the spectrum scarcity problem by enabling Dynamic Spectrum Access (DSA), defined to conciliate the existing conflicts between the ever-increasing spectrum demand growth and the currently inefficient spectrum utilization. DSA covers any innovative solution meant to share spectrum among several radio systems with sake of increasing the overall spectrum utilization. This dissertation has addressed the problem of modelling cognitive management frameworks that provide solutions for spectrum management suitable to different scenarios and use cases in the context of DSA/CR Networks (CRNs). This chapter summarizes the main conclusions derived from the investigation carried out in this dissertation as well as possible directions for future work.

6.1 Conclusions

Sustained in the concepts related to CR paradigm, DSA and ON, which represent the essential theoretical background for this Ph. D. thesis, three cognitive management frameworks and spectrum management strategies have been proposed in this dissertation. The first solution, so-called Base-line Cognitive Management Framework (BCMF), has been considered as a baseline for developing spectrum management strategies. In details, the considered Functional Architecture (FA) represents a centralized architecture made of a Dynamic Spectrum Management (DSM) developed for spectrum opportunity identification and a Cognitive system for Managing the Opportunistic Network (CMON) implemented for spectrum selection. Furthermore, the CMON is composed of a decision making process associated to creation, maintenance and termination stages that obtains the information on spectrum opportunity identification from the DSM. Moreover, in the CMON block a control mechanism has been implemented to execute the decisions taken, as well as the Knowledge Management module that enables to exploit the cognitive features and the Context Awareness (CA), which provides the necessary inputs about the radio environment conditions to the decision-making solutions.

The second framework proposed in this Ph. D. thesis, so-called Evolved Cognitive Management Framework (ECMF), has been based on the CR cycle paradigm with the aim to carry out efficient decision-making solutions for spectrum selection in CRNs. The Partially Observable Markov Decision Processes (POMDPs) have been proposed as decision-making strategy in order to exploit partial observations at specific periods of time with a statistical characterization of the system dynamics through a first definition of the belief vector concept.

The third framework, so-called Final Cognitive Management Framework (FCMF) and indeed representing a further extension of the ECMF approach, has been proposed to exploit the belief vector as a long-term means to characterize and predict the environment dynamics. Furthermore, different observation strategies have been implemented each one selected appropriately to balance the trade-off between performance and measurement requirements. The FAs of the ECMF and the FCMF are both based on: *(i)* a Knowledge Management module that includes a Knowledge Database (KD), which stores the information about the statistics of the radio environment and a Knowledge Manager (KM) that is in charge of updating such information; *(ii)* a Decision Making that selects the most appropriate spectrum block each time that a new session is established in a certain radio link; *(iii)* a CA which performs observations through measurements of the interference states triggered by the Decision Making; *(iv)* a Control module that manages message exchange between the terminals and the cognitive management frameworks to support the establishment/release of radio links. Although the main modules of these solutions are the same, essential new functionalities with the aim to characterize the radio environment dynamic have been developed in the FA of the FCMF.

The performance of the proposed spectrum management strategies implemented in the frameworks has been assessed both through simulations and testbed platform. Regarding the simulation-based methodology, performance results of the spectrum management solutions based on the CR cycle proposed in this dissertation have been obtained. The assessment of the use of partial observations in the Decision Making entity has revealed that the POMDP-based strategy implemented in the ECMF allows the achievement of similar performance in terms of reward and satisfaction as the full observation approach making decisions based on accurate knowledge about the actual interference state in all the available spectrum blocks. Nevertheless, through the combination of partial observations of the system at specific time instants and the statistical information stored in the Knowledge Database, it has been shown that the ECMF approach requires a much lower measurement rate compared to the full observation scheme. In addition, it obtains a significant performance gain in terms of reward with respect to a random spectrum selection and to a strategy that makes decisions based on static knowledge of the spectrum block statistics.

With respect to the impact of the observation strategy implemented in the Decision Making entity, it has been obtained that the POMDP-based solution characterized by an adaptive observation strategy is able to modify the observation rate requirements in accordance with the observed interference dynamics, therefore enabling a further reduction in the observation rate with respect to a periodical approach.

The analysis of the belief-based policy proposed in the FCMF has revealed that the characterization of the traffic in terms of the average session duration and the average session generation rate enables the Observation Strategy Decision Making (OSDM) entity selecting the observation strategy that better balances the trade-off between achievable performance and measurement requirements. In particular, the simulation results have demonstrated that, for long session durations a steady state-based strategy that does not require dynamic observations becomes the best approach to be selected. In turn, for short session durations the use of periodic measurements obtains a good trade-off between reward and observation rate for large session generation rates, while for low session generation rates the use of instantaneous measurements performed at the decision making time is the option selected by the OSDM.

Regarding the evaluation through testbed platform, this dissertation has described the real-time testbed platform developed through Universal Software Radio Peripherals (USRPs) to implement and assess the proposed spectrum management solutions. In details, the hardware and the software components, and the implementation of the individual node of the platform have been firstly illustrated. Moreover, the execution of the spectrum opportunity identification policy in the individual node has validated its capability to capture the actual conditions of the spectrum band in the scenario under test. In fact, the results have shown that the measurement procedure of the strategy enables the individual node to detect correctly the real interference condition of the spectrum band under study.

Then, the first version of the testbed and the emulation results of the solutions for ONs proposed in this dissertation have been illustrated. In details, a performance comparison of the proposed spectrum selection solution has been carried out against a random selection, revealing that the knowledge about the statistical behaviour of the different spectrum blocks provided by the spectrum selection approach based on the fittingness factor is able to reduce the spectrum handover ratio while keeping the desired efficiency level of the communication. Furthermore, it has been illustrated that, during the ON management phase, the spectrum selection functionality is able to trigger the necessary ON reconfiguration procedure and associated spectrum handover during the ON maintenance stage to react in front of changes in the interference that arises in the different spectrum blocks. Through this feature, it is possible to keep the on-going communication in the ON link.

Finally, the extended version of the testbed implemented for the emulation of the proposed belief-based spectrum selection policy and the performance results have been presented. In details, the spectrum selection policy has been evaluated in the real-time environment provided by the testbed taking into account also the low predictably case. Results achieved through the extended version of the testbed have validated the satisfactory performance of the belief-based spectrum selection policy obtained by the simulator also in a real-time environment. In details, it has been observed that: *(i)* IM strategy is suitable for scenarios with low predictability with short session durations or for scenarios with high predictability under low traffic conditions (i.e. short sessions and low session rates); *(ii)* PM strategy is suitable for highly predictable scenarios with traffic characterized by high session rates and short session durations; *(iii)* StS strategy is suitable for scenarios with long session durations.

It has been then shown how the knowledge management entity of the FCMF proposed in this dissertation is able to properly extract the relevant knowledge from the radio environment. In this respect, it has been illustrated how the KD acquisition entity enables to assess the degree of predictability of the interference of the different spectrum blocks through the spectrum sensing functionality provided by the USRP.

Finally, it has been illustrated how the belief-based spectrum selection policy can be exploited in a realistic application in a Digital Home (DH) scenario, demonstrating that the proposed solution enables the transmission of a high resolution streaming video compared to a random selection strategy.

Overall, the research conducted in the context of this dissertation has revealed that proper cognitive management functionalities can be extremely beneficial to support spectrum management in a wide variety of scenarios and use cases. These results provide interesting directions for several future works, as indicated in the next subsection.

6.2 Future Directions

The research conducted in this Ph. D. thesis suggests some possible directions to exploit the developed cognitive management functionalities also in other contexts discussed below. As a part of future work the solutions proposed for spectrum management in ONs can be extended to Device-to-Device (D2D) communications, which have recently attracted significant attention as a key feature of 5G wireless networks and 3rd Generation Partnership Project (3GPP) LTE release 12. In details, direct D2D communications between mobile User Equipments (UEs) in proximity, without passing through the macrocellular Base Station (BS) and core network, are a promising approach for dealing with local traffic in cellular networks. D2D communications are also expected to improve link coverage, throughput, energy consumption, and end-to-end latency, while enabling new location-based services and robust public safety communications [115].

Some important aspects under investigation in the practical feasibility of D2D communications include: device discovery procedures with the aim to detect the presence of other UEs in the neighborhood; link setup strategies in order to select the spectrum to be used in the D2D radio links between interested UEs; interference avoidance mechanisms that make possible the coexistens among D2D UEs with cellular network. Furthermore, a D2D communication may not be limited only to LTE; in fact, it can be enabled also with existing technologies that consider unlicensed bands such as WiFi APs [116]. Hence, due to the opportunistic nature of these connections the satisfactory results derived by the spectrum management strategies defined for ONs and assessed through the developed real-time platform drive towards a possible extention of these studies also for D2D connections.

Moreover, the cognitive management frameworks presented in this dissertation provide new research possibilities in the practical development of other aspects in the context of LTE that currently is the most advanced International Mobile Telecommunications (IMT) technology.

Altough LTE operating in licensed spectrum is characterized by a prominent deployment across the world, the integration of unlicensed carrier has been proposed as an innovative and promising way to further expand its capacity and to meet the growning traffic demands. This integration, which is carried out by adapting LTE air interface to operate in the unlicensed spectrum, leads to the so-called Unlicensed LTE (U-LTE) technology. Regarding the spectrum regulation in the context of U-LTE, the 5 GHz band is considered as the main candidate in terms of large amounts of unlicensed available spectrum, as well as relatively good channel propagation performance.

One of the challenging topics in the context of U-LTE is the definition of spectrum management policies [117], [118] such as mechanisms of Dynamic Frequency Selection (DFS) based on spectrum sensing strategies, which allow avoiding interference among IMT devices and to non-IMT systems working at the same band (e.g., radar systems). For instance, Listen-Before-Talk (LBT) techinques are designed and enforced by EU regulations, in order to impose a flexible and fair coexistence among IMT systems by enabling channel sensing before the use of the spectrum resource and dynamic channel occupancy. Hence, another futute direction motivaved by the satisfactory results achieved in this dissertation is the exploitation of the proposed spectrum management strategies also in the context of U-LTE technology.

Finally, in the frameworks that exploit the CR cycle paradigm, the approach employed in this dissertation to manage the interference evolution for the spectrum blocks have been modelled as discrete-time Markov processes characterized by certain transition probabilities from a particular state *k* to another one *k'*. This assumption has been motivated by the state of the art found in the literature about the characterization of the interference behaviour. This characterization allowed the exploitation of the propriety of the ergodic Markov processes throughout this dissertation such as the one expressed in equation (3.27). However, it would be particularly interesting to validate this assumption in the real-time environment provided by the testbed. This may be executed exploiting the spectrum sensing functionality implemented in each node illustrated and validated, respectively, in Section 5.2.3 and Section 5.2.4.

Appendices

Appendix A

Demonstration of the Behaviour of the Belief Vector

Theorem 1

Let us consider the eigenvalue decomposition of matrix $\mathbf{P}^{(i)T}$:

$$\mathbf{P}^{(i)T} = \mathbf{V} \cdot \mathbf{\Sigma} \cdot \mathbf{V}^{-1} \tag{A.1}$$

where $\mathbf{\Sigma} = diag\left(\lambda_0^{(i)}, \lambda_1^{(i)}, ..., \lambda_K^{(i)}\right)$ is a diagonal matrix formed by the ordered eigenvalues of $\mathbf{P}^{(i)T}$ $\left|\lambda_0^{(i)}\right| \geq \left|\lambda_1^{(i)}\right| \geq ... \geq \left|\lambda_K^{(i)}\right|$. The eigenvalues of $\mathbf{P}^{(i)T}$ are the same as those of $\mathbf{P}^{(i)}$. Since $\mathbf{P}^{(i)}$ is a stochastic irreducible matrix, the Perron-Frobenius theorem [119] ensures that the largest eigenvalue is unique and equal to $\lambda_0^{(i)} = 1$, so that $\left|\lambda_k^{(i)}\right| < 1$ for $k>0$.

Moreover, $\mathbf{V}=[\mathbf{v}_0\ \mathbf{v}_1 ...\ \mathbf{v}_K]$ is a matrix whose columns are the eigenvectors of $\mathbf{P}^{(i)T}$. By multiplying n times (A.1) the eigenvalue decomposition of matrix $[\mathbf{P}^{(i)T}]^n$ is easily obtained as:

$$\left[\mathbf{P}^{(i)T}\right]^n = \mathbf{V} \cdot \mathbf{\Sigma}^n \cdot \mathbf{V}^{-1} \tag{A.2}$$

where $\mathbf{\Sigma}^n = diag\left(\left[\lambda_0^{(i)}\right]^n, \left[\lambda_1^{(i)}\right]^n, ..., \left[\lambda_K^{(i)}\right]^n\right)$. Consequently, the following relationship is fulfilled:

$$\left[\mathbf{P}^{(i)T}\right]^n \cdot \mathbf{v}_k = \left[\lambda_k^{(i)}\right]^n \mathbf{v}_k \tag{A.3}$$

or, by transposing both sides of the equation,

$$\mathbf{v}_\mathbf{k}^\mathbf{T} \cdot \left[\mathbf{P}^{(\mathbf{i})}\right]^n = \left[\lambda_k^{(i)}\right]^n \mathbf{v}_\mathbf{k}^\mathbf{T} \tag{A.4}$$

In addition, the steady state probability vector $\boldsymbol{\pi}^{(\mathbf{i})}$ of an ergodic discrete time Markov process fulfils the following relationship [106]:

$$\boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \mathbf{P}^{(\mathbf{i})} = \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \tag{A.5}$$

By comparing (A.4) with (A.5) for the case n=0 it is observed that the steady state probability vector is the eigenvector associated to $\lambda_0^{(i)}$=1, that is:

$$\mathbf{v}_0^\mathbf{T} = \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} \tag{A.6}$$

Moreover, since the eigenvectors $\mathbf{v}_\mathbf{k}^\mathbf{T}$ are orthonormal, any arbitrary vector, and in particular the belief vector $\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t)$, can be expressed as a linear combination of these eigenvectors, that is:

$$\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t) = \sum_{k=0}^{K} a_k \mathbf{v}_\mathbf{k}^\mathbf{T} \tag{A.7}$$

Consequently, by combining (3.25), (A.4), (A.6), (A.7) it yields:

$$\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t+n) = \sum_{k=0}^{K} a_k \mathbf{v}_\mathbf{k}^\mathbf{T} \cdot \left[\mathbf{P}^{(\mathbf{i})}\right]^n = \sum_{k=0}^{K} a_k \left[\lambda_k^{(i)}\right]^n \mathbf{v}_\mathbf{k}^\mathbf{T} = a_0 \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} + \sum_{k=1}^{K} a_k \left[\lambda_k^{(i)}\right]^n \mathbf{v}_\mathbf{k}^\mathbf{T} \tag{A.8}$$

Since $\left|\lambda_k^{(i)}\right| < 1$ for all k>0, the second term of the summation in (A.8) will tend to 0 when $n \to \infty$, so the belief vector $\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t+n) \to a_0 \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}} = \boldsymbol{\pi}^{(\mathbf{i})\mathbf{T}}$ tends to the steady state. Note that necessarily a_0=1, because otherwise the summation of all the components of $\mathbf{b}^{(\mathbf{i})\mathbf{T}}(t+n)$ (i.e. the sum of the probabilities for all the states) would not be 1. Moreover, looking at the summation in (A.8) it is observed that the speed of convergence will be driven by the largest value of $\left|\lambda_k^{(i)}\right|^n$, k>0, or equivalently by the absolute value of the largest eigenvalue after $\lambda_0^{(i)}$=1, that is $\left|\lambda_1^{(i)}\right|$. The lowest the value of $\left|\lambda_1^{(i)}\right|$ the faster will be the convergence, reflecting that the scenario suffers from more variability.

Corollary 1

The dynamic evolution of the belief vector $\mathbf{b}^{(i)T}(t)$ towards the steady state is reflected in (A.8) for $n \to \infty$. The speed of convergence is driven by the term $\left[\lambda_1^{(i)}\right]^n$ whose absolute value can also be expressed as:

$$\left|\lambda_1^{(i)}\right|^n = e^{n \cdot \ln\left|\lambda_1^{(i)}\right|} \tag{A.9}$$

When increasing n this relationship is a classical exponential decay with time constant $\tau = -1/\ln\left|\lambda_1^{(i)}\right|$ time steps. Consequently, the value $-1/\ln\left|\lambda_1^{(i)}\right|$ provides a rule of thumb to roughly estimate the time needed for convergence of the belief vector $\mathbf{b}^{(i)T}(t)$.

Appendix B

Messages Sequence Illustrating the Adaptation of the Spectrum Selection to Interference Variations

Figure B.1 presents a screenshot of the Terminal 1 (i.e. Node#2) when the ON creation procedure starts. As it can be observed in the right side of the screen, the terminal has sent the *MIH_C4MS_ONN.request* message to request the support of the infrastructure (i.e. Node#1) to create the ON. Transmission has not started yet, waiting for the response of the infrastructure indicating the spectrum block to use. Figure B.2 presents the screenshot of the infrastructure node at this time.

As shown in Figure B.2, after receiving the *MIH_C4MS_ONN.request* message from Terminal 1, the infrastructure contacts Terminal 2 (i.e., Node#3) to confirm its availability to create the ON; then, it executes the spectrum opportunity identification. At the right side of the figure the list of available spectrum blocks can be observed. The spectrum selection has chosen the spectrum block centred at 2.447 GHz. This information is communicated to Terminal 1 in the *MIH_C4MS_ONN.response* message.

This triggers the *MIH_C4MS_ONC.request* message to finalise the ON creation. At this stage, it can be seen in the screenshot of Terminal 1 in Figure B.3 that, after the ON has been created the transmission has started in this spectrum block. At the left side of the figure the on-line evolution of the efficiency is shown (each point corresponds to 30s), reflecting a high level of efficiency.

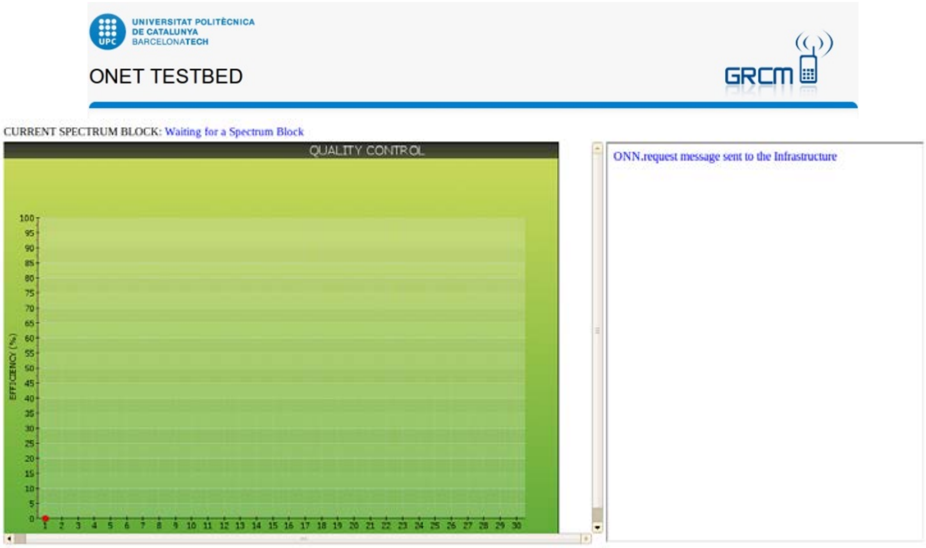


Figure B.1: Screenshot of Terminal 1 at the start of the ON creation

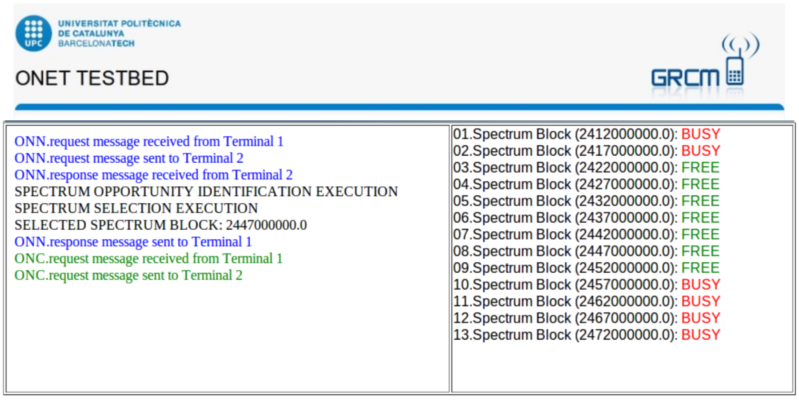


Figure B.2: Screenshot of the Infrastructure Node at the start of the ON creation

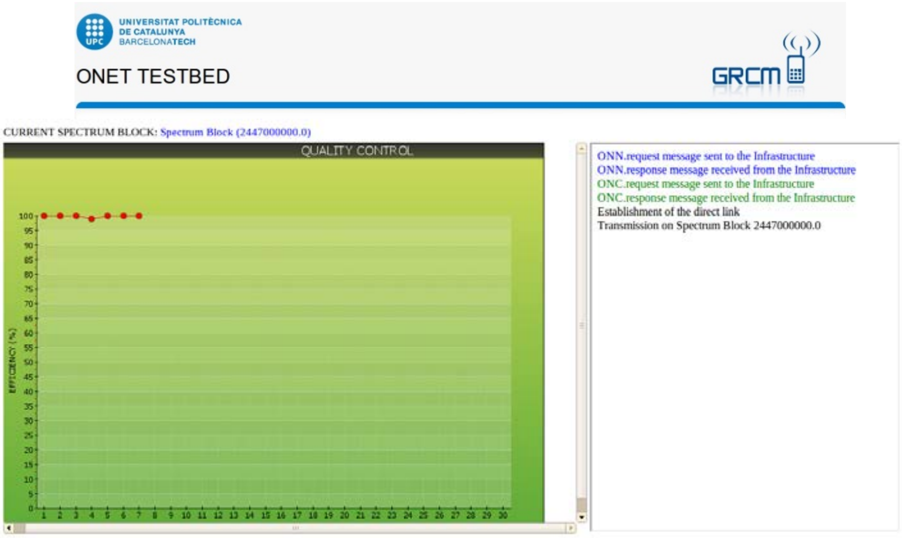


Figure B.3: Screenshot of Terminal 1 after the ON link has been established

Looking at Figure 5.15, it can be observed that the efficiency monitored by Terminal 1 is above 80% until minute 9, when the interferer source is activated in the same frequency of the link. As a consequence, Terminal 1 detects a degradation of the efficiency down to 60%. At this point, the screenshot of Terminal 1 is shown in Figure B.4. At the left side the degradation below the 80% level has been detected and correspondingly a *MIH_C4MS_ONN.request* message is sent to the infrastructure starting the ON reconfiguration procedure.

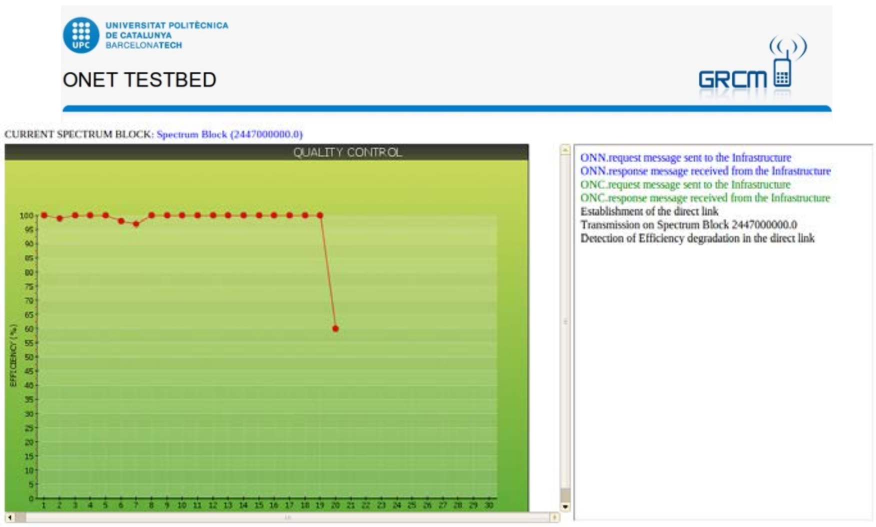


Figure B.4: Screenshot of Terminal 1 after switching on the external interferer

This can be seen in the screenshot of the infrastructure node shown in Figure B.5. At this stage, the spectrum opportunity identification is executed again and a new spectrum selection is performed, selecting spectrum block centred at 2.442 GHz. This is notified to Terminal 1 in the *MIH_C4MS_ONN.response* message.

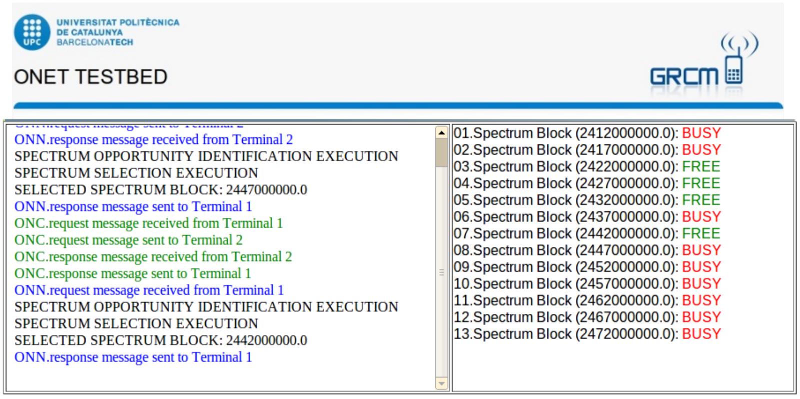


Figure B.5: Screenshot of the Infrastructure Node at ON reconfiguration

After receiving this response, in Figure B.6 the left side of the screenshot in Terminal 1 reflects that the *MIH_C4MS_ONM.request* message has been sent to Terminal 2 to reconfigure the link in the new spectrum block.

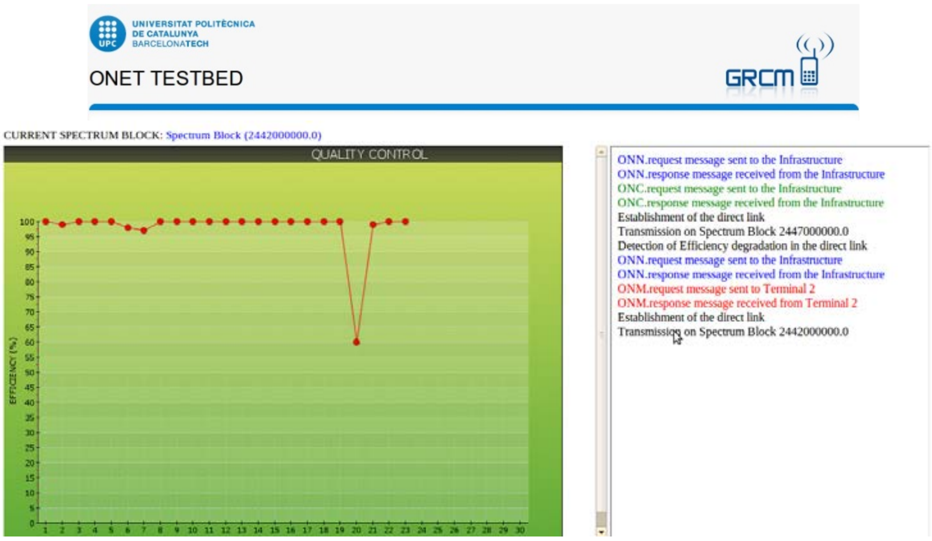


Figure B.6: Screenshot of Terminal 1 after the ON reconfiguration

The completion of the reconfiguration is observed in Figure B.7, corresponding to the screenshot of Terminal 2. In Figure B.6, as well as in Figure 5.15, it can be observed how the communication has continued, reaching again high efficiency levels.

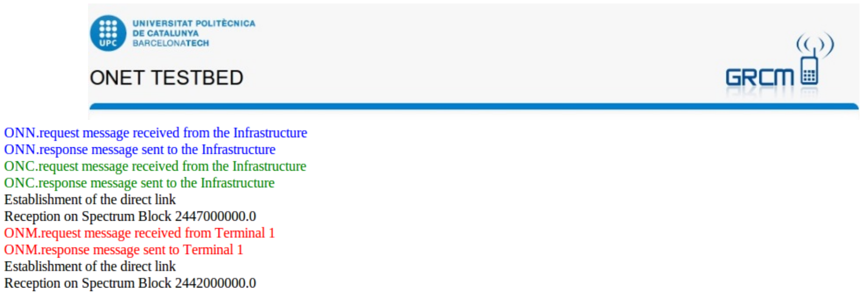


Figure B.7: Screenshot of Terminal 2 after the ON reconfiguration

Appendix C

Strategy to Compute and Store Statistical Information of the Radio Environment

The initial acquisition functionality implemented in the KD acquisition entity of the extended version of the testbed needs to perform an estimation of the parameters stored in the KD based on real time measurements of the interference state in the different spectrum blocks made through the spectrum sensing functionality provided by the node. The estimation is done by averaging a sufficient number of samples for each parameter. To ensure that the estimated value has properly converged to the real value, the γ confidence interval is used. More specifically, let us consider the estimation of a certain generic parameter A (e.g. A can be any term of a state transition probability matrix $\mathbf{P}^{(i)}$). Let define as $\overline{A(N)}$ the sample mean of this parameter after averaging a total of N samples.

The γ confidence interval is defined as the interval $\left[\overline{A_{\min}(N)}, \overline{A_{\max}(N)}\right]$ such that the real value of A falls within this interval with probability γ, that is:

$$\Pr\left[A \in \left[\overline{A_{\min}(N)}, \overline{A_{\max}(N)}\right]\right] = \gamma \qquad \text{(C.10)}$$

Assuming large-sample conditions, the values of the γ confidence interval after averaging N samples are given by:

$$\overline{A_{\min}(N)} = \overline{A(N)} - z_{(1-\gamma)/2} \frac{\overline{\sigma_A(N)}}{\sqrt{N}} \qquad \text{(C.11)}$$

$$\overline{A_{\max}(N)} = \overline{A(N)} + z_{(1-\gamma)/2} \frac{\overline{\sigma_A(N)}}{\sqrt{N}} \tag{C.12}$$

where $z_{(1-\gamma)/2} = \phi^{-1}(1-\frac{1-\gamma}{2})$ and $\phi^{-1}(\cdot)$ denotes the inverse of the normal cumulative distribution function and $\overline{\sigma_A(N)}$ is the standard deviation with *N* samples. Note that as the number of samples *N* increases the γ confidence interval gets narrower, meaning that the estimation given by the sample mean $\overline{A(N)}$ tends to converge to the real value. Then, the required number of samples *N* that provides a sufficiently accurate estimate of parameter *A* by its sample mean $\overline{A(N)}$ is the first value of *N* that fulfils the following convergence condition:

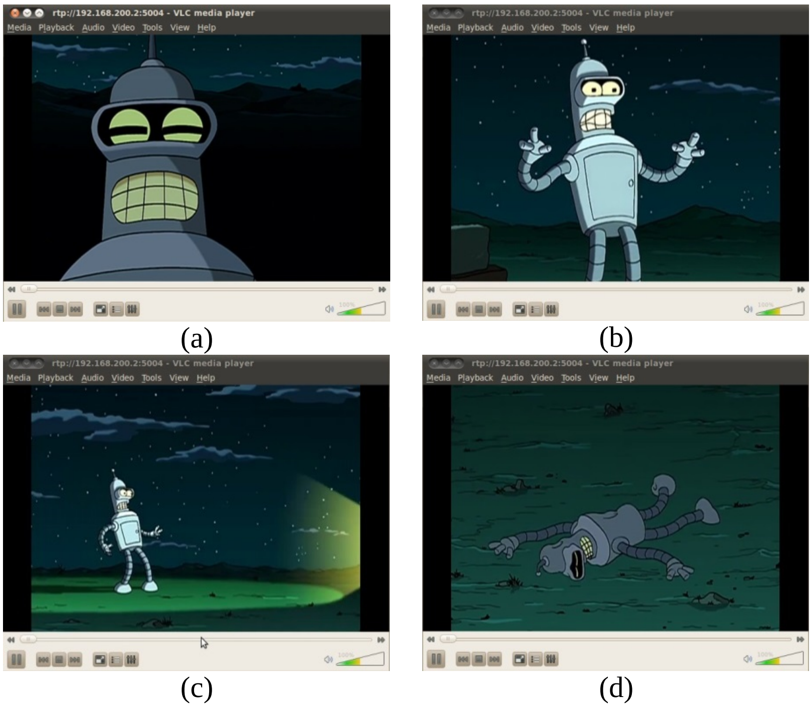
$$\overline{A_{\max}(N)} - \overline{A_{\min}(N)} < \eta \overline{A(N)} \tag{C.13}$$

where $0<\eta<1$ is a parameter to be set. Moreover, this dissertation assumes $\gamma = 95\%$, so that the term $z_{(1-\gamma)/2}$ in (C.11) and (C.12) equals 1.96.

Appendix D

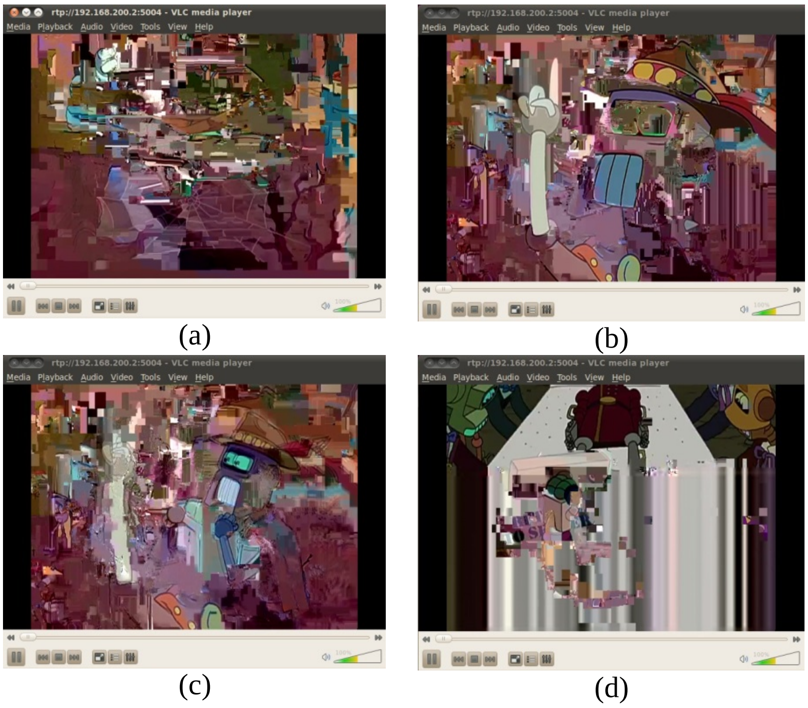
Screenshots Illustrating the Video Transmission Executed through the Extended Testbed

To analyse the impact of the interference on the resolution of the video displayed on the screen connected to Node#3, Figure D.1 and Figure D.2 illustrate some screenshots of the received frames sequence during two different cases. The first case illustrated in Figure D.1 corresponds to four screenshots of the received video on the spectrum block selected through the IM observation strategy and free of interference (i.e. SB1, see Figure 5.25). From the figure it can be observed that the implementation of the proposed observation strategy at the decision-making time, allows displaying the video characterized by high resolution. The second case shown in Figure D.2 corresponds to four screenshots of the received video on the spectrum block selected through the random strategy and affected by the interference (i.e. SB2, see Figure 5.25). In this case from the figure it can be noticed a clear degradation of the video resolution. This is due to the massive amount of both frames, the ones received erroneously and the lost frames (see Figure 5.26).



(a) (b) (c) (d)

Figure D.1: Screenshots captured during video transmission supported by IM strategy



(a) (b) (c) (d)

Figure D.2: Screenshots captured during video transmission supported by random strategy

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