Nuno Miguel Abreu Luís

Mestre em Engenharia Electrotécnica e de Computadores

Medium Access Control Design for Distributed Opportunistic Radio Networks

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Orientador:	Rodolfo Alexandre Duarte Oliveira, Prof. Auxiliar, Universidade Nova de Lisboa
Co-orientador:	Rui Miguel Henriques Dias Morgado Dinis, Prof. Associado com Agregação, Universidade Nova de Lisboa

	Júri:
Presidente:	Paulo da Costa Luís da Fonseca Pinto
Arguentes:	António Manuel Raminhos Cordeiro Grilo
	Paulo Jorge Coelho Marques
Vogais:	Luís Filipe Lourenço Bernardo
	Rodolfo Alexandre Duarte Oliveira

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To my family and friends

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Abstract

Existing wireless networks are characterized by a fixed spectrum assignment policy. However, the scarcity of available spectrum and its inefficient usage demands for a new communication paradigm to exploit the existing spectrum opportunistically. Future Cognitive Radio (CR) devices should be able to sense unoccupied spectrum and will allow the deployment of real opportunistic networks. Still, traditional Physical (PHY) and Medium Access Control (MAC) protocols are not suitable for this new type of networks because they are optimized to operate over fixed assigned frequency bands. Therefore, novel PHY-MAC cross-layer protocols should be developed to cope with the specific features of opportunistic networks.

This thesis is mainly focused on the design and evaluation of MAC protocols for Decentralized Cognitive Radio Networks (DCRNs). It starts with a characterization of the spectrum sensing framework based on the Energy-Based Sensing (EBS) technique considering multiple scenarios. Then, guided by the sensing results obtained by the aforementioned technique, we present two novel decentralized CR MAC schemes: the first one designed to operate in single-channel scenarios and the second one to be used in multichannel scenarios. Analytical models for the network goodput, packet service time and individual transmission probability are derived and used to compute the performance of both protocols. Simulation results assess the accuracy of the analytical models as well as the benefits of the proposed CR MAC schemes.

Keywords: Cognitive Radio Networks; Decentralized MAC Schemes; Performance Evaluation and Modeling.

Resumo

As redes sem fios tradicionais caracterizam-se por uma utilização do espectro que tem por base uma atribuição estática de frequências a utilizar. No entanto, devido à recente escassez de frequências disponíveis é necessário adoptar novas práticas que permitam uma utilização oportunística do espectro: o Rádio Cognitivo. Numa rede cognitiva os nós não licenciados deverão ser capazes de detectar zonas do espectro de frequências que não estejam a ser utilizadas, fazendo então um uso oportunístico das mesmas. Este facto justifica o desenho de novos esquemas de acesso ao meio capazes de suportarem as características específicas da natureza oportunística deste tipo de redes.

Esta tese tem como principal objectivo o desenho e análise de mecanismos distribuídos de controlo de acesso ao meio para redes de rádio cognitivo. De forma a considerar os mecanismos de monitorização da ocupação espectral, o trabalho começa por caracterizar a técnica de *sensing* baseada em detecção de energia para múltiplos cenários. Essa técnica é depois utilizada no desenho de dois protocolos de acesso ao meio, sendo o primeiro indicado para sistemas de um único canal e o segundo para sistemas de múltiplos canais. Os protocolos são testados em múltiplos cenários, destacando-se o seu estudo teórico através do desenvolvimento de modelos de desempenho capazes de representar o débito da rede, o tempo de serviço e até mesmo a probabilidade individual de transmissão de cada utilizador não licenciado. Os modelos são validados através de diferentes ferramentas de simulação, aferindo a precisão do trabalho teórico e as vantagens dos protocolos propostos.

Palavras-chave: Redes de Rádio Cognitivo; Protocolos de Controlo de Acesso ao Meio Descentralizados; Modelação e Avaliação de Desempenho.

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General Symbols

$\lceil x \rceil$ Ceiling function of x

$\mathbb{E}[x]$ Expected value of x

$\mathcal{N}(x, y)$ Normal (or Gaussian) distribution with mean x and variance y

$\mathcal{P}_{x,y}$ Probability regarding the single-step transition from state x to state y

$\mathcal{Q}$ Complementary distribution function of the standard Gaussian

$\mathcal{Z}_X$ Z-transform of X

$\Phi_X(x)$ Characteristic function of X

π_x Steady-state probability of state x

σ_{GPD} Shape parameter of the generalized Pareto distribution

$\mathrm{Var}[x]$ Variance of x

$F_X(x)$ Cumulative distribution function of X

j Imaginary unit

$Pr\{K = k\}$ Probability mass function of K

$Q_Z(z)$ Probability generating function of Z

x^* Optimal value of x

Spectrum Sensing Symbols

$\bar{\mathbf{X}}$ Level of dissimilarity between the channel sensing decisions

δ Ratio between the length of PUs and SUs frame

γ Energy threshold

λ Sum of samples of Signal-to-Noise Ratio collected during the sensing period

λ' Individual sample of Signal-to-Noise Ratio collected during the sensing period

$\mathcal{H}_{01}$	Spectrum sensing hypothesis regarding the arrival of a PU during the spectrum sensing period
$\mathcal{H}_0$	Spectrum sensing hypothesis regarding the absence of PU's activity
$\mathcal{H}_{10}$	Spectrum sensing hypothesis regarding the departure of a PU during the spectrum sensing period
$\mathcal{H}_1$	Spectrum sensing hypothesis regarding the presence of PU's activity
μ_s	Mean of the PUs' transmitted signals
σ_s^2	Variance of the PUs' transmitted signals
$\mathbf{X}$	Correlation matrix of the channel sensing decisions
$\mathbf{x}_{x,y}$	Sample Pearson correlation coefficient between the channel sensing decision of SU x and SU y
C_x	Criterion x used to parameterize the energy detector
N_G	Number of slots in the spectrum sensing period before the occurrence of a PU behavior change
N_S	Number of slots for spectrum sensing
N_T	Number of slots of a SU frame
P_χ	Probability of observing one PU behavior change during a SU frame
P_D	Probability of detection
$P_D^{\mathcal{H}_{01}}$	Probability of detection under the hypothesis $\mathcal{H}_{01}$
P_{FA}	Probability of false alarm
$P_{FA}^{\mathcal{H}_{10}}$	Probability of false alarm under the hypothesis $\mathcal{H}_{10}$
s	Energy collected by the EBS detector due to PU's transmissions only
T_D^{SU}	Duration of the SU spectrum access
T_F^{SU}	Duration of a SU frame
T_{OFF}^{PU}	Duration of a PU inactive (OFF) period
T_{ON}^{PU}	Duration of a PU active (ON) period
T_S^{SU}	Duration of the SU spectrum sensing
u	Energy collected by the EBS detector

W Bandwidth of the sensed channel

w Energy collected by the EBS detector due to noise only

Y Amount of energy collected by the energy detector during the sensing period

General MAC Symbols

μ_B Average duration of the PU's active (ON) period

μ_I Average duration of the PU's inactive (OFF) period

$\mu_{T^{SU}_{packet}}$ Average length of the SU's packet

$\overline{\tau^{PU}}$ Probability of a PU being inactive (OFF)

ρ Traffic intensity

τ^{PU} Probability of a PU being active (ON)

v_I Probability of a packet arriving at the head of the SU's buffer queue during a PU OFF period

B Duration of the PU's active (ON) period (random variable)

G Overall system goodput

G^{PU} Goodput achieved by the primary network

G^{SU} Goodput achieved by the secondary network

G^{SU}_{hom} Goodput achieved by the secondary network considering an homogeneous sensing scenario

I Duration of the PU's inactive (OFF) period (random variable)

$I_{periods}$ Number of PU OFF periods that a SU needs to transmit a packet (random variable)

I^{Sum}_r Duration of the sum of r PU OFF periods (random variable)

N Set of SUs contending the wireless channel

n Number of SUs contending the wireless channel

p_B Success probability parameter of the geometric distribution representing the duration of the PU ON period

P_I SU's access probability

p_I Success probability parameter of the geometric distribution representing the duration of the PU OFF period

P_{Int} Probability of interference between a SU and a PU

$P_{p,i}$ Probability of a SU i having a packet to transmit

P_{QE} Probability of queue empty

$p_{T^{SU}_{packet}}$ Success probability parameter of the geometric distribution representing the duration of the SU's packet

Q_{length} Queue length (random variable)

$Q_{waiting}$ Queue waiting time (random variable)

S^{SU}_{het} Throughput achieved by the secondary network considering an heterogeneous sensing scenario

$T^{het}_{service}$ Packet service time under the heterogeneous sensing scenario (random variable)

$T^{hom}_{service}$ Packet service time under the homogeneous sensing scenario (random variable)

Single-Channel MAC Symbols

α_C Relative gain of C2RMAC due to the second stage of contention

α_G Goodput loss of C2RMAC due to synchronization and sensing period

Ω Generic C2RMAC MAC state regarding the transmission phase

τ_1 Probability of chosing one of the mini-slots in the first stage of contention

τ_2 Probability of chosing one of the mini-slots in the second stage of contention

Υ Number of transmission cycles needed to transmit a packet (random variable)

φ Synchronization period

ξ Set of states of a SU implementing the C2RMAC MAC scheme

ζ Set of states of the SU AP implementing the C2RMAC MAC scheme

cw_1 Number of mini-slots in the first stage of contention

cw_2 Number of mini-slots in the second stage of contention

cw_1^{max} Maximum number of mini-slots in the first stage of contention

CW_{2B} Number of busy mini-slots in the second stage (random variable)

cw_2^{coll} Average number of mini-slots in the second stage of contention with a collision

cw_2^{idle} Average number of idle mini-slots in the second stage of contention

cw_2^{max} Maximum number of mini-slots in the second stage of contention

n_{Cycle}^{AP} Average number of SUs competing at each transmission phase of each transmission cycle

N_{St1} Number of SUs competing in the first stage of contention (random variable)

n_{St1} Average number of SUs selected to compete in the first stage of contention

N_{St2} Number of SUs selected to compete in the second stage of contention (random variable)

n_{St2} Average number of SUs selected to compete in the second stage of contention

P_{2St} Individual probability of a SU being selected to compete in the second stage of contention

$P_{\alpha,i}$ Probability of SU i competing in the first stage of contention after receiving the tone

$P_{\beta,i}$ Probability of SU i being able to transmit since it was competing in the second stage of contention

$P_{\gamma,i}$ Probability of SU i transmitting in the last frame of the SU AP transmission phase

$P_{cw_2^{coll}}$ Probability of finding a mini-slot with collision in the second stage of contention

$P_{cw_2^{idle}}$ Probability of finding an idle mini-slot in the second stage of contention

$P_{frames^{coll}}$ Probability of finding a frame with collision

$P_{frames^{idle}}$ Probability of finding an idle frame

$P_{St1\_St11\_Idle}^{SU}$ Transition probability of a SU from state $\mathbf{St1_{SU}}$ to state $\mathbf{Idle_{SU}}$ through state $\mathbf{St11_{SU}}$

$P_{St1\_St1\_Idle}^{SU}$ Transition probability of a SU from state $\mathbf{St1_{SU}}$ to state $\mathbf{Idle_{SU}}$ through state $\mathbf{St1_{SU}}$

$P_{St1\_St2\_Idle}^{SU}$ Transition probability of a SU from state $\mathbf{St1_{SU}}$ to state $\mathbf{Idle_{SU}}$ through state $\mathbf{St2_{SU}}$

$P_{St1\_Tx\_Idle}^{SU}$ Transition probability of a SU from state $\mathbf{St1_{SU}}$ to state $\mathbf{Idle_{SU}}$ through state $\mathbf{Tx_{SU}}$

P_{SU1} Probability of having at least one SU competing in the first stage of contention

P_{SU2} Probability of having at least one SU competing in the second stage of contention

T_{Cycle}^{AP} Length of the SU AP transmission cycle with transmission phase (random variable)

T_{Cycle}^{hom} Length of the transmission cycle under the homogeneous sensing scenario (random variable)

$T_{Idle\_St11}^{SU}$ Number of frames spent by a SU in state $\mathbf{Idle_{SU}}$, derived from state $\mathbf{St11_{SU}}$, before reaching the state $\mathbf{St1_{SU}}$ (random variable)

$T_{Idle\_St1}^{SU}$ Number of frames spent by a SU in state $\mathbf{Idle_{SU}}$, derived from state $\mathbf{Idle_{SU}}$, before reaching the state $\mathbf{St1_{SU}}$ (random variable)

$T_{Idle\_St2}^{SU}$ Number of frames spent by a SU in state $\mathbf{Idle_{SU}}$, derived from state $\mathbf{St2_{SU}}$, before reaching the state $\mathbf{St1_{SU}}$ (random variable)

$T^{SU}_{Idle\_Tx}$ Number of frames spent by a SU in state $\mathbf{Idle_{SU}}$, derived from state $\mathbf{Tx_{SU}}$, before reaching the state $\mathbf{St11_{SU}}$ (random variable)

T_{Idle} Number of idle frames during the transmission phase (random variable)

T^{SU}_{Idle} Number of frames spent by a SU in state $\mathbf{Idle_{SU}}$ before reaching the state $\mathbf{St1_{SU}}$ (random variable)

$T^{AP}_{St1\_St1}$ Number of frames spent by the SU AP to reach state $\mathbf{St1_{AP}}$ from state $\mathbf{St1_{AP}}$ (random variable)

$T^{AP}_{St2\_St1}$ Number of frames spent by the SU AP to reach state $\mathbf{St1_{AP}}$ from state $\mathbf{St2_{AP}}$ (random variable)

T^{AP}_{Trans} Number of frames observed between $l+1$ idle frames (random variable)

T^{AP}_{Tx} Length of the transmission phase (random variable)

T^{SU}_{Tx} Number of frames elapsed between the beginning of the second stage and the SU's transmission (random variable)

Multi-Channel MAC Symbols

δ_{GPD} Location parameter of the generalized Pareto distribution

η Average number of time units needed to successfully assign a data channel

$\Lambda_{i,l}$ Scheduling decisions of SU i to channel l

ψ Set of states of a SU implementing the MC-C2RMAC MAC

ξ_{GPD} Scale parameter of the generalized Pareto distribution

L Number of data channels

L_{Unass} Number of unassigned data channels (random variable)

M Number of mini-slots in the CReq period of MC-C2RMAC

n_{RTS} Average number of SUs competing for a data channel

P_{Ch_Sel} Probability of a SU being selected to transmit in a data channel

P_{CTS} Probability of successful transmission of CTS packets

P_{One_Unass} Probability of having at least one data channel unassigned

P_{RTS_Coll} Probability of collision between RTS packets

P_{Tx_End} Probability of a SU data packet transmission reaching its end

List of Acronyms

ACK ACKnowledgment packet.

AP Access Point.

ARQ Automatic Repeat reQuest.

AWGN Additive White Gaussian Noise.

BS Base Station.

CBS Cyclostationarity-Based Sensing.

CC Control Channel.

CCC Common Control Channel.

CDF Cumulative Distribution Function.

CDMA Code Division Multiple Access.

CF Characteristic Function.

CInf Channel Information.

CLT Central Limit Theorem.

CR Cognitive Radio.

CR-CSMA Cognitive Radio-based Carrier-Sensing Multiple Access.

CR-ALOHA Cognitive Radio ALOHA.

CReq Channel Request.

CRN Cognitive Radio Network.

CRTS Confirmed-RTS.

CSMA Carrier Sensing Multiple Access.

CSMA/CA Carrier Sensing Multiple Access with Collision Avoidance.

CTS Clear-To-Send.

DAB Direct Access Based.

DCF Distributed Coordination Function.

DCRN Decentralized Cognitive Radio Network.

DFH Dynamic Frequency Hopping.

DSA Dynamic Spectrum Access.

DSAllloc Dynamic Spectrum Allocation.

DSSS Direct-Sequence Spread-Spectrum.

DTMC Discrete Time Markov Chain.

EBS Energy-Based Sensing.

FCC Federal Communications Commission.

FHSS Frequency-Hopping Spread-Spectrum.

GPS Global Positioning System.

IEEE Institute of Electrical and Electronics Engineering.

INFO Information.

ISM Industrial, Scientific and Medical.

LO Local Oscillator.

MAC Medium Access Control.

MFBS Matched Filter-Based Sensing.

NAV Network Allocation Vector.

OFDM Orthogonal Frequency Division Multiplexing.

OSI Open Systems Interconnection.

PGF Probability Generating Function.

PHY Physical.

PMF Probability Mass Function.

POMDP Partially Observed Markov Decision Process.

PRN Primary Radio Network.

PU Primary User.

QoS Quality of Service.

RF Radio Frequency.

RTS Ready-To-Send.

SDR Software-Defined Radio.

SINR Signal to Interference plus Noise Ratio.

SNR Signal-to-Noise Ratio.

SU Secondary User.

SU AP Secondary User Access Point.

TVWS TV White Space.

UWB Ultra-Wide Band.

WLAN Wireless Local Area Network.

CHAPTER 1

INTRODUCTION

1.1 Motivation and Scope

Over the last two decades, wireless communications have gained more and more importance in our every day life. However, wireless communications require a very important and even more rarer resource: the radio spectrum. The radio spectrum scarcity is caused by constant advances in wireless communication systems along with an *outdated* fixed spectrum access policy. On the other hand, the unlicensed portions of the spectrum, like Industrial, Scientific and Medical (ISM) bands, have become increasingly crowded. In 2002, the Federal Communications Commission (FCC) reported that a large portion of the assigned spectrum is only used sporadically, leading to an underutilization of a significant amount of spectrum [FCC02]. In order to maintain a permanent and sustainable development of the wireless communications, novel channel access techniques should be adopted to improve the utilization of the radio spectrum.

In 1999, *Joseph Mitola* proposed a new and alternative policy of spectrum utilization to increase its usage efficiency: the Dynamic Spectrum Access (DSA) [MIM99]. In DSA scheme, one piece of spectrum can be allocated to one or more users, which are called Primary Users (PUs) or licensed users, using the traditional fixed spectrum access policy. However, these users do not own the exclusivity of accessing the licensed channel, although they have higher priority in using it. But when the licensed channel is not being used by the PUs, the channel is vacant, leading to a spectrum underutilization. In this case, other users, denominated as Secondary Users (SUs) or unlicensed users, can now dynamically access to the temporary vacant channel without interfering with PUs, hence improving the spectrum efficiency.

In order to support the DSA technique, SUs have the responsibility to sense the spectrum, searching for a vacant band, and use it as long as it is shown to be free from licensed user: this set of actions is also denoted as a cognitive capability, and SUs with this ability are usually called as CR users [MI00]. Then, following a macroscopic definition, a CR user can be defined as a user capable of identify spectrum holes, or white spaces in the spectrum [Tan+09], and using them opportunistically without causing harmful interference to PUs.

The peculiar characteristics of Cognitive Radio Networks (CRNs) distinguish them from the *traditional* wireless networks. Thus, innovative cross-layered PHY-MAC architectures are required for this type of networks. In CRNs, the PHY layer should be responsible to perform spectrum sensing tasks, enabling CR users to identify the spectrum holes, and also to reconfigure and optimize the transceiver based on the results acquired from the environment [Aky+06]. Regarding the MAC sublayer, it should be capable to perform two of the most important tasks in CR: i) to choose between the spectrum sensing and the spectrum access and ii) to coordinate the SU's access [Shi+10]. The sensing/access coordination should be based on a tradeoff between sensing opportunities requirement and spectrum access requirements. Together, using a cross-layered PHY-MAC scheme with the above characteristics, PUs and SUs should be able to successfully cohabit, maximizing the channel efficiency without diminishing the performance of PUs.

A plethora of innovative PHY-MAC protocols have already been proposed to satisfy the aforementioned CRNs' requirements. Some of these schemes assume that a SU is equipped with more than one transceiver, some take advantage of a dedicated Control Channel (CC) to be used for control message's exchange and others admit the existence of multiple licensed channels to be opportunistically explored by the secondary network. Another important feature characterizing the CR MAC architecture is the way how it manages the channel access: in a centralized architecture a single SU or a set of SUs may be responsible for the medium access control; in a distributed scenario all SUs are able to autonomously decide their medium access.

However, as we will see in Chapter 2, most of the decentralized CR MAC protocols proposed so far admit the existence of a dedicated CC which might be, in some cases, impossible to implement. Therefore, the split-phase approach, characterized by the division of the SU's operation cycle into alternating control and data periods, is an alternative solution to coordinate the medium access of the SU in a decentralized way using only one channel. A few split-phase MAC protocols have been proposed for DCRNs but, as we will see further ahead in this document, they adopt random access philosophies to manage the channel's access, which are unable to maximize the spectrum reutilization.

Motivated by the previous arguments this thesis aims to design and evaluate efficient PHY-MAC architectures for DCRNs. We start by considering a single-channel scenario where each SU is equipped with a single-transceiver, and therefore, the split-phase approach is the only solution to manage the SUs' channel access. To overcome the poor performance achieved by the random-access protocols we propose a novel distributed reservation-based algorithm. Then, using a similar reservation-based concept, we propose a second decentralized MAC protocol, however in this case to be used in a multichannel scenario, where each SU is equipped with two transceivers. Both protocols are modeled and the results are used to assess their performance showing that they can achieve high levels of spectrum utilization.

In addition, it is important to recall that SUs are not allowed to cause harmful interference to licensed users, meaning that they must keep sensing the channels periodically. In single-channel SUs, the implementation of an efficient CR MAC scheme gets even more challenging because the SU's operation cycle must account with sensing and access periods. However, how long should be the sensing period? If a SU adopts an energy detector as the spectrum sensing technique, what should be the value of the energy threshold? Prior to the description of the MAC schemes, we try to answer to these questions by characterizing the spectrum sensing framework based on the EBS technique and considering multiple scenarios.

1.2 Research Question and Hypothesis

The research question of this thesis is as follows:

Is it possible to design efficient distributed MAC techniques able to take advantage of the diversity and quality of the available licensed data channels?

The research question can be addressed by the following hypothesis:

By considering several access techniques such as reservation and random access complemented with multi-objective optimization techniques, it is possible to develop a novel distributed PHY-MAC cross-layer scheme which increases the spectrum utilization and reduces PUs' interference.

1.3 Objectives

Regarding the context of this thesis, the following research goals were defined:

- Study the performance of the spectrum sensing task in a CRN where SUs are equipped with a single transceiver, and therefore they adopt an operation cycle where sensing and transmission occur in a consecutive manner;
- Characterize the impact caused to PUs when a randomized arrival or departure of a PU may occur at any instant of the SU's operation cycle;
- Design a split-phase MAC protocol for single-channel DCRNs that should improve the network's goodput by decreasing the number of wasted transmission opportunities usually observed in random contention-based MAC schemes;
- Evaluate the proposed single-channel CR MAC protocol under the scenario of channel sensing heterogeneity;
- Design a MAC protocol for multichannel DCRNs that should take into consideration the availability of each licensed channel and the channel access requirements of each SU;
- Model the MAC layer for both single and multichannel proposals and compare the analytical results with the simulation results;
- Disseminate the obtained results in relevant and state-of-the-art scientific conferences and journals.

1.4 Contributions

The major contribution of this work is the design of novel PHY-MAC cross-layer architectures for DCRNs. Starting by the PHY layer, we study the performance of the spectrum sensing task considering a single-radio CRN where SUs adopt the EBS technique to sense the spectrum. Using classical tools from the detection theory, we provide expressions to the probabilities of detection and false alarm considering two distinct scenarios depending if the PU changes its activity during the SU's operation cycle. Considering a constant PU's behavior, we investigate new strategies to parameterize the EBS [Lui+12a] and therefore we characterize the primary network interference caused for a non-constant PU's behavior [Lui+13d]. The results show that when the length of the PU's frame is considerably large when compared to the SU's frame, it is reasonable to assume a constant PU's behavior with respect to the SU's frame.

Having characterized the spectrum sensing framework we move on to the MAC sublayer. First, we propose a novel decentralized reservation-based MAC protocol for single-radio single-channel CRNs [Lui+13c; Lui+15a]. The performance of the proposed MAC scheme is evaluated under homogeneous and heterogeneous channel sensing conditions and the results show that the proposed scheme is able to increase the network's goodput when compared to traditional random contention-based CR MAC protocols. For both homogeneous and heterogeneous channel sensing scenarios we present an analytical model for the network's goodput and packet service time, which is validated through simulation results [Lui+15c]. Then, we propose a second MAC protocol, but this time for multichannel CRNs. The proposed multichannel MAC scheme adopts a non-preemptive MaxWeight scheduling policy based on the availability of the licensed channels and the individual backlog of the SUs [Lui+15b]. Plus, we propose an innovative packet service time analysis of opportunistic access in a CRN where we characterize, through its Characteristic Function (CF), the duration of each SU's access opportunity. Two papers describing the complete analysis of the C2RMAC protocol and the packet service time analysis of opportunistic access in a CRN are currently under review in two scientific journals.

The following works are considered minor contributions because they are out of scope of this thesis. However all of them contributed somehow to the development, improvement and recognition of the work presented in this document.

The exhaustive literature review on PHY-MAC protocols for CRNs presented in Chapter 2 was published in [Lui+13a]. The work in [Rei+15] presents a new analytical model for the performance of a p-persistent slotted Aloha MAC protocol in a CRN considering a realistic PU's behavior, *i.e.*, using the analytical model proposed in Section 3.3. [Lui+12b] characterizes the interference distribution of a DCRN based on Code Division Multiple Access (CDMA). An analytical model for the multiple-access interference of a single PU network was initially proposed and thereafter extended to embrace the co-existence of a SU network. Assuming a a Ultra WideBand (UWB) CRN, the work in [Fur+14] derives a solution to estimate the level of activity of the PUs using only the information available at the MAC sublayer of each SU. At last, [Fur+13] characterizes the channel availability assessment performed by a SU adopting the EBS detector and assuming a constant and non-constant PU's behavior.

The following contributions resulted from the development of MAC schemes for distributed wireless networks. The work in [Oli+15] presents a novel MAC algorithm for single-hop distributed wireless networks designed to maximize the network throughput performance. The algorithm is mainly motivated by the shared view of the channel where the individual medium access probability and the probability of sensing an idle slot are used to estimate the number of competing nodes. The same rationale was adopted in [Oli+12] to increase the reliability regarding the transmission of broadcast messages, and in [Fur+12b] the performance of the proposed algorithm was evaluated in the presence of transmission errors.

Finally, it is important to highlight that different pieces of the work presented on this thesis, namely the spectrum sensing characterization and the analytical model regarding the realistic PU's behavior both presented in Chapter 3, as well as the decentralized single-channel MAC protocol for DCRNs described in Chapter 4, were integrated in the Opportunistic Aggregation of Spectrum and Cognitive Radios - Consequences on Public Policies (Opportunistic-CR) project[1], funded by the Portuguese Science and Technology Foundation, whose achievement was the investigation of innovative techniques to facilitate spectrum sharing and co-existence of different types of wireless networks. It is also important to mention that part of this thesis was presented in two COST Action IC-0902[2] Meetings [Fur+12a; Lui+13b], therefore contributing to the integration of the cognitive concept across all layers of communication systems.

1.5 Outline

This thesis is structured in a total of 6 chapters and 4 appendices, organized as follows:

- Chapter 2 provides an extensive literature review in CRs with special emphasis on CR MAC protocols, including traditional spectrum sensing techniques and current standardization initiatives;

- Chapter 3 studies the performance of a spectrum sensing framework based on the EBS technique, assuming a single-radio architecture. Several EBS parameterization criteria are evaluated based on the network's goodput and interference caused to PUs. Finally, we compare the primary network's interference by assuming a constant and non-constant PU's behavior during the spectrum sensing period;

- Chapter 4 is entirely dedicated to single-channel CRNs. In this chapter a novel CR MAC protocol for single-channel CRNs is presented: the C2RMAC. The MAC scheme follows a reservation policy based on two stages of reservation which are used to reduce the number of collisions and the number of unused idle frames. The protocol is modeled and evaluated considering homogeneous and heterogeneous channel sensing conditions;

- Chapter 5 focuses on multi-channel CRNs. First, an analytical model is derived for the opportunistic service time, *i.e.*, for the amount of time required by the secondary network

[1] http://www.e-projects.ubi.pt/opportunistic-cr

[2] http://newyork.ing.uniroma1.it/IC0902/

to transmit a packet in a data channel owned by the primary network. Then, a novel multi-channel MAC protocol is proposed. The opportunistic service time of each channel is used as a channel selection criterion. The secondary network's goodput and aggregate service time are modeled and evaluated;

- Chapter 6 presents the thesis's conclusions as well as some guidelines about future work;
- Appendices A to D detail some of the mathematical derivations used to support the C2RMAC analytical model.

Chapter 2

Literature Review

2.1 Introduction

In order to address the critical problem of spectrum scarcity, the FCC approved the use, under strict conditions, of unlicensed devices in licensed bands [FCC02]. Several DSA techniques have been proposed so far with one major purpose: increase the spectrum utilization, without teasing the licensed users. Hence, *recent* investigations on this topic introduced a new type of wireless communication networks, capable of comply with the aforementioned demands: the CRNs. However, the design and implementation of CRNs imposes unique challenges due to the DSA specific characteristics. The most challenging one is the definition of new PHY and MAC cross-layer schemes able to cope with the presence of PUs and operate within a desired level of Quality of Service (QoS).

CRs are characterized by their cognitive capability and reconfigurability, supporting the design and the implementation of new and *valuable* DSA techniques. The cognitive capability provides spectrum awareness, while reconfigurability enables a CR device to dynamically adapt its operating parameters to the surrounding environment [Jon05]. More specifically, a CR device can be parameterized to i) dynamically transmit and receive over widely separated frequency bands and adapt its transmission power, modulation type and frequency range, through Software-Defined Radio (SDR) technology [MI00], and ii) determine its optimal spectrum access scheme [ZS07b].

A typical CRN environment consists of a number of licensed users, or Primary Users (PUs), forming a Primary Radio Network (PRN), and a set of unlicensed users, or Secondary Users (SUs). The PRN is referred to an existing network, where PUs have the permission to operate over pre-defined licensed spectrum bands. PUs may be controlled by Base Stations (BSs) and, since they have the priority to access the channel, their operations should not be affected by SUs' transmissions. On the other hand, SUs do not have the license to communicate in licensed frequency bands but they will try to access them, by opportunistically exploiting the unused portions of the spectrum, always avoiding causing interference to licensed users.

Regarding the CRN architecture, CRNs can be classified as infrastructured CRNs or DCRNs. Infrastructured CRNs are characterized by having a central entity, usually a BS or an Access Point (AP), while the DCRNs are not coordinated by a central unit, and the communication between SUs is made through *ad hoc* connections. However, the difference between these two architectures does not rely only in the communication method. Regarding the spectrum sensing and spectrum access decisions, in infrastructured CRNs the local spectrum observations and analysis are performed by each SU and then transmitted to the central unit. By this way a central unit can make decisions on how to avoid interfering with PUs. On the other hand, in DCRNs each SU is responsible for independently sensing the spectrum and determine when and which part of the spectrum should be opportunistically used, which requires a more complex and robust MAC scheme.

In order to adapt to dynamic spectrum environments, CR devices must perform spectrum-aware/access operations that all together form the *cognitive cycle* [Hay05], [MI99]. This cycle consists of four spectrum management functions: spectrum sensing, responsible for monitoring the available spectrum searching for spectrum access opportunities; spectrum decision, capable of selecting the most appropriate frequency bands to transmit, no only in terms of availability but also in terms of their QoS requirements; spectrum sharing, responsible to provide the capability to share the spectrum with other SUs by adopting optimal resource allocation schemes; and spectrum mobility, responsible for being aware of the spectrum changes during the sensing and access periods, to detect link failures and switch the current transmissions to new and vacant frequency bands.

Traditional PHY-MAC cross-layer architectures are not prepared to support the aforementioned CR characteristics and demands. As an example, the spectrum mobility management function usually does not make part of classical MAC schemes, because all nodes have the same priority to use the spectrum. Also, the new spectrum sensing management function has to search the spectrum looking for vacant channels, using sensing techniques not adopted in the existing PHY layer schemes. Thus, several PHY-MAC cross-layer frameworks have been designed and adopted by the community to incorporate all the spectrum management functions needed to dynamically access the spectrum. Figure 2.1 illustrates the four spectrum management functions, according to its role and functionality inside the PHY-MAC cross-layer framework.

In the PHY layer, the spectrum sensing management function is an essential component that enables SUs to identify spectrum holes. The spectrum mobility management function should operate in both PHY and MAC layers because it must provide information about the spectrum changes, not only during the sensing periods (PHY responsibility), but also during the access periods (MAC responsibility). The specific spectrum management functions performed by the MAC sublayer of a CR device must include spectrum decision and spectrum sharing. The spectrum decision management function controls the sensing and access operations, establishing the transmission and sensing durations, which are based on the information sent by the spectrum sensing and spectrum mobility management blocks. Finally, the spectrum sharing management function governs the spectrum access to the identified spectrum holes after receiving the information from the spectrum decision management block.

The remaining of this chapter is organized as follows: Section 2.2 tackles the spectrum sensing

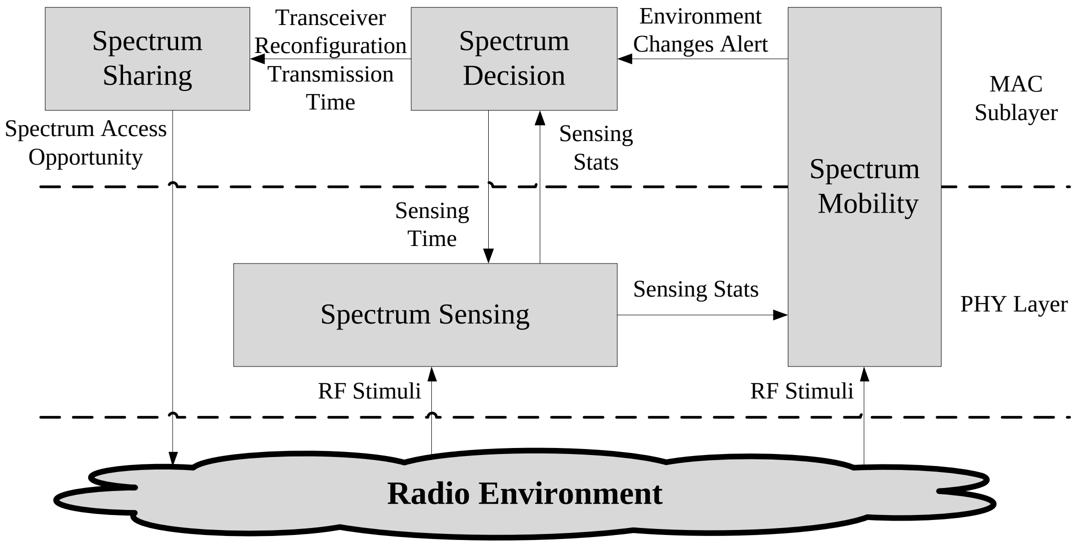


Figure 2.1: The CR spectrum management framework: an OSI model perspective [Lia+11].

problem, presenting its challenges and describing some of the most used spectrum sensing techniques; Section 2.3 overviews the importance of having an appropriate MAC sublayer scheme in CRNs and CR MAC schemes; Section 2.4 describes some standards already proposed for CRNs; and finally Section 2.5 overviews the main conclusions of this chapter.

2.2 Spectrum Sensing Framework

Cognitive radio devices are designed to be aware of and sensitive to the changes in their surrounding, which makes spectrum sensing one of the key enabling functions in CRNs. To comply with these requirements, the spectrum sensing framework can be divided into two major tasks: i) spectrum exploration in search for spectrum hole opportunities, during the spectrum sensing period, and ii) frequent spectrum monitoring, during the spectrum access periods, to detect the presence of PUs so as to avoid interference with them.

Although spectrum sensing is usually referred as measuring the spectrum content, or measuring the radio frequency energy over the spectrum, in CR context this term evolves to a more general term that includes acquiring the spectrum usage characteristics such as signals' modulations, waveforms, bandwidths, carrier frequencies, etc. [YA09]. However, this requires more powerful signal analysis techniques with additional computational complexity.

Spectrum awareness is achieved by employing multiple techniques, including: geolocation and database [H+07; Mar05; She+09; Zha+07b]; using periodic beacons [Ara+08]; and local radio observations performed by the CR devices [Cab+04; FCC03; GL05; Pro01; Sha+05; Yua+07]. Using the geolocation and database spectrum awareness techniques all PUs must be equipped with a geolocation/position technology and update their location into a database. Hence, SUs can access to this database and be aware about the spectrum band that might be available in a given location. Due to storage limitations, this technique is only used to tag fixed PUs (e.g. UHF/VHF

TV antennas). An alternative method to perform spectrum sensing is to deploy beacon transmitters on each PU, which periodically transmit *disabling beacons* with sufficiently strong power that any SU detecting the beacon will avoid using the channel [Ara+08].

However, the most used spectrum awareness technique is the local radio observation. Here, each SU periodically observes the spectrum searching for PU's activity. Spectrum sensing techniques based on local radio observations can be classified into three groups [Aky+06]: primary receiver detection, interference temperature management and primary transmitter detection. The primary receiver detection is based on the detection of PUs that are receiving data within the communication range of a SU. When operating in receiving mode, some PUs emit the Local Oscillator (LO) leakage power from its Radio Frequency (RF) front-end, which can be used by SUs to detect its presence [SB11]. However, this signal is typically weak and with very short range, which demands for a very accurate detector. This technique is frequently adopted in the detection of TV receivers [WR05].

The idea behind the interference temperature management, proposed by the FCC in 2003 [FCC03], is to set up an upper interference limit for a given frequency band, such that the SUs are not allowed to cause harmful interference to PUs. As long as SUs do not exceed this limit by their transmissions, they can use this frequency band. However, the difficulty of the interference model lies in accurately determining the interference temperature limit, because SUs cannot distinguish between the PUs' signals and noise. In 2007 the FCC decided to cease the support to the interference temperature management model, mainly because it exhibits a low performance when compared to the amount of interference it can cause to primary users [FCC07].

Due to the challenges imposed by the previous spectrum sensing approaches, most of the research in spectrum sensing focuses on the primary transmitter detection technique. This technique is similar to the primary receiver detection but, in this case, the objective is to detect PUs' transmitters. In order to distinguish between used and unused spectrum bands, SUs observe the spectrum during the sensing period and make their decisions about the spectrum occupancy based on the following hypothesis model:

$$\begin{aligned} \mathcal{H}_0 &: u(k) = w(k) \\ \mathcal{H}_1 &: u(k) = s(k) + w(k), \end{aligned} \tag{2.1}$$

where $u(k)$ is the received signal, $w(k)$ is a zero-mean Additive White Gaussian Noise (AWGN) and $s(k)$ is the PU transmitted signal. The first condition, $\mathcal{H}_0$, states that there are no PUs in a certain spectrum frequency, while the second condition, $\mathcal{H}_1$, indicates that there exists some PU activity. Section 2.2.2 describes three of the most studied primary transmitter detection schemes in the literature, and how they adapt the previous hypothesis test to decide if the sensed spectrum is occupied.

The primary transmitter detection, similarly with the others spectrum sensing techniques, presents several implementation challenges. The most crucial one is to determine the decision threshold γ, that will be used to distinguish between the hypothesis $\mathcal{H}_0$ and $\mathcal{H}_1$. The performance of the primary transmitter detector is related with two probabilities: i) the probability of detection P_D, representing the probability of detecting a signal and, ii) the probability of false alarm P_{FA}, which denotes the probability of a SU to erroneously classify the spectrum frequency as occupied, when there is no PU activity. These probabilities can be formulated as

$$P_D = Pr(Y > \gamma|\mathcal{H}_1) \tag{2.2}$$

$$P_{FA} = Pr(Y > \gamma|\mathcal{H}_0), \tag{2.3}$$

where Y is the detector output, that depends on which primary transmitter detection scheme is being used. In order to optimize the performance of the primary transmitter detector the probability of detection must be increased, to avoid causing interference to PUs, and decrease the probability of false alarm, to prevent underutilization of transmission opportunities. But, as we can see from (2.2) and (2.3), both probabilities are directly related with the decision threshold, and so γ should be selected by finding an optimum balance between P_D and P_{FA}. In practice, the decision threshold is chosen to obtain an acceptable predefined false alarm probability [Leh+05], but different criteria can be adopted [Lui+12a].

Subsection 2.2.1 briefly overviews the challenges in performing spectrum sensing operations and subsection 2.2.2 describes three of the most used spectrum sensing techniques.

2.2.1 Design and Implementation Challenges

Before detailing some of the most used spectrum sensing techniques in CR, we briefly enumerate several challenges associated with the design and implementation of the spectrum sensing framework.

2.2.1.1 Hardware Requirements

Traditional receivers are capable of processing narrow baseband signals with moderately low complexity and low power processors. However, and due to the distinctive characteristics of the spectrum sensing concept, CR terminals are required to process transmissions over a much wider band, looking for an access opportunity. Hence, CR devices should be able to capture and analyze a relatively larger band in a shorter period of time in order to identify vacant channels in the licensed radio spectrum.

Spectrum sensing can be performed via two different architectures: single-radio and dual-radio [Sha+05]. In the single-radio architecture only a specific time slot is allocated for spectrum sensing. As a result of using single-radio architecture, the SU gets a limited sensing duration and a decrease in the spectral efficiency: the single-radio has to perform spectrum sensing and spectrum access techniques in an alternate way. The obvious advantage of single-radio architecture is its simplicity and lower cost [Wan+07]. Using the dual-radio sensing architecture, one radio is dedicated for spectrum monitoring while the other is dedicated for data transmission, which increases the spectral efficiency. However, this architecture increases the power consumption and hardware costs [Yua+07].

2.2.1.2 Hidden Primary User Problem

The hidden Primary User problem is similar to the well known hidden node problem in the Carrier Sensing Multiple Access (CSMA) scheme [TL08]. Basically it occurs when a node C is within the range of a node B, but out of the range of a node A. When the node A transmits to node B, the node C can not detect the transmission, assuming that the channel is idle. The hidden Primary User problem can also be caused by other environmental factors, including severe multipath fading or shadowing observed by secondary users while scanning the spectrum for PUs' transmissions. Due to these factors, the PUs signal becomes undetected to SUs, which, in their turn, will access to the channel without permission, causing harmful interference to PUs. This problem is usually solved using cooperative sensing [GL05].

2.2.1.3 Detecting Spread Spectrum Primary Users

The reliability of wireless communications is usually improved by the wireless devices by adopting spreading-spectrum techniques such as Frequency-Hopping Spread-Spectrum (FHSS) or Direct-Sequence Spread-Spectrum (DSSS). FHSS devices are constantly changing their operational frequencies to multiple channels using an hopping pattern known by both receiver and transmitter. DSSS devices are similar to FHSS devices, however they use a single band to spread their energy. Using these two techniques, wireless devices behave robustly against natural interference, noise and jamming, increasing the communication reliability.

The spread-spectrum techniques also introduce some challenges related with PUs' detection. When the signal power of the PUs is distributed over a wide frequency range (DSSS case), or even not present in some channel at a given time instant (FHSS case), SUs may wrongly assume that the channel is free. This problem can be partially avoided by knowing the hopping pattern together with a tight synchronization with the PUs, which is a very complex procedure [Cab+04; YA09].

2.2.1.4 Sensing Duration and Frequency

One of the most challenging tasks when designing spectrum sensing frameworks for single-radio architectures, is the choice of the spectrum sensing duration and frequency. The selection of these sensing parameters establish a tradeoff between the speed and the reliability of the sensing. Sensing frequency depends on the capabilities of the SUs itself and the temporal characteristics of PUs in the environment [Jon+07]. For example, when detecting TV channels, the sensing frequency should be relaxed because it is known that a TV station does not change its frequency inside the same geographical area. Another factor that affects the sensing frequency is the interference tolerance of PUs when accessing to some licensed channel: in this case, SUs must be aware if some PU accesses the licensed channel, in order to release it immediately.

Regarding the spectrum sensing duration, this value is usually obtained through optimization problems where the goal is to maximize the average throughput of SUs while protecting PUs from causing interference [LA08; Wan+07]. Although *higher* sensing times ensure the correct detection of the spectrum, this may result in a comparatively smaller duration for accessing the channel, lowering the throughput. Similarly, by choosing a *shorter* sensing duration, SUs will have more time to access the channel, diminishing the sensing accuracy.

2.2.1.5 Cooperative Sensing

As mentioned before, cooperative sensing can be used to solve the hidden PU problem, but also to improve the sensing accuracy in a general manner. However, this solution can also become a very challenging task. When a SU detects some PU activity it should notify its observations, or decisions, to its neighbors. To this end, a reliable control channel is needed for discovering neighbors of a SU as well as exchanging sensing information. Additionally, asynchronism between SUs make it difficult to exchange information between them.

Considering that the sensing information is successfully exchanged between SUs, each one has to combine all the information and make a decision about the spectrum occupancy. For that, SUs can use one of the two methods: i) soft information combining, where the information send by each SU includes the reliability level of each measure, and the decision is usually based on the likelihood ratio test [GR07; Vis+05]; ii) or using hard information combining, where no information about each measure's reliability is send, and the decision is based on AND, OR or M-out-of-N methods [PL07]. Results presented in [GR07] show that soft information combining performs better than hard information combining methods in terms of the probability of missed opportunity. On the other hand, hard information combining methods are found to be as good as soft methods when the number of cooperating users is *high* [Mis+06].

2.2.1.6 Asynchronous Sensing/Transmission

In distributed CRNs, SUs usually have independent and asynchronous sensing and transmissions schedules. Then, each SU will possibly detect the transmission of other SUs as well as PUs during the sensing period. Assuming that each SU is using the most commonly used spectrum sensing technique, the energy detector, SUs are not able to distinguish between the transmission of other SUs and PUs. As a result, the SUs detected during the sensing period will increase the number of false alarm situations, ruining the spectrum sensing accuracy.

2.2.2 Spectrum Sensing Techniques

A number of different techniques have been proposed to identify the presence of signal transmissions [Aky+09; Aky+11; Lia+11; SB11; YA09]. The three most studied spectrum methods in the literature are the following: the EBS, the Matched Filter-Based Sensing (MFBS) and the Cyclostationarity-Based Sensing (CBS).

2.2.2.1 Energy-Based Sensing

The EBS is the most popular spectrum sensing technique due to its low computational and implementation complexities [Cab+04; GL05; Sha+05; Yua+07]. In addition, it is more generic than other methods, as receivers do not need any *a priori* knowledge on the PUs' signal. In the energy detection, SUs sense the presence or absence of the PUs based on the energy of the received signals. The received signal is squared and integrated over the sensing period. Then, the output of the integrator is compared with a threshold to decide if a PU is present [Dig+07].

Some of the challenges with the EBS include failure to differentiate interference from PUs and SUs, poor performance under low Signal-to-Noise Ratio (SNR) [Tan05] and the selection of the decision threshold, probably the most challenging task. The interference threshold depends on the noise variance, and a small noise power estimation error will cause a significant performance loss [Sah+04]. Several proposals about the interference threshold estimation are given in [Dig+07; Oli+05; Wei+05].

2.2.2.2 Matched Filter-Based Sensing

The MFBS is known as the optimum method for detection of PUs when the transmitted signal is known and the noise is AWGN [Pro01]. The matched filter detection consists in correlating the known original PU signal with the received signal during the PUs' symbol duration. Then, the output of the correlation is compared with a threshold, as in the energy detector technique.

The main advantage of MFBS, besides its accuracy, is the short time to achieve a certain probability of false alarm as compared to other methods [TS05]. However, matched-filtering requires not only *a priori* knowledge of the characteristics of the PU signal, but also the synchronization between the PU transmitter and the SU receiver. Moreover, SUs also need to have different multiple matched filters, each one for each type of PUs' signal, increasing the implementation complexity of the sensing unit.

2.2.2.3 Cyclostationarity-Based Sensing

CBS determines the presence of PUs by exploiting the cyclostationarity features of the received signals [Cab+04; Gho+06; Lun+07; Sha+05; TG97]. These cyclostationarity features are caused by the periodicity in the signal or in its statistics like mean and autocorrelation [Gar91], or they can be intentionally induced to assist spectrum sensing [Mae+07; Sut+07].

The main advantage of this detection technique is its robustness to the uncertainty in noise power and the capability to distinguish different PUs' signals. This is a result of the fact that noise is wide-sense stationary with no correlation while modulated signals are cyclostationary with spectral correlation due to the redundancy of signal periodicities [Lun+07]. Still, cyclostationarity-based detection is computationally very complex and requires significantly long sensing time and power consumption [Hur+06].

2.3 Medium Access Control Schemes

The aforementioned particular characteristics of CRNs distinguish them from traditional wireless networks. Nevertheless, many traditional MAC protocols have been adapted for CRNs, although exhibiting low performance. This is mainly because traditional MAC schemes are designed for the current static spectrum policies [GL00; Tan03; Zha+06], but they are not suitable for opportunistic spectrum access: classical MAC schemes cannot vary their operation parameters according to the changes in heterogeneous networks, typically the ones found in CRNs. Furthermore, CR MAC schemes need to consider practical constraints like the availability of spectrum opportunities and the number of transceivers available for sensing and communication operations.

As a first step in the development of MAC schemes for CRNs, several multichannel MAC protocols proposed for *traditional ad hoc* wireless networks have been adapted to operate in CR scenarios. This was mainly because both networks address the same problems [DD+12; Mo+08; Yau+08]: i) multichannel MAC protocols were proposed to increase the spectrum utilization of single-channel *ad hoc* wireless networks; ii) they operate in a multichannel context and iii) they face the multiple channel terminal problem [SV04]. However, due to their sensing functionalities, not required in traditional multichannel MAC schemes, CRs become more spectrum agile providing protection to PUs. Also, in a multichannel network the number of channels available at each user is fixed, while it varies in a cognitive scenario. Finally, the time-scale in which a CR user operates is quite different from that of a user in a multichannel *ad hoc* network: SUs must periodically sense the wireless environment and then quickly adapt their behavior to comply with interference constraints. Regarding all these differences between multichannel wireless networks and CRNs, the multichannel MAC schemes established a good starting point to the development of CR MAC protocols.

Subsection 2.3.1 overviews the main issues in designing and implementing MAC protocols for CRNs, while subsection 2.3.2 classifies and discuss some of the most cited CR MAC protocols in the literature.

2.3.1 Design and Implementation Issues

In this section its briefly discussed the main challenges in designing CR MAC protocols, such as the configuration of the common control channel or how to handle with the multichannel hidden terminal problem, among others.

2.3.1.1 Control Channel Configuration

The amount of signaling exchanged in a CRN is substantially larger than in a classical wireless network [DD+12; Tim+10]. As an example, imagine that in a DCRN two SUs want to communicate but, at that moment, they are monitoring a different set of channels. In this case, and since we are in the absence of a central coordinating unit, both SUs will have to negotiate which channels will be used to communicate. Thus, several CR MAC protocols adopt the concept of a CC[1] to perform the transmitter-receiver negotiation about the communication channel. Moreover, the CC has also another important role which is the exchange of spectrum sensing information, in case of cooperative sensing. In any way, a reliable CC should be settled to ensure the proper functioning of the CRN.

Nowadays, we can identify four implementations of CCs. These CCs are classified according to their design and implementation methods. Below are described the main characteristics of each implementation, together with the respective advantages and drawbacks:

[1]The CC is usually referred in the literature as a Common Control Channel (CCC), however it only makes sense to be treated as *common* when it is used by the entire CRN. From now on, CCC is only used when all the SUs are using the same CC, *i.e.*, a CCC is equivalent to a global CC.

- **Dedicated Common Control Channel:** In this implementation, all the SUs in the same CRN share the same dedicated channel to exchange signaling information, sensing outcome and to perform channel selection. Then, all SUs should overhear the control message exchanges, even during data exchanges, which demands for an exclusive transceiver dedicated to the Common Control Channel (CCC). In single-radio architectures, the transmission of control and data messages becomes time multiplexed, turning the MAC protocol operation more complex. Using a dedicated CCC can cause a single point of failure, become a performance bottleneck or even raise security issues. However, the major drawback of using this CCC implementation is the possibility of a PU to become active on the CCC. For this reason, existing MAC protocols often assume that the dedicated CCC is always free from the PUs, being implemented in an unlicensed band (e.g. ISM band) [Gha+08; Jia+08; Sal+09; ZS11] or in an underlay Ultra-Wide Band (UWB) [Sal+08].

- **Dynamically Configurable Control Channel:** To overcome the drawbacks of the dedicated CCC, some CR MAC protocols have been using a CC that is dynamically configurable. In a matter of fact, this implementation of CCs introduces a simple but important modification when compared to the dedicated CCs: instead of waiting for the CC to be free from PUs, SUs will renegotiate a new CC. The dynamically configurable CC has two variants: it can be a local configurable CC (single-hop awareness) or a global configurable CC (multi-hop awareness). The former one is used when the CRN is divided into cells or groups of SUs, and each group share the same local CC [Cab+05], while the last one is used for the entire CRN. Applying the dynamically configurable local CC in a multi-hop network scenario, the entire connectivity can not be assured, because different groups adopt different local CCs; using the dynamically configurable global CC, the network will spend a lot of time and control overhead converging to the same CCC available to all SUs.

- **Split Phase Control Channel:** The split phase CC allows the operation of single-radio nodes, but with a cost in terms of synchronization overheard. This implementation divides the time frame into alternating control and data periods (the main difference when compared to both previous approaches): during the control period all SUs switch their transceivers to overhear control messages and to decide which channels will be used for data transfers; in the data period, transmissions are performed [Tim+10; Zha+07a]. The split phase CC requires stronger synchronization to identify control and data periods. The advantage is that the CC is not dedicated for control messages and it can be used for data transmissions, when only one transceiver is required.

- **Hopping-Based Control Channel:** The hopping-based CC is being used as a promising technique to overcome the need for a CC, and alleviate the aforementioned CC bottleneck problem [Hu+07; KA08]. In this implementation, also denominated as blind rendezvous [The+11], all idle SUs will hop across a set of channels, following the same hopping pattern. When both CR sender and receiver successfully exchange control messages about the data channel to use, they stop hopping and start the data transmission. Once done, both SUs resynchronize back with the hopping sequence. The hopping-based CC has the advantage of using all channels for transmission and control, and does not requires a single channel to be free from PU activity. The most challenging task in this implementation is the stringent time/channel synchronization required between SUs.

We can further group the previous CC implementations into two major categories: i) non-sequenced assigned CCs, represented by the first three implementations, the dedicated CCC, dynamically configurable CC and split phase CC; and ii) sequenced assigned CCs, characterized by the hopping-based control channel implementation. The non-sequenced assigned term refers to the fact that, from the moment that the CC is established, the following control packets will be exchanged without being necessary to negotiate a new CC[2]. On the other hand, CR MAC protocols with sequenced assigned CCs do not have a predefined CC, and the control packets are exchanged while both sender and receiver hop according to the same hopping pattern, *i.e.*, the CC is given by the set of the hopping channels used for negotiation, which can be different from the following set.

The implementation of a CC is not mandatory [Zha+07a] however, in this case, the MAC design becomes more challenging because there is no predefined channel to start the negotiation with the intended receiver. In this case the CR MAC protocol must find a way to guarantee that sender and receiver will, somehow, meet in some channel in the case of a multichannel environment.

2.3.1.2 Multichannel Hidden Terminal Problem

In CRNs, each SU has to sense the spectrum searching for spectrum opportunities but, assuming that each SU is equipped with only one transceiver, it can only sense one channel at a time with a finite duration. So, when a SU is using its single transceiver to sense a single channel, important information is being exchanged in another channel (e.g. a channel negotiation between SUs, or even the return of a PU). Since the SU is not able to hear this information, there is an higher probability that it will cause unintentionally interference to PUs, or even to other SUs [SV04].

In fact this problem also exists in multi-radio architectures. One of the solutions capable to solve this problem is to have the same number of sensing transceivers as channels to sense, which is quite intolerable. However, increasing the number of transceivers will decrease the number of multichannel hidden terminal problem occurrences, but will also increase the complexity and the cost of the CR device. Other solution to handle this problem is to ensure the synchronization between SUs, hence increasing the signaling mechanism [KA08; SZ08]. Again, this solution is also very difficult to implement in a single-radio architecture, because it will increase the control overhead and does not offer any protection to PUs.

2.3.1.3 Quality of Service

Provisioning QoS in a CRN is a very challenging task, and it is impossible to achieve without the necessary support from the CR MAC protocol: the dynamic nature of the heterogeneous spectrum can cause rapid variations in the available communications channels. When in a CRN scenario,

[2] In the dynamically configurable CC implementation, the CC can be renegotiated when PUs are detected in the frequency band used by the CC. Otherwise the CC will always be the same.

we have to preserve the QoS for PUs while offering a fair, but always dependent on the available spectrum, level of service to SUs. To protect the PUs' QoS, SUs have to accurately detect the presence of PUs, which depends, not only on the propagation conditions and noise, but also on the duration of the sensing and access periods. Regarding the SUs' QoS, they should access the channel whenever possible [Zha+09b], which directly depends on the channel utilization intensity and traffic pattern of the PUs [Paw+08].

2.3.1.4 Time Synchronization

Time synchronization is a very important feature in CRNs, especially in DCRNs. Due to the lack of a cental unit, SUs have to negotiate a data channel, which becomes very difficult without time synchronization. Moreover, time synchronization is also crucial to avoid spectrum sensing mistakes: all SUs should perform spectrum sensing tasks at the same time to guarantee that all the detected spectrum activity is caused by PUs. Then, time synchronization is needed for network establishment and for coordination among SUs. However, achieving network-wide time synchronization without a central entity is a very challenging research problem. Several groups have already proposed the use of the Global Positioning System (GPS) for time synchronization [EM99; Get93; Jon+07; Tho+06].

2.3.1.5 Adapting to PU transmission

There are several licensed devices that have specific transmission patterns, e.g. television broadcast stations, which have pre-determined spectrum usage times and duration [IEE11; Shi+10; Wil+08; ZS07a], or may have occasional random access to the channel, like public service agencies [CC09] or radars. In these situations, the CR MAC protocol should be able to infer the nature of PUs and adopt new dynamic power control and transmission scheduling techniques to minimize the level of interference caused to PUs, increasing the spectrum usage.

2.3.1.6 Multi-hop Network Design

The design of multi-hop wireless networks is a very challenging task, not only in DCRNs but in any *ad hoc* wireless network, mainly due to their dynamic and heterogeneous nature [ZZ08]. In multi-hop *ad hoc* wireless networks the wireless channel is highly unreliable and its capacity may vary dramatically from hop to hop. The hidden terminal problem in a multihop network scenario is responsible for a high degradation in terms of throughput. Nodes' mobility causes rapid changes in terms of network topology which demands for a frequent update of the network topology, increasing the amount of control traffic. Finally, a decentralized multi-hop wireless network only uses the local information available to any node to adapt its parameters to optimal points of operation. Therefore, it is preferable to use distributed algorithms instead of gathering all the network information in a single node, which avoids a single point of failure and decreases the amount of control traffic.

To these classical multi-hop network issues, DCRNs add one more: the choice of the CC. The global CC addresses the multi-hop communication easily, however it is very difficult to configure a CCC for all SUs, mainly due to the difficulty of availability of the same spectrum band for all the nodes in the network [Ma+05; Tho+06]. The local CC is a better solution to address the multi-hop when compared to the CCC, however it still introduces moderate control overheads, because it is necessary to settle CCs between different groups of SUs [Zha+05]. Dynamic configurable CCs, global or local, involve higher overheads due to their repeatedly reconfiguration, which are justified by the frequent changes occurring in the network topology and in the occupancy of the bands by PUs.

2.3.2 CR MAC Schemes: Classification and Discussion

CR MAC schemes, just like the traditional wireless MAC protocols, can been classified according to several features: sometimes these features are directly related with the characteristics of the MAC protocol (e.g. CC design and medium access schemes); sometimes they are related with physical characteristics (e.g. number of existing transceivers); or even related with the network topology. Below there is a brief description of some of the features that are usually used to classify CR MAC schemes [CC09; DD+12; Jha+11b; KD09; Lia+11; Paw+09; SK09; Shi+10; Wan+08]:

- **Network Topology:** CR MAC schemes are broadly divided into two major classes according to the architecture of the wireless network: they can be infrastructured or decentralized. In infrastructured CRNs, CR MAC protocols need a central entity, such as a BS, that manages network activities, synchronizes and coordinates operations among SUs. Usually, the central unit is fixed and forms a single hop link with the SUs that are within its coverage area, being coordinated by the central unit. This architecture helps in the coordination among the SUs for collecting the spectrum sensing information from each SU, and allows the spectrum decisions to be localized. In DCRNs, SUs are responsible for making spectrum sensing and spectrum access tasks without the help of a central unit. Though this topology is scalable and has flexible deployment, the distributed spectrum sensing, sharing and access demands for an increased cooperation between SUs. Therefore, maintaining time synchronization throughout the entire network is a complex task needed to be solved in DCRNs.

- **Number of Transceivers:** CR MAC protocols can also be classified according to the number of transceivers per users. If SUs have a single transceiver, the protocols are denoted as single-transceiver architectures. If SUs are equipped with two or more transceivers, the architecture is denoted as a multi-transceiver architecture. The number of transceivers has a big influence in the performance of CR MAC protocols. In single-radio architectures, a single transceiver has to perform spectrum sensing and spectrum access. In multi-radio architectures, each SU usually has two or three transceivers: one of them is always listening the CC; the second transceiver is used for data exchange; and in some cases a third transceiver is used for advertisement functionalities, e.g., busy tones.

- **Control Channel Design:** As discussed in the previous section, the CCs can be divided into two groups. Similarly, CR MAC protocols adopt the same classification, depending on which implementation of CC they are using. CR MAC protocols can be classified as i) having a non-sequenced assigned CC, using a dedicated CCC, a dynamically configurable

CC or a split phase CC, or ii) adopting a sequenced assigned CC, if the hopping-based CC implementation is adopted.

- **Medium Access Schemes:** CR MAC protocols are also classified based on the access scheme adopted by the MAC protocol: random access, time slotted or hybrid. Random access CR MAC protocols do not need time synchronization, and are generally based on the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) principle [Tan03]. In this case, SUs monitor the spectrum searching for others SU transmissions, and transmit after a backoff period to prevent collisions. Time slotted CR MAC protocols need network synchronization and the time is divided into slots for both control and data channels. Time synchronization is considered i) global, if the periods of data transmission, channel negotiation and channel sensing are predefined and known to all SUs in the network; or ii) local, if the synchronization is just limited to neighboring SUs. Finally, hybrid CR MAC protocols apply a mix of the previous approaches: the CC is usually slotted, demanding for a synchronized access, while the data exchange does not requires time synchronization, because random access schemes are used.

- **Network Optimization:** CR MAC protocols can also be classified according to their concern about the network optimization. They can be classified as Dynamic Spectrum Allocation (DSAllloc) MAC protocols if complex optimization algorithms (e.g. graph theory, stochastic, game theoretic, genetic, etc.) are used to achieve a global efficient exploration of the available resources; or they can be classified as Direct Access Based (DAB) MAC protocols where no global network optimization is applied and each sender-receiver pair only tries to optimize its own goal. DAB MAC protocols can also be divided into two general groups: i) contention based protocols, where the sensing information is only shared between the sender and the receiver and ii) coordination based protocols, where each SU always shares its sensing information with their neighbors, improving the system overall performance.

Figure 2.2 illustrates a CR MAC protocol classification tree based on some of the features previously discussed.

2.3.2.1 Infrastructured CR MAC Protocols

In 2005 *Buddhikot et al.* proposed a centralized spectrum leasing scheme, the Dynamic Intelligent Management Spectrum for Ubiquitous Mobile-access Network (DIMSUMnet) architecture [Bud+05]. This scheme leases the channels from the range of the PUs' spectrum, which may include idle channels allocated to cellular communication systems or TV spectrum.

The architecture of DIMSUMnet is composed by four components: a) the spectrum information and management broker, responsible for constructing a geographical map of the spectrum allocation; b) the radio access network, consisting of a set of BSs; c) the radio access network manager, responsible for authenticating the spectrum access requests made by the SUs, and also for controlling the power, load, price and lease stipulations of the SUs on network operations; d) and the SU devices, that may optionally contain a spectrum-sensing component which periodically measures

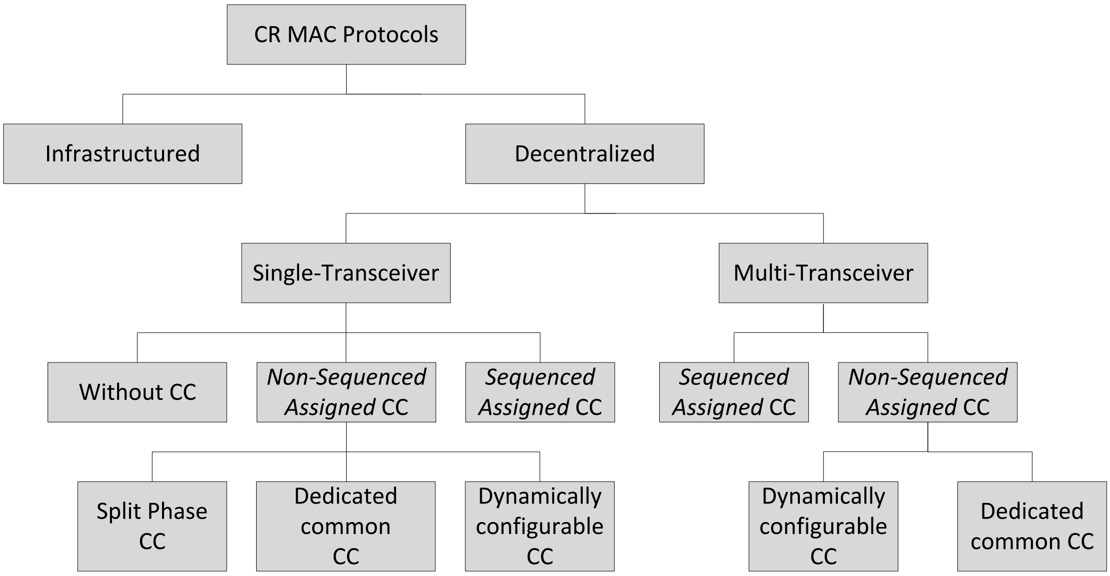


Figure 2.2: A CR MAC protocol classification tree.

the spectrum activity and communicates this information to BSs. The DIMSUMnet architecture sets up two sub-MAC protocols to be used during the negotiation phase. The first one operates between the spectrum information and management broker, the radio access network manager and BSs, while the second is used between the BS and the SU devices. Therefore, the BS work as a mediator between the SU devices and the spectrum information and management broker, and it can also apply for spectrum lease and may in turn lease spectrum to the SUs.

Later, in 2008, two other infrastructured CR MAC protocols were presented: the CSMA MAC scheme and the DSA-Driven MAC protocol. The CSMA MAC scheme, proposed by *Lien et al.*, is a CSMA based protocol for single-transceiver architectures that uses in-band signaling [Lie+08]. The CSMA MAC protocol considers that the CRN is composed by a BS and multiple SUs that attempt to transmit packets to the BS. The proposed protocol ensures the coexistence among SUs and the PUs by adapting the transmission power and rate of the CRN, *i.e.*, as long as the interference caused to PUs is contained within a predefined threshold. This adaptation is based on the distance of each SU from the CR BS and the noise power. The CSMA MAC protocol has the advantage of considering coexistence between PRNs and CRNs. However, the coexistence is based on some interaction between both networks and the transmission power for the SUs is only partitioned into two levels (high and low), which may not be sufficient to protect all PUs due to possible changes in the PRN topology.

Zou and Chigan proposed the DSA-Driven MAC, a centralized game theoretic DSA based CR MAC protocol [ZC08]. The proposed scheme adopts an hybrid medium access scheme because the data exchange occurs in pre-determined time slots, while the control signalling is transmitted by a random access scheme. It is considered infrastructured because the CRN is organized in different clusters and the game policy in each cluster is managed by a unique central unit that belongs to the cluster, solving the eventual scalability and time synchronization problems that appear when the game is played flat (by the all CRN in a non-clustered way). However, this infrastructured CR MAC proposal does not take into account several details. The first one is that the time and the number of negotiation iterations taken to converge to the Nash equilibrium may become too large, depending on the size of the cluster and on the payoff of each utility function. A too long negotiation mechanism could not be reliable in CRNs since the spectrum may become occupied at anytime. Also, the proposal faces several scalable issues since the negotiation delay increases with the number of SUs. This situation could be fixed by decreasing the number of SUs by cluster, but then, the number of clusters will increase, increasing the amount of busy tones in the CRN.

2.3.2.2 Decentralized CR MAC Protocols

Based on the classification presented in Figure 2.2, decentralized CR MAC protocols can be divided according to the number of transceivers per device. Single-transceiver CR MAC protocols are more vulnerable to the Multi Hidden Channel Problem since a SU equipped with a single transceiver can only listen a channel at any time. Therefore, the SU can miss control messages when its transceiver is busy transmitting or receiving data. Moreover, single-transceiver CR MAC protocols present a smaller theoretical channel utilization when compared to multi-transceiver CR MAC protocols. On the other hand, multi-transceiver CR MAC protocols can listen to both data and control messages simultaneously. However, the multi-radio architecture is more expensive and computationally complex.

Single-transceiver CR MAC Protocols

Besides the amount of existing transceivers, CR MAC protocols can also be classified depending on how SUs exchange control messages for channel negotiation and coordination. Distributed CR MAC protocols using a CC can be divided into two major groups: sequenced assigned CC and non-sequenced assigned CC. The protocols with a sequenced assigned CC, as is the case in [Hou+11] and [Wil+08], adopt pre-defined channel hopping patterns, solving some of the challenges imposed by the non-sequenced assigned CC approaches: CC saturation and higher probability of CC interruption. However, it is also possible to develop CR MAC protocols without using a CC (e.g. [Zha+07a]), which is described below.

Zhao et. al [Zha+07a] proposed in 2007 the Decentralized Cognitive MAC (DC-MAC) protocol, a CR MAC protocol without requiring a CC. As previously discussed, SUs with single transceiver have a limited observation of the radio spectrum. Based on this fact, the authors proposed a channel sensing/access policy which considers the partial knowledge of the licensed channels state at SUs. DC-MAC's spectrum sensing/access policy is based on the theory of Partially Observed Markov Decision Process (POMDP), which is a generalization of a Markov decision process [Bel57] where traffic characteristics of the PUs are represented as a Markov chain. DC-MAC integrates the design of spectrum access protocols at the MAC sublayer, with spectrum sensing at the PHY layer and traffic statistics determined by the application layer. Two main issues are addressed: a) joint consideration of the spectrum sensing and spectrum access issues, like sensing or access errors, and

b) transmitter-receiver synchronization without requiring a CC.

In DC-MAC the time frame is divided into slots and, at the beginning of each slot, each SU chooses a set of spectrum bands to sense and another set of bands for transmission. Those lists are formed throughout an optimization process based on the following objective: maximize the throughput of SUs while i) limiting the interference to the PUs, and ii) exploiting the past history of the spectrum band. For that, each SU maintains a list of all channels already sensed, denoted as a *belief* vector. In the end of each slot, the *belief* vector is updated with the probability of each channel to become idle or busy in the next slot, based on the previous observations. At this point, the authors assume that all the neighboring SUs have the same view of the channel, and then, they will have a similar *belief* vector. Based on this assumption, the sender will continuously visit the channels where the intended receiver is expected to be tuned with higher probability, *i.e.*, the channels listed in the *belief* vector with higher idle state probability.

DC-MAC protocol is one of the few opportunistic MAC protocols that include sensing and access errors in its design. However, the implementation of the DC-MAC protocol is limited by the assumption that the transition probabilities representing the channel state transitions of the Markov channel model are known.

Difference-Set-based asynchronous Multichannel MAC (DSMMAC) protocol and the Double Hopping (DH) scheme are examples of single-transceiver CR MAC protocols using a CC in a sequenced assigned manner. The DSMMAC protocol, proposed by *Hou et al.*[Hou+11], takes advantage of the unique rotation closure property of difference sets, which enables any two SUs to communicate with a nonzero probability without global synchronization. By combining multiple disjoint difference sets and adopting the same difference-set-based hopping sequence, two SUs will be able to meet within a certain probability, even without synchronization. When a SU joins the network, it randomly selects an initial channel and attempts to access the channel by starting a handshake process. If the transmitter-receiver pair successfully exchanges the handshake information, the pair stops hopping and starts the transmission over the same channel. DSMMAC allows multiple transmitter-receiver SUs to simultaneously rendezvous and communicate over different channels[3] without a centralized coordinator, which significantly improves the channel utilization. By using the same hopping sequence, DSMMAC reduces the signaling overhead, because there is no need for exchanging the hopping sequence, and all the available channels can be used for data transmission.

The key feature of the sequenced assigned CR MAC protocols is the hopping pattern adopted by the SUs: it allows continuous control/data transmission between PUs and simultaneously tries to assure unimpaired operation of PUs. *Willkomm et al.* [Wil+08] proposed a different hopping approach for Dynamic Frequency Hopping (DFH) in CRNs. Double Hopping (DH) is a clustering DFH scheme that proposes a distributed algorithm to generate a hopping pattern that minimizes the number of used frequencies. However, in some situations, the DFH scheme may select a large number of channels for channel hopping, becoming more difficult to guarantee a desirable level of QoS to SUs.

[3] Channel orthogonality is assumed.

Finally, we approach single-transceiver CR MAC protocols adopting a non-sequenced assigned CC. The behavior of these protocols is based on the assumption that the common CC is always in the same band/frequency. There is however an exception. Using the dynamically configurable CC approach, SUs have the possibility to negotiate a new CC, which is different from hopping following a predefined sequence: in this case the change of CC only happens exclusively because the previous one has been occupied by licensed users. Otherwise, SUs will always use the same common CC. As aforementioned, CR MAC protocols with a non-sequenced assigned CC can be divided into three categories: split-phase CC (e.g. [Che+11; Ma+07]), dynamically configurable CC (e.g. [Zha+05]) and dedicated common CC (e.g. [Jha+11a; Jia+08; TL11]).

Ma et al. [Ma+07] designed the Single-Radio Adaptive Channel (SRAC) algorithm that adaptively combines spectrum bands based on the requirements of each SU. For that, the SRAC algorithm, a random access based protocol, bases its operation on three key features: a) adaptive discrete channelization, b) cross-channel communication and c) as-needed use of spectrum. The adaptive discrete channelization is a tradeoff between performance and practicality because it assumes that any piece of spectrum is a permissible channel, meaning that spectrum can be channelized with essentially arbitrary values for carrier frequency and bandwidth. The idea behind the cross-channel communication is that a SU can transmit on any channel but it can only receive on a unused channel, called *receive channel*. This way, two SUs are able to communicate when there are multiple jamming sources and there is no common idle spectrum between the sender and the receiver. The information about available *receive channels* is delivered using the Automatic Repeat reQuest (ARQ) mechanism to guarantee that the information is received by all the neighbors. Finally, the use-as-needed spectrum usage policy guarantees that each SU should keep the same receiving channel unless required by its own needs, *i.e.*, to avoid jamming and PUs, or to provide more capacity in response to high channel load. Using this feature, the SRAC algorithm keeps the number of used channels low for a better multi-hop support.

Later, in 2011, *Chen et al.* [Che+11] proposed two new distinct medium access schemes to deal with the packet scheduling in a single-transceiver CRN considering a split-phase CC: the *slotted* Cognitive Radio ALOHA (CR-ALOHA) and the Cognitive Radio-based Carrier-Sensing Multiple Access (CR-CSMA). The *slotted* CR-ALOHA is developed from the conventional slotted ALOHA [Tan03], which differs in the discrete channel access time and the constraint of protecting the primary network. The authors assume that, for each frame, the data transmission duration is slotted, and the slot size is equal to the length of a fixed packet transmission time together with the propagation delay. By this way, in each frame duration slot, more than one SU can compete for channel access which reduces the waiting time. As illustrated in Figure 2.3, the *slotted* CR-ALOHA operates as follows:

- If a SU detects that the channel is available in the current frame, any packet arriving in the last slot of the previous frame will be transmitted in the first slot of the current frame; otherwise, if the packet arrives in the nth remaining slots, it will start to transmit the packet at the beginning of the $(n+1)$th slot;

- If the channel is unavailable, any packet arrival within this frame up to the next-to-last slot will be blocked to the end of this frame, and then uniformly retransmitted with a backoff window;

- The current transmission is successful when there is only one packet that was transmitted; otherwise a collision occurs, and the packets involved will be retransmitted using non-related random delays to avoid continuously repeated conflicts;

- Finally, any arrival in the last slot of one frame will be processed in the next frame.

It is know that the conventional slotted ALOHA protocol presents a maximum throughput of around 0.368. However, with this approach the authors show that the maximum throughput achieved by the *slotted* CR-ALOHA underperforms the traditional one, since the presence of PUs increases the number of collisions.

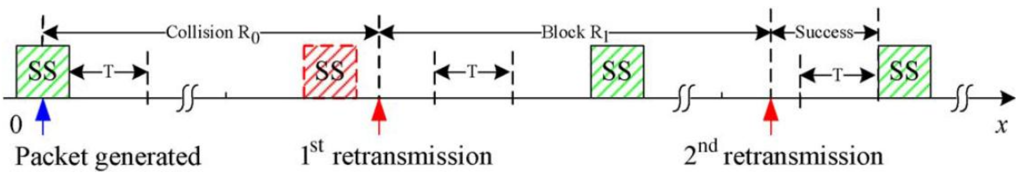


Figure 2.3: Frame structure of the *slotted* CR-ALOHA MAC protocol [Che+11].

In CR-CSMA the authors assume that the data transmission duration of each frame is now divided into minislots having a similar duration to the slot time used in the Institute of Electrical and Electronics Engineering (IEEE) 802.11 Distributed Coordination Function (DCF) (20 μs). The concepts of slot and minislot are different due to the different schemes' behavior. CR-CSMA requires that each packet must be transmitted at the beginning of the next minislot. The details of CR-CSMA are illustrated in Figure 2.4 and can be described as follows:

- If a SU detects that the spectrum is free from PUs during the current frame, any arrival during the last mininslot of the previous frame will be transmitted in the first minislot; otherwise, if it arrives in the nth remaining minislots, the following conditions hold: a) if the channel is idle, it will be transmitted at the beginning of the next minislot; b) if the channel is busy, SU keeps sensing until the channel becomes idle again and then tries to transmit;

- If a SU detects that a PU is active, any arrival within the current frame up to the next-to-last minislot will be blocked until the end of this frame, and then, the SU chooses a uniformly distributed backoff time to retransmit;

- Again, the current transmissions will be successful if there are no other packets being transmitted at the same time; otherwise, the transmission fails and the packet will be retransmitted after a random delay to avoid repeated conflicts;

- Finally, any packet arriving during the last frame's minislot must wait to be processed in the next frame.

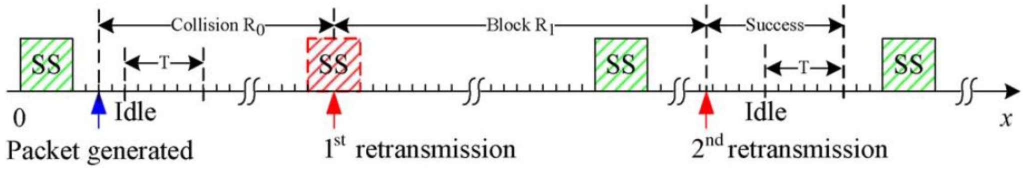


Figure 2.4: Frame structure of the slotted CR-CSMA MAC protocol [Che+11].

The difference between *slotted* CR-ALOHA and CR-CSMA is that: in *slotted* CR-ALOHA SUs transmit only from the beginning of a slot, and so they do not have to keep sensing the channel until the end of the frame. On the other hand, under CR-CSMA SUs become more aggressive, because they keep sensing until the channel becomes idle. The performance comparison presented by the authors for the same sensing time conclude that CR-CSMA always outperforms CR-ALOHA in terms of throughput and delay. The performance gain is due to a more efficient packet scheduling scheme where the packets suffer a lower transmitting service time.

The Heterogeneous Distributed MAC (HD-MAC) protocol is an example of a single-transceiver CR MAC protocol with a dynamically configurable CC. The HD-MAC [Zha+05] presents a new channel selection metric that jointly considers traffic load, connectivity and interference (latter denominated as *score*), and where neighbor SUs self organize in local groups where coordination is handled through a local CC. This local CC, here denoted as coordination channel, is dynamically configured depending on the channel availability within each group. The MAC structure is organized in super-frames consisting in a beacon period (used for neighboring discovery), a coordination window and a data transmission period. During the coordination window period, SUs hop to the coordination channel to manage channels negotiation. The access is made according to the CSMA/CA protocol.

The data channel negotiation is as follows: i) transmitter i sends a channel request message to receiver j including its queue size, related to SU j, and a channel information message related to its available channel list; ii) after receiving the channel request message, SU j combines the channel *score* of both nodes and selects the common channel between both SUs with the lower *score* value; iii) the selected channel is sent back to SU i in a channel respond message, together with the volume of pending packets; iv) upon receiving the channel respond message, SU i sends a channel confirmation message to SU j, including the length of the pending packets. Neighbor SUs which overhear the confirmation and respond messages obtain traffic information and update the channel interference accordingly.

HD-MAC allows SUs to use previous data channels without a so complex negotiation: if SUs i and j have marked the channel as "outstanding", for the next data transmissions both SUs will spend less time in the negotiation phase, assuming that the same channel *score* has not been changed. The HD-MAC however presents a moderate reconfiguration, control and communication overheads due to the negotiation mechanism. It also requires tight synchronization among SUs.

Time synchronization becomes an important feature for CR MAC protocols with single-transceiver and dedicated common CC. In this situation SUs can not remain tuned to the common CC when they are transmitting. Then, time synchronization among SUs is needed to make sure that

SUs know when they have to tune to the common CC for control messages exchange and when they can resume data transmissions. Time synchronization can be achieved through either local (e.g. [Jia+08]) or global (e.g. [Jha+11a] and [TL11]) synchronization.

Jha et al. [Jha+11a] proposed the Opportunistic Multichannel Cognitive-MAC (OMC-MAC) protocol for single-transceiver CRNs where a dedicated global common CC is assumed. The OMC-MAC time frame is divided into beacon intervals used by the SUs for synchronizing purposes. Additionally, the beacon interval is divided into three phases: sensing, contention and data transmission.

During the sensing period, SUs are not allowed to transmit and therefore, the sensing result is free from interference from other SUs. Each SU senses the channel independently and maintains a list of available channels at the end of the sensing phase. During the contention phase, each SU that has data to send contends for the common CC to participate in a channel negotiation. The contention is based on a contention backoff similar to IEEE 802.11 DCF. Using a three-way handshake (Ready-To-Send (RTS)/Clear-To-Send (CTS)/Confirmed-RTS (CRTS)) mechanism with the information about the negotiated data channel, OMC-MAC guarantees that other SUs will set some kind of Network Allocation Vector (NAV) to remind that channel can not be used until the end of the time-frame. This solution effectively addresses the Multi Hidden Channel Problem because all SUs are tuned into the common CC during the negotiation phase. During the data transmission phase, data messages are exchanged without the need for a contention because the channels are already reserved.

The results presented by the authors show that the OMC-MAC is highly robust in decreasing the effect of sensing error on PUs. The results also show that OMC-MAC effectively avoids collision among SUs during the data transmission phase in order to efficiently utilize the opportunistically available licensed frequencies.

Tan and Le [TL11] proposed a distributed synchronized MAC protocol for CRNs incorporating spectrum-sensing operations. In fact they have proposed two CR MAC protocols, one for single-channel and other for multichannel. Regarding the single-channel approach, the time-frame is divided into three phases: the sensing phase, the synchronization phase and the data transmission phase. During the sensing phase, all SUs perform spectrum sensing on the underlying channel. Since all SUs are assumed to be synchronized, the sensing results will only reflect the activity of the PUs. Then, only SUs whose sensing outcomes indicate an available channel proceed to the next phase (denoted as active SUs). In the synchronization phase, active SUs broadcast beacon messages for synchronization purposes. In the third phase, active SUs perform channel contention, using a backoff mechanism, and the wining SU can finally transmit the data during this last phase. All these phases occur in the same channel.

The multichannel CR MAC protocol proposed by the authors is somehow similar to the previous one (single-channel). However, in this case, there is one dedicated global common CC assumed to be always available, and several data channels owned by PUs with the possibility of being explored by SUs. Each SU is equipped with only one transceiver that can be tuned to the CC or vacant data channels. In the multichannel approach the time-frame is divided into four phases. In the sensing phase, all SUs perform spectrum sensing in all underlying channels. During the synchronization phase, all SUs tune to the common CC to exchange beacons to achieve synchronization. To participate in the data transmission phase, SUs must have at least one sensed free data channel. Then, SUs will compete for the common CC using a backoff mechanism, and the winning SU, using a two-way handshake (RTS/CTS) will negotiate with the receiver about the data channels to use. In the end of the transmission, the receiver will confirm the data transmission using an ACKnowledgment packet (ACK) message.

The Hardware-Constrained MAC [Jia+08] protocol is quite different from the previous ones because it does not requires for a global synchronization, which means that there are synchronization only among neighboring SUs. However the main characteristic of HC-MAC protocol is that it tries to perform efficient spectrum sensing and spectrum access by considering several hardware constraints, such as, the aforementioned operational limitations of a single-transceiver, partial spectrum sensing and spectrum aggregation limits. Hardware constraints can be divided into two categories: sensing constraints, concerned with the tradeoff between the time taken for sensing and the resulting accuracy, and transmission constraints, related to the limitations posed by the Orthogonal Frequency Division Multiplexing (OFDM) technique that decides the bandwidth range, as well as the maximum allowed number of subcarriers.

One of the main contribution of HC-MAC is the sensing decision adopted by the SU. Limited by the hardware constraints of a single-transceiver, each SU must use an appropriate stopping rule for successive channel sensing. By choosing a greater number of channels, the available bandwidth increases, leading to a higher data rate. However, the cost of sensing, especially if the channel is found to be occupied must be also considered. So the goal is to find an optimal stopping rule such that the reward is maximized.

The HC-MAC operation mode is divided into three phases, however in this case, the contention phase happens before the sensing phase. The last phase is reserved for data transmission. In the contention phase, C-RTS and C-CTS packets are sent over the common CC to gain access to the channel. The winning sender-receiver pair conducts sensing in each channel and exchange S-RTS and S-CTS on the common CC if that channel is available for both slides, *i.e.*, one set of S-RTS/S-CTS packet for each channel. The end of the sensing round is decided by a stopping rule, and any common free data channel can be used. At the end of the transmission T-RTS and T-CTS messages are exchanged on the common CC, releasing the channel for other SUs. The major drawbacks of HC-MAC are: the high number of control messages that may saturate the common CC earlier, when compared to *classical* RTS-CTS based CR MAC protocols; the fact that remaining unused channels are not used by other SUs until the current transmission is ended, leading to inefficient spectrum utilization; and the Multi Channel Hidden Terminal Problem caused by the absence of a global synchronization together with a single-radio architecture.

Multi-transceiver CR MAC Protocols

Multi-transceiver CR MAC protocols, can also be divided into two categories depending on how the CC is implemented. [KA08] is an example of a multi-transceiver CR MAC protocol that adopts a sequenced assigned CC. On the other hand we have CR MAC protocols with a non-sequenced assigned CC that can assume a dedicated common CC (e.g. [Sal+09] and [Tim+10]) or a dynamically configurable CC (e.g. [Ma+05]). A common problem with MAC protocols that use dynamically configured CCs is the interruption of their MAC operations. These interruptions can occur quite frequently since the PU network can reclaim the CC at any time. Moreover, DCRNs do not have central support to gather the topology information and hence rely on local coordination. The existence of a dedicated common CC makes it much easier to gather topology information compared to the case of DCRNs with dynamically configurable CCs. However, the majority of the CR MAC protocols with dedicated common CCs assume that the CC is always available.

Kondareddy and Agrawal [KA08] proposed in 2008 a Synchronized MAC protocol for multi-hop CRNs, the SYN-MAC, which avoids the exploitation of a dedicated CC. Each SU is equipped with two radios, one dedicated to control signal exchange and the other for data transmission. In SYN-MAC the time is divided into time slots and each slot represents a data channel. Then, the control signal exchange occurs in the channels represented by the slots, while data transfer can occur in any channel that is found idle for both sender and receiver. It means that the control signaling is similar to slow frequency hopping. During the network initialization state, at the beginning of each time slot, SUs broadcast a beacon in all available channels to exchange information about the list of available channels and to synchronize their radios. The channel advertisement technique adopted by the SYN-MAC avoids the multichannel hidden terminal problem and keep track of primary user's presence. Interested SUs answer with their own list of available channels, and further communications will be made in one of those selected channels.

When a SU wants to transfer data, it first chooses one of the channels being shared with the receiver. Then it waits for the time slot representing the selected channel, and starts a negotiation process using a backoff mechanism similar to IEEE 802.11 DCF. If it wins the contention then it starts the data exchange in that channel. SYN-MAC protocol has the advantage of not using a dedicated common CC, and due to the dedicated listening is also able to avoid the multichannel hidden terminal problem. However, this protocol does not offer fast protection of PUs since their detection is notified to neighbors only in specific slots.

In 2009, *Salameh et al.* [Sal+09] proposed a contention based CR and asynchronous MAC protocol that tries to satisfy QoS constraints by limiting the number of used channels per SU. The COgnititive MAC (COMAC) assumes that SUs are equipped with two or more transceivers, in which one of them is tuned in an always available CC, that can be dedicated to the CRN or in the unlicensed ISM band. The COMAC exploits the underlay spectrum access, *i.e.* it allows SUs to use the licensed band while limiting the generated interference to PUs. Each SU determines the maximum transmission power over various channels such that the PU receiver outage probability is kept below a predefined value. For that, a stochastic model is proposed to represent the aggregate interference within the PRN and for the primary to secondary interference.

Regarding the COMAC data channel negotiation, each SU maintains a list of its locally available channels, which is the set of channels that are not being used by any of its neighbors. This list is continuously updated through the exchange of control packets. When two SUs want to communicate, the pair exchanges their lists of channels over the CC, and the intended receiver selects the channels to support the communication according to the spectrum state information, the maximum allowable transmission power for channel and the requested data rate. According to these parameters, when the receiver gets the sender's RTS packet it will compare the sender list with its own, and selects the common available channels. Then, the common available channels whose received Signal to Interference plus Noise Ratio (SINR) are below a fixed threshold are removed from the list, and the remaining channels are sorted in descending order of their data rate. Finally, selected channels are chosen from the sorted list until the request data rate is satisfied or the list is exhausted.

While COMAC permits parallel transmissions to take place in the same neighborhood, the multichannel hidden terminal problem is not completely solved due to possible collisions on the common CC within neighbors SUs transmissions. Furthermore, as previously mentioned, the interference temperature implementation typically results in poor performance, leading the authorities (FCC) to lay down this concept.

Later, in 2010, *Timmers et al.* [Tim+10] presented the MMAC-CR, an energy-efficient distributed multichannel MAC protocol for CR networks considering a non-sequenced assigned dedicated common CC. By allowing the SUs to enter a dozen state when no communication is taking place, the MMAC-CR protocol achieves energy-efficient communication. Furthermore, the MMAC-CR also presents a two-stage sensing algorithm: i) a low-power inaccurate scan and ii) a high-power accurate scan. By using the low-power scan for periodically scheduled scans and only using the accurate scan when the low-power scan detects a change, the sensing algorithm also achieves energy-efficient operation. MMAC-CR uses a dedicated CCC free of PUs to perform network synchronization and common information exchange.

Besides the energy consumption awareness, the other contribution of this proposal is its evaluation using realistic power models of the SDR: the benefits of MMAC-CR are presented in a more realistic setting compared to other proposals. However, MMAC-CR reliability strongly depends on the quality of the CC, mainly during the procedure of sharing the sensing results.

In 2011 *Zhang and Su* [ZS11] proposed the Cognitive Radio-EnAbled Multichannel MAC (CREAM-MAC), a CR PHY-MAC framework that integrates the cooperative sequential spectrum sensing at PHY layer and packet scheduling at MAC sublayer over the wireless DSA networks. The CREAM-MAC protocol employs a CCC as the rendezvous channel where SUs can exchange the control packets for data channel communication: the authors state that the CCC can be either dedicated (located in the ISM band) or dynamically configurable. Under the CREAM-MAC protocol, each SU is equipped with a single half-duplex transceiver and multiple sensors. These sensors are only used to perform spectrum sensing.

It is also important to notice that, this recent protocol, continues to consider the interference temperature limit by allowing SUs to transmit even with the presence of PUs, keeping the level of interference to a minimum tolerable. For that, each SU transmission can not exceed the maximum tolerable interference period which is computed based on the assumption that the activity of PUs is modeled as an ON/OFF model, with birth and death rates following exponential distributions. Regarding the data channel negotiation, the CREAM-MAC protocol uses two pairs of control packets, exchanged in the dedicated CCC: the already and often referred RTS/CTS and the Channel-State-Transmitter (CTS)/Channel-State-Receiver (CSR). The first pair is exchanged, after a period of contention, for control channel reservation and to solve the hidden terminal problem. The second pair aims to synchronize the vacant channel information between sender and receiver, by exchanging their lists of available channels. Once the negotiation is complete, sender and receiver can exploit all the common available free data channels.

The CREAM-MAC protocol is presented with an extensive theoretical analysis about its performance under two distinct scenarios: with and without saturated traffic conditions, which has a strong influence in the performance of the dedicated CCC. In the saturated network scenario, the CREAM-MAC protocol throughput increases as the number of sensors also increases. However, there is a point when the number of free channels is so high that the number of control packets will also be too high for the capacity of the CCC, resulting in a saturated dedicated CCC.

Finally, it is worth to refer the Dynamic Open Spectrum Sharing (DOSS) MAC protocol, a multi-transceiver MAC protocol considering a dynamically configurable CC that requires three transceivers: one for monitoring the dynamically configurable CC, a second one to communicate in the data channels and a third one to transmit busy tones. The DOSS protocol [Ma+05] applies the concept of using busy tones to tackle the multichannel hidden terminal problem: it exclusively allocates a narrow band for the busy tones and, for each used data channel a busy tone will be transmitted in the frequency band associated with that channel. The DOSS protocol consists of five steps: a) PU's detection, b) setting-up three frequency band/channels (data communication, monitoring and signaling), c) spectrum mapping, d) spectrum negotiation, and e) data transfer.

The DOSS scheme uses the concept of receiver initiated busy tones to mitigate the hidden and exposed multichannel terminal problems. However, several complications can arise when the busy tones come under the influence of PUs. For instance, a data channel might be available but its corresponding busy tone may become temporarily occupied by a PU. Besides, the device cost and complexity is increased due to the use of three transceivers.

Table 2.1 gives a comparison of the aforementioned decentralized CR MAC protocols according to the following characteristics: number of transceivers, CC configuration and CC implementation. From the table we can see that most of the protocols were designed to operate with a single transceiver, reducing the implementation cost. We can also see that a large number of MAC schemes requires a dedicated channel to exchange control information, which is usually implemented in the unlicensed band, free from primary activity. However, there are also some proposals exchanging control messages in the same channel that is used for data exchange, therefore overcoming the impossibility of implementing a dedicated CC.

2.4 CR PHY-MAC Standards

Although CR is still an emerging technology, a few standardization initiatives have already been approved to regulate its use. The first CR standards were designed to exploit the analogue TV White Spaces (TVWSs) originated by the appearance of modern digital TV systems, as is the case of IEEE 802.22 and IEEE 802.11af. Other proposals try to explore unused satellite frequency bands, which include IEEE 802.11y and IEEE 802.11h protocols, or even to facilitate the coexistence of different wireless technologies, e.g. IEEE 802.16h.

Table 2.1: Characteristics of decentralized CR MAC protocols.

	Number of Transceivers	CC Configuration	CC Implementation
DC-MAC [Zha+07a]	1	Without CC	—
DSMMAC [Hou+11]	1	Sequenced Assigned	—
DH [Wil+08]	1	Sequenced Assigned	—
SRAC [Ma+07]	1	Non-Sequenced Assigned	Split-Phase
CR-ALOHA [Che+11]	1	Non-Sequenced Assigned	Split-Phase
CR-CSMA [Che+11]	1	Non-Sequenced Assigned	Split-phase
HD-MAC [Zha+05]	1	Non-Sequenced Assigned	Dynamically Configurable
OMC-MAC [Jha+11a]	1	Non-Sequenced Assigned	Dedicated
Tan et al. [TL11]	1	Non-Sequenced Assigned	Dedicated
HC-MAC [Jia+08]	1	Non-Sequenced Assigned	Dedicated
SYN-MAC [KA08]	2	Sequenced Assigned	—
COMAC [Sal+09]	≥ 2	Non-Sequenced Assigned	Dedicated
MMAC-CR [Tim+10]	2	Non-Sequenced Assigned	Dedicated
CREAM-MAC [ZS11]	≥ 2	Non-Sequenced Assigned	Dedicated
DOSS [Ma+05]	3	Non-Sequenced Assigned	Dynamically Configurable

2.4.1 IEEE 802.22

IEEE 802.22 [IEE11] was the first centralized CR PHY-MAC layer standard for Wireless Regional Area Networks (WRANs) developed to exploit vacant TV spectrum bands (UHF and VHF bands). IEEE 802.22 standard divides the CRN into cells, each one composed by a BS, covering an area of radius spanning from 17 km to 100 km, and several WRAN end users, here denoted as Customer Premise Equipments (CPEs). The IEEE 802.22 is designed to provide a data rate of around 22.69 Mb/s when a 6 MHz channel is considered. OFDM modulation is used to overcome possibly excessive delay [Ste+09]. In addition, the standard provides PU protection including spectrum sensing and geolocation database for PU-SU coexistence, and also supports self-coexistence between WRANs via the Coexistence Beacon Protocol (CBP).

The IEEE 802.22 standard specifies a time slotted operation, where each time-frame is denoted as superframe, as shown in Figure 2.5. The superframe is composed of multiple MAC frames preceded by the respective preamble. A preamble in the beginning of each superframe is used to synchronize the CPEs with the BS, followed by a Superframe Control Header (SCH) that is used to inform the SUs about the current available channels and supported bandwidths.

Each MAC frame comprises a DownStream (DS) frame and an UpStream (US) frame, as illustrated in Figure 2.6. The DS subframe contains a single packet burst from the BS, while the US subframe has multiple packets bursts, each one transmitted by different CPEs. The remaining fields have the following utility: in the DS subframe, the preamble deals with synchronization and channel estimation, the Frame Control Header (FCH) contains the size of the DS- and US-MAP fields, and the DS- and US-MAPs give the scheduling information for user bursts. In the US subframe, the Urgent Coexistence Situation (UCS) notification informs about recently detected PUs, while the

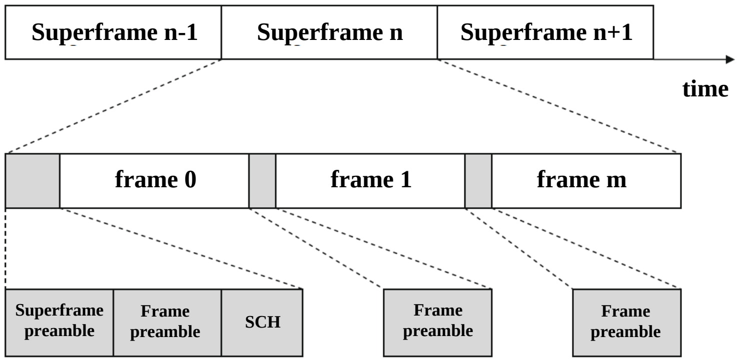


Figure 2.5: Superframe structure in IEEE 802.22.

other fields are used to derive the distance from the BS, and the individual bandwidth requests.

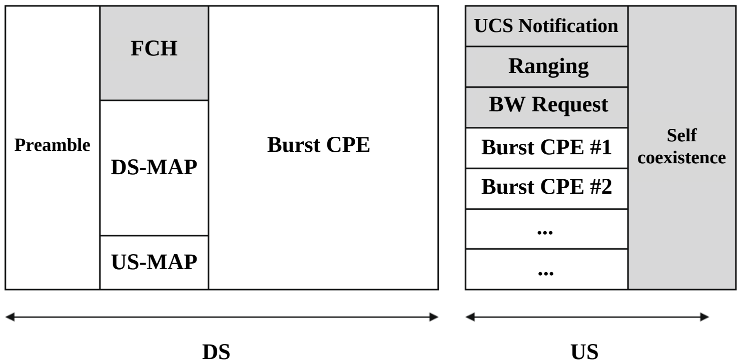


Figure 2.6: MAC frame structure in IEEE 802.22.

Regarding the protection to PUs and spectrum awareness, the IEEE 802.22 standard offers two methods to cope with these important tasks. In the first method, the knowledge of SUs location combined with a database of licensed transmitters can be used to determine which channels are locally available. This method is usually referred as geolocation/database. The other method, a Two-Stage Sensing (TSS) mechanism, consists of observing the spectrum to identify which channels are occupied by licensed transmissions, as shown in Figure 2.7. TSS's first stage, denominated Fast Sensing, is done at the rate of 1 $ms/channel$, and the sensing results are used to decide if a subsequent fine sensing stage is needed. This means that the sensing is completed quickly and with low accuracy. The second sensing stage, denoted as Fine Sensing, is performed on-demand at the rate of 25 $ms/channel$, which allows SUs to meet the strict QoS requirements by decreasing the rate of false alarm and misdetection. By using a distributed sensing mechanism, the BS delegates groups of CPEs to scan different channels, where the sensing information will be sent back to the BS.

Just like in the other CRNs, in the case of a PU appearance SUs will have to interrupt their communication and restart it in another channel. In order to minimize the effects of this interruption, the standard protocol offers a mechanism denoted as the Incumbent Detection Recovery Protocol (IDRP), that enables the CRN to restore normal operation with minimal performance degradation.

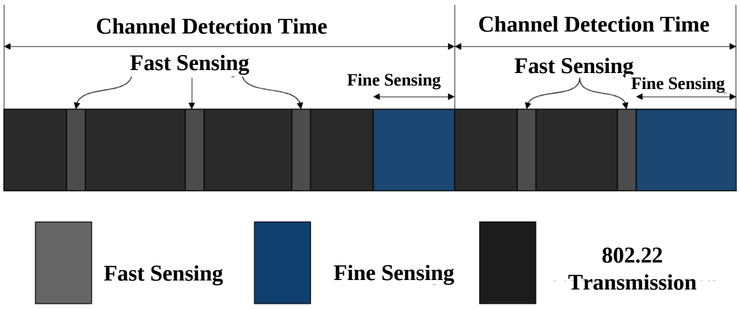


Figure 2.7: Two-stage Sensing (TSS) mechanism in IEEE 802.22.

In IDRP, backup channels are used to restore the communication in case a channel needs to be released after PU appearance. These channels, shared by the CPEs and BS, are kept in a list and used whenever a CPE looks for a BS during the recovery process.

IEEE 802.22 standard also allows the coexistence with other IEEE 802.22 CRNs through the Coexistence Beacon Protocol (CBP). The communication between cells is undertaken by the CBP beacons, which carry information about the cells and the DS/UP bandwidth allocations for the CPEs. These packets are exchanged using contention-based schemes during the periods labeled as self-coexistence windows, as illustrated in Figure 2.6.

2.4.2 IEEE 802.11af - *White-Fi*

IEEE presented in 2015 another standard to exploit the TVWSs in a more domestic scenario (personal and portable devices). The IEEE 802.11af, or White-Fi [KE10], adapts the current IEEE 802.11 standard [IEE12] to make use of the TVWSs, just like the IEEE 802.22, but considering a smaller transmission range (up to 1 km). The IEEE 802.11af network is formed by the following entities [Flo+13]:

- **Geolocation Database (GDB):** The GDB is a database that stores, by geographic location, the permissible frequencies and operating parameters for SUs to fulfill regulatory requirements. GDBs are authorized and administrated by regulatory authorities and therefore, a GDB's operation depends on the security and time requirements of the applied regulatory domain;

- **Registered Location Secure Server (RLSS):** This entity operates as a local database that contains the geographic location and operating parameters for a small number of Basic Service Sets (BSSs). The RLSS distributes the permitted operation parameters to the APs and Stations (STAs) within the BSSs under the RLSS's control;

- **GDD-enabling Station:** The Geolocation-Database-Dependent-enabling station is the equivalent of the entity commonly known as the AP. However, in the 802.11af standard this entity controls the operation of the STAs in its serving BSS. The GDD-enabling STA can securely access the GDB to attain the operating frequencies and parameters permitted in its coverage region. With this information the GDD-enabling STA has the authority to enable and control the operation of the STAs under its service, identified as GDD-dependent STAs. Specifically, the parameters obtained from the GDB are represented through a White Space Map (WSM). The GDD-enabling STA ensures the maintenance and distribution of a valid WSM;

- **GDD-dependent Station:** The GDD-dependent station can be identified as the SUs in the BSS architecture. However, the IEEE 802.11af standard specifies that the operation of the GDD-dependent STAs is controlled by the serving GDD-enabling STAs. The GDD-dependent STAs obtain the permitted operating frequencies and parameters in a form of a WSM from either the GDD-enabling STA or RLSS.

Regarding the communication between each entity, the IEEE 802.11af standard only defines the communication protocol between the GDD-dependent STAs, GDD-enabling STAs, and RLSS. Figure 2.8 illustrates two infrastructure BSSs containing all the entities of the *IEEE* 802.11af architecture previously described. As shown in Figure 2.8, the RLSS and GDD-enabling STAs obtain white space availability through the Internet. Within the 802.11af scope, the RLSS only communicates with the GDD-enabling STAs through infrastructure and operates bidirectionally. Finally, the GDD-dependent STAs perform bidirectional over-the-air communication with GDD-enabling STAs, within either the TVWS band or other ISM bands.

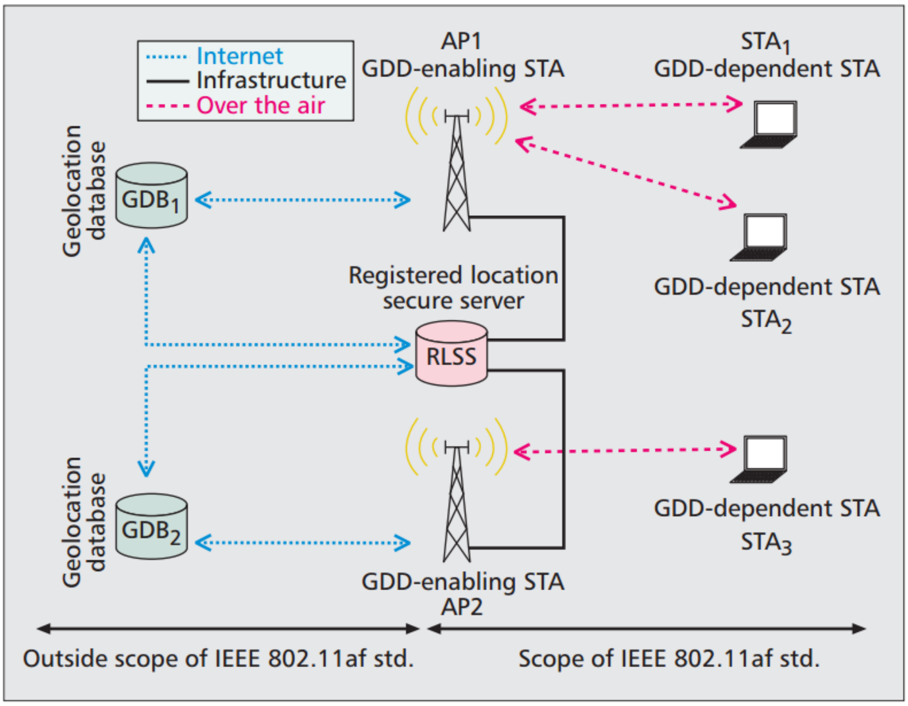


Figure 2.8: The IEEE 802.11af architecture [Flo+13].

The opportunistic spectrum access in the TVWS band is based on the regulatory requirement of non-interference to protected licensed devices. To avoid interfering with protected devices, a SU must be aware of the operating frequency and region of all protected devices. A SU has limited capabilities and sometimes it might be helpful to obtain this information from a regulated GDB. IEEE 802.11af implements two methods of operating with the GDB: an open-loop GDD and a closed-loop GDD. The open-loop GDD system is implemented by the FCC. Under this regulation, TVWS operation is allowed in 6 MHz channels within the frequencies 54–698 MHz in TV channels 2, 5, 6, 14–35, and 38–51. The STA follow an up to 48-hour schedule that provides the list of available channels in this time period, under which a static set of maximum transmit power rules are followed. Under this regulation SUs have a flexible operating region because they authenticate with the GDB once a day. However, fixed and conservative transmit power is required due to the large timescale of the feedback, leading to rigid or binary operation of channel availability. The main drawback to this approach is that, as a result of the rigid power regulation, a large part of the potential white space channels becomes unavailable, limiting white space implementation to rural areas and minimizing the development of spectrum-sharing technologies [Web12].

On the other hand, the closed-loop GDD system implemented by the 802.11af standard admits frequent interaction between the GDB and the SUs, allowing flexible operating parameters that apply to a specific device characteristics and location. The closed-loop GDD system is followed by the European (European Telecommunications Standards Institute (ETSI)) and United Kingdom (Ofcom) regulators. SUs are allowed to operate in 8 MHz channels within the frequencies 470–790 MHz [Flo+13]. Unlike the static parameter regulation of the open-loop system, the closed-loop approach has granular parameter regulations that apply to a specific device and location. This allows STAs to have flexible transmission power dependent on location, frequency, and time. This translates into higher average transmission power when the STA is at a greater distance from the incumbent user, and further apart in frequency to avoid adjacent channel interference.

2.4.3 IEEE 802.11h

IEEE 802.11h-2003, or just IEEE 802.11h, refers to the amendment to the IEEE 802.11 standard [IEE12] for Spectrum and Transmit Power Management Extensions[4]. The original purpose of IEEE 802.11h was to extend Wireless Local Area Network (WLAN) operation in Europe to the 5 GHz band, where WLAN devices (unlicensed users) need Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) to coexist with the primary users bands support-radar and satellite communication systems (licensed users) [Kon+05]. According to European regulations, when a WLAN device operating in the 5 GHz band detects a radar signal on its current operational frequency channel, it must switch to another channel. In a similar way, when a WLAN device detects a satellite signal, it must limit its transmit power to 3 dB below the regulatory maximum [Eur08; Wi-07]. To meet these requirements, IEEE 802.11h defines DFS and TPC mechanisms on top of IEEE 802.11a PHY and MAC layers.

An IEEE 802.11h WLAN uses DFS for dynamically switching the operational frequency channel. Besides fulfilling the regulatory requirements, the change in the operational frequency channel can also occur when the condition of its current channel becomes poor due to the interference from neighboring devices. In an infrastructured scenario, the BS determines when to switch and which channel to switch to. For that, the BS monitors the status of the current channel, and it might also request that other stations measure and report the status of the current channel, or also

[4] Actually integrated in the IEEE 802.11-2007 standard.

those at other frequencies. There are three types of measurements: a) the basic measurement that determines whether a non-802.11 OFDM signal, and unidentified signal, or a radar signal is using the measured channel; b) the Clear-Channel Assessment (CCA), that measures the fraction duration of the channel's busy period during the total measurement interval; and c) the Received Power Indication (RPI), responsible for measuring the histogram of the quantized measures of the received energy power levels seen at the antenna connector during the measurement interval. Based on these measurements, the BS decides if a new operational channel will be used.

The TPC mechanism was implemented to fulfill the following requirements: a) to improve the near-far problem[5]; b) to minimize interference to and from other cells/clusters; and c) to improve the system performance on fading channels, by compensating for fading dips, *i.e.*, samples with lower signal strength. The standard also specifies two TPC-related functions: i) the BS advertises the regulatory and local maximum-power level for the current frequency channel, by using TPC-Beacon/TPC-Probe beacons; ii) a reporting mechanism (TPC-Request/TPC-Report) to inform the BS about the power used to transmit the frame to the BS (TPC-Report), and also with the ratio of the received signal (TPC-Request) strength to the minimum desired by the station.

By using DFS and TPC mechanisms, it is possible to improve the performance of WLAN devices operating in the 5 GHz band in the Europe and simultaneously reduce the energy consumed by each terminal. By estimating the link quality between itself and the receiver, a terminal is able to determine the proper transmission power level, reducing the excessive energy wasted during its transmissions.

2.4.4 IEEE 802.11y

In 2005, FCC opened 3.65-3.7 GHz band, originally reserved for fixed satellite service networks, for public use. However, a regulatory policy was needed. Then, later in 2007, IEEE started to develop an amendment to the IEEE 802.11-2007 [IEE12] that enables high powered Wi-Fi terminals to operate on a co-primary basis in the 3.65-3.7 GHz band in the United States, except when near a grandfathered satellite earth station. This amendment was approved for publication in 2008, and it is known as IEEE 802.11y [IEE08] or "The US 3650 MHz rules".

This standard allows for registered station to operate at much high power than traditional Wi-Fi terminals (up to 20 W). Hence, by combining the increased power transmission with several new key elements and enhancements made to the IEEE 802.11-2007 MAC timing structure, it will be possible to develop IEEE 802.11 terminals operating in long transmission distances (5 km or more). As for the new key elements, IEEE 802.11y introduces two categories of stations:

- **Enabling Stations:** Enabling stations are high-powered fixed stations with authority to control when and how a dependent station can operate. An enabling station communicates an initial enabling signal to their dependent stations over the air, always including its location

[5] The near-far problem occurs when all terminals transmit at the same power level, and the strongest received signals, usually those emitted by closer terminals, will be captured by the receiver. Then, it is impossible to detect the weak signals transmitted by distant terminals. This problem is characteristic of CDMA networks because all the transmitters share the same frequencies and transmission times [Tor05].

information. The GPS coordinates and altitude information of each enabling station are also registered in a public database to avoid interference with other enabling stations.

- **Dependent Stations:** Dependent stations are devices in the network that are not registered, but instead receive authorization to transmit from a registered enabling station. If a dependent station does not receive the periodic enabling beacons, it should suspend its transmission until it is re-enabled. A dependent station may be fixed or mobile.

Regarding the new enhancements introduced in the standard, IEEE 802.11y adds three concepts to the 802.11-2007 standard:

- **Dynamic Station Enablement (DSE):** Dynamic Station Enablement is the process by which an enabling station grants permission and dictates operational procedures to dependent stations. Beyond addressing the regulatory requirements for the 3.65 GHz frequency band, DSE offers other channel management and coordination benefits: for example, since the enabling station is not required to serve as the BS for each of its dependent stations, DSE can reduce the likelihood of a dependent station contributing to radio interference by allowing the dependent station to complete the enablement process via a geographically closer BS.

- **Contention Based Protocol Incorporating Regulatory Class Information:** Enhancements have been made to the carrier sensing and energy detection mechanisms of IEEE 802.11 in order to meet the FCC's definition of a contention based protocol: IEEE 802.11y devices can sense both IEEE 802.11 and non-802.11 devices and identify available spectrum as small as 5 MHz. Also, IEEE 802.11y BSs' beacons identify the country and the regulatory domain for their physical location. By incorporating both channel use and regulatory class information, IEEE 802.11y devices can identify available channels and adjust operating parameters to the laws of the country in which the access point resides.

- **Extended Channel Switch Announcement (ECSA):** ECSA is used to coordinate a move from one channel to another with less contention or to change channel bandwidth. Specifically, an enabling station can identify the channel with the least aggregate interference to all of the stations that are connected to it on a completely dynamic basis. This capability ensures the best SNR at lower power levels conditions.

2.4.5 IEEE 802.16h - *Cognitive WiMAX*

IEEE 802.16 [IEE09], also denoted as Worldwide Interoperability for Microwave Access (WiMAX), in its second amendment introduced mechanisms for license-exempt operation, *i.e.*, it has defined a set of cognitive radio capabilities for WiMAX networks, and is denoted by IEEE 802.16h [IEE10].

In a real scenario a WiMAX network may coexist with licensed users (denoted in [IEE10] as specific spectrum users) and other unlicensed users (denoted as non specific spectrum users) sharing the same frequency band. In such case, the interference that the WiMAX system may cause to each of the users can be different. IEEE 802.16h defines three possible levels of interference: a) acceptable interference, admissible in both licensed and unlicensed users, which does not cause degradation in the receiver performance for a given choice of modulation and/or coding; b) harmful interference, not admissible in licensed links, refers to strong interference that decreases the link performance; and c) destructive interference, when the receiver is not capable of decoding the receiver signal for any available modulation at the transmitter.

IEEE 802.16h proposes a PHY-MAC cross-layer framework characterized by two different profiles: the first one provides uncoordinated coexistence mechanisms (WirelessMAN-UCP), without requiring much interaction among the different systems operating below 11 GHz in license-exempt bands, while the second profile offers coordinated coexistence mechanisms (WirelessMAN-CX), which addresses the required coordination of neighboring systems in order to reduce the interference among them [IEE10].

In the uncoordinated profile, IEEE 802.16h allows distributed architectures for the radio resource management within the network formed by one IEEE 802.16 BS and its associated subordinated terminals. Each BS has a Distributed Radio Resource Management entity to execute the spectrum sharing policies and to build up a database for sharing information related to actual and intended future usage of radio spectrum. This database can be recovered from a master entity with the required information, or from different devices, e.g. using the GPS or informed by the operator.

On the other hand, with the coordinated coexistence mechanism, multiple secondary networks coexisting in the same region can collaborate in order to coordinate their transmissions and build a neighbor relationship. The amendment considers three basic mechanisms for achieving coexistence: a) MAC Frame Synchronization, for separating transmissions and enabling operation in synchronized zones; b) Dynamic Channel Selection (DCS) and Adaptive Channel Selection (ACS) for finding a less interfered or less used frequency channel; and c) Separation of the remaining interference in the time domain, by using a Coexistence Frame, coordinated scheduling, and a fairness approach, thus allowing the usage of a frequency channel by more than one system. In the coordinated profile a Coexistence Control Channel is used for inter-network coordination.

2.4.6 IEEE P1900 - *Dynamic Spectrum Access Networks*

The IEEE 1900 projects form a new standardization initiative within the IEEE focusing the development of standards in the area of DSA, CR, interference management, coordination of wireless systems and advanced spectrum management. The IEEE 1900, or Dynamic Spectrum Access Networks (DySPAN) standards committee, was established in March 2005 jointly by the IEEE Communications Society and IEEE Electromagnetic Compatibility Society, and in 2007 it was placed under the Standard Coordinator Committee 41 (SCC 41).

The IEEE DySPAN standard committee is divided into 7 Working Groups (WG) (IEEE 1900.x), each one responsible for addressing different CR and spectrum management issues. From those 7 WGs, only IEEE 1900.3, responsible for "Recommended Practice for Conformance Evaluation of Software Defined Radio Software Modules", was not able to develop an approved standard. In the context of cognitive radio networks, we highlight the IEEE 1900.4 WG, which handles the "Architecture and Enablers for Optimized Radio and Spectrum Resource Usage" and IEEE 1900.6 WG, that deals with "Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum

Access and other Advanced Radio Communication Systems".

The IEEE 1900.4 WG has aimed at standardizing architectures and functions for distributed decision making in order to optimize radio resource usage. IEEE 1900.4 is intended to apply to a heterogeneous wireless environment, which may include multiple operators, multiple Radio Access Technologies (RATs), multiple Radio Access Networks (RANs), and multiple terminals. As the main subject of optimization, like in other DSA standards, advanced spectrum management capabilities are considered in IEEE 1900.4: e.g. the assignment of spectrum to RANs can be dynamically changed, where "spectrum assignment" may be characterized as a carrier frequency, a signal bandwidth, among others. Terminals to which IEEE 1900.4 is applicable are reconfigurable and, for backward compatibility, IEEE 1900.4 does not rule out legacy terminals coexisting in the network.

Regarding the IEEE 1900.6, the scope of this standard is to define the interfaces and structures enabling the information exchange between spectrum sensors and their clients, in radio communication systems [Moe+11]. By defining these entities, the standard facilitates interoperability between independently developed devices, allowing separate evolution of spectrum sensors and other system functions. Figure 2.9 illustrates how the sensing information is exchanged between sensors and clients. The term clients includes the Cognitive Engines (CEs), Data Archive (DA) and Sensors (Ss). The CE is defined as the portion of the Cognitive Radio System (CRS) containing the policy-based control mechanism and the cognitive control mechanism, which must have knowledge about the current state and a set of attainable states, and also the cost associated with each state transition (cost of the reconfigurable radio platform). The DA is defined as a logical entity where sensing information obtained from spectrum sensors or other information sources, and regulatory and policy information are stored. The sensors can receive information from one or more sensors and forward it to a CE or the DA.

As for the interfaces, IEEE 1900.6 considers three different interfaces between spectrum sensors and their clients. The CE/DA-S interface is used for exchanging sensing information between a CE or DA and a sensor: the CE/DA-S interface is used in scenarios where a given CE or a DA obtains sensing information from one or several sensors, or a given sensor provides sensing information to one or several CEs or a DA. The S-S interface is used for exchanging sensing information between sensors; this is needed in cases where one sensor may not be able to obtain all required information, or in scenarios where sensors A and B exchange sensing information for collaborative or cooperative sensing. The CE-CE/DA interface is used for exchanging sensing information between CEs or between a CE and a DA: the CE-CE/DA interface is used in scenarios where two CEs exchange sensing information for collaborative or cooperative sensing. The CE-CE/DA interface is also used in scenarios where a CE obtains sensing information as well as policies and regulatory information from a DA.

2.5 Conclusions

The current chapter provided an extensive and comprehensive literature review of the actual trends and common challenges in CRNs. Section 2.1 starts by introducing the CR concept and its enabling

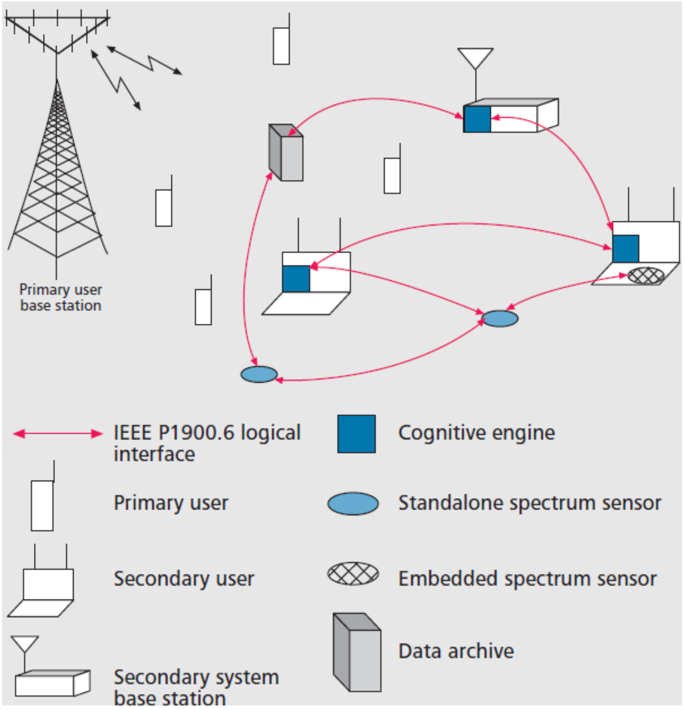


Figure 2.9: Exchanging sensing information in IEEE 1900.6 [Moe+11].

philosophy. We identify the main actors of a CRN, the PUs and the SUs, and broadly divide the CRNs according to their architecture in infrastructured and decentralized (*ad hoc*). For each CRN architecture we enumerate its characteristics, advantages and drawbacks, concluding that infrastructured CRNs can be more reliable to handle the SU's coordination, while DCRNs can be more scalable and more flexible in terms of deployment, but require higher complexity in terms of synchronization and coordination. Finally, we have seen that in order to adapt to dynamic spectrum environment, the CR devices must adopt new spectrum-aware/access operations, forming *the cognitive cycle* which can be divided into four management functions: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility. Besides underlining the importance of each management function, we also compare the traditional PHY-MAC architecture with the CR PHY-MAC architecture, by analyzing the four CR management functions disposed in the classical Open Systems Interconnection (OSI) model perspective.

Section 2.2 introduces the main issues associated with the spectrum sensing activities. We start by stressing the importance of performing an accurate spectrum sensing and several spectrum awareness methods are enumerated, including the geolocation/database, the use of periodic beacons and local radio spectrum monitoring. The last one is described in detail. Several challenges regarding the spectrum sensing operation including the choice of the sensing duration and frequency, how to avoid the hidden PU problem, or even the detection of spread spectrum PUs are also discussed. Moreover, three spectrum sensing techniques are briefly described. The most used one, the EBS technique, is characterized by sensing the presence of licensed users based on the energy of the received signals. The major challenge of this technique is the computation of the decision threshold used to classify the spectrum state (idle/occupied).

Section 2.3 overviews PHY-MAC cross-layered protocols for CRNs. The differences between classical MACs and CR MACs are enumerated and the most challenging implementation issues are discussed, including the configuration of the control channel, how to handle with the multichannel hidden terminal problem, or even the different QoS requirements for each PUs and SUs. Then, based on several intrinsic features such as the architecture, type of control channel, channel access method, among others, a CR MAC classification tree is presented. A large number of CR MAC protocols are described, at least one for each classification, and their advantages and drawbacks are identified. Finally, Section 2.4 briefly describes several standardization initiatives in the cognitive radio domain. We have seen that most of them were proposed for centralized architectures, namely to explore the vacant frequencies left by the analog TV system, and also to cope with the coexistence of different wireless systems such as IEEE 802.11 (Wi-Fi) and IEEE 802.16 (WiMAX).

CHAPTER 3

SPECTRUM SENSING CHARACTERIZATION

3.1 Introduction

The spectrum sensing task plays an important role in CRNs: it is responsible for detecting the availability of vacant portions (holes) of spectrum that might be used by the secondary network. As aforementioned in the previous chapter, SUs equipped with a single transceiver are unable to sense the spectrum for access opportunities and transmit simultaneously, and therefore single-radio SUs adopt an operation cycle where sensing and transmission operations occur in a consecutive manner. SUs start to sense the spectrum during a fixed amount of time (sensing period) and, depending on the output of the sensing, they can transmit during a fixed amount of time (transmission period).

Most of the existing single-radio CR schemes, such as the IEEE 802.22 standard [IEE11], adopt the EBS technique to characterize the activity of licensed users, mainly because it does not require any a *priori* knowledge of the PU's signal. As mentioned in Section 2.2, the EBS performance depends on the number of channel samples collected during the sensing period, and on the energy threshold used to decide about PUs' activity. Several studies already characterized the optimal sensing period duration that maximizes SU's throughput for a given interference constraint. In [GS07] the detection probability is initially assigned to a fixed regulatory constraint that imposes the maximum level of admissible interference, and the authors determine the optimal duration of the sensing period for a given energy threshold. The detection probability is achieved by adopting a constant energy threshold and by finding the number of channel samples that meet the probability value and maximize SUs' throughput. In [LA08] the energy threshold is defined as a value that equals the sensing error probabilities when PUs use or do not use the channel. While [GS07] and [LA08] follow different strategies to parameterize the energy threshold, both guarantee PUs protection by determining the right amount of channel samples needed to meet the interference constraint. However, these works consider that PUs only change their behavior in the beginning of the sensing period, which is a quite unrealistic assumption because they consider that SUs are synchronized with the PUs.

The main objective of this chapter is to study the performance of the spectrum sensing task considering a single-radio CRN where SUs adopt the EBS spectrum sensing technique. Two scenarios are considered: first we assume that a PU does not change its state (active/inactive) during the SU's operation cycle; then we admit that a PU is able to change its state during the operation cycle, which may occur during the sensing period or during the transmission period. For both scenarios we characterize and derive closed-form expressions for the probabilities of detection (P_D) and false alarm (P_{FA}).

Departing from the assumption that PUs do not change their behavior during the SU's operation cycle, we investigate new strategies to parameterize the EBS detector. The goal is to analyze different parameterization criteria for the energy threshold taking the level of activity of the PU into account. The goodput of such a system is characterized, as well as the interference caused to the primary network for an extended range of sensing period durations. Then, extending the previous analysis, we characterize the interference caused to PUs when a randomized arrival or departure of a PU can occur in the entire SU's operation cycle. The interference caused to PUs is compared with the case when timing synchronization is assumed, concluding that the synchronization assumption leads to an underevaluation of the level of interference caused to PUs. It is also shown that the interference caused to PUs decreases as more SU's operation cycles are performed per active/inactive PU's activity state.

This chapter is structured as follows: in Section 3.2 different strategies to parameterize the EBS technique assuming a single-radio CRN are studied; In the same section, and assuming a constant PU's behavior, the secondary network's goodput and the interference experienced by the primary network are characterized; Section 3.3 extends the analysis performed in Section 3.2 by considering a non-constant PU's behavior; finally, Section 3.4 summarizes the main conclusions of the chapter.

3.2 Constant PU's behavior

Let us consider a cognitive network formed by a pair of PUs licensed to access the channel and a pair of SUs that will access the channel opportunistically. SUs are equipped with a single radio transceiver. However, because SUs are unable to distinguish SUs and PUs transmissions, each SU splits its operation cycle (frame structure) into spectrum sensing and spectrum access periods, with durations T_S^{SU} and T_D^{SU} respectively, as illustrated in Figure 3.1.

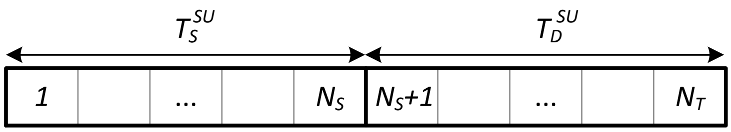


Figure 3.1: SU's frame structure.

The SU's frame lasts $T_F^{SU} = T_S^{SU} + T_D^{SU}$ and contains N_T slots, where each slot duration is given by the channel sampling period adopted in the spectrum sensing task. The first N_S slots define the sensing period duration, and the remaining ones ($N_S + 1$ to N_T) represent the transmission period duration. It is assumed that the SUs always have data to transmit and all SUs are synchronized in the beginning of the frame.

Regarding the interference model, it is assumed a worst case scenario where a PU is unable to decode a received frame when it overlaps in time with a SU transmission.

3.2.1 Spectrum Sensing

The assumption of constant PU's behavior adopted in several works [GS07; LA08; Lia+08; Wan+12], indicates the case when PUs maintain their behavior during the SU's frame duration (equivalent to assume that PUs are synchronized with SU's operation cycle). Under this assumption, PUs will not change their activity state during the SU's frame, *i.e.*, the beginning of PU's transmission always matches with the beginning of SU's sensing period.

To distinguish between occupied and vacant spectrum bands, the SUs sample the channel during the sensing period T_S^{SU}, and for each sample k two hypotheses can be distinguished

$$\begin{aligned} &\mathcal{H}_0 : u(k) = w(k) && k = 1, 2, ..., N_S \\ &\mathcal{H}_1 : u(k) = w(k) + s(k) && k = 1, 2, ..., N_S, \end{aligned} \tag{3.1}$$

where $s(k)$ denotes the transmitted signals by PUs, modeled as a Gaussian variable with mean μ_s and variance σ_s^2, *i.e.*, $s(k) = \mathcal{N}(\mu_s, \sigma_s^2)$. $w(k)$ is assumed to be a zero-mean AWGN with unit variance, *i.e.*, $w(k) = \mathcal{N}(0, 1)$. The condition $\mathcal{H}_0$ represents the case when PUs are absent, while $\mathcal{H}_1$ indicates that there exists a signal transmitted by a PU.

As discussed in Section 2.2.2, the traditional spectrum sensing techniques includes different approaches including, but not limited to, the MFBS, the CBS and the EBS. Due to its simplicity and the fact that it does not need any *a priori* knowledge of PU's signal, it is assumed that every SU employs the EBS spectrum sensing technique to detect PU's activity. The EBS relies on the classical energy detector [Urk67]. In the detection stage, each SU determines the amount of energy received in N_S samples, given by

$$Y = \sum_{k=1}^{N_S} |u(k)|^2, \tag{3.2}$$

and compares it with the energy threshold γ to decide whether a PU is present or absent. Under the hypothesis $\mathcal{H}_0$, the decision variable Y follows a central chi-square distribution with N_S degrees of freedom. Under the hypothesis $\mathcal{H}_1$, Y follows a non-central chi-square distribution also with N_S degrees of freedom, and a non centrality parameter λ representing the sum of N_S samples of SNR collected from the channel during the sensing period (λ'), which is given by [Dig+03]

$$\lambda = \sum_{k=1}^{N_S} \left(\frac{\mu_s}{1 + \sigma_s} \right)^2 = \sum_{k=1}^{N_S} \lambda'. \tag{3.3}$$

If the number of samples N_S is large enough[1], it is possible to use the Central Limit Theorem (CLT)

[1]The channel sampling period must satisfy the Nyquist sampling theorem.

to approximate the chi-square distribution to a Gaussian distribution [Tan05]:

$$\Upsilon \sim \begin{cases} \mathcal{N}(N_S, 2N_S), & \mathcal{H}_0 \\ \mathcal{N}(N_S+\lambda, 2(N_S+2\lambda)), & \mathcal{H}_1. \end{cases} \tag{3.4}$$

Therefore, for a single SU the probabilities of detection (P_D) and false alarm (P_{FA}) are represented by

$$P_D = Pr(\Upsilon > \gamma|\mathcal{H}_1) = \mathcal{Q}\left(\frac{\gamma-(N_S+\lambda)}{\sqrt{2(N_S+2\lambda)}}\right), \tag{3.5}$$

$$P_{FA} = Pr(\Upsilon > \gamma|\mathcal{H}_0) = \mathcal{Q}\left(\frac{\gamma-N_S}{\sqrt{2N_S}}\right), \tag{3.6}$$

where $\mathcal{Q}(.)$ is the complementary distribution function of the standard Gaussian. By observing equations (3.5) and (3.6) we can see that both P_D and P_{FA} only depend on the number of samples (N_S) and energy threshold (γ).

3.2.2 PU Activity Model

Since the PUs are licensed users, it is possible to characterize their average active/busy period duration, T_{ON}^{PU}, and inactive period duration, T_{OFF}^{PU}. Because the system performance heavily relies on SU's sensing reliability, the SU's operation cycle duration should be shorter than the PU's active/inactive period, $T_F^{SU} < \min\left(T_{ON}^{PU}, T_{OFF}^{PU}\right)$, and the length of the SUs operation cycle should be chosen according to $T_F^{SU} = \min\left(T_{ON}^{PU}, T_{OFF}^{PU}\right)/\delta$, with $\delta > 1$.

To model the PU's activity, we consider the periodic channel sampling process described in the previous subsection, which is modeled by the Markov chain illustrated in Figure 3.2. Considering the stationary behavior of a PU during a SU's frame, we can derive the probabilities of a PU changing its behavior to active and inactive, $\mathcal{P}_{0,1}$ and $\mathcal{P}_{1,0}$, respectively, or maintaining its behavior inactive or active, $\mathcal{P}_{0,0}$ or $\mathcal{P}_{1,1}$ as follows

$$\begin{aligned} \mathcal{P}_{1,0} &= \frac{1}{\delta N_T}, \\ \mathcal{P}_{1,1} &= 1-\mathcal{P}_{1,0}, \\ \mathcal{P}_{0,1} &= \frac{\tau^{PU}}{\delta N_T \overline{\tau^{PU}}}, \\ \mathcal{P}_{0,0} &= 1-\mathcal{P}_{0,1}, \end{aligned} \tag{3.7}$$

where τ^{PU} represents the probability of a PU accessing the channel and $\overline{\tau^{PU}} = 1-\tau^{PU}$ denotes the complementary event of τ^{PU}, *i.e.*, the probability of a PU being absent.

Under the assumption of constant PU's behavior, which is the scenario discussed in this subsection, the probabilities of a PU changing its behavior during the same SU's frame, $\mathcal{P}_{0,1}$ and $\mathcal{P}_{1,0}$, are zero which is achieved by imposing that the PU's transmission always matches with the beginning of a SU's sensing period.

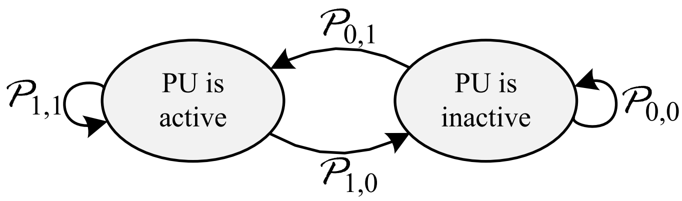


Figure 3.2: A two state birth-death process describing the PU activity model.

3.2.3 System Goodput

Let us assume that a PU access the channel with a probability τ^{PU}. Considering the probabilities of detection and false alarm with respect to the channel condition, a SU decides that the channel is vacant, and consequently accesses that channel, with probability P_I, given by [GS07]

$$P_I = \overline{\tau^{PU}}(1 - P_{FA}) + \tau^{PU}(1 - P_D), \tag{3.8}$$

where the first term in equation (3.8) is due to the successful identification of an unused channel, while the second one represents the case when the channel is erroneously deemed idle due to a detection error.

Following the same rationale, we derive the expression for the Probability of Interference P_{Int}, *i.e.*, the probability of misdetecting a PU when it is transmitting,

$$P_{Int} = \tau^{PU}(1 - P_D). \tag{3.9}$$

The overall system goodput, is defined as the sum of both goodputs achieved by PUs and SUs. The expected goodput achieved by a SU is defined as the ratio between the expected frames successfully transmitted and the frame's duration as follows

$$G^{SU} = \frac{T_D^{SU}\overline{\tau^{PU}}(1 - P_{FA})}{T_F^{SU}}. \tag{3.10}$$

On the other hand, PUs' goodput is only limited by the occurring miss-detection events, which can be approximated by

$$G^{PU} = \tau^{PU} P_D. \tag{3.11}$$

Therefore, the goodput achieved by PUs and SUs is

$$G = \frac{T_D^{SU}\overline{\tau^{PU}}(1 - P_{FA})}{T_F^{SU}} + \tau^{PU} P_D. \tag{3.12}$$

3.2.4 Spectrum Sensing Parameterization Criteria

This subsection introduces the different spectrum sensing parameterization criteria that can be used to setup the energy detector. We aim to compare different EBS parameterization criteria (C_x) for the decision threshold (γ) adopted by SUs and analyze the parameterization for variable spectrum sensing durations (N_S). We compare the parameterization criteria adopted in [GS07] and [LA08], together with other variants.

3.2.4.1 Parameterization Criteria

Parameterization Criterion C_1

Let us start by one of the first and most studied parameterization criterion in the literature: the limitation of the admissible interference, which works as a level of protection to PUs. For that, P_{Int} is set to the PUs' maximum admissible level of interference. Rewriting (3.9) as

$$P_D = 1 - \frac{P_{Int}}{\tau^{PU}}, \tag{3.13}$$

and using (3.5), the decision threshold γ can be obtained as follows:

$$\gamma = \mathcal{Q}^{-1}\left(1 - \frac{P_{Int}}{\tau^{PU}}\right)\sqrt{2(N_S + 2\lambda)} + N_S + \lambda. \tag{3.14}$$

This criterion guarantees a determined protection to PUs, depending on P_{Int}. However, it does not consider the probability of false alarm in γ's parameterization, which may decrease the performance of SUs. This criterion was adopted in [GS07].

Parameterization Criterion C_2

The second criterion parameterizes γ in order to maximize the product between the non-interfering probability and the SU access probability. This criterion can be stated as

$$\begin{aligned} &\text{Find:} && \gamma^* \\ &\text{Maximize:} && C_2 = (1 - P_{Int})P_I \\ &\text{Subject to:} && N_S \geq 2WT_S^{SU}, \end{aligned} \tag{3.15}$$

where γ^* is the optimal decision threshold. The constraint $N_S \geq 2WT_S^{SU}$ imposes the Nyquist sampling rate, where W represents the bandwidth of the sensed band. While C_2 does not limit the level of interference caused to PUs, it achieves the best tradeoff between the amount of interference caused by SUs and their chances of accessing the channel.

Parameterization Criterion C_3

The third criterion tries to maximize the sensing success by maximizing the product between the probability of detection and the probability of correct rejection $(1 - P_{FA})$. C_3 can be expressed as follows

$$\begin{aligned} &\text{Find:} && \gamma^* \\ &\text{Maximize:} && C_3 = P_D(1 - P_{FA}) \\ &\text{Subject to:} && N_S \geq 2WT_S^{SU}. \end{aligned} \tag{3.16}$$

Parameterization Criterion C_4

The fourth criterion takes into account the fact that if a PU accesses the channel with probability τ^{PU}, then the SU has a maximum channel access probability equal to $\overline{\tau^{PU}}$. Hence, this criterion finds the parameterization that equals SUs' channel access probability to the maximum channel access probability, which can be written as

$$P_I = \overline{\tau^{PU}}, \tag{3.17}$$

which by equation (3.8) is equivalent to the condition

$$\overline{\tau^{PU}}P_{FA} - \tau^{PU}(1 - P_D) = 0. \tag{3.18}$$

This criterion finds the decision threshold that solves the previous equation (3.18) and is described as follows

$$\begin{array}{ll} \text{Find:} & \gamma^* \\ \text{Where:} & \overline{\tau^{PU}}P_{FA} - \tau^{PU}(1 - P_D) = 0 \\ \text{Subject to:} & N_S \geq 2WT_S^{SU} \end{array} \tag{3.19}$$

C_4 is the parameterization criterion adopted in [LA08].

Parameterization Criterion C_5

Finally, the fifth parameterization criterion relates the probability of detection with the probability of SUs transmission. C_5 finds the best tradeoff between the two probabilities by maximizing its product:

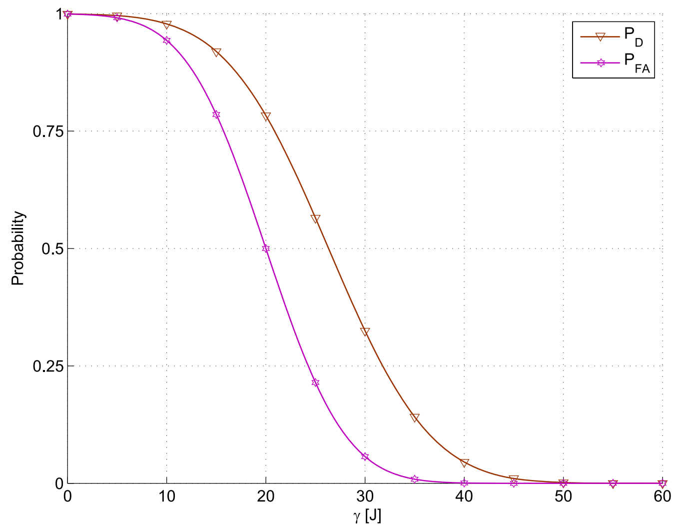
$$\begin{array}{ll} \text{Find:} & \gamma^* \\ \text{Maximize:} & C_5 = P_D P_I \\ \text{Subject to:} & N_S \geq 2WT_S^{SU} \end{array} \tag{3.20}$$

This criterion is similar to C_2. However, in C_2 PU's protection is considered by incorporating the probability of interference, which depends on the PU's access probability (see (3.9)). In this case the level of PU's protection is measured by P_D's value and does not depend on the activity of the PUs.

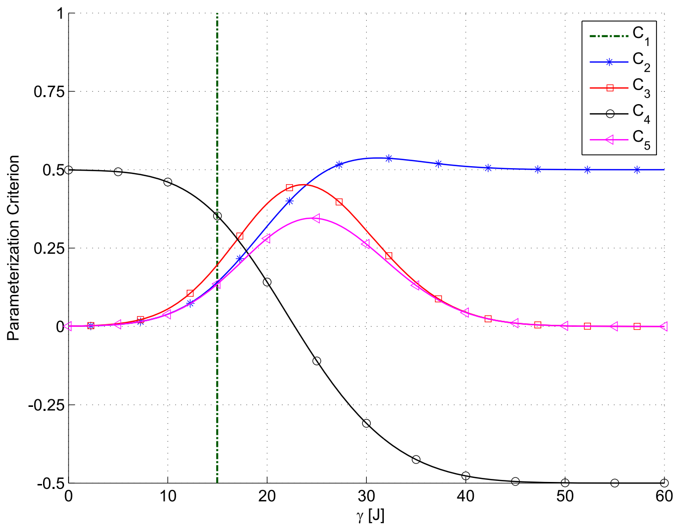
3.2.4.2 Parameterization Criteria Analysis

The probabilities P_D and P_{FA}, given in (3.5) and (3.6) respectively, are plotted in Figure 3.3(a) for different values of decision threshold γ, considering a constant number of spectrum sensing samples $N_S = 20$, $\lambda = -5$dB and $\tau^{PU} = 0.5$. Figure 3.3(b) illustrates the numeric values obtained for each criterion obtained for each threshold, which are determined by (3.15), (3.16), (3.19) and (3.20). We also represent the decision threshold computed with (3.14) for $P_{Int} = 0.04$. From both figures we can see that due to the low SNR condition (λ), P_D and P_{FA} curves are very close to each other, meaning that the energy detector can not operate near the optimal point of operation, where $P_D \approx 1$ and $P_{FA} \approx 0$. Another consequence is that the optimal decision thresholds calculated with the proposed criteria lie in a small range - from approximately 23J (C_4) to 31J (C_2). This means that C_2 offers the lowest level of PU's protection against SU's interference, because the probability of detection exhibits the smallest value for the optimal threshold determined by C_2.

Figure 3.4 plots the same curves for better signal conditions, *i.e.* $\lambda = 5$dB. In this case the descending zone of P_{FA} and P_D are more distant. We observe the same relationship regarding the distance between the thresholds achieved by each parameterization criterion. The lowest optimal decision threshold stands for C_4, which is maximized when the P_{FA} and the $1 - P_D$ exhibit the same value. C_3 and C_5 achieve similar thresholds, around $\gamma \approx 40$J. Finally, the criterion C_2 achieves the highest decision threshold, around 83J. As in the previous figure, C_2 is still the criterion that offers



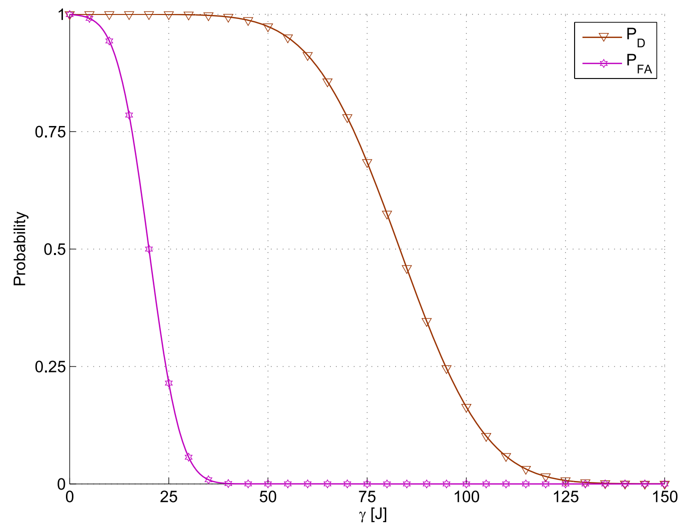
(a)



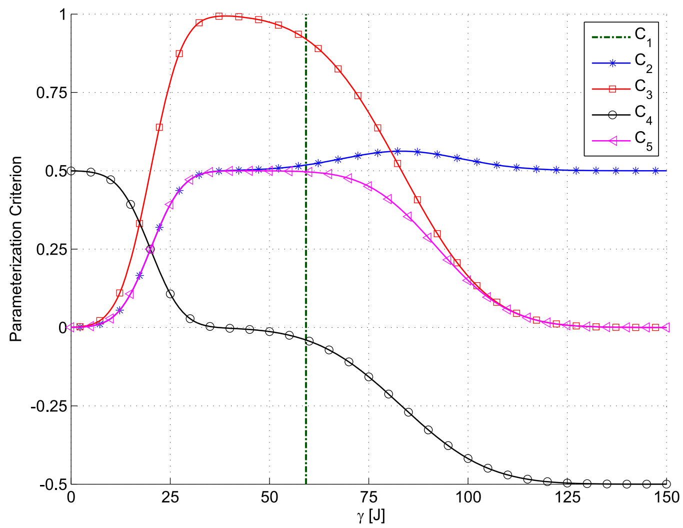
(b)

Figure 3.3: P_D, P_{FA} and parameterization criteria C_2, C_3, C_4, C_5 for different thresholds γ ($\lambda = -5$dB, $\tau^{PU} = 0.5$ and $N_S = 20$). $''C_1''$ indicates the threshold computed with criterion C_1 given $P_{Int} = 0.04$.

the lowest protection to PUs because $P_D \approx 0.49$ for the optimal threshold determined by C_2, while P_D is close to 1 for the thresholds achieved with C_3, C_4 and C_5.



(a)



(b)

Figure 3.4: P_D, P_{FA} and parameterization criteria C_2, C_3, C_4, C_5 for different thresholds γ ($\lambda =$ 5dB, $\tau^{PU} = 0.5$ and $N_S = 20$). "C_1" indicates the threshold computed with criterion C_1 given $P_{Int} = 0.04$.

3.2.5 Performance Analysis

This subsection evaluates the performance achieved by SUs and PUs considering the parameterization criteria previously described. The performance of each criterion is evaluated through the goodput obtained by SUs and the interference caused to PUs.

The results presented in this subsection represent simulation results obtained using the *MATLAB* software [MAT14]. We have considered a scenario formed by one PU transmitter-receiver pair and one SU transmitter-receiver pair. The operation mode of PUs and SUs is as described in the previous subsections. The interference was measured as the amount of time a PU communication is mistakenly interrupted by a SU, and the SU's goodput as the amount of time that the channel was successfully used by the secondary network, when it was not being used by the primary network. The performance is evaluated in three different scenarios $\tau^{PU} = 0.3$, $\tau^{PU} = 0.5$ and $\tau^{PU} = 0.7$. $P_{Int} = 0.04$ was adopted for the parameterization criterion C_1, while the remaining simulation parameters are described in Table 3.1.

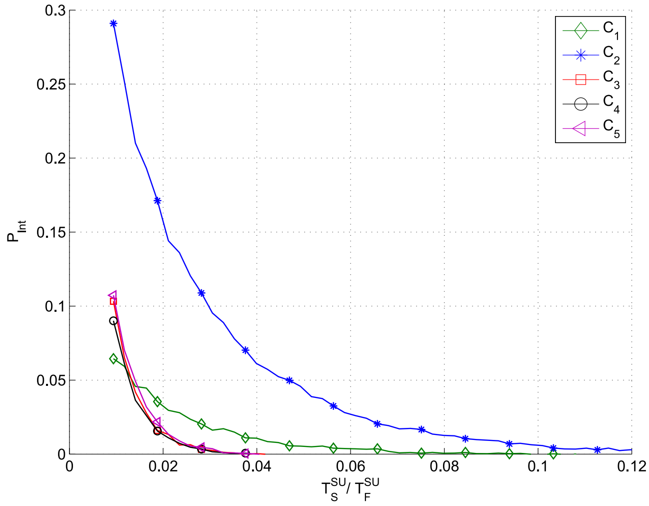
Table 3.1: Simulation parameters used for performance evaluation in the constant PU's behavior scenario.

Parameter	Value
W	10 kHz
Channel Sampling Period	50 μs
T_F^{SU}	21.3 ms
λ (SNR)	5 dB
μ_s	3.16 (5dB)
σ_s^2	3

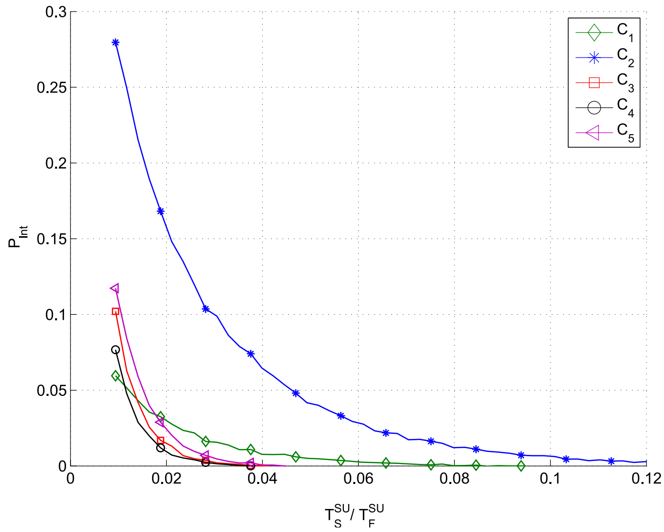
The parameterization criteria were applied for different N_S values that comply with the Nyquist sampling rate. By this way it is possible to analyze the effect of the sensing duration in the performance of the parameterization criterion. Figure 3.5 illustrates the interference caused to PUs for each parameterization criterion at different spectrum sensing periods. Figure 3.6 illustrates the SU's goodput obtained for the same scenarios presented in Fig. 3.5.

From the results we conclude that while C_3 and C_4 exhibit the lowest level of interference caused to PUs, they guarantee almost full protection to PUs when the sensing duration lasts longer than 0.05 T_S^{SU}/T_F^{SU}. Regarding the criteria C_2 and C_5, they need a higher sensing duration to approximate the interference caused to PUs to zero. This means that both C_2 and C_5 underperform C_3 and C_4 because they need sensing durations greater than 0.1 T_S^{SU}/T_F^{SU} to approximate the interference caused to PUs to zero. Compared to its maximum value, the goodput of the SUs achieved with C_2 and C_5 significantly decreases when higher sensing durations are adopted, as can be observed in Fig. 3.6. Thus, C_2 and C_5 fail to guarantee a good level of protection to PUs and also fail to obtain the maximum goodput in the secondary system.

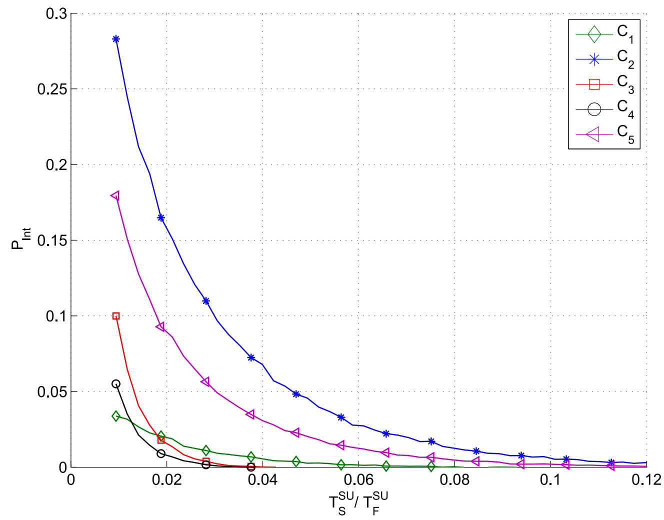
The criterion C_1 was parameterized to limit the interference to 4%. However the interference level exceeds 4% if the sensing duration is too short. While C_1 achieves a good performance in terms of SUs' goodput, it is noticeable that the goodput achieved by SUs underperforms all the other criteria for sensing durations shorter than 0.06 T_S^{SU}/T_F^{SU} if C_1 is parameterized to limit the interference to very small values (lesser than 1%). This means that if C_1 is parameterized to protect the PUs with interference levels close to C_3 and C_4, it underperforms the other criteria in terms of SUs' goodput. By this way, C_3 and C_4 can be considered advantageous when we require high levels of protection to PUs and higher goodput to SUs. Therefore, comparing C_3 and C_4, we can observe that they guarantee a similar level of protection to PUs for the sensing duration that maximizes the



(a) $\tau^{PU} = 0.3$.

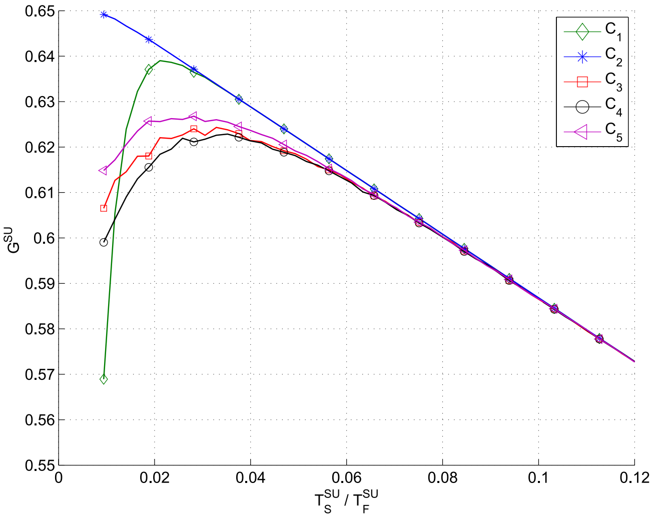


(b) $\tau^{PU} = 0.5$.

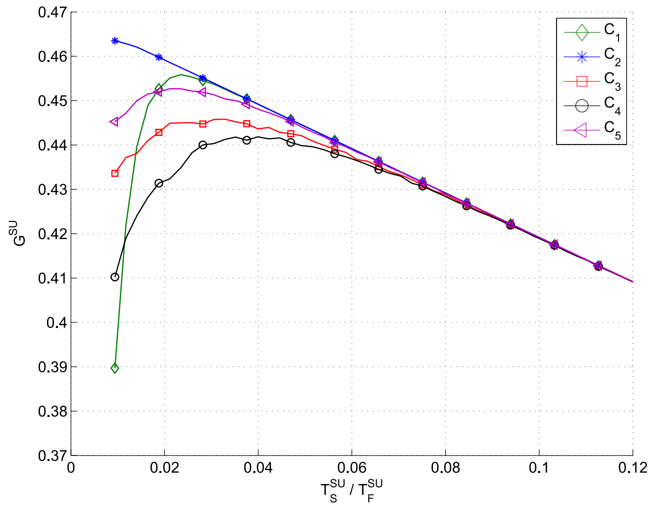


(c) $\tau^{PU} = 0.7$.

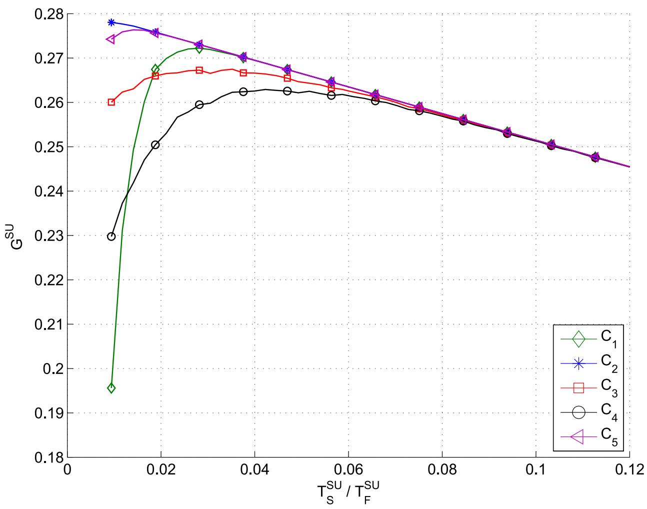
Figure 3.5: Interference caused to PUs ($\lambda = 5$dB).



(a) $\tau^{PU} = 0.3$.



(b) $\tau^{PU} = 0.5$.



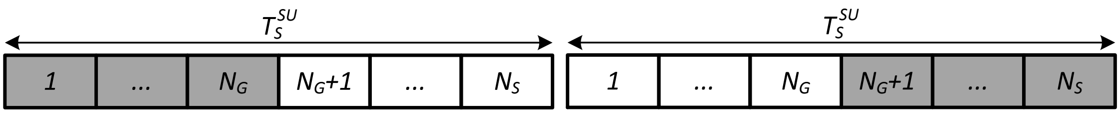
(c) $\tau^{PU} = 0.7$.

Figure 3.6: SUs' goodput for the scenarios depicted in Fig. 3.5.

SUs goodput. For these sensing durations, C_3 outperforms C_4 in terms of SUs' goodput, and it can be considered the highest ranked criterion in terms of the trade-off between PUs' protection and SUs' goodput.

3.3 Non-constant PU's behavior

In this section it is considered the case when PUs can randomly arrive or depart during the entire SUs' frame, which may occur during T_S^{SU} or T_D^{SU} periods. When the change occurs during the spectrum sensing period T_S^{SU}, two scenarios must be considered. As illustrated in Figure 3.7(a), during the spectrum sensing task the PU's behavior may change from active to inactive, where the first N_G slots denote the presence of PUs, and the remaining ones $(N_G + 1$ to $N_S)$ represent the absence of PUs. On the other hand, Figure 3.7(b) illustrates the opposite scenario when PUs may change from inactive to active during the sensing period. These scenarios are respectively represented by the hypotheses $\mathcal{H}_{10}$ and $\mathcal{H}_{01}$.



(a) (b)

Figure 3.7: PU's activity change: (a) from active to inactive; (b) from inactive to active. Gray slots denote PU's activity

3.3.1 Spectrum Sensing

The output of the energy detector, under the assumption of non-constant PU's behavior, admits four hypothesis, rather than two. The output of the energy detector under the hypothesis $\mathcal{H}_{01}$ is given by

$$Y_{\mathcal{H}_{01}} = \sum_{k=1}^{N_G} |w(k)|^2 + \sum_{k=N_G+1}^{N_S} |w(k) + s(k)|^2, \tag{3.21}$$

where the left-hand sum, $Y^a_{\mathcal{H}_{01}} = \sum_{k=1}^{N_G} |w(k)|^2$, follows a central Chi-square distribution with N_G degrees of freedom, while the right-hand sum, $Y^b_{\mathcal{H}_{01}} = \sum_{k=N_G+1}^{N_S} |w(k) + s(k)|^2$, follows a non-central Chi-square distribution with $N_S - N_G$ degrees of freedom, and a noncentrality parameter λ. If N_G and $N_S - N_G$ are large enough the CLT holds and $Y^a_{\mathcal{H}_{01}}$ and $Y^b_{\mathcal{H}_{01}}$ can be approximated as follows

$$Y^a_{\mathcal{H}_{01}} \sim \mathcal{N}\Big(N_G, 2N_G\Big), \tag{3.22}$$

$$Y^b_{\mathcal{H}_{01}} \sim \mathcal{N}\Big(N_S - N_G + \lambda, 2(N_S - N_G + 2\lambda)\Big). \tag{3.23}$$

Assuming that $Y^a_{\mathcal{H}_{01}}$ and $Y^b_{\mathcal{H}_{01}}$ are independent and identically distributed, $Y_{\mathcal{H}_{01}}$ can be stated as the sum of two Gaussian random variables $Y_{\mathcal{H}_{01}} \sim \mathcal{N}\Big(N_S + \lambda, 2N_S + 4\lambda\Big)$. Since PUs are only active in $N_S - N_G$ samples, λ is now given by $\lambda = (N_S - N_G)\lambda'$. Following the same rationale for the remaining hypothesis, the output of the energy detector considering the four hypothesis is written as follows

$$Y \sim \begin{cases} \mathcal{N}(N_S, 2N_S), & \mathcal{H}_{00} \\ \mathcal{N}(N_S + \lambda' N_G, 2(N_S + 2\lambda' N_G)), & \mathcal{H}_{10} \\ \mathcal{N}(N_S + \lambda'(N_S - N_G), 2N_S + 4\lambda'(N_S - N_G)), & \mathcal{H}_{01} \\ \mathcal{N}(N_S + \lambda, 2(N_S + 2\lambda)), & \mathcal{H}_{11}. \end{cases} \tag{3.24}$$

Under the hypothesis $\mathcal{H}_{10}$ a PU is not active at the end of the sensing period and the probability of false alarm is given by

$$P_{FA}^{\mathcal{H}_{10}} = Pr(Y > \gamma|\mathcal{H}_{10}) = \mathcal{Q}\left(\frac{\gamma - N_S - N_G\lambda'}{\sqrt{4N_G\lambda' + 2N_S}}\right). \tag{3.25}$$

On the other hand, under the hypothesis $\mathcal{H}_{01}$ a PU is always active at the end of the sensing period. In this case the probability of detection is given by

$$P_{D}^{\mathcal{H}_{01}} = Pr(Y > \gamma|\mathcal{H}_{01}) = \mathcal{Q}\left(\frac{\gamma - N_S - \lambda'(N_S - N_G))}{\sqrt{2N_S + 4\lambda'(N_S - N_G)}}\right). \tag{3.26}$$

Finally, the probability of detection under the hypothesis $\mathcal{H}_{11}$ is given by (3.5), while the probability of false alarm under the hypothesis $\mathcal{H}_{00}$ is given by (3.6).

3.3.2 Probability of Interference

During a SU's frame, the Markov chain represented in Figure 3.2 has up to N_T realizations. Since the frame length of the SUs is such that at most once PU's behavior change is observed during a SU's frame, the N_T realizations of the Markov chain do not consider the probability $1 - P_\chi$ of occurring two or more changes, and consequently P_χ is used to normalize the probability set

$$P_\chi = \tau^{PU}\mathcal{P}_{1,1}^{N_T} + \overline{\tau^{PU}}\mathcal{P}_{0,0}^{N_T} + \overline{\tau^{PU}}\sum_{k=0}^{N_T-1}\mathcal{P}_{0,0}^{k}\mathcal{P}_{0,1}\mathcal{P}_{1,1}^{N_T-k-1} + \tau^{PU}\sum_{k=0}^{N_T-1}\mathcal{P}_{1,1}^{k}\mathcal{P}_{1,0}\mathcal{P}_{0,0}^{N_T-k-1}. \tag{3.27}$$

We start describing the different scenarios that contribute to the PU's goodput, which are summarized as follows:

A) a PU is active with probability τ^{PU} when the SU's frame begins and it goes inactive until the end of the sensing period. Since the SU is not transmitting during the spectrum sensing period, the PU's transmission will not be interfered by SUs. Then, the expected value of PU's goodput is

$$G_A^{PU} = \frac{1}{P_\chi}\tau^{PU}\sum_{k=1}^{N_S}\left(k + \frac{1}{2}\right)\mathcal{P}_{1,1}^{k}\mathcal{P}_{1,0}\mathcal{P}_{0,0}^{N_T-k-1}, \tag{3.28}$$

where $\frac{1}{2}$ represents the average goodput of the transition slot.

B) a PU is active with probability τ^{PU} when the SU's frame begins and it changes its state during the SU's transmission period. In this case the success of the PU's transmission depends on the probability of detection, *i.e.*, if the SU is able to detect the PU during the sensing period:

$$G_B^{PU} = \frac{1}{P_\chi}\tau^{PU}\mathcal{P}_{1,1}^{N_S}\sum_{k=1}^{N_T-N_S-1}\mathcal{P}_{1,1}^{k}\mathcal{P}_{1,0}\mathcal{P}_{0,0}^{N_T-N_S-k-1}\left(N_S+\left(k+\frac{1}{2}\right)P_D^{\mathcal{H}_{11}}\right); \tag{3.29}$$

C) a PU is active with probability τ^{PU} during the entire SU's frame and the success of the PU's transmission also depends on the probability of detection:

$$G_C^{PU} = \frac{1}{P_\chi}\tau^{PU}N_T\mathcal{P}_{1,1}^{N_T}P_D^{\mathcal{H}_{11}}; \tag{3.30}$$

D) a PU is inactive with probability $\overline{\tau^{PU}}$ when the SU's frame begins, and it goes active during the SU's transmission period. Since during the sensing period SUs do not detect PUs' activity, they start transmitting, interfering with the PU transmission occurring during the transmission period. Consequently, the PU transmission only succeeds under a situation of false alarm:

$$G_D^{PU} = \frac{1}{P_\chi}\overline{\tau^{PU}}\mathcal{P}_{0,0}^{N_S}P_{FA}^{\mathcal{H}_{00}}\sum_{k=1}^{N_T-N_S-1}\left(k+\frac{1}{2}\right)\mathcal{P}_{0,0}^{N_T-N_S-k-1}\mathcal{P}_{0,1}\mathcal{P}_{1,1}^{k}; \tag{3.31}$$

E) this particular case occurs when a PU is inactive in the beginning of the SU's frames and becomes active during the last slot of the sensing period (slot N_S). The PUs will only succeed if SUs consider the spectrum as occupied. This decision is based in a single busy slot. The expected value for the PU's goodput in this case is

$$G_E^{PU} = \frac{1}{P_\chi}\overline{\tau^{PU}}\mathcal{P}_{0,0}^{N_S-1}\mathcal{P}_{0,1}\mathcal{P}_{1,1}^{N_T-N_S}\left(N_T-N_S+\frac{1}{2}\right)P_D^{\mathcal{H}_{01}}|_{N_G=N_S-1}; \tag{3.32}$$

F) a PU is inactive when the SU's frame begins and it goes active before the end of the spectrum sensing period. In this case the PU's goodput depends on the SU's probability of detection, which is based on the $N_S - N_G$ slots when the PU is active. The PU's goodput is

$$G_F^{PU} = \frac{1}{P_\chi}\overline{\tau^{PU}}\mathcal{P}_{1,1}^{N_T-N_S}\sum_{k=1}^{N_S-1}\mathcal{P}_{0,0}^{N_S-k-1}\mathcal{P}_{0,1}\mathcal{P}_{1,1}^{k}\left(k+\frac{1}{2}+(N_T-N_S)P_D^{\mathcal{H}_{01}}|_{N_G=N_S-k}\right). \tag{3.33}$$

The expected value for the overall PU's goodput can be written as being the sum of all the partial goodputs over the amount of slots in a SU's frame, *i.e.*,

$$G^{PU} = \frac{G_A^{PU}+G_B^{PU}+G_C^{PU}+G_D^{PU}+G_E^{PU}+G_F^{PU}}{N_T}.$$

Because the steady-state probability of a PU staying active, τ^{PU}, represents the maximum achievable PU's goodput, the probability of interference P_{Int} caused to PUs can be represented by the following deviation

$$P_{Int} = 1 - \frac{G^{PU}}{\tau^{PU}}. \tag{3.34}$$

3.3.3 Performance Analysis

To evaluate the impact of considering non-constant PU's behavior in the spectrum sensing process we have adopted the same scenario used in the previous section: one transmitter-receiver pair of SUs trying to access the channel when it is shown to be unused by one pair (transmitter and receiver) of PUs. However, in this scenario SUs and PUs are not synchronized, meaning that a PU can change its state (from active to inactive and from active to inactive) at most once during the same SU's frame.

Besides evaluating the impact of different spectrum sensing duration ratios $\left(T_S^{SU}/T_F^{SU}\right)$ in the PU's interference, we also analyze the influence of performing different SU's operation cycles during a PU's transmission (different δ values). The energy detector threshold (γ) was parameterized according to the criterion C_4 described in Subsection 3.2.4 for $\lambda = 5$ dB, *i.e.*, $\gamma^* \approx 40$ J. The simulation results, obtained with the *MATLAB* software [MAT14], are represented by markers. The theoretical results, obtained through (3.34) are represented by solid lines. The PU's frame durations were obtained through a truncated exponential distribution with mean $\delta \cdot T_F^{SU}$. The remaining parameters adopted in the evaluation are described in Table 3.2.

Table 3.2: Parameters used for performance evaluation in the non-constant PU's behavior scenario.

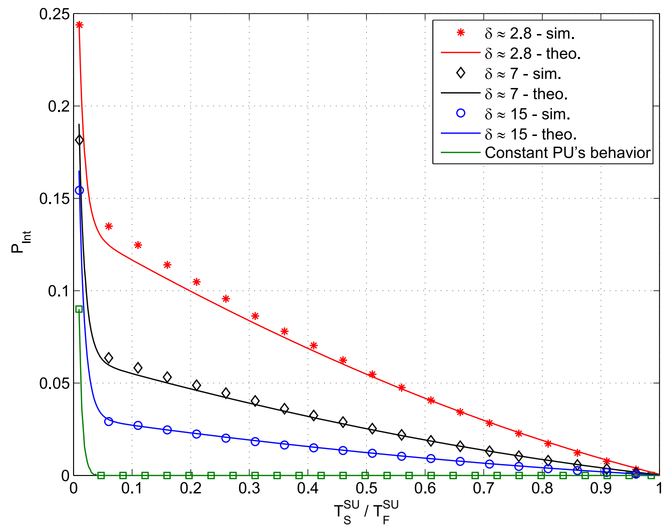
Parameter	Value
W	10 kHz
Channel Sampling Period	50 μs
T_F^{SU}	21.3 ms
λ (SNR)	5 dB
μ_s	3.16 (5dB)
σ_s^2	1 (0dB)

Figure 3.8 plots the simulation and theoretical results of interference caused to PUs for $\delta \approx 2.8$, meaning that the average duration of PUs' frame during the simulations is approx. 2.8 times greater than SUs' frame. $\delta \approx 7$ and $\delta \approx 15$ were also considered. The figure also includes a curve titled "Constant PU's behavior" representing the simulation results of the interference caused to PUs for a constant PU's behavior with $\delta = 3$. The results are plotted for $\tau^{PU} = 0.3$ (Figure 3.8(a)), $\tau^{PU} = 0.5$ (Figure 3.8(b)) and $\tau^{PU} = 0.7$ (Figure 3.8(c)).

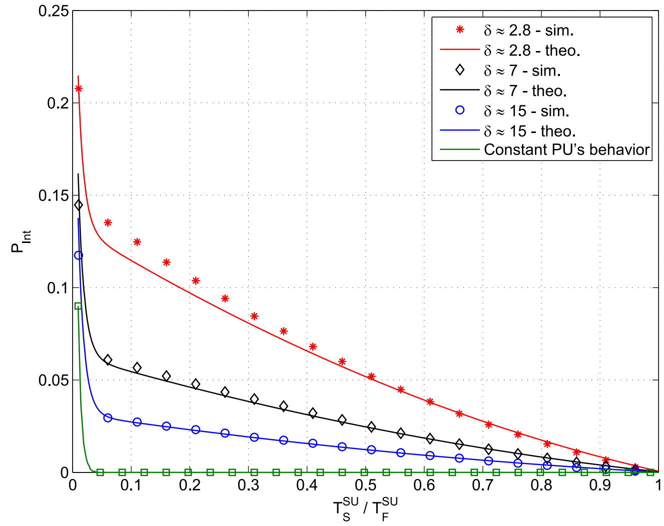
As a first remark, the results plotted in Figure 3.8 indicate that higher values of interference occur for:

1. longer SU's operation cycles when compared to PU's ON/OFF periods (smaller δ values);
2. shorter sensing periods $\left(T_S^{SU}/T_F^{SU}\right)$.

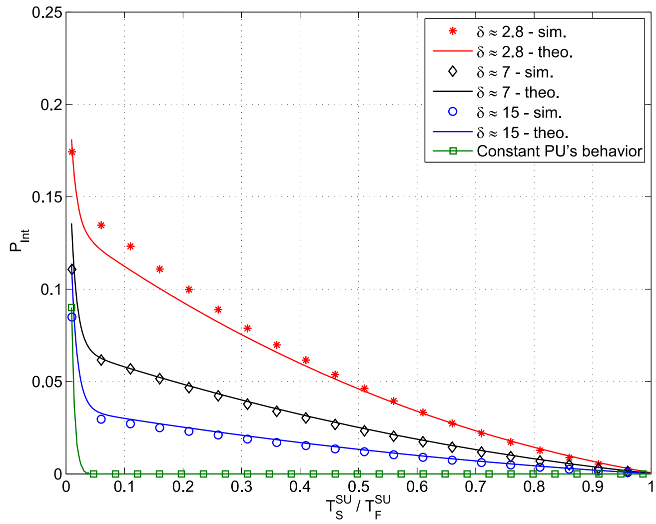
The first observation is mainly due by the interference caused when PUs start to use the channel without being detected by SUs. Consequently, if SUs adopt a shorter operation cycle, their impact in terms of PUs' interference will be smaller: as more SU operation cycles are performed during a PU's transmission (higher δ), the activity state of the PU during the SU's transmission period



(a) $\tau^{PU} = 0.3$.



(b) $\tau^{PU} = 0.5$.



(c) $\tau^{PU} = 0.7$.

Figure 3.8: PU's interference for a non-constant PU's behavior.

is more likely to be in the state detected during the SU's sensing period. Regarding the second observation, it is easily explained by the fact that a longer sensing period increases the accuracy of the spectrum occupancy decision, which leads to a decrease of the interference caused to PUs.

Comparing the simulation results with the numerical ones it is observed that for small values of δ, the model slightly underestimates the simulations. This is mainly due to the truncated exponential distribution used to sample the duration of the activity of the PUs, which slightly deviates from an exponential distribution as δ becomes smaller. However, when the PUs' frame duration is considerably higher than the SUs's frame duration ($\delta = 7$ or $\delta = 15$), which favors the interference decrease, the model's accuracy is high.

Comparing the interference values for constant $(\delta = 3)$ and non-constant PU's behavior $(\delta \approx 2.8)$, it is observed that when the PU is synchronized with SU's operation cycle the interference caused to the PU is negligible for T_S^{SU}/T_F^{SU} values greater than 5%. However, when PUs randomly arrive or depart during the SU's operation cycle, the "$\delta \approx 2.8$" curve shows that PUs suffer approximately 12% of interference for the reference value of $T_S^{SU}/T_F^{SU} = 10\%$. This result indicates that the interference models adopted in several works, including but not limited to [GS07; LA08; Lia+08; Wan+12], underestimate the interference caused to PUs, which can introduce a significant error depending on the system parameters chosen $(\delta$ and $T_S^{SU}/T_F^{SU})$. Regarding this point, the results highlight that a constant PU's behavior may also be a good approximation, namely when higher values of δ are considered. This can be observed for $\delta \approx 15$, where the interference caused to PUs is less than 3% when $T_S^{SU}/T_F^{SU} > 10\%$, for any value of τ^{PU}.

3.4 Conclusions and Final Remarks

The current chapter presents an exhaustive analysis on the performance of the spectrum sensing task in single-radio CRNs using the EBS as the spectrum sensing technique. Starting from the assumption that a PU does not changes its behavior during the same SU's operation cycle, an assumption widely adopted in the literature, we characterize and derive closed-form expressions for the probabilities of detection and false alarm, as well as the system goodput and the interference caused to the primary network. Following the same assumption, different parameterization criteria are compared to determine the decision threshold used in the EBS. Each criterion is evaluated according to the system goodput and primary network's interference and the results show that, depending on the system network requirements, some criteria may be preferred to others. For example, while C_1 and C_4 are frequently adopted in the literature, the results have showed that C_3 can exhibit almost the same behavior in terms of the interference caused to PUs and it outperforms C_4 in terms of SUs' goodput. On the other hand, if the level of admissible interference of the PU's system is high (*e.g.* for CDMA systems), C_2 and C_5 can be a good criteria because they exhibit better performance in terms of SUs' goodput.

In the second part of this chapter we analyze the impact of considering that PUs always keep their activity state during the SU's spectrum sensing task. In order to evaluate the impact of this approximation, we study a scenario where a PU changes its activity state at most once during the same SU's operation cycle. First we derive new closed-form expressions for the probabilities of detection and false alarm, and then we derive a new analytical model for the primary network's interference, whose accuracy is assessed through simulation results. The results show that the interference caused to PUs is always underestimated when a constant PUs' behavior is considered, *i.e.*, when a PU does not change its behavior during a SU's frame. However, we also prove that even considering a constant PUs' behavior, the interference caused to the primary network can be almost negligible when the frame length of the PUs is too large when compared to the SUs' operation cycle.

CHAPTER 4

MAC Scheme: a Single-Channel Approach

4.1 Introduction

MAC schemes take huge responsibility when handling the medium access control and coordination over wireless channels. In wireless networks, several users may compete for the wireless spectrum in a simultaneous way, increasing the number of access collisions and the interference between them. As described in Chapter 2, the peculiar characteristics of CRNs increase the complexity of MAC protocols that should be able to adapt to the unique features of CRNs and be capable of use the spectrum opportunities even in highly dynamic environments.

The development of a CR MAC protocol must take into consideration different features of the network, including but not limited to the number of opportunistic access channels and the number of radios available in each SU. An important requirement is the type of MAC architecture. In several scenarios a single SU or a set of SUs may be responsible for the medium access control (centralized architecture). In other scenarios a distributed architecture is desirable, where all SUs are able to autonomously decide their medium access. In this chapter we focus our attention in the development of a CR MAC scheme capable to successfully operate in a single-channel scenario and in a decentralized way.

Different MAC protocols have already been proposed for DCRNs. Most of them adopt random access philosophies to implement a SU's distributed channel access [Che+11; Lie+08; Zha+07a]. However, random contention-based schemes may exhibit low performance, because they tradeoff between the minimization of the probability of collision and the probability of finding idle medium access slots [Heu+05]. Differently, reservation-based schemes have been proposed to reduce the number of idle slots needed to schedule a SU's transmission. This is an important advantage since the idle slots decrease the network's performance due to the waste of transmission opportunities. Numerous reservation-based MAC protocols have been proposed for wireless networks [Nat+13]. The works in [Zha+10] and [Hon+10] aim to decrease the end-to-end delay and power consumption in wireless sensor networks when bursty and high traffic load is considered by taking advantage of the already used control packets (RTS-CTS) to reserve the transmission. The asynchronous nature of this protocol is not indicated for DCRNs because all SUs need to be synchronized to sense the spectrum. Regarding the CRNs, most of the reservation-based MAC schemes addressed in the literature [CC09; DD+12; Lia+11] are focused on multichannel scenarios assuming the availability of a CCC [Wan+11], or demand for more than one transceiver [KA08; SZ08].

Differently from the works described before, in this chapter we present an innovative and, as far as we know, the first reservation-based split-phase CR MAC protocol for DCRNs: the Cognitive Radio Reservation MAC protocol (C2RMAC). The C2RMAC protocol can be particularly advantageous when high dissimilarity of spectrum sensing decisions achieved by the different SUs is observed in a given frame. When this occurs the number of competing SUs is a time-varying parameter and the reservation scheme can efficiently accommodate the competing SUs by dynamically varying the number of reserved frames according to the number of SUs requesting for transmission. By this way, we avoid the underperformance caused by the use of traditional random contention schemes, namely when the level of nodes' contention does not take the number of competing nodes into account.

The main innovation of the proposed MAC protocol is its design. The C2RMAC relies on two stages. The first stage lasts a single SU's frame and is used to decrease the probability of collision between SUs, by reducing the number of competing SUs. The second stage starts with a reservation phase where SUs may schedule their transmissions, and finishes with the transmission phase, where the SUs effectively access the channel. Therefore, C2RMAC is able to reduce the number of idle frames usually left unused by the secondary network, thus increasing the network's goodput when compared to traditional random contention-based CR MAC protocols.

We start this chapter by detailing the operation mode of the proposed CR MAC protocol. Then, and assuming a scenario of homogeneous channel sensing conditions, which occurs when all SUs equally decide about the channel's occupancy, an analytical model for the secondary network's goodput and service time is derived. The performance of C2RMAC is evaluated for different network scenarios and an optimization study is presented.

Different from what is usually found in the literature, the performance of the proposed MAC scheme is also evaluated under the scenario of channel sensing heterogeneity, which may occur when different SUs achieve different sensing outcomes, making the number of SUs competing for the medium a time-varying parameter. As far as we know this is the first work to handle such scenario, which increases the complexity of the MAC protocol modeling task. Under the assumption of sensing heterogeneity a new analytical model for the service time achieved by the protocol is derived. The model relies on two independent Discrete Time Markov Chains (DTMCs), which model the behavior of a transmitting SU, and the operating mode of the SU responsible for the synchronization of the protocol, respectively. The individual throughput achieved by a SU is also characterized and validated. For both homogeneous and heterogeneous channel sensing scenarios it is provided a comparison of the performance achieved by C2RMAC with other reference protocols.

This chapter is organized as follows: the description of the system, including the system assumptions and the principle of operation of the proposed single-channel CR MAC protocol, is presented in Section 4.2; Section 4.3 models and evaluates the goodput and the packet service time achieved with C2RMAC considering homogeneous spectrum sensing conditions; the performance of the proposed protocol under heterogeneous spectrum sensing conditions is evaluated in Section 4.4; finally the chapter's conclusions are presented in Section 4.5.

4.2 System Characterization

The system characterization adopted to evaluate the performance of the proposed MAC protocol is presented in this section. Subsection 4.2.1 introduces the system assumptions and Subsection 4.2.2 describes the operation of the protocol.

4.2.1 System Assumptions

In this chapter a single-hop single-channel network is considered, where several SUs may transmit in an opportunistic way when the channel is not being used by PUs. The proposed MAC scheme works in a distributed way, without being coordinated by a central node. While C2RMAC can be adopted in a scenario where each node transmits to a random destination, this chapter considers that SUs always transmit to a fixed destination, which is referred to as a Secondary User Access Point (SU AP), as illustrated in Figure 4.1. Both SUs and the SU AP are within the transmission range of each other, and each node is equipped with a single radio transceiver.

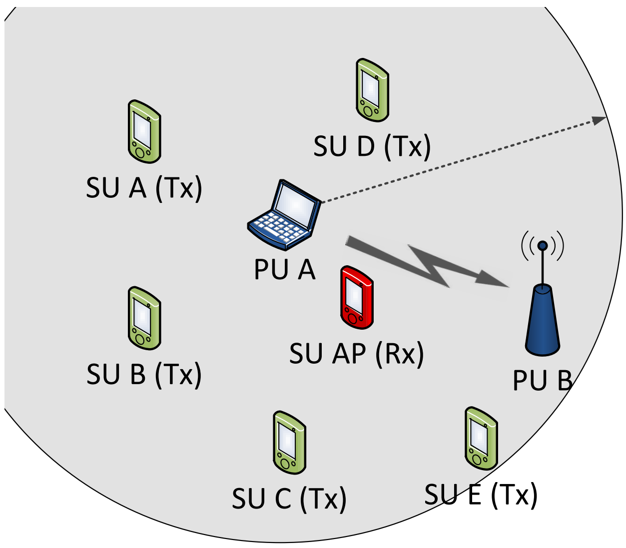


Figure 4.1: The CRN architecture considered under homogeneous channel sensing conditions.

As discussed in the previous chapter, a SU equipped with a single transceiver has to divide its operation cycle (frame structure) into spectrum sensing and spectrum access periods, with durations T_S^{SU} and T_D^{SU} respectively. However, in order to ensure the correct operation of the proposed MAC scheme under heterogeneous spectrum sensing conditions, the SU's frame structure will have to account with an additional time interval needed to synchronize the SUs, denoted by φ as illustrated in Figure 4.2. Therefore, the SU's frame lasts for $T_F^{SU} = T_S^{SU} + \varphi + T_D^{SU}$.

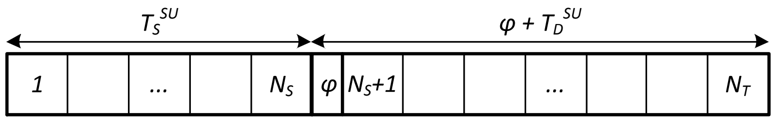


Figure 4.2: SU's frame structure with synchronization time interval φ.

Initially, a SU assumes the synchronization task if it does not receives synchronization information during a pre-defined time interval. This is similar to the synchronization schemes already proposed for distributed MAC schemes of wireless sensor networks, where any node can start transmitting a SYNC packet [Ye+02]. For the sake of simplicity, in what follows, we consider that the SU AP is always responsible for the synchronization of the SUs. The synchronization is done by transmitting a narrow out-of-band tone.

Regarding the spectrum sensing task it is adopted the study presented in the previous chapter. By assuming that SU frames are small enough compared with PU frames, we can consider, without loss of generality, that PUs will not change their activity state (active or inactive) during the same SU's frame. Therefore, considering that τ^{PU} represents the probability of having a PU currently transmitting in the channel, and that $\overline{\tau^{PU}}$ denotes the opposite case, the probability of a SU deciding that the channel is vacant is given by (as derived in (3.8))

$$P_I = \overline{\tau^{PU}}(1 - P_{FA}) + \tau^{PU}(1 - P_D), \tag{4.1}$$

and different notations $P_{I,i}$ and $P_{I,AP}$ are introduced for the probability P_I of the i-th SU and the SU AP, respectively. From hereafter we denote as idle frames the frames where the spectrum sensing scheme does not detect any PUs' activity with probability P_I, and busy frames to denote the opposite case with probability $1 - P_I$.

4.2.2 A Single-Channel CR MAC Protocol: C2RMAC

Figure 4.3 introduces C2RMAC protocol, in which a **transmission cycle** comprises two stages of contention. The out-of-band tone transmitted by the SU AP always indicates the current stage of contention. The **first stage of contention** aims to decrease the number of collisions between SUs by reducing the number of competing SUs. This stage lasts a single idle frame (1^{st} frame in the example depicted in Figure 4.3), being its spectrum access period T_D^{SU} divided in cw_1 mini-slots[1]. In the beginning of the first stage the SUs randomly select a mini-slot with probability $\tau_1 = 1/cw_1$, which serves to announce its intention to access the medium. However, a SU will only transmit its mini-packet if the previous mini-slots were found idle, *i.e.* if a SU senses a SU's transmission in a mini-slot before the randomly selected one, it will postpone the transmission attempt to the next transmission cycle. According to this rule only the SUs that have transmitted a mini-packet in the first stage will be able to compete in the second stage. In Figure 4.3, SUs B and C transmit a mini-packet in the second mini-slot of the 1^{st} frame, while SU A will not transmit its mini-packet

[1]Note that the term mini-slots is used for MAC purposes, while the term slot, adopted in Section 3.1, is only used for channel sensing purposes.

scheduled for the 4^{th} mini-slot because SUs B and C had already transmitted. This means that only SUs B and C will compete in the second contention stage, since they were the first nodes accessing a mini-slot in the frame[2].

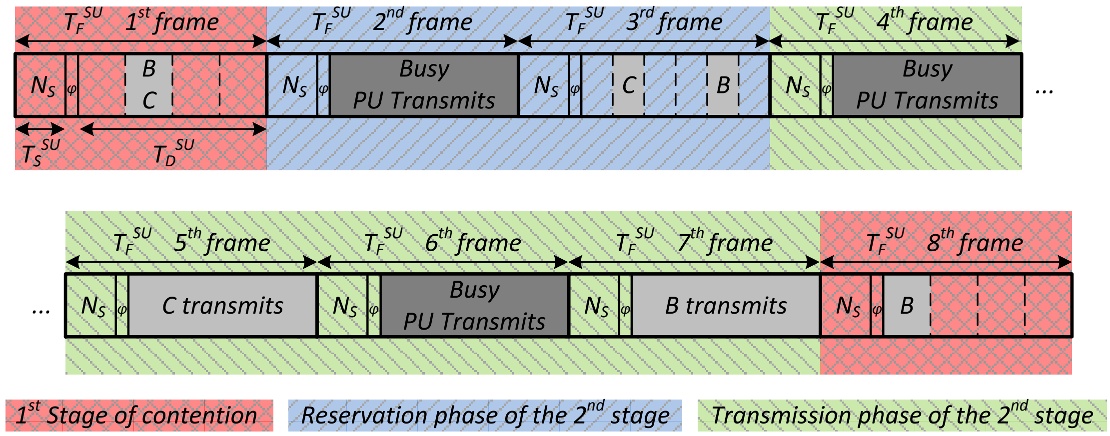


Figure 4.3: C2RMAC transmission cycle ($cw_1 = 4$ and $cw_2 = 6$).

Nodes selected in the first stage will be able to compete in the **second stage of contention**. The spectrum access period T_D^{SU} of the first idle frame in the second stage is divided into cw_2 mini-slots ($cw_2 = 6$ in this case), which are used to reserve at most cw_2 future idle frames for transmission. This is called the **reservation phase of the second stage**. Admitting that n_{St2} SUs compete for medium access in the second stage, they reserve an idle frame by transmitting a mini-packet in one of the frame's mini-slots $\{1, 2, ..., cw_2\}$. Each SU chooses a mini-slot in the second stage with probability $\tau_2 = 1/cw_2$. In the example illustrated in Figure 4.3, the second stage of contention begins in the 2^{nd} frame, however the reservation phase only occurs in the next idle frame, which is the 3^{rd} frame. The SU C transmits a mini-packet in the second mini-slot and the SU B transmits its mini-packet in the fifth mini-slot. The number of idle frames reserved for future transmission is equal to the number of busy mini-slots, and the assignment of the idle frames follows the sequence of accesses observed in the cw_2 mini-slots. Because the protocol is decentralized, each SU assigns itself an idle frame, *i.e.* if a SU transmits a mini-packet in the k-th busy mini-slot, $1 \leq k \leq cw_2$, it reserves the subsequent k-th idle frame for its own transmission[3]. Implicitly, it is assumed that if multiple SUs access in the same mini-slot, they will collide in the reserved frame. This fact is taken into account in the proposed analysis.

After elapsing the cw_2 mini-slots of the reservation phase, the SUs use the reserved frames to transmit, and this period is denominated **transmission phase of the second stage**. In the example illustrated in Figure 4.3, the first idle frame occurring after the 3^{rd} frame is reserved for the transmission of node C, which occurs in the 5^{th} frame illustrated in Figure 4.3. The same follows for the reservation done by node B, which transmits in the 7^{th} frame. The transmission cycle lasts

[2]For the sake of simplicity, PU's frames were illustrated having the same size as SU's frame.

[3]To this purpose, it is assumed that the SUs are able to detect a transmission of one or more mini-packets in a mini-slot before the one where they access, which is nowadays a reality in every MAC protocol following a carrier sensing approach.

for the first 7 frames and a new transmission cycle begins in the 8^{th} frame. Neglecting the number of busy frames occupied by PU's transmissions ($2^{nd}, 4^{th}$ and 6^{th} frames in the example), the second stage lasts for the number of idle frames equal to the number of busy mini-slots observed in the reservation phase (5^{th} and 7^{th} frames), plus the idle frame where the cw_2 mini-slots were defined (3^{rd} frame).

4.3 Homogeneous Channel Sensing Conditions

This section tackles the performance of the proposed single-channel MAC scheme under homogeneous channel sensing conditions, *i.e.*, when all the SUs have the same sensing decision output for the same sensing period. Subsection 4.3.1 derives an analytical model for the goodput and packet service time achieved by the proposed protocol. Subsection 4.3.2 discusses the protocol optimization and Subsection 4.3.3 evaluates the performance of the proposed scheme under saturated and unsaturated conditions.

4.3.1 System Analysis

In this section we formulate an analytical model for the goodput and packet service time achieved by C2RMAC considering homogeneous channel sensing conditions.

4.3.1.1 Goodput

The system model considers a secondary network formed by the set N of n SUs, where each SU i generates packets with a probability $P_{p,i}, \forall i \in N$. Under saturated traffic generation, all nodes always have a packet to transmit $(P_{p,i} = 1, \forall i \in N)$ and the expected number of SUs competing in the first stage is given by $n_{St1} = n$. However, since both saturated and non-saturated traffic generation conditions are considered, the number of SUs competing in the first stage, represented by the random variable N_{St1} with Probability Mass Function (PMF) $Pr\{N_{St1} = i\}$, will depend on the probability of each SU generating a packet $(P_{p,i})$.

Since only a single busy mini-slot is observed in the first stage, the SUs transmitting in the busy mini-slot will compete in the second stage. Assuming that i SUs compete in the first stage, which occurs with probability $Pr\{N_{St1} = i\}$, and being N_{St2} a random variable representing the number of nodes selected to compete in the second stage, the PMF of N_{St2} (derived in the Appendix A) is given by

$$Pr\{N_{St2} = k\} = \begin{cases} \binom{i}{k} \dfrac{1}{{cw_1}^i} \displaystyle\sum_{m=0}^{cw_1-2} (cw_1 - m - 1)^{(i-k)}, & 1 \leq k < i \\ \dfrac{cw_1}{{cw_1}^i}, & k = i \end{cases}. \tag{4.2}$$

For a secondary network formed by n SUs, the expected number of SUs selected to compete in the second stage is given by

$$n_{St2} = \sum_{i=1}^{n} Pr\{N_{St1} = i\} \sum_{k=1}^{i} k\, Pr\{N_{St2} = k\}. \tag{4.3}$$

As mentioned in Section 4.2, the SUs selected in the first stage do not start accessing the medium in the first idle frame of the second stage. Instead, the transmission period T_D^{SU} of the first idle frame in the second stage is divided into cw_2 mini-slots, which are used to reserve future idle frames for transmission. The number of idle frames reserved for the transmission phase of the second stage is equal to the number of busy mini-slots observed during the reservation phase. Admitting that n_{St2} nodes compete for the medium in the reservation phase of the second stage, and being CW_{2B} a random variable indicating the number of busy mini-slots in the reservation phase, the PMF of CW_{2B} (derived in Appendix B) is given by

$$Pr\{CW_{2B} = x\} = \begin{cases} \frac{1}{cw_2^{\lceil n_{St2} \rceil}} \binom{cw_2}{x} \sum_{k=0}^{x-1} (-1)^k \binom{x}{k} (x-k)^{\lceil n_{St2} \rceil}, & 1 \leq x \leq \min(cw_2, \lceil n_{St2} \rceil) \\ 0, & \text{otherwise.} \end{cases} \tag{4.4}$$

Consequently, the expected number of idle frames reserved for transmission is given by

$$\mathbb{E}[CW_{2B}] = \sum_{x=1}^{\min(cw_2, \lceil n_{St2} \rceil)} x \, Pr\{CW_{2B} = x\}. \tag{4.5}$$

Note that neglecting the frames sensed busy, the first and the second contention stages, *i.e.* the transmission cycle, lasts on average for $2 + \mathbb{E}[CW_{2B}]$ idle frames, since 2 idle frames are used to implement the cw_1 and cw_2 mini-slots, and the remaining ones are reserved for SUs transmissions.

The aggregate goodput of this scheme represents the useful throughput achieved by the n_{St2} nodes, *i.e.*, the ratio of SU's frames with a single SU's transmission without PU's activity, and is given by

$$G_{hom}^{SU} = \lceil n_{St2} \rceil \tau_2 (1 - \tau_2)^{\lceil n_{St2} \rceil - 1} \overline{\tau^{PU}} (1 - P_{FA}) \alpha_G \alpha_C, \tag{4.6}$$

where $\alpha_C = cw_2 / (2 + \mathbb{E}[CW_{2B}])$ represents a ratio between the maximum number of frames allowed to be reserved, cw_2, and the expected number of idle frames needed to complete one transmission cycle. Equation (4.6) defines a bound for the maximum achievable goodput for the case when all SUs have an homogeneous detection of the spectrum sensing occupancy. We highlight that by assuming homogeneous spectrum sensing, the realization of the spectrum sensing process provides the same outcomes for every SU. Thus, a generic probability of false alarm (P_{FA}) can be used in (4.6). $\alpha_G = T_D^{SU} / (T_S^{SU} + \varphi + T_D^{SU})$, with $\alpha_G < 1$, represents a loss of goodput due to the sensing period (T_S^{SU}) and the time needed to synchronize the SUs in the beginning of the first and second contention stages (φ).

4.3.1.2 Packet Service Time

The packet service time is traditionally defined as the interval from the instant when a packet arrives at the head of the transmitter's buffer queue, until the instant when its transmission ends. In the proposed scheme the decision to transmit a packet occurs if a node is able to send its reservation mini-packet in the reservation phase of the second contention stage. We consider that a packet can arrive uniformly during the transmission cycle $k - 1$, and its transmission during the transmission cycle k is also uniformly distributed. When the packet is transmitted within a single transmission cycle its service time lasts on average one transmission cycle. The expected length of one transmission cycle is measured in SU's frames and is given by

$$\mathbb{E}\left[T_{Cycle}^{hom}\right] = \frac{2 + \mathbb{E}\left[CW_{2B}\right]}{P_I}, \tag{4.7}$$

where $2 + \mathbb{E}\left[CW_{2B}\right]$ represents the expected number of idle frames in a transmission cycle. $\mathbb{E}\left[T_{Cycle}^{hom}\right]$ is normalized by the probability of detecting idle frames (P_I) to account with the expected number of frames detected busy (occupied by the PUs) during the transmission cycle.

In the best case, a packet arriving during the k-th transmission cycle is transmitted in the $k+1$-th one. However, depending on the selection that have occurred in the first stage, a packet may wait multiple transmission cycles to be effectively transmitted. Let Y be a random variable representing the number of transmission cycles needed to transmit a packet, whose PMF is given by

$$Pr\left\{\mathrm{Y} = k\right\} = \begin{cases} P_{2St}(1 - P_{2St})^{k-1}, & k \geq 1 \\ 0, & \text{otherwise,} \end{cases} \tag{4.8}$$

where P_{2St} represents the individual probability of a SU being selected to compete in the second stage, which occurs when a SU competes in the busy mini-slot with probability τ_1, and none of the remaining SUs have transmitted in the x idle mini-slots prior to the busy one with probability $\left[(1-\tau_1)^{(\lceil n_{St1}\rceil - 1)}\right]^x$, *i.e.*,

$$P_{2St} = \sum_{x=0}^{cw_1 - 1} \tau_1 (1 - \tau_1)^{(\lceil n_{St1}\rceil - 1)x}. \tag{4.9}$$

n_{St1} is the expected number of SUs competing in the first contention stage and is given by

$$n_{St1} = \mathbb{E}\left[N_{St1}\right] = \sum_{i=0}^{n} i \; Pr\left\{N_{St1} = i\right\}. \tag{4.10}$$

Let $T_{service}^{hom}$ be a discrete random variable to denote the packet service time measured in units of SU frame's duration. The Probability Generating Function (PGF) for the packet service time is given by

$$Q_{T_{service}^{hom}}(z) = \sum_{k=1}^{\infty} Pr\left\{\mathrm{Y} = k\right\} z^{k\,\mathbb{E}\left[T_{Cycle}^{hom}\right]}, \tag{4.11}$$

and we can easily obtain the average packet service time as follows

$$\mathbb{E}\left[T_{service}^{hom}\right] = \frac{\partial}{\partial z} Q_{T_{service}^{hom}}(z)\bigg|_{z=1} = Q'_{T_{service}^{hom}}(1), \tag{4.12}$$

where $Q'_{T_{service}^{hom}}(1)$ refers to the first-order derivative of $Q_{T_{service}^{hom}}(z)$ at $z = 1$.

4.3.2 Protocol's Optimization

C2RMAC was optimized to achieve the maximum aggregated goodput in the secondary network guaranteeing a given level of protection to the primary network. For that, C2RMAC was optimized for different number of SUs by finding the optimal number of sensing samples N_S and mini-slots $(cw_1$ and $cw_2)$.

In order to guarantee that all SUs have the same probability of false alarm, we fixed the energy detector threshold (θ) and the goodput achieved by C2RMAC is optimized as follows

$$\begin{aligned} \max_{cw_1, cw_2, N_S} \quad & G^{SU}_{hom}, \\ \text{s.t.} \quad & P_D \geq P_D^{min} \\ & N_S^{min} \leq N_S \leq N_T \\ & 1 \leq cw_1 \leq cw_1^{max} \\ & 1 \leq cw_2 \leq cw_2^{max}. \end{aligned}$$

Basically the optimal goodput is computed taking into account several constraints: $P_D \geq P_D^{min}$ guarantees a minimum level of protection to PUs; $N_S \geq N_S^{min}$ assures the minimum number of sensing samples needed to approximate P_D; and cw_1 and cw_2 are limited to the maximum number of mini-slots that a frame can hold[4].

The scenario considered for the protocol's optimization was the following: one pair of PUs (a transmitter and a receiver) use the channel with probability $\tau^{PU} = 0.1$ and multiple SUs opportunistically transmit to a single SU AP, when the channel is sensed to be vacant from primary activity. The adopted parameters for the PU's transmitting signal and for the energy detector implemented in the SUs are described in Table 4.1. The energy detector threshold (θ) was defined to 38.3 Joules, following the parametrization criterion C_4 defined in Subsection 3.2.4 and considering a SNR of $\lambda = 2dB$. In order to protect the primary network we assume that all the SUs have the same detection performance with $P_D^{min} = 0.95$ and $P_{FA} = 0.01$. The maximum number of mini-slots in the first and second stages, based on a SU's frame duration of $T_F^{SU} = 20ms$, was set to $cw_1^{max} = cw_2^{max} = 100$.

Table 4.1: Parameters used in the energy detection (μ_s, σ_s, μ_w and σ_w represent the mean and variance of the PU's transmitted signal and noise, respectively).

Parameter	Value
W	10 kHz
Channel Sampling Period	50 μs
T_F^{SU}	20.0 ms
N_S^{min}	20
μ_s	1.58 (2dB)
σ_s^2	3
μ_w	1 (0dB)
σ_w^2	1

[4]It is assumed that the minimum mini-slot length is long enough to comprise the transmission of an ACK, similarly to the IEEE 802.11g technology.

C2RMAC consists of two contention stages. As explained in Subsection 4.2.2, the first stage is used to decrease the number of SUs competing in the second stage, which consequently decreases the number of collisions in the second stage. The second stage is used to eliminate all the idle frames that will not be used during the transmission period: the number of busy mini-slots in the second stage represents the number of idle frames reserved for transmission during the transmission period. If we take into consideration (4.6), and based on the aforementioned explanation, we can see that C2RMAC achieves the highest goodput when it reduces the number of collisions during the second stage $(\lceil n_{St2} \rceil \tau_2 (1-\tau_2)^{\lceil n_{St2} \rceil - 1})$. For that, the solution of the optimization problem indicates that the number of mini-slots in the second stage (cw_2) should be the highest possible. Regarding cw_1, the solution of the optimization problem indicates that cw_1 increases with the number of competing nodes.

In order to sustain the previous analysis, Figure 4.4 shows the theoretical results of the aggregated normalized goodput achieved by the CRN - obtained from (4.6)-, considering different values of cw_1 and cw_2. We can see that for a small number of SUs $(n = 25)$, the highest goodput is achieved when the number of mini-slots in the first stage is close to 1, and consequently the importance of the first stage is marginal. However, as the number of SUs increases (to $n = 50$ and $n = 100$ in Figures 4.4(b) and 4.4(c), respectively) the number of mini-slots in the second stage are not enough to avoid collisions between SUs, and then the number of mini-slots in the first stage is increased to reduce the number of SUs competing in the second stage.

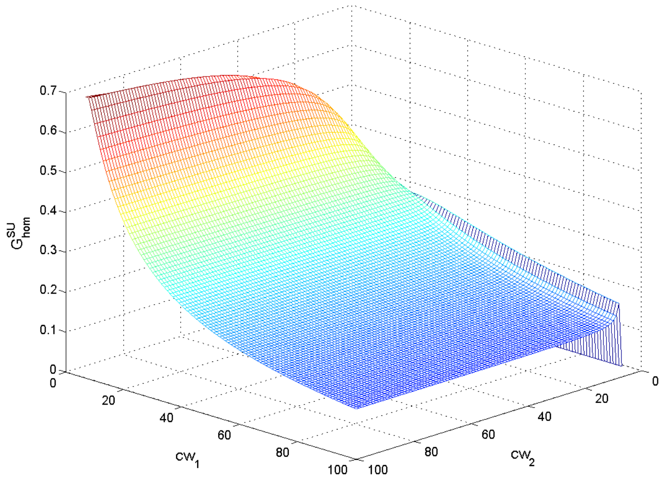
Regarding the optimal number of mini-slots in the second stage, Figure 4.4 shows that for any number of SUs, the highest goodput is achieved when cw_2 is the highest possible. However, although we have set the maximum number of mini-slots in the second stage to $cw_2^{max} = 100$, the optimal value of cw_2 never exceeds 94 because the SU's frame has to account with the spectrum sensing task, and therefore reducing the amount of time available in the spectrum access period (T_D^{SU}) to perform the second stage of contention.

As stated before, C2RMAC was designed to achieve high levels of spectrum utilization by reducing the collision between SUs and the number of idle frames unused by the secondary network. Therefore, it is also important to study and compare the amount of idle frames and frames with collisions observed with our proposal. The expected number of idle mini-slots in the second stage is directly given by

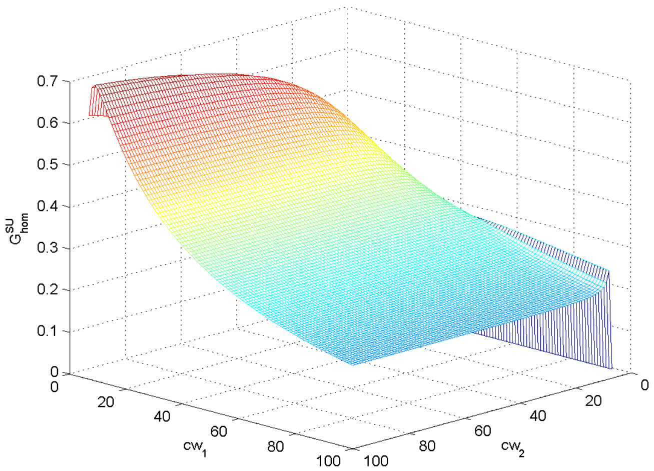
$$cw_2^{idle} = cw_2 - \mathbb{E}\left[CW_{2B}\right], \tag{4.13}$$

however its value does not impacts the length of the transmission period, because the length of the transmission period only depends on the number of busy mini-slots (being its average given by $\mathbb{E}\left[CW_{2B}\right]$). On the other hand, the amount of mini-slots in the second stage where a collision is observed will have impact in the performance of C2RMAC. This is because the number of collisions observed during the second stage will be also observed during the transmission period, and its average number is given by

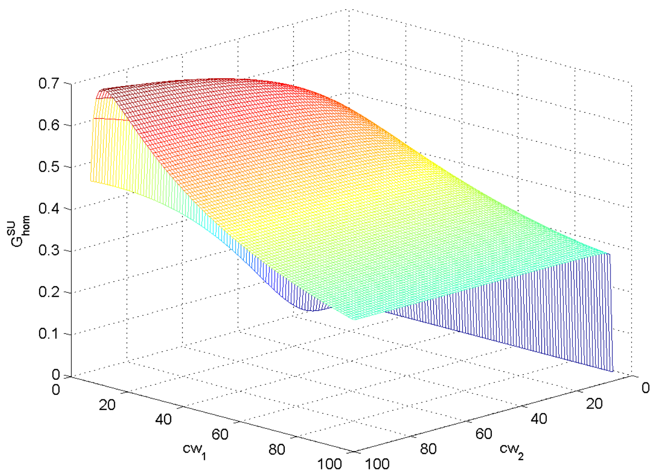
$$cw_2^{coll} = cw_2 - cw_2^{idle} - cw_2 \lceil n_{St2} \rceil \tau_2 \left(1-\tau_2\right)^{\left(\lceil n_{St2} \rceil - 1\right)}.$$



(a) $n = 25$.



(b) $n = 50$.



(c) $n = 100$.

Figure 4.4: Aggregated normalized goodput for different values of cw_1 and cw_2 and network sizes.

The probabilities of finding an idle mini-slot ($P_{cw_2^{idle}}$) and a mini-slot with a collision ($P_{cw_2^{coll}}$) can be derived as follows

$$P_{cw_2^{idle}} = \frac{cw_2^{idle}}{cw_2}, \tag{4.14}$$

$$P_{cw_2^{coll}} = \frac{cw_2^{coll}}{cw_2}. \tag{4.15}$$

Table 4.2 contains the optimal values of cw_1 and cw_2 that maximize the aggregated normalized goodput of the secondary network (G_{hom}^{SU}), as well as the probabilities $P_{cw_2^{idle}}$ and $P_{cw_2^{coll}}$ for different number of SUs, when $\tau^{PU} = 0.1$. We can see that, although the probability of finding an idle mini-slot is very high for any value of n, it does not affect the performance of C2RMAC, because only the slots found busy will be used for reservation. Thus the important point here is to assure that the probability of collision is kept low, which is observed.

Table 4.2: C2RMAC protocol: optimal values of cw_1 and cw_2 for different number of SUs, as well as the optimal goodput, the idle mini-slot probability and the probability of finding busy mini-slots.

	Number of SUs - n									
	10	20	30	40	50	60	70	80	90	100
$G_{hom}^{SU}(\times 10^{-2})$	66.51	68.58	68.46	68.58	68.63	68.58	68.66	68.58	68.66	68.63
cw_1	1	1	2	2	3	3	4	5	5	6
cw_2	94	94	94	94	94	94	94	94	94	94
$P_{cw_2^{idle}}$ $(\times 10^{-2})$	89.86	80.74	85.18	80.74	83.67	80.74	82.93	84.27	82.49	83.67
$P_{cw_2^{coll}}$ $(\times 10^{-2})$	0.48	1.89	1.08	1.89	1.33	1.89	1.46	1.23	1.55	1.33

For comparison purposes, Table 4.3 presents the probabilities of finding idle frames and frames where a collision was observed for *slotted* CR-ALOHA and CR-CSMA protocols [Che+11], two of the most cited contention-based CR MAC protocols in the literature. The same scenario was maintained, and the backoff window used by of the *slotted* CR-ALOHA and CR-CSMA was set to $2n$.

Table 4.3: Probabilities of finding idle frames and frames with collision for *slotted* CR-ALOHA and CR-CSMA MAC protocols, for different number of SUs.

	Number of SUs - n									
	10	20	30	40	50	60	70	80	90	100
	slotted CR-ALOHA									
$P_{frames^{idle}}$ $(\times 10^{-2})$	34.91	34.93	34.91	34.90	34.92	34.91	34.90	34.89	34.86	34.89
$P_{frames^{coll}}$ $(\times 10^{-2})$	22.22	23.21	23.49	23.60	23.72	23.81	23.85	23.87	23.90	23.85
	CR-CSMA									
$P_{frames^{idle}}$ $(\times 10^{-2})$	32.08	30.99	30.57	30.35	30.28	30.21	30.15	30.18	30.15	30.22
$P_{frames^{coll}}$ $(\times 10^{-2})$	14.29	16.83	17.62	18.13	18.36	18.53	18.73	18.81	18.76	18.82

As we can see, the probability of collision of both contention-based schemes is considerably higher when compared with C2RMAC. Regarding the idle probability, we highlight that C2RMAC's $P_{cw_2^{idle}}$, can not be compared with *slotted* CR-ALOHA and CR-CSMA's $P_{frames^{idle}}$, because in *slotted*

CR-ALOHA and CR-CSMA it effectively represents unused frames, while in C2RMAC it only represents unused idle mini-slots during the second stage. It can be seen that when *slotted* CR-ALOHA and CR-CSMA are adopted, a large amount of idle frames are left unused, contributing for the poor performance of the protocols.

4.3.3 Model Validation and Performance Analysis

This subsection validates the accuracy of the analytical model for the goodput and packet service time achieved by the C2RMAC, derived in Subsection 4.3.1. The performance of the C2RMAC protocol is also compared with the two contention-based CR MAC protocols previously discussed, the *slotted* CR-ALOHA and the CR-CSMA.

The analytical models for the goodput and packet service time are compared with simulation results. The theoretical values of the goodput, G_{hom}^{SU}, are obtained using (4.6), while the theoretical results for the packet service are obtained by multiplying $\mathbb{E}\left[T_{service}^{hom}\right]$, computed from (4.12), with the SU's frame length, T_F^{SU}, because the packet service time is illustrated in time units (seconds). The simulated scenario is the same as mentioned in the beginning of this section, *i.e.*, it is formed by a pair of PUs (transmitter and receiver) and n SUs trying to transmit to a SU AP. The goodput and the packet service time of the secondary network is evaluated for different network sizes, $n = 25, 50$, and 100, and for different levels of spectrum availability rate, $\overline{\tau^{PU}}$. The goodput achieved by the secondary network is validated under saturated network conditions, while the packet service time is validated for both saturated and non-saturated network conditions. Theoretical results are represented by lines and simulation results are represented by markers.

Figures 4.5(a) and 4.5(b) illustrate the effects of the spectrum availability rate and the network size in the secondary network's goodput and packet service time, respectively. The first observation goes to the accuracy of the analytical model where we can see that the theoretical results clearly match with the simulation results. Regarding the goodput achieved by the SUs, the results presented in Figure 4.5(a) show us that, for any value of spectrum availability, the C2RMAC protocol is able to use at most around 75% of the unused spectrum. For example for a spectrum availability of $\overline{\tau^{PU}} = 0.8$ the secondary network achieves a goodput of around 0.6, meaning that around 25% of the unused spectrum is spend a) the most part in the reservation process and b) a smaller part, as observed in the previous subsection, in collisions. From Figure 4.5(a) we can also see that the value of goodput keeps monotonically increasing with $\overline{\tau^{PU}}$ because, as $\overline{\tau^{PU}}$ increases, SUs would get more opportunities to access the channel. Furthermore, we observe that the number of competing SUs have a small effect on the aggregated goodput achieved by the secondary network.

Regarding the packet service time, it is observed that as the number of SUs increase, the average packet service time also increases. This fact is explained due to the SU's selection occurred in the first stage of contention: as the number of SUs increase, the chance of a SU to compete in the the second stage and transmitting a packet decreases, therefore increasing the packet service time. Figure 4.5(c) shows the packet service time versus the total offered traffic load, for the case when $\overline{\tau^{PU}} = 0.9$. As the total offered traffic load increases the packet service time also increases until reaching its maximum value, meaning that we have reached the network's saturation. Similar to

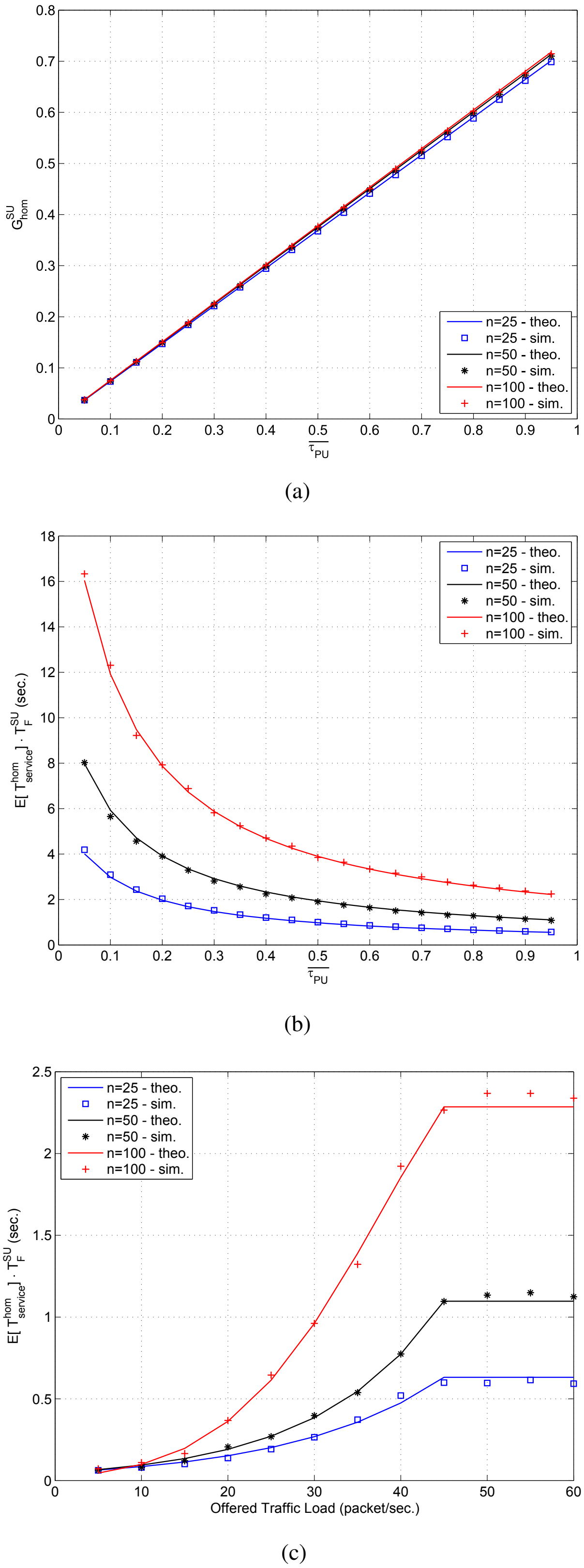


Figure 4.5: Achieved performance of secondary network in homogeneous spectrum sensing conditions: (a) aggregated normalized goodput; (b) average packet service time under saturated network conditions; (c) average packet service time versus the total offered traffic load with $\overline{\tau^{PU}} = 0.9$.

Fig. 4.5(b), as the number of SUs increase, the packet service time also increases explained by the increasing number of SUs competing for the channel.

Lastly, Figure 4.6 compares the goodput achieved by C2RMAC with *slotted* CR-ALOHA and CR-CSMA under saturated traffic conditions. The performance results plotted for the *slotted* CR-ALOHA and the CR-CSMA protocols were obtained from [Che+11], where the SU's frame duration was set to $T_S^{SU} + T_D^{SU} = 100\ ms$ and the backoff windows was set to a fixed value regardless the number of competing SUs. From Figure 4.6 we can see that the goodput achieved by C2RMAC protocol increased when compared to the one presented in Figure 4.5(a). This happens because the cost of the spectrum sensing period is almost negligible when the duration of the SU's frame is increased. Figure 4.6 also shows that C2RMAC achieves higher goodput than *slotted* CR-ALOHA and CR-CSMA protocols, mainly due to its design: the reservation stages of C2RMAC are able to reduce the number of idle frames and frames with collision observed in the contention-based medium access schemes, such as the *slotted* CR-ALOHA and the CR-CSMA.

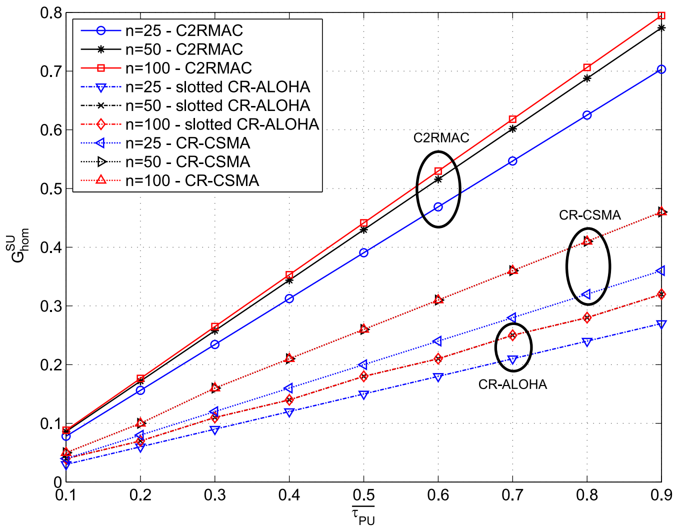


Figure 4.6: SU's goodput comparison among *slotted* CR-ALOHA, CR-CSMA and C2RMAC.

4.4 Heterogeneous Channel Sensing Conditions

One of the main contributions of this thesis relies on the fact that the proposed single-channel CR MAC scheme, C2RMAC, is evaluated in an heterogeneous spectrum sensing scenario, *i.e.*, for the same spectrum sensing period and due to imperfect sensing, channel conditions (e.g. fading and/or shadowing), or even due to the network topology as illustrated in Figure 4.7, all SUs (including the SU AP) may obtain different spectrum sensing outcomes. This means that, in the worst case, spectrum decisions achieved by each SU during the same spectrum period may be independent of each other.

Therefore, at each moment the operation of each SU and SU AP may be in different MAC states, requiring that the MAC states of the SU AP and the MAC states of each SU must be modeled in an independent manner. For that, we have decided to resort to DTMCs: one DTMC to model

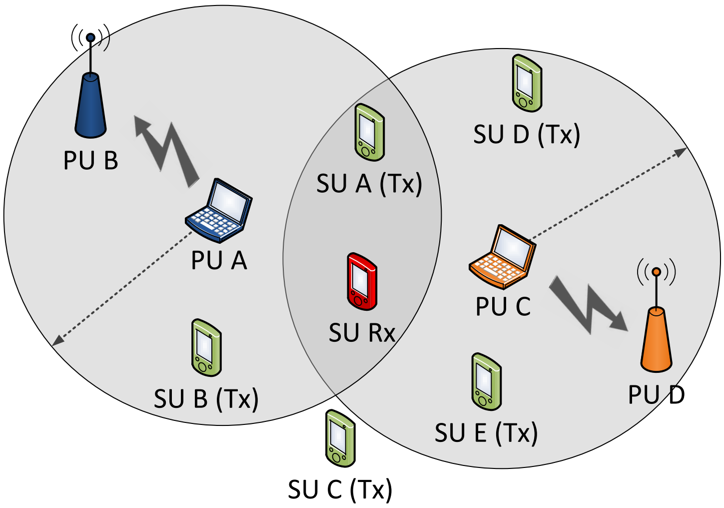


Figure 4.7: Hypothetical scenario of a network with heterogeneous channel sensing outputs due to the network topology. Here the SUs (SU A, SU B, SU C, SU D, SU E and SU Rx) may sense different channel states at the same instant of time, due to the different behavior of the PUs located in their neighborhood.

the SU AP and another DTMC to model the individual behavior of each SU. Before going into the details of each DTMC, let us overview the protocol's operation when a SU and the SU AP obtain different spectrum sensing outcomes for the same spectrum sensing period. When this occurs, the following scenarios must be considered:

1. The channel is busy for the SU AP and idle for a SU:
   a) if the protocol is in the reservation phase, the SU AP will not transmit the tone regarding the first and the second stage, and consequently the SU will not compete for the channel;
   b) if the protocol is in the transmission phase, the SU will transmit, and the transmission will not be considered for throughput because the channel is busy for the SU AP.
2. The channel is busy for the SU and idle for a SU AP:
   a) in this case, whether the protocol is in the reservation's phase or in the transmission's phase, the SU will lose the opportunity to compete or to transmit, while other SUs sensing the channel as being idle will advance with the protocol's operation.

4.4.1 System Analysis

In this subsection we formulate an analytical model for the individual transmission probability, packet service time and throughput achieved by the secondary network using the C2RMAC protocol under heterogeneous channel sensing conditions.

4.4.1.1 SU AP's Discrete Time Markov Chain

The DTMC illustrated in Figure 4.8 models the SU AP operation cycle. In the beginning of the cycle the SU AP is initially at state $\mathbf{Idle_{AP}}$. After sensing an idle frame, with probability $P_{I,AP}$, the SU AP proceeds to the first stage of contention ($\mathbf{St1_{AP}}$), where it will remain while the frames are declared idle and no SUs compete for the first stage (with probability $1 - P_{SU1}$).

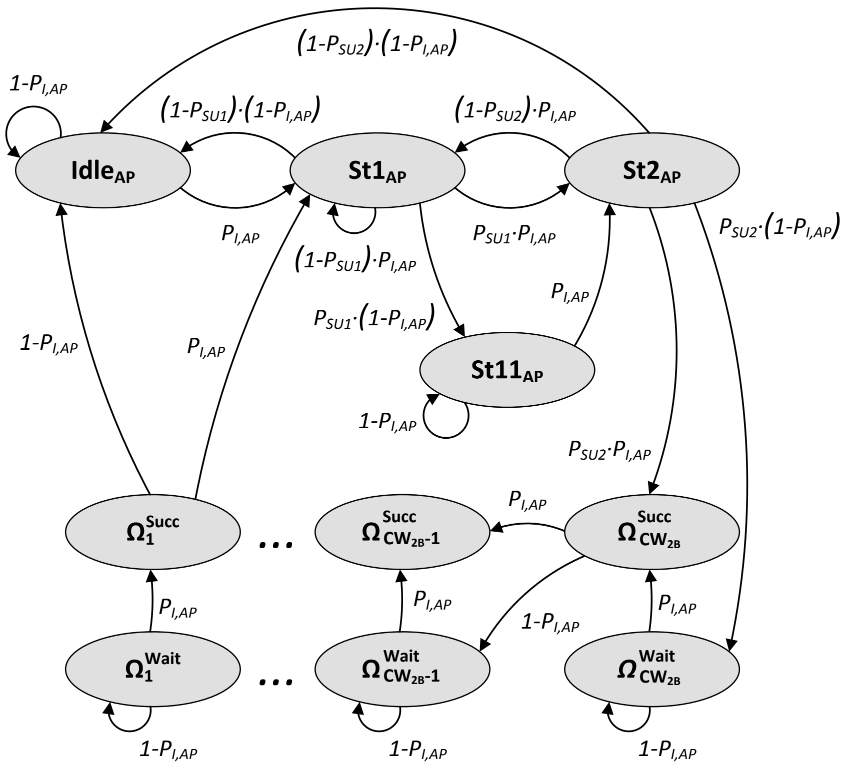


Figure 4.8: DTMC illustrating the SU AP's operation mode.

While in $\mathbf{St1_{AP}}$ if a busy frame is detected without having SUs competed in the first stage, the SU AP will return to the initial idle state ($\mathbf{Idle_{AP}}$). In the case of having SUs competing in the first stage, which occurs with probability P_{SU1}, the SU AP will proceed to the second stage ($\mathbf{St2_{AP}}$) in the next idle frame, or proceed to state $\mathbf{St11_{AP}}$ as busy frames are detected. Because it is assumed that SUs and the SU AP may experience different spectrum sensing results, it can happen that during the stage $\mathbf{St2_{AP}}$ all the SUs selected to compete in the second stage may declare a busy frame, and no one will compete. The probability of not having SUs competing in the second stage is given by $1 - P_{SU2}$. This situation makes the SU AP to restart the operation cycle by going from state $\mathbf{St2_{AP}}$ back to $\mathbf{St1_{AP}}$ or $\mathbf{Idle_{AP}}$ in the next frame, depending if the frame is declared idle or busy, respectively.

In the case of having SUs competing in the second stage, which occurs with probability P_{SU2}, the SU AP starts the transmission phase, which will be used by the SUs to communicate with the SU AP. The transmission phase starts when a transition from $\mathbf{St2_{AP}}$ to $\Omega^{\mathbf{Wait}}_{\mathbf{CW_{2B}}}$ or $\Omega^{\mathbf{Succ}}_{\mathbf{CW_{2B}}}$ is observed. During the transmission phase, the SU AP has to wait for CW_{2B} idle frames before completing the operation cycle: after observing CW_{2B} idle frames the SU AP reaches the state

$\Omega_{\mathbf{1}}^{\mathbf{Succ}}$, restarting the cycle from $\mathbf{Idle_{AP}}$ or $\mathbf{St1_{AP}}$, depending on the spectrum status.

The formal treatment of heterogeneous spectrum opportunities raises several issues that do not occur when all SUs and the SU AP share the same view of the channel's occupancy. The biggest one is to guarantee that each SU is doing the right action in the corresponding frame, e.g., to assure that a SU does not compete in the second stage in frames representing the first stage of contention (state $\mathbf{St1_{AP}}$). For that, we assume that the SU AP transmits two different and distinguishable narrow band tones - *i.e.* out-of-band tones in a different band than the one used by the PUs -, one in each stage frame represented by the states $\mathbf{St1_{AP}}$ and $\mathbf{St2_{AP}}$, so they can be detected even when the channel is declared busy for the SUs. This way, all the SUs have the possibility to get aligned with the SU AP, when they listen the tone indicating the beginning of the first stage of contention (state $\mathbf{St1_{AP}}$) or the beginning of the second stage of contention (state $\mathbf{St2_{AP}}$).

Let $\{R_k\}_{k\geq 0}$ be a discrete-time stochastic process representing the generic ζ MAC state of the SU AP at frame k, with $\zeta \in \mathcal{G} = \{\mathbf{Idle_{AP}}, \mathbf{St1_{AP}}, \mathbf{St11_{AP}}, \mathbf{St2_{AP}}, \Omega_{\mathbf{CW_{2B}}}^{\mathbf{Wait}}, \Omega_{\mathbf{CW_{2B}}}^{\mathbf{Succ}}, ..., \Omega_{\mathbf{1}}^{\mathbf{Wait}}, \Omega_{\mathbf{1}}^{\mathbf{Succ}}\}$. The matrix $\mathcal{P}^{\mathrm{AP}} = \{\mathcal{P}_{\zeta_A,\zeta_B}^{\mathrm{AP}}\}_{\zeta_A,\zeta_B\in\mathcal{G}}$ denotes the $|\mathcal{G}| \times |\mathcal{G}|$ transition matrix of the stochastic process R, where $|.|$ denotes the cardinality of a set, and with $\mathcal{P}_{\zeta_A,\zeta_B}^{\mathrm{AP}} = Pr\{R_{k+1} = \zeta_B | R_k = \zeta_A\}$ representing the probability regarding the single-step transition from the generic state ζ_A to ζ_B. Since $\mathcal{P}_{\zeta_A,\zeta_B}^{\mathrm{AP}}$ is independent of k, and the Markov property can be applied, then R is said to be a homogeneous DTMC. Moreover, if a stationary distribution π with respect to the DTMC R exists, for $\zeta, \chi \in \mathcal{G}$ the following conditions hold

$$\begin{aligned} 0 \leq \pi_\zeta &\leq 1 \\ \sum \pi_\chi \cdot \mathcal{P}_{\chi,\zeta}^{\mathrm{AP}} &= \pi_\zeta \\ \sum \pi_\zeta &= 1 \,, \end{aligned} \tag{4.16}$$

and the steady-state distribution of state ζ is given by π_ζ. Considering that the DTMC R is aperiodic and positive recurrent [PP02], the expected value of the return time to a given state $\zeta \in \mathcal{G}$, also know as regenerative time, is given by $\left[\pi_\zeta\right]^{-1}$, as derived in the Appendix C. Therefore, and following the classical definition of relative frequency of occurrence of an event, we can approximate the probability of having a SU i competing in the first stage of contention as follows

$$P_{SU1,i} = \frac{\left[\pi_{\mathbf{St1_{AP}}}\right]^{-1}}{\left[\pi_{\mathbf{St1_{SU,i}}}\right]^{-1}} = \frac{\pi_{\mathbf{St1_{SU,i}}}}{\pi_{\mathbf{St1_{AP}}}}, \tag{4.17}$$

where $\left[\pi_{\mathbf{St1_{SU,i}}}\right]^{-1}$ refers to the regeneration time of the SU i with respect to the first stage of contention, which will be defined in Subsection 4.4.1.3. Similarly, $P_{SU2,i}$ refers to the probability of the SU i compete in the second stage of contention, and it is obtained following the same rationale as $P_{SU1,i}$, *i.e.*

$$P_{SU2,i} = \frac{\left[\pi_{\mathbf{St2_{AP}}}\right]^{-1}}{\left[\pi_{\mathbf{St2_{SU,i}}}\right]^{-1}} = \frac{\pi_{\mathbf{St2_{SU,i}}}}{\pi_{\mathbf{St2_{AP}}}}. \tag{4.18}$$

Figure 4.8 shows that there are two key probabilities expressing the similarity between the SU AP and the SUs spectrum occupancy, therefore deciding if the SU AP completes the transmission cycle. These are the probability of having at least one SU competing in the first stage, given by

$$P_{SU1} = 1 - \prod_{i=1}^{n} (1 - P_{SU1,i}), \tag{4.19}$$

and the probability of having at least one SU competing in the second stage, given by

$$P_{SU2} = 1 - \prod_{i=1}^{n} (1 - P_{SU2,i}). \tag{4.20}$$

4.4.1.2 SU Discrete Time Markov Chain

Figure 4.9 illustrates the DTMC used to model the SU operation cycle. Just like the SU AP, in the beginning of the transmission cycle a SU i is initially at state $\mathbf{Idle_{SU}}$ waiting for the first stage of contention. When a SU has a packet to transmit, and after receiving the tone representing the first stage of contention, if the channel is sensed idle a SU will compete in that stage (represented by the state $\mathbf{St1_{SU}}$). If the SU i is selected to compete in the second stage, which occurs with a probability P_{2St} given by (4.9), it will be able to do it in the next idle frame marked by the SU AP as being the frame designated to accommodate the second stage of contention (represented by the state $\mathbf{St2_{SU}}$). While in $\mathbf{St1_{SU}}$, if the channel is sensed busy the SU it will have to wait in state $\mathbf{St11_{SU}}$ for the next idle frame to compete in the second stage. If a SU is not selected to compete in the second stage $(1 - P_{2St})$, or if a selected SU loses the opportunity to compete in the second stage due to heterogeneous spectrum sensing results $(P_{I,AP}(1 - P_{I,i}))$, the SU will return from the state $\mathbf{St1_{SU}}$ or state $\mathbf{St11_{SU}}$, respectively, to the idle state $(\mathbf{Idle_{SU}})$, and wait for the beginning of the next cycle.

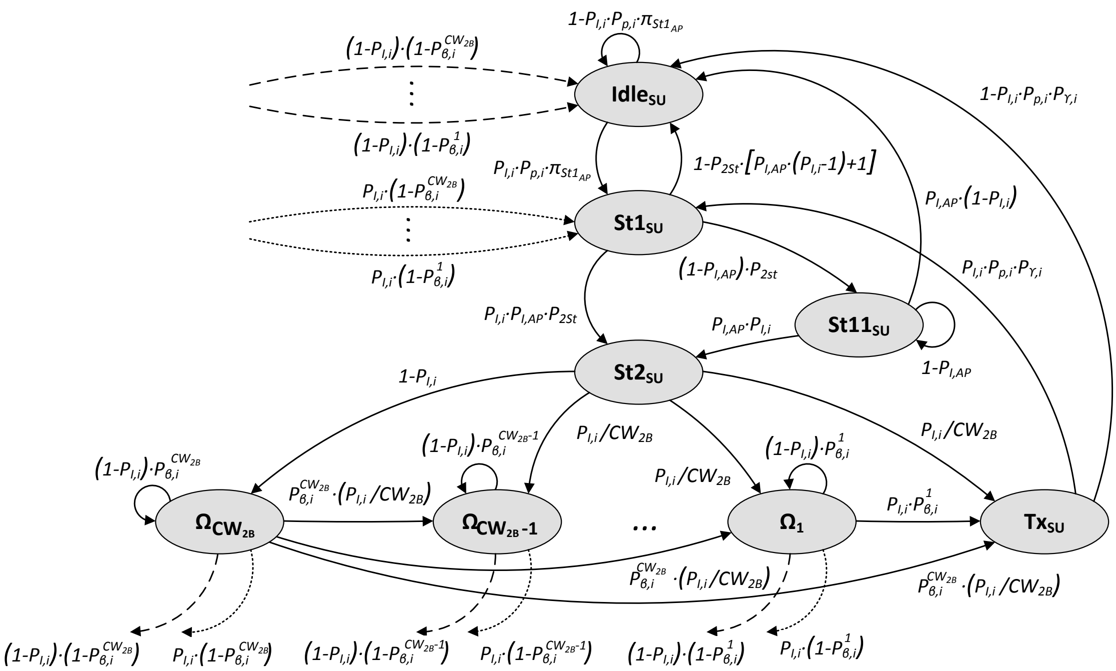


Figure 4.9: DTMC illustrating the SU's operation mode.

After competing in the second stage ($\mathbf{St2_{SU}}$), the SU enters in the transmission phase when the transition from state $\mathbf{St1_{SU}}$ to one of the states $\Omega_{\mathbf{CW_{2B}}}$, $\Omega_{\mathbf{CW_{2B}}-1}$, ..., $\Omega_{\mathbf{CW_1}}$, $\mathbf{Tx_{SU}}$ is observed. In this phase, the SU can access the medium by randomly selecting a single idle frame in the interval $\{1, 2, ..., CW_{2B}\}$, meaning that a frame is chosen with probability $1/CW_{2B}$. After reaching the transmission state $\mathbf{Tx_{SU}}$, the SU will restart its transmission cycle in states $\mathbf{Idle_{SU}}$ or $\mathbf{St1_{SU}}$, depending on the individual spectrum sensing results $(P_{I,i})$ and also if the SU has transmitted in the last frame of the SU AP transmission phase (with probability $P_{\gamma,i}$ that will be defined in the next subsection).

However, during the transmission's phase and due to heterogeneous spectrum sensing results, each SU selected to transmit may become state-delayed or in advance when compared to the SU AP, which has the following implications:

- SUs may transmit during frames considered busy by the SU AP ($\Omega^{\mathbf{Wait}}_{\mathbf{CW_{2B}}}$, $\Omega^{\mathbf{Wait}}_{\mathbf{CW_{2B}}-1}$, ..., $\Omega^{\mathbf{Wait}}_{\mathbf{1}}$, $\mathbf{Idle_{AP}}$). In this case we admit that the SU AP is not able to decode the transmission and so it will not be considered for throughput.

- SUs may lose their opportunity to transmit. This situation occurs every time a SU senses more busy frames than the SU AP, meaning that the SU AP will end the transmission phase while the SU is still contending to transmit in state Ω_x, $x \in \{1, 2, ..., CW_{2B}\}$. This situation is illustrated in Figure 4.9 through the probability $1 - P^x_{\beta,i}$, which represents the probability of the SU AP has reached the beginning of a new transmission cycle, while the SU is still contending for transmission in the contention state Ω_x.

The first observation will be handled in Subsection 4.4.1.4, while the latter one will be tackled in the next subsection.

As stated before, C2RMAC adopts the use of two distinguishable tones to indicate the frame where the SU AP executes stages one and two. In our model, SUs can go from state $\mathbf{Idle_{SU}}$ to $\mathbf{St1_{SU}}$ if they listen the tone regarding the stage one, which is represented in the DTMC illustrated in Figure 4.9 by the steady-state probability of the state $\mathbf{St1_{AP}}$, represented by $\pi_{\mathbf{St1_{AP}}}$. However, the steady-state probability of state $\mathbf{St1_{AP}}$ does not represent the probability of a SU to receive the tone while in $\mathbf{Idle_{SU}}$. For that, we would have to synchronize both SU AP and SUs' DTMCs, which is not possible due to the fact that the synchronization states $\{\mathbf{St1_{AP}}, \mathbf{St1_{SU}}, \mathbf{St2_{AP}}, \mathbf{St2_{SU}}\}$ may exhibit different steady state probabilities due to the different probability spaces of the SUs and SU AP [AB07]. Therefore, we have decided to replace the probability of the transition from $\mathbf{Idle_{SU}}$ to $\mathbf{St1_{SU}}$ by $P_{\alpha,i}$, which will be explained and derived in the next subsection.

4.4.1.3 Simplification of the SU Discrete Time Markov Chain

The DTMC illustrated in Figure 4.9 shows that from every transmission's contention state ($\Omega_{\mathbf{CW_{2B}}}$, $\Omega_{\mathbf{CW_{2B}}-1}$, ..., $\Omega_{\mathbf{1}}$) it is possible to reach $\mathbf{Idle_{SU}}$ or $\mathbf{St1_{SU}}$ with probability $1 - P^{CW_{2B}}_{\beta,i}$, $1 - P^{CW_{2B}-1}_{\beta,i}$, ..., $1 - P^{1}_{\beta,i}$, respectively. Each transmission's contention state x has its own $1 - P^x_{\beta,i}$ probability, however they represent the same event: the SU AP's DTMC has reached the beginning of a new cycle ($\mathbf{St1_{AP}}$) while the SU is still waiting for its opportunity to transmit. Thus, in order to improve the easiness of the analysis, the SU's DTMC presented in Figure 4.9 was simplified by embedding the transmission contention mechanism in states $\mathbf{Idle_{SU}}$ and $\mathbf{Tx_{SU}}$, while the probabilities $1 - P^{x}_{\beta,i}$ were simply replaced by $1 - P_{\beta,i}$ with the following equivalent meaning: the SU i that competed in the second stage was not able to transmit, because due to heterogeneity the SU was not able to identify its assigned idle frame before the SU AP has reached the beginning of a new transmission cycle. The probability representing the transition from $\mathbf{Idle_{SU}}$ to $\mathbf{St1_{SU}}$ was also replaced by the aforementioned $P_{\alpha,i}$.

Let $\{V_k\}_{k\geq 0}$ be a discrete-time stochastic process representing the generic ξ MAC state of the SU at frame k, with $\xi \in \mathcal{H} = \{\mathbf{Idle_{SU}}, \mathbf{St1_{SU}}, \mathbf{St11_{SU}}, \mathbf{St2_{SU}}, \mathbf{Tx_{SU}}\}$. The matrix $\mathcal{P}^{\text{SU}} = \{\mathcal{P}^{\text{SU}}_{\xi_A,\xi_B}\}_{\xi_A,\xi_B\in\mathcal{H}}$ denotes the $|\mathcal{H}| \times |\mathcal{H}|$ transition matrix of the stochastic process V, with $\mathcal{P}^{\text{SU}}_{\xi_A,\xi_B} = Pr\{V_{k+1} = \xi_B | V_k = \xi_A\}$. Since $\mathcal{P}^{\text{SU}}_{\xi_A,\xi_B}$ is independent of k, and the Markov property can be applied, then V is said to be a homogeneous DTMC. Moreover, if a stationary distribution π with respect to the DTMC S exists, then for $\zeta, \chi \in \mathcal{H}$ the conditions expressed in (4.16) hold, and the steady-state distribution of state ξ is given by π_ξ. Considering that the DTMC V is aperiodic and positive recurrent [PP02], the expected value of the return time to a given state $\xi \in \mathcal{H}$ is given by $[\pi_\xi]^{-1}$. The probabilities $P_{\beta,i}$, $P_{\gamma,i}$ and $P_{\alpha,i}$ are derived following the simpler version of the SU's DTMC illustrated in Figure 4.10.

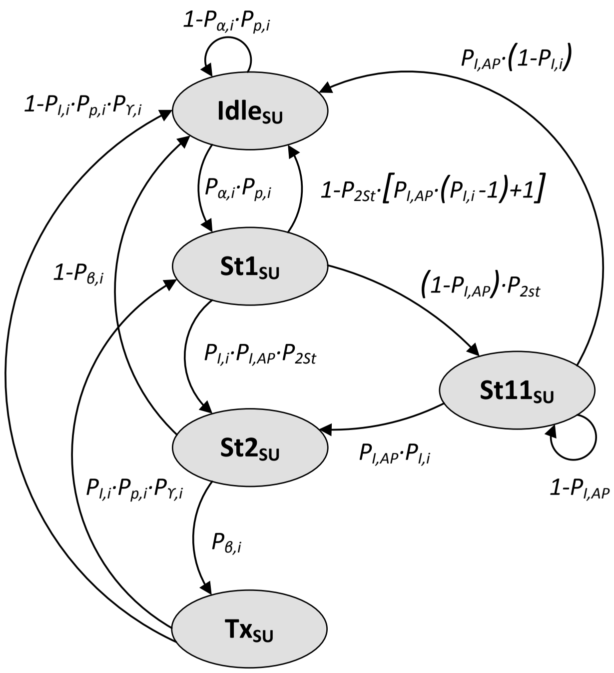


Figure 4.10: Simplified version of the SU's DTMC illustrated in Figure 4.9.

Firstly we address the probability $P_{\beta,i}$. As stated before, SUs that have competed in the second stage, and so those that are allowed to transmit during the current transmission phase, may not be able to do it if the SU AP's transmission phase finishes when a SU is still contending (in Ω_x) in the transmission phase. In an equivalent way, we can say that a SU will only transmit if the transmission phase of the SU AP is longer or at least equal than the transmission phase of the SU.

This fact can be translated into

$$P_{\beta,i} = \sum_{x=1}^{cw_2} Pr\left\{CW_{2B} = x | P_{SU2}\right\} Pr\left\{T_{Tx}^{AP} \geq T_{Tx}^{SU}\right\}. \tag{4.21}$$

T_{Tx}^{AP} is a discrete random variable expressing the duration of the SU AP transmission phase of the second stage, *i.e.*, the amount of frames spent by the SU AP from the moment it leaves the second stage of contention until the next first stage of contention. The sequence of states illustrating the aforementioned duration is represented in Figure 4.11.

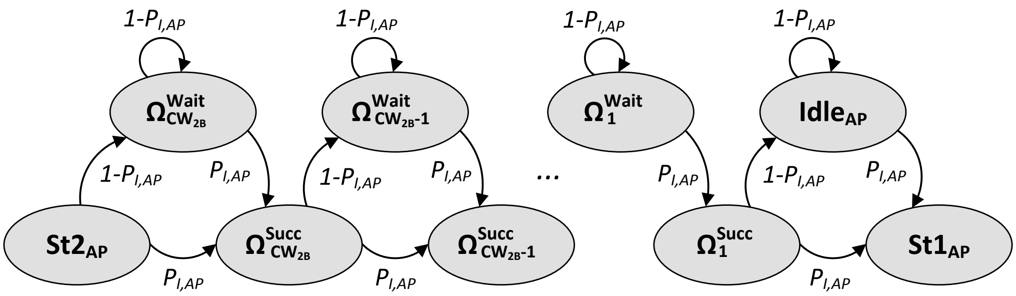


Figure 4.11: Sequence of states representing the SU AP transmission phase of the second stage.

Figure 4.11 shows that the number of frames needed to reach the next idle frame (e.g. from $\mathbf{St2_{AP}}$ to $\Omega_3^{\mathbf{Succ}}$) follows a geometric distribution with parameter $P_{I,AP}$. Since the sum of l geometric distributions with the same parameter $P_{I,AP}$ can be written as a negative binomial distribution [Pit93], the PMF of the number of frames observed between $l+1$ idle frames, T_{Trans}^{AP}, is given by

$$Pr\left\{T_{Trans}^{AP} = k | L = l\right\} = \begin{cases} 0, & k < l \\ \binom{k-1}{k-l} P_{I,AP}{}^{l}\left(1 - P_{I,AP}\right)^{(k-l)}, & k \geq l, \end{cases} \tag{4.22}$$

where the PMF of T_{Tx}^{AP} is a particular case of (4.22) when $L = CW_{2B} + 1$.

On the other hand, let T_{Tx}^{SU} be a discrete random variable expressing the number of frames elapsed between the beginning of the second stage (in state $\mathbf{St2_{SU}}$) and the SU's transmission (in state $\mathbf{Tx_{SU}}$). The sequence of states representing the SU's transmission phase is detailed in Figure 4.12.

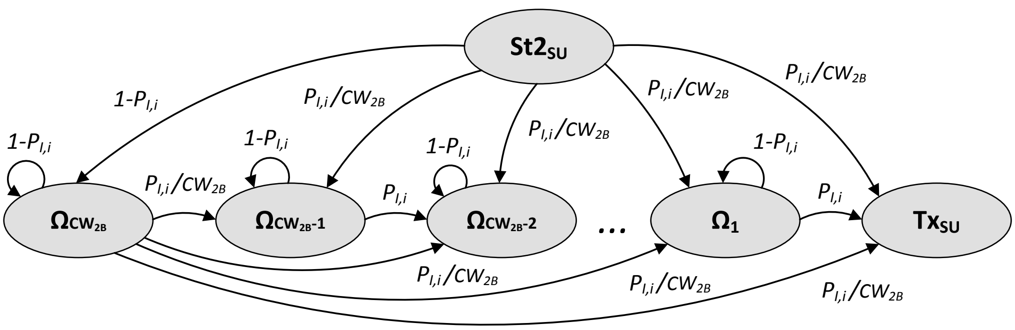


Figure 4.12: Sequence of states representing the SU's transmission phase.

In order to derive the PMF of T_{Tx}^{SU} we adopted the same rationale used to derive the PMF of T_{Tx}^{AP}. However, unlike the SU AP, SUs do not always wait a fixed number of idle frames to transmit. In the second stage, SUs independently selected a mini-slot according to a uniform distribution. Then, in an equivalent way, during the transmission phase each SU will transmit in the self-assigned idle frame, following the sequence of busy mini-slots observed during the reservation phase. However, the sensing heterogeneity may cause SUs to achieve different sensing outcomes (idle or busy) for the same frame. Therefore, SUs end up transmitting in an idle frame uniformly and independently from the other SUs. Depending on the mini-slot randomly selected to transmit the mini-packet, the SU follows one of the CW_{2B} sequences of states from the beginning of the second stage of contention (state $\mathbf{St2_{SU}}$) until the effective transmission, represented by the state $\mathbf{Tx_{SU}}$. Therefore, and as shown in Appendix D, the PMF of T_{Tx}^{SU} is given by

$$Pr\left\{T_{Tx}^{SU} = k|CW_{2B} = x\right\} = \frac{1}{x} \sum_{v=1}^{min(k,x)} \binom{k-1}{v-1} P_{I,i}{}^{v} \left(1 - P_{I,i}\right)^{(k-v)}. \tag{4.23}$$

After replacing (4.22) and (4.23) in (4.21), the probability of a SU being able to transmit since it was competing in the second stage, $P_{\beta,i}$, is given by

$$P_{\beta,i} = \sum_{x=1}^{cw_2} Pr\left\{CW_{2B} = x|P_{SU2}\right\} \sum_{k=1}^{\infty} Pr\left\{T_{Trans}^{AP} = k|L = x+1\right\} \times \sum_{l=0}^{k-1} Pr\left\{T_{Tx}^{SU} = l|CW_{2B} = x\right\}, \tag{4.24}$$

where $Pr\left\{CW_{2B} = x\right\}$ is written as in (4.4). However, the expected number of SUs selected to compete in the second stage, n_{St2}, used in (4.4) and expressed by (4.3), have to be adapted for the heterogeneous sensing scenario because, due to potential different spectrum sensing outcomes, the SUs selected to compete in the second stage may not compete if they sense the idle frame of the reservation phase as being busy. Then, for an heterogeneous spectrum sensing scenario, each SU i competes in the second stage with a probability $P_{SU2,i}$. Consequently, under heterogeneous spectrum sensing conditions the expected number of SUs competing in the second stage is given by

$$n_{St2} = \sum_{i=1}^{n} 1 \cdot P_{SU2,i}. \tag{4.25}$$

Similarly, the expected number of SUs competing in the first stage of contention, n_{St1}, is now given by

$$n_{St1} = \sum_{i=1}^{n} 1 \cdot P_{SU1,i}. \tag{4.26}$$

If a SU transmits in the frame k, in the next frame $(k+1)$ the SU will be able to reach one of the following two states: the idle state $\mathbf{Idle_{SU}}$ or the first stage state $\mathbf{St1_{SU}}$. If the SU transmits in the last frame of the SU AP transmission phase, which occurs with a probability $P_{\gamma,i}$, in the next frame the SU will restart the cycle from the first stage state, if the medium is considered idle. Otherwise, if the SU does not transmit in the last frame of the SU AP transmission phase, the SU will have to wait in state $\mathbf{Idle_{SU}}$ for the SU AP to finish the transmission phase. By following the same rationale adopted to compute $P_{\beta,i}$, $P_{\gamma,i}$ is given by

$$P_{\gamma,i} = \frac{1}{P_{\beta,i}} \sum_{x=1}^{cw_2} Pr\left\{CW_{2B} = x | P_{SU2}\right\} \times \sum_{k=1}^{\infty} Pr\left\{T_{Trans}^{AP} = k | L = x+1\right\} Pr\left\{T_{Tx}^{SU} = k-1 | CW_{2B} = x\right\}. \quad (4.27)$$

At this moment, only the probability of the transition from $\mathbf{Idle_{SU}}$ to $\mathbf{St1_{SU}}$, $P_{\alpha,i}$, is missing in the SU's DTMC. As stated in the previous subsection, it is not possible to represent the transmission of the tone regarding the first stage of contention in the SU's DTMC, and the the steady-state probability of the SU's AP first stage fails to represent that event due to the different probabilities spaces of the SUs and SU AP. Therefore, we have decided to represent the probability of the transition from state $\mathbf{Idle_{SU}}$ to $\mathbf{St1_{SU}}$ by $P_{\alpha,i}$ based on the following rationale: the transition probability defines the amount of occurrences that a process leaves a state over the amount of occurrences that it stays in that state. Then, if the number of frames spent by a SU in state $\mathbf{Idle_{SU}}$ before reaching the state $\mathbf{St1_{SU}}$, represented by $\mathbb{E}\left[T_{Idle}^{SU}\right]$, is known, we can approximate $P_{\alpha,i}$ by

$$P_{\alpha,i} \approx \frac{1}{\mathbb{E}\left[T_{Idle}^{SU}\right]}. \quad (4.28)$$

To compute $\mathbb{E}\left[T_{Idle}^{SU}\right]$, we have to consider the transitions that can bring a SU to state $\mathbf{Idle_{SU}}$, and therefore write the expected number of frames spent in that state before reaching $\mathbf{St1_{SU}}$. From Figure 4.10 we can see that a SU returns to $\mathbf{Idle_{SU}}$ from:

- $\mathbf{St1_{SU}}$, in the case of not being selected to compete in the second stage. In this case, the expected number of frames spent in state $\mathbf{Idle_{SU}}$ before reaching $\mathbf{St1_{SU}}$ is given by

$$\mathbb{E}\left[T_{Idle\_St1}^{SU}\right] = \sum_{k=1}^{\infty} \left(k\,\mathbb{E}\left[T_{St1\_St1}^{AP}\right] - 1\right) P_{I,i}P_{p,i}\left(1 - P_{I,i}P_{p,i}\right)^{k-1}; \quad (4.29)$$

- $\mathbf{St11_{SU}}$, if it was selected to compete in the second stage but it lost the opportunity to compete due to heterogeneous spectrum sensing conditions. In this case, the average number of frames spent in state $\mathbf{Idle_{SU}}$ is

$$\mathbb{E}\left[T_{Idle\_St11}^{SU}\right] = \sum_{k=0}^{\infty} \left(k\,\mathbb{E}\left[T_{St1\_St1}^{AP}\right] + \mathbb{E}\left[T_{St2\_St1}^{AP}\right] + 1\right) P_{I,i}P_{p,i}\left(1 - P_{I,i}P_{p,i}\right)^{k}; \quad (4.30)$$

- $\mathbf{St2_{SU}}$, in the case of not being able to transmit. The expected number of frames in state $\mathbf{Idle_{SU}}$ before reaching the state $\mathbf{St1_{SU}}$ for this case is

$$\mathbb{E}\left[T_{Idle\_St2}^{SU}\right] = \sum_{k=0}^{\infty} \left(k\,\mathbb{E}\left[T_{St1\_St1}^{AP}\right] + \mathbb{E}\left[T_{Tx}^{AP}\right]\right) P_{I,i}P_{p,i}\left(1 - P_{I,i}P_{p,i}\right)^{k}; \quad (4.31)$$

- $\mathbf{Tx_{SU}}$, if the transmission did not occur in the last frame of the SU AP transmission phase of the second stage. The expected number of frames in state $\mathbf{Idle_{SU}}$ is given by

$$\mathbb{E}\left[T_{Idle\_Tx}^{SU}\right] = \sum_{k=0}^{\infty} \left(k\,\mathbb{E}\left[T_{St1\_St1}^{AP}\right] + \mathbb{E}\left[T_{Tx}^{AP}\right] - \frac{\mathbb{E}\left[CW_{2B}\right]}{2}\right) P_{I,i}P_{p,i}\left(1 - P_{I,i}P_{p,i}\right)^{k}. \quad (4.32)$$

$\mathbb{E}\left[T^{AP}_{St1\_St1}\right]$ represents the expected number of frames spent by the SU AP to reach state $\mathbf{St1_{AP}}$ from state $\mathbf{St1_{AP}}$ and is given by

$$\begin{aligned}\mathbb{E}\left[T^{AP}_{St1\_St1}\right] = \;& (1-P_{SU1})\sum_{k=1}^{\infty} k\, Pr\left\{T^{AP}_{Trans}=k|L=1\right\}+\\ & P_{SU1}\left(1-P_{SU2}\right)\sum_{k=1}^{\infty} k\, Pr\left\{T^{AP}_{Trans}=k|L=2\right\}+\\ & P_{SU1}P_{SU2}\left(\sum_{k=1}^{\infty} k\, Pr\left\{T^{AP}_{Trans}=k|L=1\right\}+\right.\\ & \left.\sum_{k=1}^{\infty} k\sum_{x=1}^{cw_2} Pr\left\{CW_{2B}=x|P_{SU2}\right\} Pr\left\{T^{AP}_{Trans}=k|L=x+1\right\}\right),\end{aligned} \tag{4.33}$$

showing that the SU AP can return to state $\mathbf{St1_{AP}}$ from: (a) directly from $\mathbf{St1_{AP}}$ if there were no SUs competing in the first stage (with probability $1-P_{SU1}$); (b) through $\mathbf{St2_{AP}}$ if there were no SUs competing in the second stage (with probability $P_{SU1}(1-P_{SU2})$); (c) and finally by completing the entire transmission cycle (with probability $P_{SU1}P_{SU2}$). $\mathbb{E}\left[T^{AP}_{St2\_St1}\right]$ follows the same rationale as $\mathbb{E}\left[T^{AP}_{St1\_St1}\right]$, but in this case it represents the expected number of frames spent by the SU AP to reach state $\mathbf{St1_{AP}}$ from state $\mathbf{St2_{AP}}$, and is given by

$$\begin{aligned}\mathbb{E}\left[T^{AP}_{St2\_St1}\right] = (1-P_{SU2})\sum_{k=1}^{\infty} k\, Pr\left\{T^{AP}_{Trans}=k|L=1\right\}+&\\ P_{SU2}\left(\sum_{k=1}^{\infty} k\sum_{x=1}^{cw_2} Pr\left\{CW_{2B}=x|P_{SU2}\right\} Pr\left\{T^{AP}_{Trans}=k|L=x+1\right\}\right).&\end{aligned} \tag{4.34}$$

At last, $\mathbb{E}\left[T^{AP}_{Tx}\right]$ represents the expected duration of the transmission phase, and is given by

$$\mathbb{E}\left[T^{AP}_{Tx}\right] = \sum_{k=1}^{\infty} k\sum_{x=1}^{cw_2} Pr\left\{CW_{2B}=x|P_{SU2}\right\} Pr\left\{T^{AP}_{Trans}=k|L=x+1\right\}. \tag{4.35}$$

We can use (4.29), (4.30), (4.31) and (4.32) to write $\mathbb{E}\left[T^{SU}_{Idle}\right]$ as follows

$$\begin{aligned}\mathbb{E}\left[T^{SU}_{Idle}\right] = \mathbb{E}\left[T^{SU}_{Idle\_St1}\right] P^{SU}_{St1\_St1\_Idle} + \mathbb{E}\left[T^{SU}_{Idle\_St11}\right] P^{SU}_{St1\_St11\_Idle}+&\\ \mathbb{E}\left[T^{SU}_{Idle\_St2}\right] P^{SU}_{St1\_St2\_Idle} + \mathbb{E}\left[T^{SU}_{Idle\_Tx}\right] P^{SU}_{St1\_Tx\_Idle},&\end{aligned} \tag{4.36}$$

where $P_{St1\_St1\_Idle}$, $P_{St1\_St11\_Idle}$, $P_{St1\_St2\_Idle}$ and $P_{St1\_Tx\_Idle}$ represent the probabilities that lead a SU to go from state $\mathbf{St1_{SU}}$ to state $\mathbf{Idle_{SU}}$ by different DTMC trajectories, and are given by

$$\begin{cases} P^{SU}_{St1\_St11\_Idle} = \mathcal{P}^{SU}_{\mathbf{St1_{SU}},\mathbf{St11_{SU}}}\mathcal{P}^{SU}_{\mathbf{St11_{SU}},\mathbf{Idle_{SU}}}\\ P^{SU}_{St1\_St2\_Idle} = \left(\mathcal{P}^{SU}_{\mathbf{St1_{SU}},\mathbf{St2_{SU}}}+\mathcal{P}^{SU}_{\mathbf{St1_{SU}},\mathbf{St11_{SU}}}\mathcal{P}^{SU}_{\mathbf{St11_{SU}},\mathbf{St2_{SU}}}\right)\mathcal{P}^{SU}_{\mathbf{St2_{SU}},\mathbf{Idle_{SU}}}\\ P^{SU}_{St1\_Tx\_Idle} = \left(\mathcal{P}^{SU}_{\mathbf{St1_{SU}},\mathbf{St2_{SU}}}+\mathcal{P}^{SU}_{\mathbf{St1_{SU}},\mathbf{St11_{SU}}}\mathcal{P}^{SU}_{\mathbf{St11_{SU}},\mathbf{St2_{SU}}}\right)\mathcal{P}^{SU}_{\mathbf{St2_{SU}},\mathbf{Tx_{SU}}}\mathcal{P}^{SU}_{\mathbf{Tx_{SU}},\mathbf{Idle_{SU}}}\\ P^{SU}_{St1\_St1\_Idle} = 1-\left(P^{SU}_{St1\_St11\_Idle}+P^{SU}_{St1\_St2\_Idle}+P^{SU}_{St1\_Tx\_Idle}\right). \end{cases} \tag{4.37}$$

Finally, the probability of the transition from state $\mathbf{Idle_{SU}}$ to state $\mathbf{St1_{SU}}$, $P_{\alpha,i}$, can be obtained using (4.36) in (4.28).

4.4.1.4 Packet Service Time and Throughput

In the next steps we characterize the packet service time and throughput for the heterogeneous spectrum sensing scenario. Regarding the packet service time, and since a saturated network traffic condition is assumed for the heterogeneous spectrum sensing scenario, the expected packet service time for a SU can be expressed by

$$\mathbb{E}\left[T_{service}^{het}\right] = \left[\pi_{\mathbf{Tx_{SU}}}\right]^{-1}. \tag{4.38}$$

In order to obtain an approximation for the throughput, we have used some of the steady-state probabilities of the SU AP DTMC. Let us start by deriving the expected length of a SU AP transmission cycle with transmission phase as follows

$$\mathbb{E}\left[T_{Cycle}^{AP}\right] = \left[\pi_{\mathbf{St2_{AP}}} \, P_{SU2}\right]^{-1}. \tag{4.39}$$

The second step is to approximate the average number of SUs that are competing at each transmission phase of each SU AP transmission cycle, which is given by

$$n_{Cycle}^{AP} = \sum_{i=1}^{n} P_{SU2,i} \, P_{\beta,i} \; , \tag{4.40}$$

where $P_{\beta,i}$ represents the probability of SU i being able to transmit since it competes in the second stage. n_{Cycle}^{AP} is used to derive the average number of idle frames during the transmission phase as follows

$$\mathbb{E}\left[T_{Idle}\right] = \mathbb{E}\left[T_{Tx}^{AP}\right]\left(1 - \frac{1}{\mathbb{E}\left[T_{Tx}^{AP}\right]}\right)^{n_{Cycle}^{AP}} , \tag{4.41}$$

where $\mathbb{E}\left[T_{Tx}^{AP}\right]$, the expected duration of the transmission phase, was previously derived in (4.35). Finally, the aggregated normalized throughput of the secondary network, *i.e.*, the ratio of SU's frames with at least one SU's transmission and without PU's activity in the SU AP, can be approximated by

$$S_{het}^{SU} = \frac{\left(\mathbb{E}\left[T_{Tx}^{AP}\right] - \mathbb{E}\left[T_{Idle}\right]\right) P_{I,AP}}{\mathbb{E}\left[T_{Cycle}^{AP}\right]}. \tag{4.42}$$

4.4.2 Performance Analysis

This subsection evaluates the performance of C2RMAC considering a heterogeneous spectrum sensing scenario. To evaluate the impact of the channel sensing heterogeneity in the performance of the C2RMAC protocol, we propose a metric to characterize the level of sensing dissimilarity achieved by the different SUs at the same instant of time.

Let $\vec{P}_{I,i}$ represent a vector with consecutive l channel decisions achieved by a SU i in a finite period of time. We adopt the sample Pearson product-moment correlation coefficient [LG08] to measure the correlation between the channel decisions of a SU i and the remaining SUs, resulting in the following correlation matrix

$$\mathbf{X} = \begin{bmatrix} \sqrt{\mathbf{x}_{1,1}^2} & \sqrt{\mathbf{x}_{1,2}^2} & \cdots & \sqrt{\mathbf{x}_{1,n}^2} \\ \sqrt{\mathbf{x}_{2,1}^2} & \sqrt{\mathbf{x}_{2,2}^2} & \cdots & \sqrt{\mathbf{x}_{2,n}^2} \\ \vdots & \vdots & \ddots & \vdots \\ \sqrt{\mathbf{x}_{n,1}^2} & \sqrt{\mathbf{x}_{n,2}^2} & \cdots & \sqrt{\mathbf{x}_{n,n}^2} \end{bmatrix}, \tag{4.43}$$

where $\mathbf{x}_{i,t}$ is the sample Pearson's correlation coefficient between SUs i and t given by

$$\mathbf{x}_{i,t} = \frac{\sum_{k=1}^{l} \left(\vec{P}_{I,i}(k) - \mathbb{E}[\vec{P}_{I,i}]\right)\left(\vec{P}_{I,t}(k) - \mathbb{E}[\vec{P}_{I,t}]\right)}{\sqrt{\sum_{k=1}^{l} \left(\vec{P}_{I,i}(k) - \mathbb{E}[\vec{P}_{I,i}]\right)^2}\sqrt{\sum_{k=1}^{l} \left(\vec{P}_{I,t}(k) - \mathbb{E}[\vec{P}_{I,t}]\right)^2}}. \tag{4.44}$$

By computing the average of all the elements of the strictly upper triangular matrix of $\mathbf{X}$, which is denoted by $\bar{\mathbf{X}}$, we obtain a single value for the mean correlation for each scenario. The parameter $\bar{\mathbf{X}}$ is used to characterize the level of dissimilarity of the channel sensing decisions of each scenario, indicating higher levels of heterogeneity as $\bar{\mathbf{X}}$ approaches 0 and lower levels of heterogeneity as $\bar{\mathbf{X}}$ approaches 1.

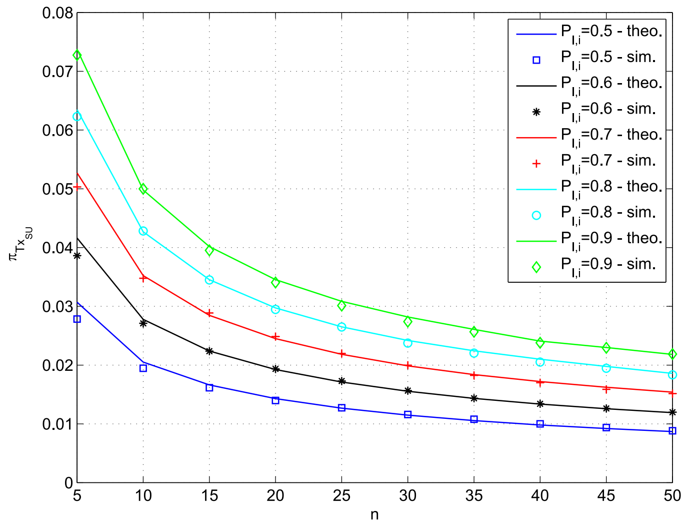
4.4.2.1 Individual Transmission Probability, Packet Service Time and Throughput Performance Results

The results in this subsection characterize the performance of C2RMAC protocol under heterogeneous channel sensing conditions. The results include the individual transmission probability, the packet service time and the throughput of the secondary network. The theoretical results, represented with solid lines, are compared with simulation results, illustrated with markers, in order to assess the accuracy of the analytical model.

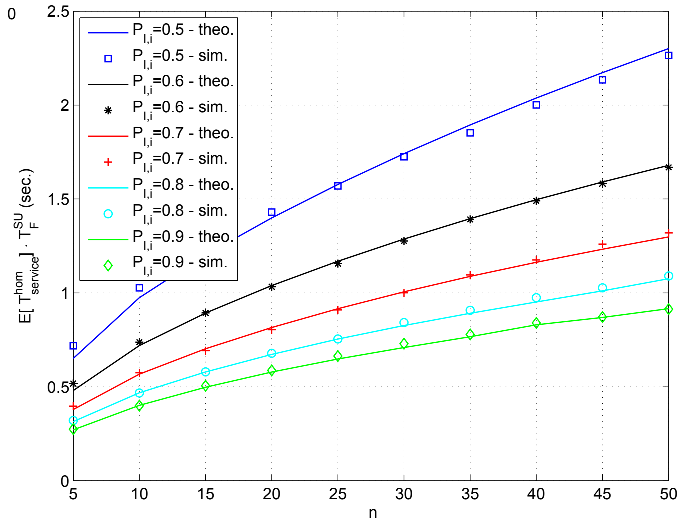
Following the same network topology adopted in the previous evaluation, the secondary network is formed by a variable range of n SUs transmitting to a SU AP. The energy detector of the SUs and SU AP are parameterized with the optimal values of energy threshold and number of sensing samples (θ and N_S) in order to achieve the same values of sensing accuracy as in the homogeneous channel sensing scenario, *i.e.*, $P_D^{min} = 0.95$ and $P_{FA} = 0.01$. A saturated secondary network was considered and fixed $cw_1 = 2$ and $cw_2 = 14$ values were adopted.

The primary network is formed by three pairs of PUs (transmitter and receiver), creating a scenario with a high level of sensing heterogeneity, $\bar{\mathbf{X}} \approx 0.154$. As a result of the communications originated by the PU transmitters, the overall probability of the SU AP's channel availability was set to $P_{I,AP} = 0.7$, while the individual SU's channel availability was changed from 0.5 to 0.9 in the individual transmission probability and packet service time analysis, and from 0.1 to 0.9 in the throughput analysis. These idle channel probabilities were achieved by varying the position of the SUs with respect to the PUs.

Figure 4.13 shows the individual transmission probability and the average packet service time, represented in seconds, achieved by a SU in heterogeneous spectrum sensing conditions for different number of SUs. Different curves for different SU's channel availability probabilities are also provided. The theoretical results of the individual transmission probability were computed



(a)



(b)

Figure 4.13: Achieved performance of secondary network in heterogeneous spectrum sensing conditions and $P_{I,AP} = 0.7$: (a) individual transmission probability, $\pi_{\mathbf{Tx_{SU}}}$; (b) average packet service time, $\mathbb{E}\left[T^{het}_{service}\right]$.

using the individual steady-state probability of state $\mathbf{Tx_{SU}}$, $\pi_{\mathbf{Tx_{SU}}}$, while the theoretical values for the average packet service time were obtained by multiplying $\mathbb{E}\left[T^{het}_{service}\right]$, computed from (4.38), with the SU's frame length, T_F^{SU}. As a general comment we can observe that the analytical results closely fit the simulation results. When the number of SUs increase the individual transmission probability presented in Figure 4.13(a) decreases because each SU will have less opportunities to transmit. Moreover, an inverse behavior occurs when $P_{I,i}$ increases, because more opportunities of spectrum access will occur. As for the packet service time illustrated in Figure 4.13(b), the behavior is the same as for homogeneous spectrum sensing opportunities, *i.e.*, the packet service time increases when the number of SUs increases, and decreases for small values of $P_{I,i}$ because SUs will have to wait more time to get the opportunity to transmit.

Finally, Figure 4.14 compares the aggregated normalized throughput achieved by the secondary network in heterogeneous spectrum sensing conditions for different SU's channel availability probabilities. We also plot different curves for different number of SUs. The curves show that the analytical model closely matches the simulation results when the SU's channel availability probability $P_{I,i}$ is lower or equal than the SU AP channel availability probability, $P_{I,AP}$. When the SU's channel availability rate is higher than the SU AP availability rate the analytical model becomes slightly pessimistic/optimistic for smaller/larger network sizes, which could be explained by the difficulty to estimate the right number of SUs.

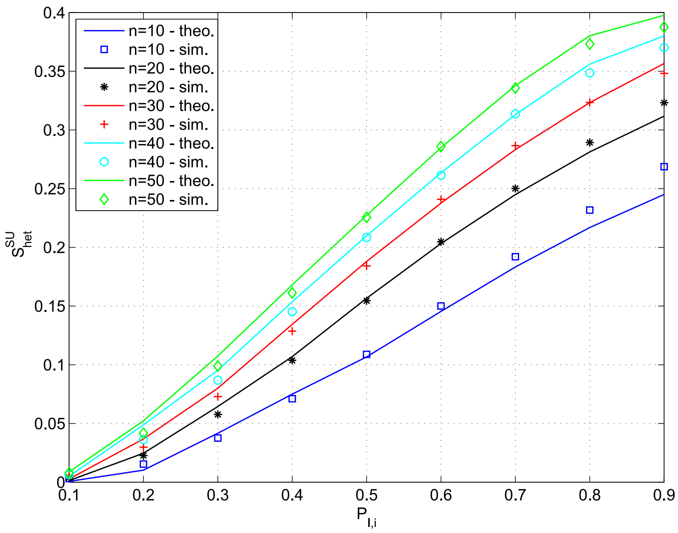


Figure 4.14: Aggregated normalized throughput achieved by the secondary network in heterogeneous spectrum sensing conditions and $P_{I,AP} = 0.7$.

4.4.2.2 The Impact of Different Levels of Sensing Heterogeneity

The current subsection evaluates the performance of C2RMAC, as well as *slotted* CR-ALOHA and CR-CSMA in terms of the aggregated normalized goodput achieved by the secondary network, for different levels of sensing heterogeneity. To that end we created three scenarios with different levels of dissimilarity:

a) a scenario with *low* (Low) dissimilarity where only one pair of PUs was placed in the scenario;

b) a second scenario with *medium* (Med) dissimilarity, where two pairs of PUs were placed in the scenario to create a moderated level of heterogeneity in the SU's channel sensing decisions;

c) and finally, a third scenario with *high* ($High$) dissimilarity consisting of three pairs of PUs.

In the aforementioned scenarios the average channel availability on each SU and the SU AP is approximately 70%, *i.e.* $P_{I,i} = P_{I,AP} \approx 0.7$. The average of the correlation coefficients, $\bar{\mathbf{X}}$, achieved in each scenario was[5]: $\bar{\mathbf{X}}_{Low} \approx 0.781$, $\bar{\mathbf{X}}_{Med} \approx 0.455$ and $\bar{\mathbf{X}}_{High} \approx 0.154$. Regarding the C2RMAC parameterization the number of mini-slots in the first and second stages was set to $cw_1 = 3$ and $cw_2 = 100$, respectively, while the *slotted* CR-ALOHA and CR-CSMA protocols were evaluated considering a backoff window of $4n$, an higher backoff window compared with the one adopted in Section 4.3.2 in order to account with an hypothetical variation in the number of SUs introduced by the sensing heterogeneity. The SU's frame length was set to $T_F^{SU} = 20ms$ and the energy detector kept the previous parameterization. Only simulation results are presented in this subsection.

Before evaluating the impact of heterogeneous spectrum sensing conditions on CR MAC schemes, we evaluate their performance under homogeneous spectrum sensing decisions, *i.e.*, when all the SUs and the SU AP share the same view of the channel. This way, we have a bound for the maximum achievable goodput. Figure 4.15 compares the aggregated normalized goodput achieved by *slotted* CR-ALOHA, CR-CSMA and C2RMAC protocols for a different number of SUs competing for the medium.

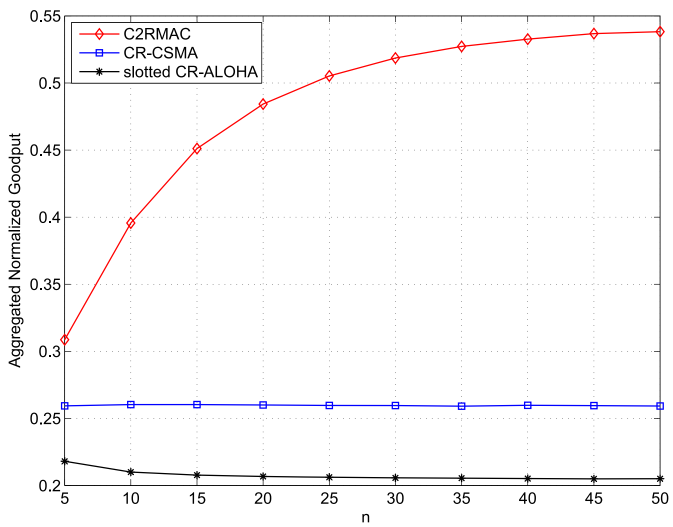


Figure 4.15: Goodput comparison among slotted CR-ALOHA, CR-CSMA and C2RMAC considering an homogeneous channel sensing scenario.

[5]The coefficient of correlation is approximately the same for every pair of SUs.

Observing the simulations results we can see that, as observed in Subsection 4.3.3, the reservation-based scheme achieves higher goodput when compared to the others, even when the number of mini-slots in the first and second stages are not optimized. We can also observe that for a small number of SUs, the cost of having two frames exclusively for reservation purposes impacts negatively the goodput achieved by the reservation-based protocol. However, when the number of SUs increases, the impact of the reserved frames becomes negligible when compared to the transmission period. Regarding *slotted* CR-ALOHA and CR-CSMA protocols, their goodput does not depend on the number of SUs because the SUs' contention window is linearly increased with the number of SUs.

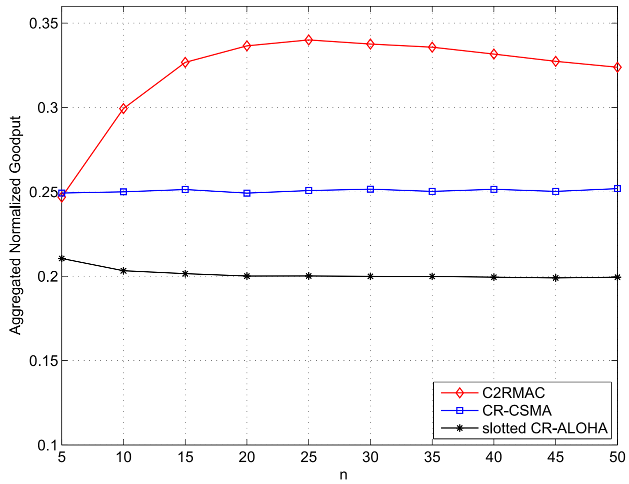
Figure 4.16 compares the performance of *slotted* CR-ALOHA, CR-CSMA and C2RMAC under heterogeneous channel sensing conditions. The first observation goes to the impact of heterogeneity in the random access MAC schemes. As we can see, and comparing the goodput presented in Fig. 4.15 for homogeneous channel sensing outputs, the heterogeneity does not significantly decreases the performance of these schemes. We highlight that even for homogeneous channel sensing decisions, these schemes already present a low performance due to the collision of multiple SUs' transmissions. Since the sensing heterogeneity mainly impacts the successful transmissions, their impact in the aggregate goodput will be almost negligible.

Regarding the performance of C2RMAC, we can see that it significantly decreases as the sensing heterogeneity increases. This is mainly due to the fact that during the reservation period, the protocol reserves the optimal number of frames to be used for transmission assuming that all SUs share the same view of the channel. However, as the level of sensing heterogeneity increases, the SUs experience different views of the channel in the same time instant, and the number of frames reserved for transmission during the second stage of contention is sub-optimal. Nonetheless, the reservation-based protocol is able to reduce some of the impact of the heterogeneity, since the number of reserved frames used for transmission depends on the number of busy mini-slots during the second stage of contention, showing the dynamic behavior of this scheme.

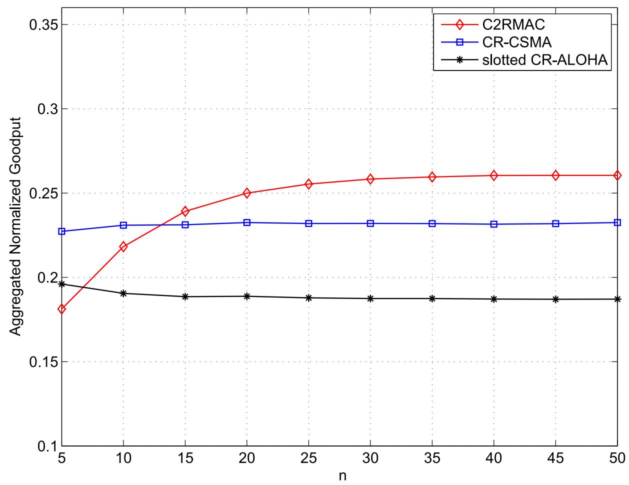
4.5 Conclusions and Final Remarks

In this chapter we present the C2RMAC protocol: a novel and efficient two-stage MAC protocol for single-radio CRNs. In the first stage the number of competing SUs is decreased to reduce the probability of collision, while in the second stage the selected SUs assign their packet transmissions, thus reducing the number of idle frames and consequently increasing the spectrum occupancy. Considering homogeneous spectrum sensing, which occurs when all SUs equally decide about channel's occupancy, we derive expressions for the goodput and the packet service time, which are validated through simulations for different number of SUs, spectrum availability ratios and total traffic loads. C2RMAC protocol is also compared with other relevant CR MAC protocols showing the effectiveness of our proposal, mainly due to its innovative design.

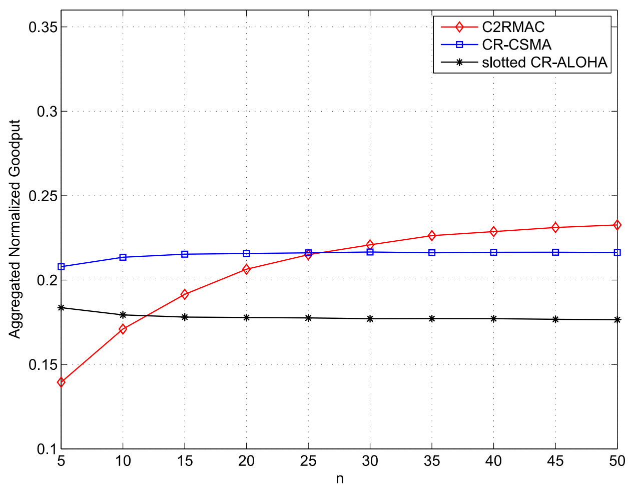
As a contribution of this work, we evaluate the impact of assuming heterogeneous channel sensing decisions in the performance of the proposed MAC scheme. Under this scenario, an analytical model for the individual channel access probability, packet service time and aggregated



(a) Low dissimilarity.



(b) Medium dissimilarity.



(c) High dissimilarity.

Figure 4.16: Goodput comparison among *slotted* CR-ALOHA, CR-CSMA and C2RMAC considering different heterogeneous channel sensing scenarios.

throughput based on two independent DTMCs is also derived, and successfully validated through simulations. Three scenarios with different levels of dissimilarity in the spectrum sensing decisions are defined, and the performance of C2RMAC and two other random access schemes are evaluated. The results show that under heterogeneous channel sensing decisions, the number of frames reserved for transmission during the second stage of contention of the C2RMAC protocol is sub-optimal, which considerably decreases the throughput. Regarding the random contention-based MAC protocols, the underperformance introduced by the sensing heterogeneity is almost negligible than the one observed in the proposed MAC protocol, mainly because the channel access mechanism employed by these protocols are not influenced by the sensing heterogeneity. However, the results show that in the majority of the scenarios, with and without sensing heterogeneity, the C2RMAC protocol is able to achieve better goodput when compared to the evaluated contention-based MAC schemes.

CHAPTER 5

MAC SCHEME: A MULTICHANNEL APPROACH

5.1 Introduction

As mentioned in Chapter 2, most of the proposed CR-based networks were designed to operate in a multiple channel environment. By exploiting multiple channels, it is possible to achieve a higher network throughput than using one channel, because multiple transmissions can take place simultaneously by exploring the channels' diversity in terms of its idleness [Jeo+12]. In these networks, a CR node transmits data traffic using one or more channels that are identified as being idle at the time of the data transmission. Therefore, MAC schemes for multichannel CRNs have to manage the SUs among the available data channels, which turns the design of an efficient CR MAC scheme extremely challenging, especially in DCRNs where the SUs are not managed by a central coordinator [TS14].

In this chapter we propose a novel multichannel CR MAC protocol for DCRNs, following a similar reservation-based concept adopted in C2RMAC. In order to distribute the SUs among the available data channels, we propose an innovated scheme entitled MC-C2RMAC, which adopts a non-preemptive MaxWeight scheduling policy based on the availability of the licensed channels and the individual backlog of the SUs. In MC-C2RMAC the channels with more spectrum opportunities are assigned to SUs with more packets awaiting for transmission. Each SU competes for a data channel using the two-way handshake RTS-CTS mechanism that takes place in a CCC, and the channel assignment is conducted by a distributed algorithm working without the need of a central entity. An analytical model for the individual SU's transmission probability, packet service time, and network aggregate goodput is proposed, which relies on a DTMC used to model the SU MAC behavior. Several simulation results considering different network sizes and data channels are used to assess the proposed model, characterizing the level of idle spectrum utilization achieved by the proposed MAC protocol.

Motivated by the fact that MC-C2RMAC first assigns the channels with higher access opportunities, it is important to find a way to characterize the amount of time that a SU needs to transmit a packet, which is usually denominated as service time. In this way, a channel exhibiting a shorter service time (in average) is capable of providing more access opportunities to the SUs. A few works have already characterized the packet service time. Specifically, the average packet service time was studied in [SL09] and [Zha+09a] under different preemptive priority queueing models such as M/D/1 and M/G/1 [Bol+98]. Nevertheless, neither of these works examine the role of the size of the SU's and PU's packets, nor the impact of different PU's activity rates on the average service time. The work in [Li+12] considers a priority virtual queue to model the joint coexistence of PU and SU traffic. Based on the model, the authors obtain an expression for the expected packet service time of SU's traffic through a M/G/1 preemptive priority queueing model. In [GZ12] the service response time, defined as the duration from the instant that a SU requests a data file from the central controller until it completes the reception, is analyzed for a single channel CRN with centralized control. The work is extended in [GZ13], where different mathematical expressions for the average service response time of elastic data with three service disciplines are derived. [GZ12; GZ13] assume that the PU activity follows an ON-OFF behavior with ON and OFF durations following exponential distributions. The authors compare the average service time of the three service disciplines under service time requirement distributions with different tail properties, and demonstrate that the preemption reduces the mean response time when the service time requirement follows a heavy tailed distribution. In [LH10] the authors propose a simplified model of PU interruptions based in a Markov chain analysis, being the queueing analysis carried out for the cases of two-server-single-queue (two channels and one SU) and two-queues-single-server (two SUs and one channel). In the former scenario a semi-analytic result is obtained for the generating function of the queue length, while in the latter case the authors derive an expression for the average queue length. More recently, [Usm+14] derived expressions for the distribution of the packet service time considering fixed-length SU packets, and continuous and periodic sensing strategies. As far as we know this is the only work where an expression for the distribution of the service time is derived. However, its contribution is only valid for fixed-length SU's data packets.

Hereupon, prior to the presentation of the MC-C2RMAC protocol, this chapter starts with a packet service time analysis of opportunistic access in a CRN. Assuming a discrete-time model and considering that SUs may generate variable packet lengths in saturated and non-saturated traffic conditions, we derive the probability of a SU's transmission occupying exactly k periods of time when the PU is inactive. Contrarily to previous works, which only consider that the transmission of the SU starts in the beginning of the PU's inactive period, we have considered that a SU may start its transmission at any instant of the PU's inactive period. Then, we derive the service time characteristic function, which is valid for a general scenario. Furthermore an approximation for the distribution of the service time is proposed, which uses the characteristic function to estimate the parameters of the distribution through the method of moments. We provide several numerical results obtained with the proposed model, which are compared with simulation results. Finally, we assess the accuracy of the average service time obtained in a real-time estimation process, evaluating the accuracy of the estimation for different lengths of the sample set.

The current chapter is structured as follows: Section 5.2 studies the opportunistic service time, *i.e.*, the time spent by a SU to transmit a packet using the radio spectrum licensed to PUs. Section

5.3 proposes and evaluates the MC-C2RMAC protocol. Finally, Section 5.4 overviews the chapter's conclusions.

5.2 Opportunistic Service Time

In this section we propose an innovative packet service time analysis of opportunistic access in a CRN assuming that a SU is already assigned to a wireless channel to transmit a packet. In this way this framework can be used in both single or multichannel protocols that consider an exclusive use of the channel by a SU to transmit its packet and no spectrum handoff is performed during the packet transmission. Departing from the work in [Wel+09], which confirms that the PU activity may be represented by a geometric distribution when small periods of PU's inactivity are considered, we describe several steps required to derive the expressions for the distribution of the SU's service time considering PU interruptions. Assuming that the SU's packet length follows a geometric distribution [Che+11; Paw+09; Zha+07a], we start by deriving an expression for the probability of a SU transmitting its packet when $k > 0$ periods of PU's inactivity are observed. Then, we extend the previous analysis and derive the CF of the service time, which in turn is used to approximate the distribution of the service time.

5.2.1 System Characterization

To characterize the opportunistic service time we consider the same network configuration discussed in Chapter 3: one pair of licensed PUs (sender and receiver) operating in a wireless channel and one pair of SUs (sender and receiver) trying to use the same channel in an opportunistic way. For this purpose we assume that SUs are able to identify the access opportunities through spectrum sensing operations as the ones discussed in Subsection 3.2.4, *i.e.*, in the beginning of the SU's frame a period of time of duration T_S^{SU} will be used to sense the channel and decide if it is free from primary activity. For time accounting purposes, we consider a minimum discrete time duration denoted as a time unit, and the index $k = x$ is used to indicate the x-th time unit.

Regarding the PU behavior, in this chapter we follow the results in [Wel+09], obtained with real traces collected from cellular users, that states that both PU active and inactive period durations can be modeled by geometric distributions. Therefore, the PU active period duration is represented by the random variable B. Similarly, the PU inactive duration is distributed according to the random variable I. The random variable denoting the PU active period duration is modeled by a geometric distribution with parameter $p_B = 1/\mu_B$, while I follows a geometric distribution with parameter $p_I = 1/\mu_I$. μ_B and μ_I represent the average PU active and inactive period durations, respectively, measured in time units (time slots). Thus, in this chapter the probabilities of a PU staying ON and OFF will be respectively given by $\tau^{PU} = \mu_B/(\mu_I + \mu_B)$ and $\overline{\tau^{PU}} = 1 - \tau^{PU} = \mu_I/(\mu_I + \mu_B)$. Finally, the terminology active/ON and inactive/OFF PU's periods will be used to denote the amount of time that a PU is active/ON or inactive/OFF, respectively.

As stated before, the SU transmitter may use the channel whenever it is not being used by the licensed users. In this chapter, and unlike the previous chapters where we assume a fixed SU's packet duration equal to the SU's transmission period duration, it is considered that the packet duration generated by the SU follows a geometric distribution. Therefore, in this section the SU's packet duration is represented by the random variable T^{SU}_{packet} which follows, as stated before, a geometric distribution with parameter $p_{T^{SU}_{packet}} = 1/\mu_{T^{SU}_{packet}}$, meaning that the average packet duration is $\mu_{T^{SU}_{packet}}$ time slots. Furthermore, we consider that a SU's packet of length $\mu_{T^{SU}_{packet}}$ requires $\mu_{T^{SU}_{packet}}$ time units (time slots) of PU's inactivity in order to be completely transmitted. However, the proposed analysis may be easily extended for different transmission rates, or even for scenarios where a fixed amount of the time unit is used by the SUs for spectrum sensing.

If a SU is able to transmit a packet using only one PU OFF period, the packet service time is exactly $\mu_{T^{SU}_{packet}}$ time slots. For example, following the hypothetical sequence of PU ON and OFF periods illustrated in Figure 5.1, this occurs when a SU starts the transmission of a packet of length 2 in the first time unit $(k = 1)$ of the first PU OFF period. However, when the length of the SU's packet is higher than the PU OFF period, a SU will have to interrupt the packet's transmission, and resume it in the following PU OFF period. This case may occur when a packet of length of 4 starts to be transmitted in the second time unit ($k = 2$) of the first PU OFF period illustrated in Figure 5.1. In this case the packet service time will not only depend on the size of the packet's length, but also on the length of the PU ON and OFF periods.

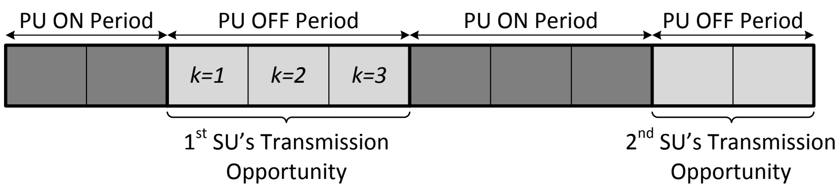


Figure 5.1: Hypothetical sequence of PU OFF and ON periods.

Since a SU must know the availability of the channel before starting a transmission, we assume that the spectrum sensing information is available in the beginning of the SU's time frame illustrated in Figure 5.1. In the analysis it is assumed that the SU's time frame lasts at least a time unit, meaning that we neglect the sensing duration. However, the proposed analysis is also applicable for a non-null spectrum sensing duration, by subtracting the sensing time to the time unit.

5.2.2 Service Time Characteristic Function

This section characterizes the service time of a packet transmitted by a SU. The proposed analysis starts by characterizing the number of PU OFF periods that a SU needs to transmit a packet, taking into account the length of the packet as well as the duration of the ON and OFF PU's periods. Then, we derive an expression for the CF of the service time, as well as the first- and the second-order moments, which will be used to approximate the distribution of the packet service time.

5.2.2.1 Service Interruptions

Let us start by deriving the number of PU OFF periods that a SU needs to transmit a packet, which is represented by the random variable $I_{periods}$. Assuming that a SU starts its transmission in the first time unit of the PU OFF period ($k = 1$ in Figure 5.1), the SU will be able to transmit the entire data packet in a single PU OFF period if the duration of the period (I) is longer or equal than the duration of the data packet, *i.e.*,

$$Pr\left\{I_{periods} = 1\right\} = Pr\left\{I \geq T^{SU}_{packet}\right\} \tag{5.1}$$

Since I and T^{SU}_{packet} are independent random variables, the probability of $I - T^{SU}_{packet}$ can be found using the cross-correlation between the two random variables as follows

$$Pr\left\{I - T^{SU}_{packet} = t\right\} = \sum_{k=1}^{+\infty} Pr\left\{T^{SU}_{packet} = k\right\} \cdot Pr\left\{I = k + t\right\} \ , \tag{5.2}$$

and therefore (5.1) becomes

$$Pr\left\{I_{periods} = 1\right\} = \sum_{k=0}^{+\infty} Pr\left\{I - T^{SU}_{packet} = k\right\}. \tag{5.3}$$

When a single PU OFF period is not enough to transmit the SU's data packet, the transmission of the packet is resumed to the next PU OFF period. Following the same rationale used in (5.1), we can write the probability of the SU's transmission be spanned in one or two PU OFF periods as follows

$$Pr\left\{I_{periods} \leq 2\right\} = Pr\left\{I + I \geq T^{SU}_{packet}\right\}. \tag{5.4}$$

Since the multiple realizations of the duration of a PU OFF period are i.i.d. we can write the probability of $I + I$, the sum of two geometric distributions with the same parameter $p_I = 1/\mu_I$, by the means of a binomial distribution with the parameters $r = 2$ and $p = p_I$, *i.e.*,

$$Pr\left\{I + I = t\right\} = \begin{cases} \binom{t-1}{1} {p_I}^2 \left(1 - p_I\right)^{t-2} \ , & t \geq 2 \\ 0 \ , & t < 2 \end{cases}. \tag{5.5}$$

In general, we can represent the duration of the sum of r PU OFF periods by the random variable I^{Sum}_r, whose PMF is given by

$$Pr\left\{I^{Sum}_r = t\right\} = \begin{cases} \binom{t-1}{r-1} {p_I}^r \left(1 - p_I\right)^{t-r} \ , & t \geq r \\ 0 \ , & t < r \end{cases}. \tag{5.6}$$

Using (5.5) in (5.4), the probability of a SU being able to transmit a data packet lasting T^{SU}_{packet} time units using two or less PU OFF periods is given by

$$Pr\left\{I_{periods} \leq 2\right\} = \sum_{k=0}^{+\infty} Pr\left\{I^{Sum}_2 - T^{SU}_{packet} = k\right\} \ , \tag{5.7}$$

where $Pr\left\{I^{Sum}_2 - T^{SU}_{packet} = t\right\}$ follows the same rationale as in (5.2) and is given by

$$Pr\left\{I^{Sum}_2 - T^{SU}_{packet} = t\right\} = \sum_{k=1}^{+\infty} Pr\left\{T^{SU}_{packet} = k\right\} \cdot Pr\left\{I^{Sum}_2 = k + t\right\}. \tag{5.8}$$

However, the probability $Pr\left\{I_{periods} \leq 2\right\}$ accounts for all the cases when a data packet with length T^{SU}_{packet} fits in two PU OFF periods, and includes the case when the packet is entirely transmitted in a single PU OFF period. Therefore, since we focus on the probability that a data packet is transmitted in exactly k PU OFF periods, we must consider the cases when the packet was not completely transmitted in the previous $r-1$ PU OFF periods. Consequently, the PMF of $I_{periods}$ becomes

$$Pr\left\{I_{periods} = r\right\} = \sum_{t=0}^{+\infty} Pr\left\{I_r^{Sum} - T^{SU}_{packet} = t\right\} - \sum_{t=0}^{+\infty} Pr\left\{I_{r-1}^{Sum} - T^{SU}_{packet} = t\right\} , \tag{5.9}$$

which depends only on the duration of the PU ON period μ_B and the SU's packet length $\mu_{T^{SU}_{packet}}$. The term $\sum_{t=0}^{+\infty} Pr\left\{I_r^{Sum} - T^{SU}_{packet} = t\right\}$ represents the probability of the transmission occupying at most k PU OFF periods, while the term $\sum_{t=0}^{+\infty} Pr\left\{I_{r-1}^{Sum} - T^{SU}_{packet} = t\right\}$ represents the probability of the transmission last at most $r-1$ PU OFF periods.

As stated before, we are assuming that a SU starts the packet transmission in the first time unit of the PU OFF period. In fact, a SU may start the packet transmission in any time unit of the PU OFF period. If we consider a saturated network, where SUs always have a packet to transmit, the beginning of a new packet transmission will only depend on when the previous transmission was finished. On the other hand, if we consider a non-saturated network, the beginning of a new packet transmission will also depend on the arrival instant of a new data packet. However, since we are considering geometric distributions to represent the duration of the PU ON and OFF periods, the memoryless property of these distributions can be used to justify that the number of PU OFF periods that a SU needs to transmit a packet does not depend on which time unit the packet transmission has started.

5.2.2.2 Characteristic Function

The definition of the CF of the service time is based on the number of PU's OFF periods observed during the SU's transmission. The service time of a SU's data packet is defined as the interval from the instant when a packet arrives the head of the transmitter's queue, until the instant when its transmission ends. The packet service time, measured in discrete units of time, is represented by the random variable $T_{service}$, while its CF is denoted by $\Phi_{T_{service}}$.

To derive the CF in a comprehensive manner, we divide its derivation in three different scenarios represented by the following Lemmas. We start by deriving the CF of the packet service time for a specific scenario (Lemma 5.2.1) and then we improve to a more generic scenario (Lemma 5.2.3).

Lemma 5.2.1. *When a SU always has a packet to transmit and the previous packet transmission ends in any time unit of the PU OFF period except the last one, e.g. $k=1$ and $k=2$ of the first PU OFF period illustrated in Figure 5.1, the CF of the packet service time is given by*

$$\Phi_{T_{service}}(k) = \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \frac{p_{T^{SU}_{packet}} e^{jk}}{1-\left(1-p_{T^{SU}_{packet}}\right) e^{jk}} \cdot \left(\frac{p_B e^{jk}}{1-\left(1-p_B\right) e^{jk}}\right)^{r-1} . \tag{5.10}$$

Proof. When a SU is able to transmit the entire packet in a single PU OFF period the service time depends only on the size of the data packet, *i.e.*,

$$\Phi_{T_{service}}(k) = \Phi_{T^{SU}_{packet}}(k), \tag{5.11}$$

where $\Phi_{T^{SU}_{packet}}(k)$ represents the CF of the packet duration in terms of k time units and is given by

$$\Phi_{T^{SU}_{packet}}(k) = \frac{p_{T^{SU}_{packet}} e^{jk}}{1 - \left(1 - p_{T^{SU}_{packet}}\right) e^{jk}}, \tag{5.12}$$

which represents the CF of a geometric distribution for $k > 0$ (j represents the imaginary unit) [LG08]. If a SU requires two PU OFF periods to transmit the packet, the packet service time will have to account for one PU ON period as follows

$$\Phi_{T_{service}}(k) = \Phi_{T^{SU}_{packet}}(k) \cdot \Phi_B(k), \tag{5.13}$$

where $\Phi_B(k)$ represents the CF of the duration of a PU ON period, and is given by

$$\Phi_B(k) = \frac{p_B e^{jk}}{1 - (1 - p_B) e^{jk}}. \tag{5.14}$$

Following the same rationale, under the assumptions considered in this Lemma, we can write the CF of the packet service time based on the number of required PU OFF periods as follows

$$\Phi_{T_{service}}(k) = \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \Phi_{T^{SU}_{packet}}(k) \cdot \Phi_B^{r-1}(k). \tag{5.15}$$

□

Lemma 5.2.2. *When a SU always has a packet to transmit and the previous packet transmission ends in any time unit of the PU OFF period, e.g. $k = 1, ..., 3$ of the first PU OFF period in Figure 5.1, the CF of the packet service time is given by*

$$\begin{aligned}\Phi_{T_{service}}(k) = (1 - p_I) \cdot \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \frac{p_{T^{SU}_{packet}} e^{jk}}{1 - \left(1 - p_{T^{SU}_{packet}}\right) e^{jk}} \cdot \left(\frac{p_B e^{jk}}{1 - (1 - p_B) e^{jk}}\right)^{r-1} + \\ p_I \cdot \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \frac{p_{T^{SU}_{packet}} e^{jk}}{1 - \left(1 - p_{T^{SU}_{packet}}\right) e^{jk}} \cdot \left(\frac{p_B e^{jk}}{1 - (1 - p_B) e^{jk}}\right)^{r}.\end{aligned} \tag{5.16}$$

Proof. Considering the definition of service time described before, if the previous transmission ends in the last time unit of the PU OFF period ($k = 3$ of the first PU OFF period in Figure 5.1) a new packet arrives at the head of the SU's buffer queue in the first time unit of a PU ON period. When this occurs, the packet service time will have to account for an entire PU ON period before any PU OFF period. Therefore, if a SU is able to transmit the entire packet in a single PU OFF period, the service time is given by

$$\Phi_{T_{service}}(k) = \Phi_{T^{SU}_{packet}}(k) \cdot \Phi_B(k). \tag{5.17}$$

Following the same rationale as before, if two PU OFF periods are required to transmit the entire packet, the service time of a data packet that arrived at the head of the queue in the first time unit of a PU ON period is given by

$$\Phi_{T_{service}}(k) = \Phi_{T^{SU}_{packet}}(k) \cdot \Phi^2_B(k). \tag{5.18}$$

In general, the service time of a data packet arriving at the head of the SU's buffer in the first time unit of the PU ON period is given by

$$\Phi_{T_{service}}(k) = \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \Phi_{T^{SU}_{packet}}(k) \cdot \Phi^r_B(k). \tag{5.19}$$

Let v_I be the probability of a packet arriving at the head of the SU's buffer queue during a PU OFF period. Considering that Lemma 5.2.2 assumes that the previous transmission ends in any time unit of the PU OFF period, and both PU ON and OFF periods follow geometric distributions, the memoryless property of the geometric distribution tells us that the probability of the previous SU's transmission ending in a given time unit of the PU OFF period is equal for any time unit $1, ..., \mu_I$. However, because this lemma also considers that a SU always has a packet to transmit, only the cases when the previous transmission ends at time units $1, 2, .., \mu_I - 1$ lead to a new packet arriving at the head of the SU's buffer queue during a PU OFF period. Therefore, the probability of a packet arriving at the head of the SU's buffer queue during a PU OFF period is given by

$$\begin{aligned} v_I &= \frac{\mu_I - 1}{\mu_I} \\ &= 1 - p_I. \end{aligned} \tag{5.20}$$

Thus, the CF of the service time for the second scenario is given by

$$\begin{aligned} \Phi_{T_{service}}(k) = v_I \cdot \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \Phi_{T^{SU}_{packet}}(k) \cdot \Phi^{r-1}_B(k) + \\ (1 - v_I) \cdot \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \Phi_{T^{SU}_{packet}}(k) \cdot \Phi^r_B(k). \end{aligned} \tag{5.21}$$

□

Lemma 5.2.3. *The CF of the packet service time for a general scenario,* i.e., *without any restrictions regarding the beginning of the packet's transmission and the SU's traffic condition (saturated or non-saturated), is given by*

$$\begin{aligned} \Phi_{T_{service}}(k) = &\left(1 - p_I + P_{QE}\left(-1 + p_I + \overline{\tau^{PU}}\right)\right) \times \\ &\sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \frac{p_{T^{SU}_{packet}} e^{jk}}{1 - \left(1 - p_{T^{SU}_{packet}}\right) e^{jk}} \cdot \left(\frac{p_B e^{jk}}{1 - (1 - p_B) e^{jk}}\right)^{r-1} + \\ &\left(p_I - P_{QE}\left(-1 + p_I + \overline{\tau^{PU}}\right)\right) \times \\ &\sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \frac{p_{T^{SU}_{packet}} e^{jk}}{1 - \left(1 - p_{T^{SU}_{packet}}\right) e^{jk}} \cdot \left(\frac{p_B e^{jk}}{1 - (1 - p_B) e^{jk}}\right)^{r}. \end{aligned} \tag{5.22}$$

Proof. This lemma considers a more general scenario without restrictions about i) the beginning of the data packet transmission, and ii) assuming that a SU may or may not have a packet to transmit after a successful transmission, which occurs with probability $1 - P_{QE}$ and P_{QE}, respectively.

Under saturated network conditions, $P_{QE} = 0$, a new packet arrives at the head of the SU's buffer queue during a PU OFF period if the previous packet's transmission has not ended in the last time unit of the PU OFF period. This scenario was tackled in the previous lemma and v_I is the same as in (5.20). However, under non-saturated network conditions $(P_{QE} \neq 1)$, a new data packet may arrive randomly at any time unit of the PU's frame, and therefore v_I for this case is given by

$$\frac{\mu_I}{\mu_I + \mu_B}. \tag{5.23}$$

Since we are considering a general scenario which takes into account any SU's traffic condition, the probability of a packet arriving at the head of the SU's buffers queue during a PU OFF period is now given by

$$v_I = (1 - P_{QE}) \cdot \frac{\mu_I - 1}{\mu_I} + P_{QE} \cdot \frac{\mu_I}{\mu_I + \mu_B}. \tag{5.24}$$

(5.24) is derived using the total law of probability, where $(1 - P_{QE})$ represents the probability of a SU having always a packet to transmit, and $\frac{\mu_I - 1}{\mu_I}$ represents the probability of a packet arriving in a slot of the OFF period given that a SU has always a packet to transmit. In the right-hand side, P_{QE} represents the probability of a SU not having a packet to transmit in a slot, and $\frac{\mu_I}{\mu_I + \mu_B}$ represents the probability of a packet arriving in a slot of the OFF period given that a SU has not always a packet to transmit (we assume that a packet may arrive at any slot of the OFF period with equal probability). After some mathematical simplifications we can rewrite v_I as

$$v_I = 1 - p_I + P_{QE}\left(-1 + p_I + \overline{\tau^{PU}}\right). \tag{5.25}$$

Finally, the CF of the service time considering a generic scenario can be obtained by replacing (5.25) in (5.21) and is given by

$$\begin{aligned}\Phi_{T_{service}}(k) &= \left(1 - p_I + P_{QE}\left(-1 + p_I + \overline{\tau^{PU}}\right)\right) \cdot \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \Phi_{T^{SU}_{packet}}(k) \cdot \Phi_B^{r-1}(k) \\ &+ \left(p_I - P_{QE}\left(-1 + p_I + \overline{\tau^{PU}}\right)\right) \cdot \sum_{r=1}^{+\infty} Pr\left\{I_{periods} = r\right\} \cdot \Phi_{T^{SU}_{packet}}(k) \cdot \Phi_B^{r}(k).\end{aligned} \tag{5.26}$$

□

5.2.2.3 Expectation and Variance

Using the CF of the service time it is possible to compute the expected value and the variance of the service time by the means of the first- and second-order statistics of the packet service time. The expected value of the service time, $\mathbb{E}\left[T_{service}\right]$, is given by

$$\mathbb{E}\left[T_{service}\right] = j^{-1}\left[\Phi'_{T_{service}}(k)\right]_{|k=0}, \tag{5.27}$$

while the variance of the service time, $\text{Var}[T_{service}]$, is given by

$$\text{Var}[T_{service}] = j^{-2} \left[\Psi'' (k) \, \Phi''_{T_{service}} (k) \right]_{|k=0} , \tag{5.28}$$

where $\Psi(k) = e^{-\mathbb{E}[T_{service}]jk}$ represents the coefficient needed to obtain the second centralised moment of $T_{service}$, *i.e.*, its variance.

5.2.3 Distribution of the Service Time

Having the characteristic function of the service time derived in the previous section as a starting point, the first- and the second-order moments will be used in this section to approximate the distribution of the packet service time. Based on the validation of the proposed approximation, a PMF for the packet service time is proposed.

5.2.3.1 Approximation to a Generalized Pareto Distribution

Using multiple sets of simulation results we have compared the distribution of the service time achieved by simulation with different distributions (e.g. Generalized Pareto, Normal, Exponential, Extreme Value, Gamma, Log-logistic, Logistic, Lognormal, Nakagami, Neg. binomial, Poisson, Rayleigh and Weibull). The comparison was made adopting the log-likelihood goodness of fit. The log-likelihood test indicated that the generalized Pareto distribution is the one that better approximates the simulation results (as confirmed by the results presented in Figure 5.4). Based on this observation, we used the characteristic function of the service time derived in the previous section to parametrize the generalized Pareto distribution. Since the generalized Pareto distribution is a continuous distribution, an associated discrete distribution can be obtained by discretizing the continuous generalized Pareto distribution, which is described below.

The continuous generalized Pareto distribution is defined in terms of the Cumulative Distribution Function (CDF) as follows [Col01]

$$F_{GPD}(x) = \begin{cases} 1 - \left(1 + \dfrac{\xi_{GPD}(x - \delta_{GPD})}{\sigma_{GPD}}\right)^{-1/\xi_{GPD}} , & \xi_{GPD} \neq 0 \\ 1 - e^{-\frac{x-\delta_{GPD}}{\sigma_{GPD}}} , & \xi_{GPD} = 0 \end{cases} , \tag{5.29}$$

for $x \geq \delta_{GPD}$ when $\xi_{GPD} \geq 0$, and $\delta_{GPD} \leq x \leq \delta_{GPD} - \sigma_{GPD}/\xi_{GPD}$ when $\xi_{GPD} < 0$, where δ_{GPD}, σ_{GPD} and ξ_{GPD} are respectively the location, scale and shape parameters of the generalized Pareto distribution. The survival function, $\bar{F}_{GPD}(x) = 1 - F_{GPD}(x)$, of the generalized Pareto distribution can be written as

$$\bar{F}_{GPD}(x) = \begin{cases} \left(1 + \dfrac{\xi_{GPD}(x - \delta_{GPD})}{\sigma_{GPD}}\right)^{-1/\xi_{GPD}} , & \xi_{GPD} \neq 0 \\ e^{-\frac{x-\delta_{GPD}}{\sigma_{GPD}}} , & \xi_{GPD} = 0 \end{cases} , \tag{5.30}$$

and the PMF of the discrete generalized Pareto distribution can be obtained by applying the following expression [GDCO11; NO75; Roy04]

$$Pr\{X = x\} = \bar{F}_{GPD}(x) - \bar{F}_{GPD}(x+1) . \tag{5.31}$$

Therefore, the PMF of the discrete generalized Pareto distribution capable to model the packet service time is given by

$$Pr\{T_{service} = x\} = \begin{cases} \left(1 + \frac{\xi_{GPD}(x - \delta_{GPD})}{\sigma_{GPD}}\right)^{-1/\xi_{GPD}} - \\ \quad - \left(1 + \frac{\xi_{GPD}(x + 1 - \delta_{GPD})}{\sigma_{GPD}}\right)^{-1/\xi_{GPD}}, & \xi_{GPD} \neq 0 \\ e^{-\frac{x-\delta_{GPD}}{\sigma_{GPD}}} - e^{-\frac{x+1-\delta_{GPD}}{\sigma_{GPD}}}, & \xi_{GPD} = 0 \end{cases}, \tag{5.32}$$

for $x \geq \delta_{GPD}$ when $\xi_{GPD} \geq 0$, and $\delta_{GPD} \leq x \leq \delta_{GPD} - \sigma_{GPD}/\xi_{GPD}$ when $\xi_{GPD} < 0$. According to [HW87], the expected value and the variance of the generalized Pareto distribution are given by

$$\mathbb{E}\left[T_{service_{GPD}}\right] = \delta_{GPD} + \frac{\sigma_{GPD}}{1 - \xi_{GPD}}, \tag{5.33}$$

and

$$\mathrm{Var}\left[T_{service_{GPD}}\right] = \frac{\sigma^2_{GPD}}{(1 - \xi_{GPD})^2 (1 - 2\xi_{GPD})}, \tag{5.34}$$

respectively. Assuming that the packet service time domain $(T_{service})$ is in $\{1, 2, ..., +\infty\}$, the location parameter δ_{GPD} of the discrete generalized Pareto distribution is set to $\delta_{GPD} = 1$. Thus, equaling (5.27) to (5.33) and (5.28) to (5.34), and assuming that $\sigma_{GPD} \geq 0$, we define a system of two equations $(\mathrm{Var}[T_{service}] = \mathrm{Var}[T_{service_{GPD}}], \mathbb{E}[T_{service}] = \mathbb{E}[T_{service_{GPD}}])$, being its solution numerically computed to obtain the scale (σ_{GPD}) and shape (ξ_{GPD}) parameters of the generalized Pareto distribution as follows

$$\begin{cases} \sigma_{GPD} \approx \mathbb{E}[T_{service}](1 - \xi_{GPD}) - 1 + \xi_{GPD} \\ \xi_{GPD} \approx \frac{1}{2} - \frac{(\mathbb{E}[T_{service}] - 1)^2}{2\mathrm{Var}[T_{service}]} \end{cases}. \tag{5.35}$$

5.2.3.2 Queueing Modeling

The characteristic function of the service time presented in (5.26) includes the probability of a SU having a packet to transmit ($1 - P_{QE}$), which has not yet been set. To define P_{QE}, this subsection adopts a queueing model to account with the statistics involved in the transmission queue.

A queueing model is characterized by the arrival process, the service time distribution with a certain service discipline and the number of servers at the queueing node. In the previous subsection we have presented an approximation for the service time distribution, which depends on the probability of finding the queue empty, P_{QE}.

Assuming that the packet arrival process at the SU follows a Poisson distribution with average arrival rate $\lambda_{arrival}$ (packets/time unit) and a single data channel is used for transmission (number of servers = 1), a M/G/1 queueing model can be considered [Bol+98]. The PGF of the queue length of a M/G/1 queueing model is given by [Bol+98]

$$Q_{Q_{length}}(z) = \frac{(1-z)(1-\rho)\,\mathcal{Z}_{T_{service}}(\lambda_{arrival}(1-z))}{\mathcal{Z}_{T_{service}}(\lambda_{arrival}(1-z)) - z}, \tag{5.36}$$

where $\mathcal{Z}_{T_{service}}$ is the Z-transform of the service time distribution and Q_{length} is the random variable representing the queue length. $\mathcal{Z}_{T_{service}}$ takes only nonnegative values, and it can be obtained by replacing jk in (5.26) by $-z$. ρ is a variable that expresses the traffic intensity and it is related with the mean arrival rate of frames at the SU's queue $(\lambda_{arrival})$ and the mean service time $(\mathbb{E}[T_{service}])$ as follows

$$\rho = \lambda_{arrival} \cdot \mathbb{E}[T_{service}]. \tag{5.37}$$

At this point, we can use the probability of finding the queue empty, given by [Bol+98]

$$P_{QE} = \frac{Q^{(0)}_{Q_{length}}(z)}{0!}\Big|_{z=0}, \tag{5.38}$$

as well as the expressions in (5.27) and (5.37) to build the following system of non-linear equations

$$\begin{cases} \rho = \lambda_{arrival} \cdot \mathbb{E}[T_{service}] \\ P_{QE} = \dfrac{Q^{(0)}_{Q_{length}}(z)}{0!}\Big|_{z=0} \\ \mathbb{E}[T_{service}] = j^{-1}\left[\Phi'_{T_{service}}(k)\right]_{|k=0} \end{cases}. \tag{5.39}$$

where P_{QE}, ρ and $\mathbb{E}[T_{service}]$ are unknown. For a given $\lambda_{arrival}$ we can solve the system numerically and compute the probability of finding the queue empty P_{QE}, as well as the mean packet service time $\mathbb{E}[T_{service}]$.

Following *Little's* Theorem, the packet's average queue waiting time $\mathbb{E}[Q_{waiting}]$ for an M/G/1 queueing model in steady state, *i.e.* when $\rho < 1$, is given by [Bol+98]

$$\mathbb{E}[Q_{waiting}] = \frac{\lambda_{arrival}\mathbb{E}[T_{service}{}^2]}{2(1-\rho)}, \tag{5.40}$$

where $\mathbb{E}[T_{service}{}^2]$ is the second moment of the packet service time. Following the Pollaczek-Khinchine formula the average queue length $\mathbb{E}[Q_{length}]$ is given by [Bol+98]

$$\begin{aligned} \mathbb{E}[Q_{length}] &= \rho + \frac{\rho^2 + \lambda^2_{arrival}\mathrm{Var}[T_{service}]}{2(1-\rho)} \\ &= \rho + \frac{\rho^2\left(1 + \mathbb{E}^2[T_{service}] \cdot \mathrm{Var}[T_{service}]\right)}{2(1-\rho)}, \end{aligned} \tag{5.41}$$

where $\mathrm{Var}[T_{service}]$ denotes the variance of the service time given in (5.28).

5.2.4 Validation and Numerical Results

This subsection presents a set of simulations and numerical results to validate the PMF of the SU's transmission interruptions (eq. (5.9)), the mean packet service time for different SU's packet durations (eq. (5.27)), and the approximation of the packet service time (eq. (5.29)). Considering a M/G/1 queueing model we will also validate the packet's average queue waiting time for different ρ values (eq. (5.40)).

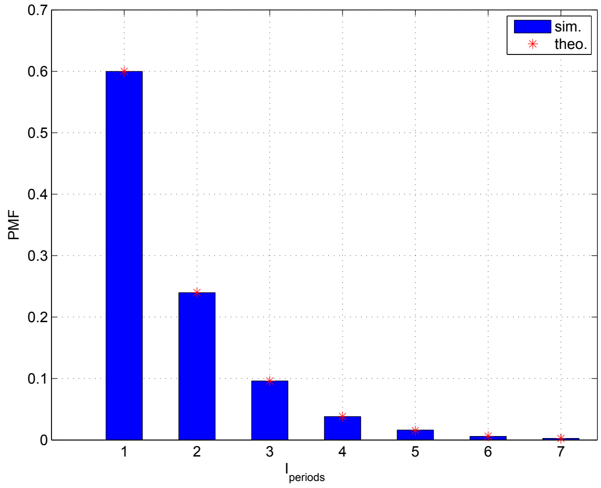
The simulation scenario is the same as described in Section 5.2.1, formed by one pair of PUs, transmitter and receiver, using one wireless licensed channel. Both active and inactive durations of the PU are modeled by geometric distributions with mean μ_B and μ_I, respectively. A pair transmitter-receiver of SUs completes the CRN and the SU transmits in the licensed channel when it is declared vacant by the spectrum sensing. Without loss of generality, ideal spectrum sensing is assumed, *i.e.*, the channel is declared as being idle or busy whenever it is not used by the PUs or a PU transmission takes place, respectively. In Subsections 5.2.4.1, 5.2.4.2, 5.2.4.3 and 5.2.4.4 a saturated secondary network is assumed, while in Subsection 5.2.4.5 we evaluate the proposed model under a non-saturated secondary network. As mentioned before, the SU's packet duration follows a geometric distribution with mean $\mu_{T^{SU}_{packet}}$.

5.2.4.1 SU's Transmission Interruptions

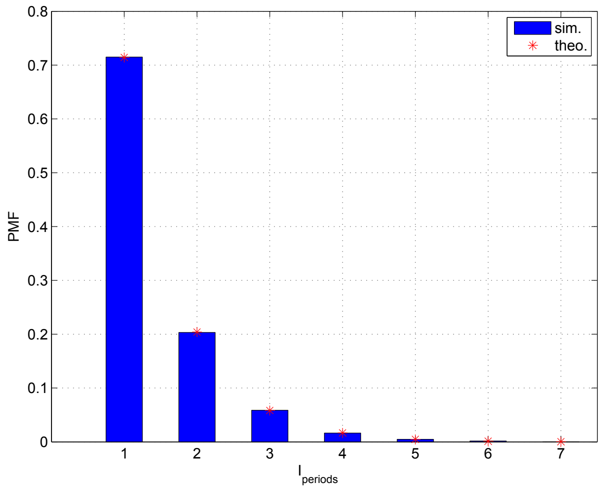
We start by validating the distribution of the number of PU OFF periods that a SU needs to transmit a packet, $I_{Periods}$, derived in Subsection 5.2.2.1. Figure 5.2 evaluates the distribution of $I_{Periods}$ considering three scenarios with different mean PU OFF period durations (μ_I). The average PU ON duration is set to $\mu_B = 3$ for all the simulations presented in this subsection. However, as we can see from (5.9), the number of PU OFF periods need to transmit a SU's packet is not influenced by the duration of the PU ON periods. In order to validate the analytical model we plot the analytical results obtained with (5.9) (represented by the red markers) against the simulation results (represented by the blue bars). The simulation results validate the accuracy of the analytical model. Furthermore, as expected the results show that for a fixed mean packet length, PU OFF periods with longer durations reduce the number of PU OFF periods needed to completely transmit a data packet.

5.2.4.2 Average Packet Service Time

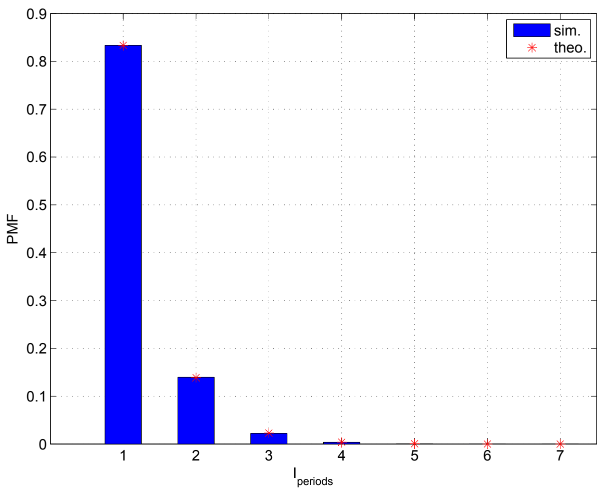
Figure 5.3 compares the theoretical average packet service time computed with (5.27) (curves) with the simulation results (markers). Different SU's packet durations, $\mu_{T^{SU}_{packet}}$, and PU's inactivity rates, $\overline{\tau^{PU}}$, are considered. The PU's frame length is set to $\mu_B + \mu_I = 10$ slots for any value of $\overline{\tau^{PU}}$, meaning that, for example, when $\overline{\tau^{PU}} = 0.2$, the average PU active and inactive durations are $\mu_B = 8$ and $\mu_I = 2$, respectively. The results show that the theoretical model successfully validates the simulation results. However, for higher SU's mean packet durations and lower PU's inactivity rates the average packet service time obtained through the theoretical model is slightly inferior when compared to the simulations results. This fact is explained by the higher variance introduced by the geometric distributions used to obtain the length of the SU's packet duration.



(a) $\mu_I = 3$



(b) $\mu_I = 5$



(c) $\mu_I = 10$

Figure 5.2: PMFs of the number of PU OFF periods that a SU requires to complete the transmission of a data packet of length $\mu_{T_{packet}^{SU}} = 3$, for different PU OFF period durations, μ_I.

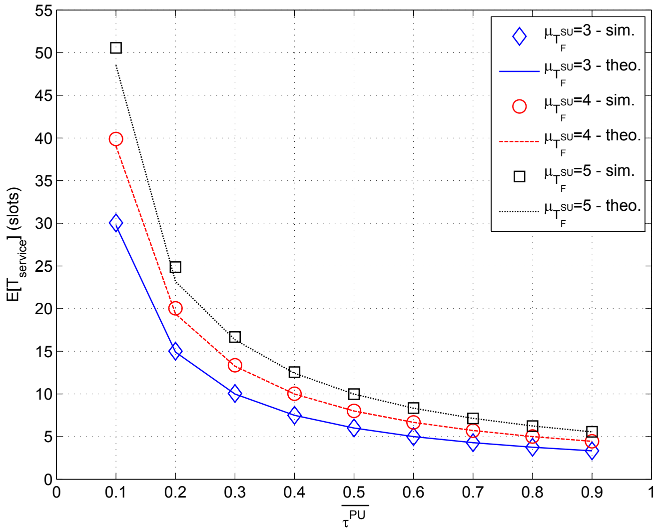
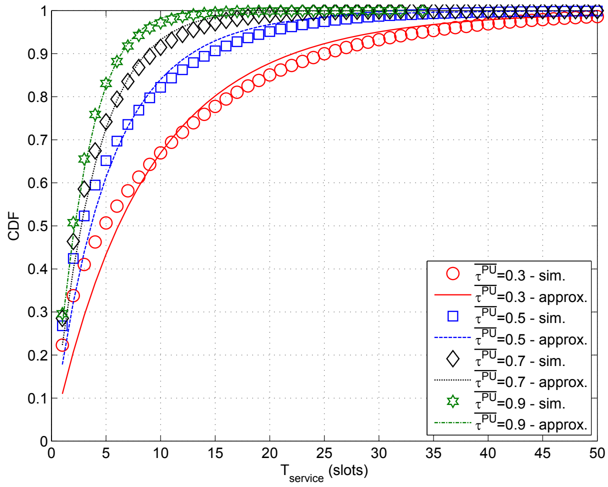


Figure 5.3: Average packet service time for different SU's mean packet durations $\mu_{T^{SU}_{packet}}$ and PU's inactivity rate $\overline{\tau^{PU}}$. The average PU's frame length is set to $\mu_B + \mu_I = 10$ slots.

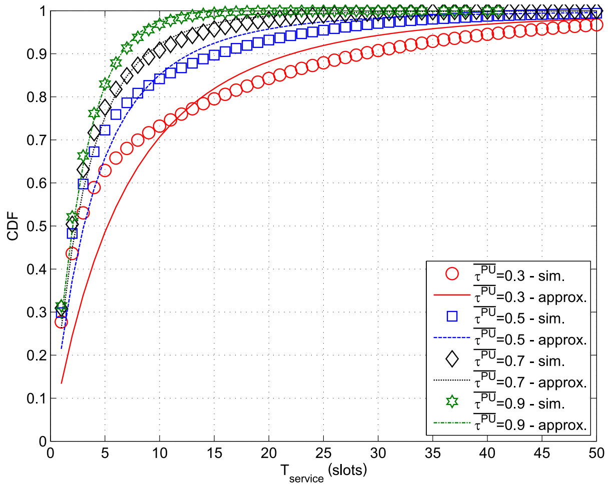
5.2.4.3 Validation of Discrete Generalized Pareto Approximation

This subsection validates the approximation of the packet service time by the means of a discrete generalized Pareto distribution as described in Subsection 5.2.2.3. Figure 5.4 illustrates the CDF of the packet service time for different values of $\overline{\tau^{PU}}$: in Figure 5.4(a) it is considered a PU's frame length of 10 discrete time units (time slots), while in Figure 5.4(b) it is considered a PU's frame length of 20 slots. For each scenario the discrete generalized Pareto approximation obtained with (5.29) is also plotted. Both Figures show that the packet service time can be approximated by the discrete generalized Pareto distribution, especially for higher values of PU's inactivity rate ($\overline{\tau^{PU}} > 0.5$), which is the scenario of interest in cognitive networks.

From Figures 5.4(a) and 5.4(b) we can also observe that, for a fixed PU's frame length the approximation becomes less accurate for lower values of $\overline{\tau^{PU}}$ (e.g., comparing the red and the black results in Figure 5.4(a)). This is because when the probability $\overline{\tau^{PU}}$ becomes smaller, the number of PU OFF periods needed to transmit a packet will increase. Consequently, when the number of SU's transmission interruptions increases, the number of observed PU ON periods also increases. Therefore, the packet service time tends to be more influenced by the variance introduced by the distribution of the PU ON period duration, which decreases the approximation's accuracy. Moreover, when we compare the approximations considering the same $\overline{\tau^{PU}}$ but different PU's frame length (e.g. the blue curves in both Figures 5.4(a) and 5.4(b)), we can also observe that longer PU's frame lengths decrease the approximation's accuracy. This is because for higher PU's frame durations, the variance of the duration of the PU ON and OFF periods is higher, which decreases the accuracy of the model.



(a) $\mu_B + \mu_I = 10$ slots.



(b) $\mu_B + \mu_I = 20$ slots

Figure 5.4: CDFs of the packet service time and the discrete generalized Pareto approximation when $\mu_{T^{SU}_{packet}} = 3$ for different values of PU's inactivity rate and PU's frame lengths.

5.2.4.4 Packet Service Time Estimation

Let us now evaluate the possibility of estimating the packet service time based on real-time observations, *i.e.*, using a set of service time samples acquired by a SU. For each set of samples, a SU computes the average and the variance of the packet service time, which are used to compute the scale and the shape parameter of the discrete generalized Pareto distribution, through (5.35) and setting the location parameter $\delta_{GPD} = 1$.

Figure 5.5 presents the CDF of the packet service time obtained through simulation, as well as their estimates based on a set of 10 samples. For each PU's inactivity rate, the estimated CDF represents the average of 1000 estimated CDFs based on the real-time observations (*i.e.* 1000 packet service time observations). Figure 5.5 shows that it is possible to approximate the packet service time CDF using a small sample set of 10 samples. Similarly to the approximations obtained using the theoretical model and observed in the previous section, the approximations become more accurate for higher values of $\overline{\tau^{PU}}$.

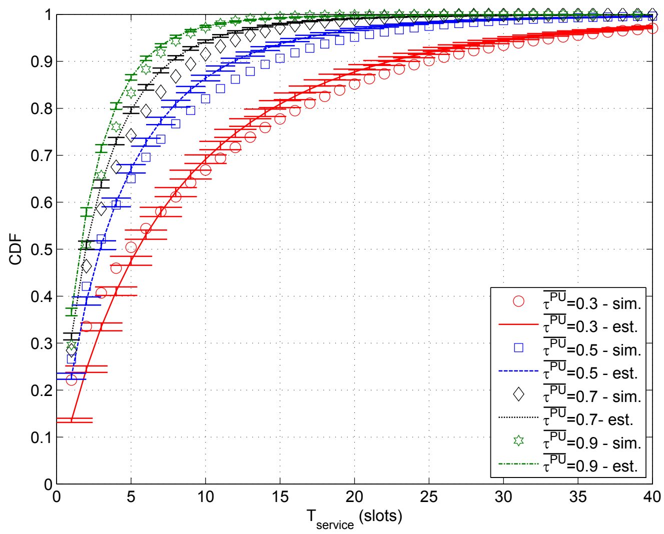


Figure 5.5: CDFs of the packet service time and the discrete generalized Pareto approximation based on real-time observations when $\mu_{T^{SU}_{packet}} = 3$, $\mu_B + \mu_I = 10$, with 10 samples.

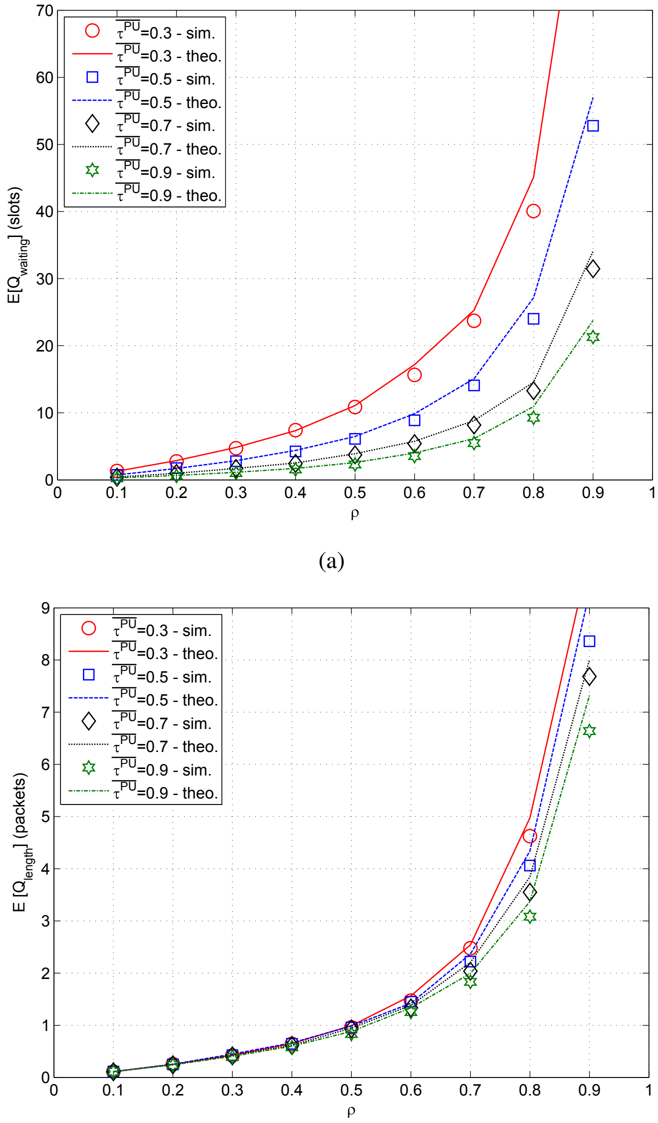
Table 5.1 contains the average packet service time and the confidence interval for 95% of confidence level computed with the estimated distributions. Different lengths of the sampling set are considered. The results show that, for the considered sampling set lengths, the average packet service time obtained from the estimated distribution closely matches with the average packet service time obtained through simulation.

Table 5.1: Estimated average packet service time using different sample sizes, for different PU's inactivity rates.

	$\overline{\tau^{PU}}$=0.3	$\overline{\tau^{PU}}$=0.5	$\overline{\tau^{PU}}$=0.7	$\overline{\tau^{PU}}$=0.9
model	10.42	6.05	4.29	3.50
est. 5 samples	10.43 ± 0.354	6.04 ± 0.186	4.27 ± 0.114	3.50 ± 0.082
est. 10 samples	10.42 ± 0.250	6.04 ± 0.133	4.28 ± 0.078	3.50 ± 0.059
est. 20 samples	10.43 ± 0.175	6.05 ± 0.089	4.27 ± 0.048	3.51 ± 0.041
est. 50 samples	10.40 ± 0.100	6.07 ± 0.057	4.27 ± 0.027	3.52 ± 0.024

5.2.4.5 Average Packet Waiting Time and Queue Length Under Non-saturated Conditions

Finally, Figures 5.6(a) and 5.6(b) illustrate the average packet waiting time, $\mathbb{E}[Q_{waiting}]$, and the average queue length, $\mathbb{E}[Q_{length}]$, respectively, for different values of traffic intensity, ρ, and PU's inactivity rates, $\overline{\tau^{PU}}$. The analytical results obtained with (5.40) and (5.41) are represented by the lines, while the simulation results are represented by the markers. As it is shown, the simulation results are close to the analytical model for most of the simulated scenarios. The model performance becomes slightly pessimistic especially for small values of $\overline{\tau^{PU}}$.



(a)

(b)

Figure 5.6: Average packet waiting time a) and average queue length b) for different PU's inactivity rates $\overline{\tau^{PU}}$. The average PU's frame length is set to $\mu_B + \mu_I = 10$ slots and the SU's mean packet duration is set to $\mu_{T^{SU}_{packet}} = 3$.

Regarding the average packet waiting time for the different simulated scenarios, Figure 5.6(a) shows that for small values of $\overline{\tau^{PU}}$ each packet waits more time in the queue before being transmitted, because more time is needed to transmit the packets that were already in the queue. As for the average queue length, Figure 5.6(b) shows that for small values of ρ the number of packets in the queue is almost the same, no matter the PU's inactivity rate. From (5.41) we can see that the average queue length is a function of the traffic intensity, the mean of the service time and variance of the service time. Considering that ρ is the same for any value of $\overline{\tau^{PU}}$, the term $\mathbb{E}^2\left[T_{service}\right] \cdot \mathrm{Var}\left[T_{service}\right]$ in (5.41) remains constant to keep the average packet queue also constant, irrespective of $\overline{\tau^{PU}}$.

However, when the system approaches the saturation, the different PU's inactivity rates will introduce different levels of variance in the service time, leading to slight differences in the average queue length for the same value of traffic intensity (ρ).

5.3 A Multichannel CR MAC Protocol: MC-C2RMAC

In this section we introduce a multichannel CR MAC scheme for DCRNs: the MC-C2RMAC. We adopt the use of a dedicated CCC where the SUs can 1) compete for a data channel and 2) disseminate information about the data channels primary's occupancy. The SUs compete for a data channel using the RTS-CTS mechanism. In order to assign the data channels among the SUs we propose a distributed channel selection algorithm implementing a MaxWeight scheduling policy, without the need of a central entity. The channel's average service time, calculated using the framework developed in the previous section, takes a crucial role in the proposed scheduling policy since the main goal is to assign the SUs with more packets waiting in the queue to data channels with lower packet service times. By assuming a reserved mini-slot for each data channel we can guarantee that each CTS packet is sent without colliding with any other control packet. Furthermore, by regularly disseminating the data channel availabilities each SU is able to maintain an updated statistic about all the data channels primary's occupancy. Overall, MC-C2RMAC presents a very simple architecture, being able to reduce the control channel starvation and eliminating the multichannel hidden terminal problem.

The remaining of this section is as follows. In the next subsection we characterize the system model. Subsection 5.3.2 overviews the MC-C2RMAC operation mode with special emphasis in the signaling message exchange and channel assignment algorithm. Subsection 5.3.3 derives an analytical model for the individual transmission probability, aggregate secondary goodput and aggregate packet service time achieved by the MC-C2RMAC. Finally, Subsection 5.3.4 evaluates the performance of the proposed multichannel CR MAC scheme considering different number of data channels and channel availabilities.

5.3.1 System Characterization

The system model assumes the following network configuration: a licensed spectrum band consisting of L data channels where each channel l is occupied by one pair of PUs (transmitter and receiver). The PU's behavior will be the same as discussed in the previous section where both PU active and inactive period durations are modeled by two geometric distributions with parameters p_B and p_I, respectively. By assuming that a PU transmitter l occupies the data channel l with probability τ_l^{PU}, we can follow the results obtained in Section 5.2 and admit that the average packet service time of channel l with respect to the transmission of a data packet of duration T_{packet}^{SU} is given by $\mathbb{E}[T_{service,l}]$ time units, computed using (5.27).

Additionally, a CCC without primary activity is exclusively used for channel access negotiation and channel state information exchange. In order to take full advantage of the CCC and the multitude number of data channels, it is assumed that each SU is equipped with two half-duplex transceivers:

one operates exclusively in the CCC while the other one is able to tune to any L data channels to sense primary activity, or exchange data information with other SUs if the channel is not being used by PUs.

The cognitive radio network is formed by the set N of $n \geq L$ pairs of SUs (transmitter and receiver) where the transmitter always have a packet to transmit. As for the SU's frame we follow the structure defined in Section 3.2, *i.e.*, one period of spectrum sensing with fixed length T_S^{SU} time units and one period of spectrum transmission with fixed length T_D^{SU} time units. At last, and following the previous section, we continue to assume that data packets generated by each SU follow a geometric distribution with mean $\mu_{T^{SU}_{packet}}$ time units. We should recall that we are assuming that the SU's sensing duration is considerably small when compared to the PU's frame length, and therefore, a SU's packet of length $\mu_{T^{SU}_{packet}}$ is completely transmitted in $\mu_{T^{SU}_{packet}}$ PU's idle time units.

5.3.2 Protocol's Description

Figure 5.7 shows the principle of MC-C2RMAC. The structure of the CCC timing frame is divided into two periods, which forms the SU signaling frame. In the first period, denoted as Channel Request (CReq) period, the SUs without an assigned data channel and with a data packet to transmit send an RTS packet in order to compete for an unassigned data channel. The RTS packets are sent randomly and contain information about the intended receiver and the number of packets awaiting for transmission (queue backlog). It is assumed that only RTS packets not involved in a collision with other packets will be eligible to compete for a data channel. A second period, denominated Channel Information (CInf) period, is formed by as many mini-slots as data channels. In the CInf period two types of packets can be sent:

1. If the l-th data channel is being used by a SU pair, then the SU receiver will send an Information (INFO) packet in the l-th mini-slot of the CInf containing information about the channel primary's occupancy, as well as if the SU's transmission has reached its end;

2. on the other hand, if the channel is unassigned, the corresponding mini-slot is used by a SU receiver to send a CTS packet as an answer to the RTS packet previously sent, informing the other SUs that the reservation is completed.

Once a SU is awarded with a data channel, and in order to avoid interfering with licensed users, it has to keep track of the primary activity in the channel. To that end, each SU divides its operation cycle between spectrum sensing and spectrum access periods, with durations T_S^{SU} and T_D^{SU}, respectively, as illustrated in Figure 5.7. The SU sender only transmits if the channel is sensed idle during T_S^{SU}.

Between the CReq period and the CInf period it is necessary to assign the data channels among the competing SUs. To that end we propose a distributed algorithm of channel assignment working without the need of a central entity and based on the following premise: SUs with higher backlog, *i.e.*, with more packets waiting in the queue, should be assigned to data channels with lower packet service times, so that SUs can reduce the length of the their queues more quickly, increasing the network capacity. In order to avoid collisions between SUs during the transmission of data packets,

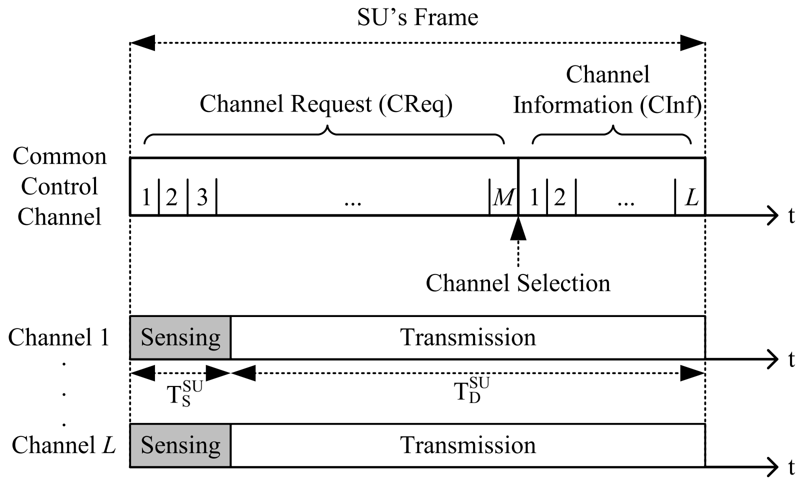


Figure 5.7: MC-C2RMAC: principle of operation.

it is assumed that a data channel can only be assigned to one SU pair (transmitter and receiver) at a time.

A MaxWeight scheduling policy is adopted to assign a SU i to a channel l following the aforementioned premise. As stated in the previous section the number of packets in the queue is represented by Q_{length}. Thus, if we use $Q_{length,i}(k)$ to denote the number of packets in the queue of a SU i at instant k and $T_{service,l}$ to denote the packet service time of data channel l, a SU $i^*(k)$ is assigned to the channel l such that

$$i^*(k) \in \arg\max_{i} \frac{Q_{length,i}(k)}{T_{service,l}} . \tag{5.42}$$

When multiple data channels are considered, the MaxWeight scheduling is translated by the following optimization problem

$$\max_{\Lambda_{i,l}} \sum_{l,i} \Lambda_{i,l}(k) \frac{Q_{length,i}(k)}{T_{service,l}} , \tag{5.43}$$

where $\Lambda_{i,l} \in \{0,1\}$ represents the scheduling decision of the SU i to the channel l. The MAC address of SUs and data channels will be used for tie breaking: a lower MAC address will have priority over a higher MAC address. In order to successfully implement the MaxWeight policy it is necessary that the SUs keep track of the information sent in the INFO packets so they have knowledge about the data channel availabilities and the queue backlog of the SUs competing for the channel assignment.

To better understand the proposed protocol, Figure 5.8 illustrates an example with 5 pairs of SUs and 3 data channels. Let us assume that for the analyzed time window all the data channels are free from primary activity, and at the beginning of frame k the data channel 1 is already assigned to SU B, which will release the channel at the end of the $k+1$-th frame. The data channel 2 is assigned to SU D until the end of the k-th frame while the data channel 3 is assigned to SU E until the end of the $k+5$-th frame. The CReq period is divided into 4 mini-slots $(M = 4)$.

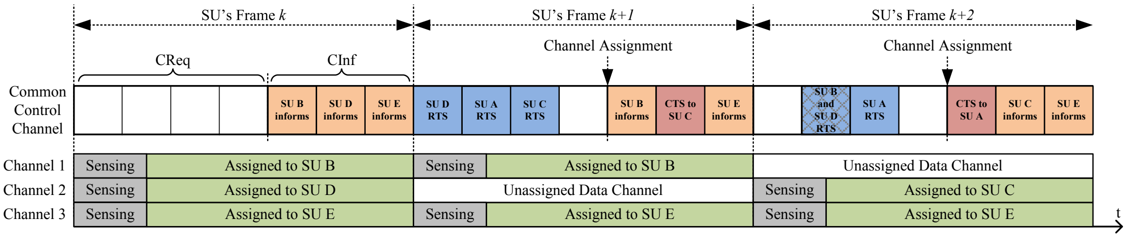


Figure 5.8: Channel negotiation and reservation process considering 3 data channels (1, 2 and 3) and 5 pairs of SUs (A, B, C, D and E).

Since all the data channels are currently in use, there will be no RTS packets exchange during the CReq period of frame k. During the CInf period, the SU receivers will update the information regarding the data channel primary's activity. Furthermore, the SU D will also notify the other SUs that the data channel 2 will be unassigned in the next frame, *i.e.*, SU D and its receiver will leave the channel 2 at the end of frame k. During the CReq period of frame $k+1$, SUs A, C and D will send RTS packets by randomly selecting a mini-slot with probability τ_{CReq}. Then, each of the intending SU receivers will apply the channel assignment in (5.43) to select which SU pair will be able to transmit in data channel 2. Since SU C has the higher backlog between all the competing SUs, it will be granted to transmit in data channel 2, and the corresponding SU receiver will send a CTS packet (CTS to SU C in frame $k+1$) to finish the channel negotiation. Meanwhile in the first mini-slot of the CInf period of frame $k+1$ the SU receiver of SU B had also notified the other SUs that data channel 1 will be released. Therefore, a similar process as described before occurs in frame $k+2$. However since the RTS packets from SUs B and D have collided, SU A is selected to transmit in data channel 1.

5.3.3 System Analysis

In this section we develop an analytical model to describe the individual SU's transmission probability and packet service time, as well as the secondary network aggregate goodput achieved with MC-C2RMAC. The analytical model relies on the DTMC illustrated in Figure 5.9, which models the individual SU MAC states.

Initially a SU is in the **Idle** state where it will remain until at least one data channel is found vacant from secondary activity, which occurs with probability P_{One_Unass}. When one or more data channels become unassigned, the SU competes for a channel by transmitting an RTS packet, and therefore it proceeds to **Competing** MAC state. Once the SU competes for a data channel, the probability that it will be selected to transmit in a data channel will depend on three factors:

- a) if the RTS packet was successfully sent, *i.e.*, without colliding with any other RTS packets, which occurs with probability $1 - P_{RTS\_Coll}$;
- b) if the channel assignment algorithm has selected the SU to transmit in one of the available data channels, which occurs with probability P_{Ch_Sel};
- c) and if the intending receiver has transmitted the CTS packet P_{CTS}.

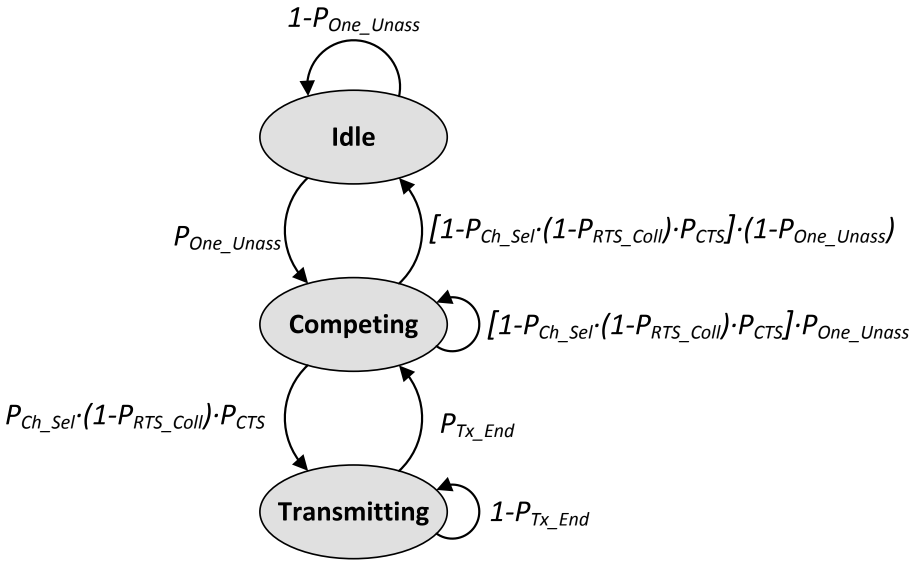


Figure 5.9: DTMC illustrating the SU's operation mode.

If the SU was not able to get a data channel it will be allowed to compete again in the next frame if any other data channel becomes unassigned, and so the SU remains in the **Competing** MAC state. However, if there will be no data channels unassigned in the next frame, the SU will proceed to the **Idle** state. If the SU is awarded with a data channel, in the following frame it will proceed to state **Transmitting**, where it will remain until the end of the packet transmission P_{Tx_End}.

5.3.3.1 Individual Transmission Probability

Considering $\{U_k\}_{k\geq 0}$ a discrete-time stochastic process representing the generic ψ MAC state of a SU at frame k, the stationary distribution of the chain is expressed by the notation $\pi_\psi = lim_{k\rightarrow+\infty}Pr\{U_k = \psi\}$, with $\psi \in \{\textbf{Idle}, \textbf{Comp}, \textbf{Trans}\}$. The steady-state probability of a SU transmitting $\pi_{\textbf{Trans}}$ is given by

$$\pi_{\textbf{Trans}} = \frac{P_{Ch\_Sel}P_{One\_Unass}\left(-1+P_{RTS\_Coll}\right)P_{CTS}}{-P_{Tx\_End}+P_{Ch\_Sel}\left(-1+P_{RTS\_Coll}\right)P_{CTS}\left(P_{One\_Unass}+\left(-1+P_{One\_Unass}\right)P_{Tx\_End}\right)}. \tag{5.44}$$

In order to compute $\pi_{\textbf{Trans}}$ we have to derive the following probabilities: P_{One_Unass}, P_{Ch_Sel}, P_{RTS_Coll} and P_{Tx_End}. Let us start by deriving the probability of finding at least one data channel free from secondary activity P_{One_Unass}. As we stated in the protocol's description, a SU is assigned to a data channel for a period of time long enough to transmit its packet, which depends on the packet length T^{SU}_{packet} and on the data channel availability given by the idle probability of the PU associated to that channel. Then, the average duration of a data channel assignment is given by $\mathbb{E}\left[T_{service}\right]$. After $\mathbb{E}\left[T_{service}\right]$ time units the data channel becomes unassigned and available for negotiation. If we consider η as being the average number of time units needed to successfully assign a data channel, the probability of finding the channel l unassigned is given by

$$P_{Ch\_Unass,l} = \frac{\eta}{\mathbb{E}\left[T_{service,l}\right] + \eta}\ , \tag{5.45}$$

while the complementary, $1 - P_{Ch\_Unass,l}$, represents the probability of finding the channel l assigned to a SU. If L data channels with independent probabilities $P_{Ch\_Unass,l}$ are considered, the average number of unassigned data channels at a given instant is given by

$$\mathbb{E}\left[L_{Unass}\right] = \sum_{l=1}^{L} P_{Ch\_Unass,l}\ , \tag{5.46}$$

where L_{Unass} is a discrete random variable representing the number of unassigned data channels at the beginning of each SU's frame, which follows a Poisson distribution with mean $\mathbb{E}\left[L_{Unass}\right]$. Thus, the probability of finding at least one unassigned data channel is given by

$$P_{One\_Unass} = 1 - Pr\{L_{Unass} = 0\}. \tag{5.47}$$

In order to compete for a data channel a SU transmits an RTS packet by randomly selecting one of the M mini-slots of the CReq period, which means that each mini-slot is selected with a probability $\tau_{CReq} = 1/M$. Therefore, the probability of an RTS packet being sent without colliding with any other RTS packets in a single mini-slot M is given by

$$\tau_{CReq}\left(1 - \tau_{CReq}\right)^{(n_{RTS}-1)}. \tag{5.48}$$

Considering that an RTS packet is sent in one of the M mini-slots, the probability of it being successfully sent during the CReq period, $1 - P_{RTS\_Coll}$, is given by

$$\begin{aligned} 1 - P_{RTS\_Coll} &= M\tau_{CReq}\left(1 - \tau_{CReq}\right)^{(n_{RTS}-1)} \\ &= \left(1 - \tau_{CReq}\right)^{(n_{RTS}-1)}. \end{aligned} \tag{5.49}$$

n_{RTS} represents the average number of SUs competing for a data channel and is given by

$$n_{RTS} = \frac{1}{P_{One\_Unass}} \sum_{l=1}^{L} Pr\{L_{Unass} = l\}\left(N - (L - l)\right). \tag{5.50}$$

The distributed channel selection algorithm assigns the channels with less packet service time to SUs with more packets awaiting for transmission. In the long-term, and assuming that all the SUs adopt a similar packet arrival rate and average packet size, all SUs have the same channel access opportunities. This means that if the RTS packet of a SU is successfully transmitted, each SU has the same opportunity to be assigned to a data channel as other SUs that are currently competing. Therefore, the probability of a SU being assigned to a data channel is given by

$$P_{Ch\_Sel} = \frac{1}{P_{One\_Unass}} \sum_{l=1}^{L} Pr\{L_{Unass} = l\} \frac{l}{n_{RTS}\left(1 - P_{RTS\_Coll}\right)}\ , \tag{5.51}$$

which is valid when the number of eligible competing SUs is higher or equal to the average number of available data channels, *i.e*,

$$n_{RTS}\left(1 - P_{RTS\_Coll}\right) \geq \sum_{l=1}^{L} Pr\{L_{Unass} = l\} l. \tag{5.52}$$

Once a SU is assigned to a data channel it remains there until it transmits the entire packet to the SU receiver, *i.e.*, during $\mathbb{E}\left[T_{service,l}\right]$ time units. However, because we do not know which channel will be assigned to each SU, and assuming that the data channels have different packet service times, the average transmission duration is given by $\frac{1}{L}\sum_{l=1}^{L}\mathbb{E}\left[T_{service,l}\right]$. Thus, the probability that a SU has finished the packet transmission is expressed as

$$P_{Tx\_End} = \frac{1}{\dfrac{1}{L}\displaystyle\sum_{l=1}^{L}\mathbb{E}\left[T_{service,l}\right]}. \tag{5.53}$$

5.3.3.2 Aggregate Service Time for Multiple Channels

In the previous subsection we have derived the packet service time when a packet is served in a single channel, when the PU active and inactive periods, as well as the length of the packet, are generated from geometric distributions. However, in a multichannel environment a SU may use any of the available data channels, which influences the packet service time. To that end we will consider a new random variable, $T_{service}^{Agg}$, denoting the aggregate packet service time under multichannel environments.

Although in a multichannel environment, we will follow the same definition of packet service time that has been used up to this point: the interval from the instant when a packet arrives at the head of the transmitter's buffer queue, until the instant when its transmission ends. In the MC-C2RMAC the decision to transmit a packet occurs after the channel selection algorithm takes place. Therefore, in order to compute the average aggregate packet service under the time for multiple channels $\mathbb{E}\left[T_{service}^{Agg}\right]$, we must relate the steady-state probability of state **Comp** with the probability of the transition from the state **Comp** to the state **Trans** as follows

$$\mathbb{E}\left[T_{service}^{Agg}\right] = \frac{1}{\pi_{\mathbf{Comp}} P_{Ch\_Sel}\left(1 - P_{RTS\_Coll}\right) P_{CTS}}. \tag{5.54}$$

5.3.3.3 Goodput

The aggregate secondary goodput of MC-C2RMAC represents the amount of time unused by primary users that is opportunistically used by the secondary network. If we consider a system with a single data channel, and knowing that the channel will be vacant from any secondary activity during η negotiation frames, the aggregate normalized secondary goodput G_1^{SU} of the proposed scheme is given by

$$G_1^{SU} = \frac{T_D^{SU}}{T_F^{SU}} \frac{\mu_{T_{packet}^{SU}}}{\mathbb{E}\left[T_{service,1}\right] + \eta}, \tag{5.55}$$

where the ratio $\frac{T_D^{SU}}{T_F^{SU}}$ represents a loss of throughput due to the sensing period. However, since we are considering a system with L data channels, the network aggregate normalized goodput achieved by the secondary network G^{SU} is given by

$$G^{SU} = \frac{T_D^{SU}}{T_F^{SU}} \sum_{l=1}^{L} \frac{\mu_{T_{packet}^{SU}}}{\mathbb{E}\left[T_{service,l}\right] + \eta}. \tag{5.56}$$

5.3.4 Performance Evaluation

In this subsection we evaluate the performance of MC-C2RMAC and compare it with the analytical model. First we analyze the impact of the length of the CReq period - number of mini-slots M - in the individual SU's transmission probability. Then, using the same number of mini-slots M for the rest of the simulations, we evaluate the performance of the proposed protocol and validate the accuracy of the analytical model in terms of individual transmission probability, aggregate packet service time and network aggregate goodput, for different number of SUs and different number of data channels.

In order to detect primary activity, each SU adopts the same energy detector technique that was used in the evaluation of C2RMAC. The energy detector threshold γ is set to 38.3 Joules and a SNR of $2dB$, using the parameterization criterion C_4 described in Subsection 3.2.4. To guarantee a high level of PU's protection the probability of detection is set to $P_D = 0.95$, and the probability of false alarm is set to $P_{FA} = 0.05$ which implies a spectrum sensing duration ratio of $\frac{T_S^{SU}}{T_F^{SU}} = 0.05$. The average length of PU's frame, $\mu_B + \mu_I$ is set to 10 time units. Table 5.2 presents the parameters used in the simulations.

Table 5.2: Parameters used in the simulations regarding the evaluation of MC-C2RMAC.

Parameter	Value
$\mu_B + \mu_I$	10 time units
SNR	2 dB
P_D	0.95
P_{FA}	0.05
T_{packet}^{SU}	5 time units
$\overline{\tau_I^{PU}}$	$\{0.5, 0.6, 0.7, 0.8, 0.9\}$
P_{CTS}	1

Figure 5.10 evaluates the impact of the number of mini-slots M during the CReq period in the individual SU's transmission probability. In this case 3 data channels were used with the following availability rates: $\overline{\tau_1^{PU}} = 0.5$, $\overline{\tau_2^{PU}} = 0.6$ and $\overline{\tau_3^{PU}} = 0.7$. Figure 5.10 shows that when the ratio N/M becomes considerably large, the individual probability of transmission remains almost constant. This fact is explained as follows: although a higher number of mini-slots M will increase the probability of successfully transmitting an RTS (5.49), the probability of a SU being assigned to a data channel will decrease (5.51). Therefore, since the increase in $1 - P_{RTS\_Coll}$ is inversely proportional to the decrease in P_{Ch_Sel}, the probability regarding the transition from the state **Comp** to the state **Trans**, given by $P_{Ch\_Sel}\left(1 - P_{RTS\_Coll}\right) P_{CTS}$, remains approximately constant.

However, when the number of mini-slots in the CReq period is much smaller when compared to the number of SUs, e.g. $n = 40$ and $M = 5$, the individual SU's transmission probability decreases because the number of mini-slots during the CReq period is too small. The small number of mini-slots decreases the probability of a SU being able to successfully transmit an RTS packet,

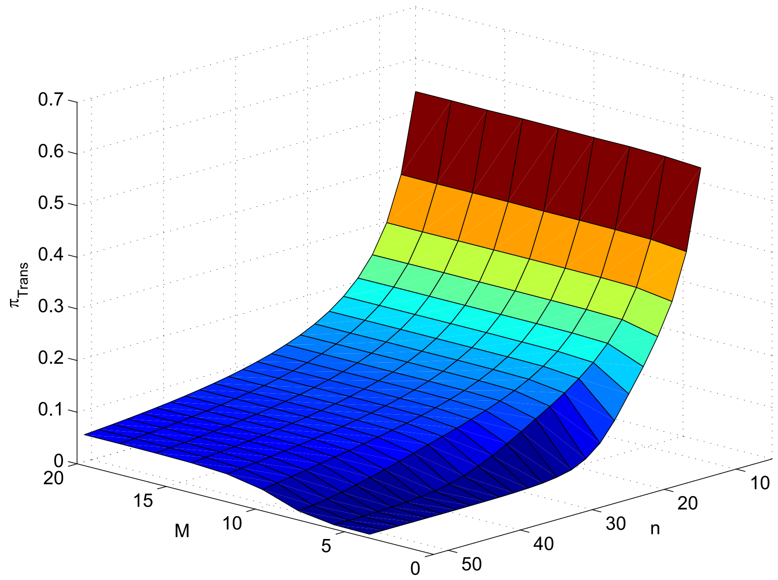
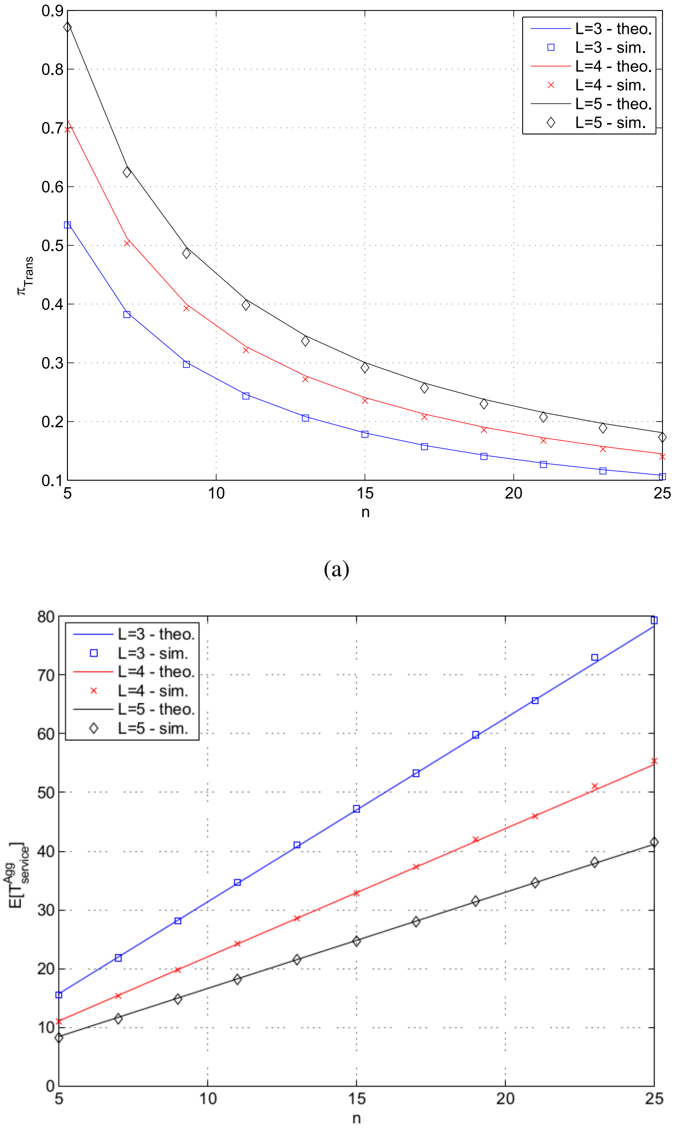


Figure 5.10: Simulation results regarding the individual transmission probability $\pi_{\mathbf{Trans}}$ against the number of mini-slots in the CReq period and the number of SUs, for $L = 3$.

decreasing the probability of it being assigned to a data channel. For the remaining simulations, the number of mini-slots in the CReq period was set to $M = 10$ and $\eta = 1$.

Figures 5.11(a) and 5.11(b) show the individual transmission probability $\pi_{\mathbf{Trans}}$ and the average packet service time $\mathbb{E}\left[T_{service}\right]$, respectively (5.44) and (5.54), for a different number of SUs and data channels. The first observation goes to the accuracy of the analytical model. As we can see, for any number of data channels the theoretical results (solid lines) match with the simulation results (symbols), for both individual probability of transmission and average packet service time metrics. Moreover, for a fixed L, the individual probability of transmission decreases with n because each SU will have less opportunities to transmit. The same rationale is used to justify the decrease in the average packet service time when n increases. From Figures 5.11(a) and 5.11(b) we can also see that, as L increases, there will be more opportunities to transmit, and as expected, the individual transmission probability increases and the average packet service time decreases.

Finally, Figure 5.12 compares the aggregate throughput achieved by the secondary network for a different number of SUs and data channels. In addition to theoretical and simulation results we also plot the maximum aggregate goodput that can be achieved by the secondary network (dashed lines). For example, if we consider $L = 4$ with the following availabilities $\overline{\tau_1^{PU}} = 0.5$, $\overline{\tau_2^{PU}} = 0.6$, $\overline{\tau_3^{PU}} = 0.7$ and $\overline{\tau_4^{PU}} = 0.8$, the maximum aggregate goodput is $\sum_{l=1}^{L} \overline{\tau_l^{PU}} = 2.6$. Again, the first observation goes to the accuracy of the analytical model. As we can see, the theoretical results for the network aggregate goodput obtained from (5.56) closely match the simulation results. The second observation goes to the amount of available spectrum utilization, which is considerably high for any value of L. The gap between the maximum available goodput and the total achieved by the secondary network is justified by 1) the amount of time needed to sense the channel T_S and 2) by the number of frames needed to negotiate an unassigned data channel. In these cases, the data channel cannot be used for secondary transmissions, and therefore it is not possible to achieve the



(a)

(b)

Figure 5.11: Individual transmission probability $\pi_{\mathbf{Trans}}$ (a) and average packet service time $\mathbb{E}\left[T^{Agg}_{service}\right]$ (b) for different number of SUs and data channels.

maximum available goodput.

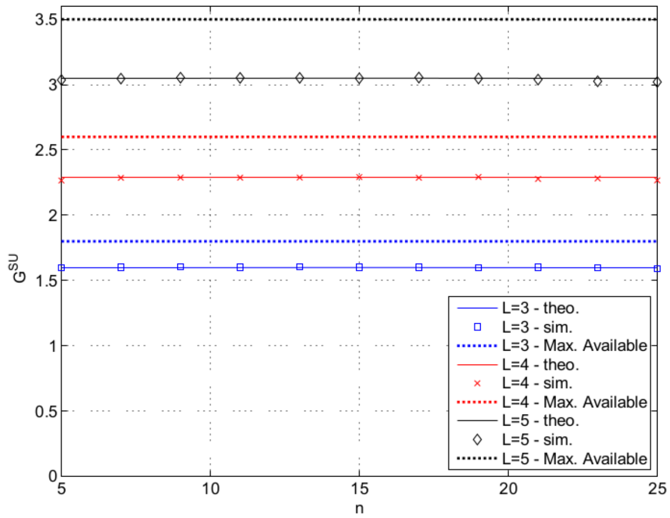


Figure 5.12: Aggregate goodput for different number of SUs and data channels. The maximum available aggregate goodput for each set of data channels is also displayed.

From Figure 5.12 we can also see that the aggregate goodput achieved by the secondary network is almost constant. This is explained by the fact that, for the considered number of mini-slots ($M = 10$), there is always at least one SU scheduled to a data channel, *i.e.*, with an RTS packet that was sent without suffering a collision. However, as showed in Figure 5.10, if we increase the number of SUs while keeping the same number of mini-slots M, the individual probability of transmission will decrease, and therefore decreasing the network goodput.

5.4 Conclusions and Final Remarks

While Chapter 4 was focused on single-channel CRNs this chapter approaches a multichannel environment. The chapter was divided in two parts. In the first part we have proposed an innovative packet service time analysis of opportunistic access in CRN. Assuming that the SU's packet length follows a geometric distribution, we have derived an expression for the probability of a SU transmitting its packet when $k > 0$ periods of PU's inactivity are observed. Then, we derived the characteristic function of the service time, which in turn was used to approximate the distribution of the service time. By computing the average and the variance of a small service time sampling set, we proposed an estimation method based on the method of moments. We highlight the general conditions assumed in the model, which include variable packet length, the possibility of a SU to start transmitting at any instant within a PU's OFF period, as well as the possibility of expressing the traffic condition through the probability of finding the transmission queue empty. Several simulations were used to assess the accuracy of the proposed model considering different SU's packet lengths, PU's inactivity rates and traffic conditions. Assuming that the SU's packet length and the PU ON and OFF period durations are represented by geometric distributions, the simulations results showed that the distribution of the packet service time can be approximated by a discrete generalized Pareto distribution, especially for higher values of PU's inactivity rates, *i.e.*, when a PU spends most of its time inactive.

In the second part of this chapter we have proposed a novel CR MAC protocol for a multiple channel scenario that improves the cognitive radio network throughput and overall spectrum utilization. Under the proposed protocol, the MC-C2RMAC, each SU competes for a data channel by adopting a RTS-CTS handshake and a distributed and non-preemptive MaxWeight scheduling policy. As a result of the distributed channel assignment algorithm, which distributes the data channels with lower packet service times (computed using the model derived in the first part of this chapter) among the competing SUs with more packets to transmit, a single CTS packet is sent in a single slot free of collision, solving the traditional multichannel hidden terminal problem. An analytical model to describe the individual SU's transmission probability, the packet service time and the network aggregate goodput was presented and validated through simulations. Several scenarios considering different number of data channels and SUs were simulated, and the results showed that MC-C2RMAC is able to achieve a substantial level of idle spectrum utilization.

CHAPTER 6

CONCLUSIONS

6.1 Synthesis

The CR technology has been proposed in recent years as a promising technology geared to solve the spectrum scarcity problem by opportunistically identifying and using the vacant portions of the spectrum, while ensuring that licensed users are not affected. This necessitates adapting to the dynamically changing spectrum resource, learning about the spectrum occupancy and making decisions on the quality of the available spectrum resource. Thus, the introduction of spectrum awareness brings more challenges for the PHY-MAC protocol design under the CRN scenario when compared with *conventional* wireless networks. Additional challenges must be considered when designing MAC schemes for DCRNs because each SU is responsible for the spectrum sensing/access coordination without the help of a central entity.

Chapter 2 overviewed an extensive list of spectrum sensing techniques, performed at the PHY level, and a comprehensive set of MAC schemes designed to overcome the aforementioned peculiar characteristics of a CRN. Starting from the PHY layer, several spectrum awareness methods were detailed, concluding that the local radio spectrum monitoring is the most employed method in the literature, specially among decentralized CR architectures. Hardware requirements, the hidden PU problem and the sensing duration and frequency are some of the implementation challenges associated with the design of the spectrum sensing framework that were elaborated. Finally, three of the most spectrum sensing techniques were depicted: the EBS, the most popular sensing technique due to its low computational and implementation complexities, the MFBS and the CBS. CR MAC schemes were also detailed in Chapter 2. The differences between classical wireless MAC schemes and CR MAC schemes were enumerated, and the most challenging implementation issues were discussed. A CR MAC classification tree was presented, and for each category at least one scheme was presented. Chapter 2 closed with a description of several standardization initiatives in the CR domain, most of them proposed for centralized architectures to explore the vacant frequencies left by the analog TV system.

The extensive literature review on decentralized CR MAC protocols presented in Chapter 2, showed that most of the MAC protocols proposed for single-channel configurations admit the existence of a dedicated CCC, or an additional channel, to be used for control messages exchange. However, the extra CCC might be, in some cases, impossible to implement, and therefore the split-phase approach is an alternative solution to coordinate the medium access of the SUs in a decentralized way. A few split-phase MAC protocols have been proposed for DCRNs, however they adopt random access philosophies to manage the channel's access, which are unable to maximize the spectrum reutilization. Motivated by the previous arguments this thesis aims to develop innovative efficient PHY-MAC architectures for CRNs, able to be implemented in a decentralized manner.

Chapter 3 characterizes the performance of the spectrum sensing task considering a single-radio CRN where each SU adopts a specific spectrum sensing technique: the EBS. The chapter was divided in two parts. In the first part we have characterized and analyzed the performance of the EBS detector assuming that PUs keep a constant behavior during the SU's operation cycle. Under this assumption, roughly adopted by the majority of the works presented in the literature, we have derived closed-form expressions for the system goodput and for the interference caused to the primary network. Several EBS's parameterization criteria based on different objectives, e.g. PU's protection or network's goodput, were compared and the results showed that, depending on the network's requirements some criteria may be preferred to others. In the second part of the third chapter we have derived closed-form expressions for the probability of detection and false alarm, as well as the interference caused to the primary network, under the assumption that PUs may arrive or depart during the SU's frame. Results showed that the interference caused to PUs is always underestimated when a constant PU's behavior is considered. However, the results also showed that the error introduced by the constant PU's behavior assumption becomes considerably smaller when the length of the PU's frame is too large when compared to the length of the SU's frame.

Chapter 4 was dedicated to single-channel DCRNs. A novel reservation-based MAC scheme for single-channel DCRNs, the C2RMAC, was presented with the purpose to manage the SU's access in a distributed and efficient way. The results showed that the two-stage MAC protocol is able to reduce the collisions between SUs by reducing the number of competing nodes, and decrease the number of unused idle frames, therefore increasing the spectrum occupancy. An analytical model for the goodput and packet service time was also proposed considering two distinct scenarios: homogeneous and heterogeneous channel sensing decisions, depending if different SUs achieve different sensing outcomes for the same spectrum sensing period. Simulation results, considering different network sizes, spectrum availability ratios and traffic loads were used to assess the accuracy of the analytical models. The results also showed that the proposed MAC scheme outperforms two popular decentralized split-phase MAC protocols proposed in the literature.

Chapter 5 was dedicated to multichannel DCRNs. First, an innovative packet service time analysis for opportunistic access in a CRN was proposed. As a result we have derived the characteristic function of the service time, which in turn was used to approximate the distribution of the service time. The analytical model was developed taking into consideration generic conditions such as variable packet length and saturated and non-saturated traffic conditions. Simulation results evaluated the performance of the analytical model considering several network configurations such as different SU's packet lengths, inactivity rates and traffic conditions. Results showed that if the PU ON and OFF period durations follow geometric distributions, the packet service time can be approximated by a discrete generalized Pareto distribution. The proposed analysis, and mainly the estimation of the service time, presents high potential of applicability in several practical scenarios, including but not limited to buffering management and improvement of the quality of service. Additionally, Chapter 5 presented a novel multichannel MAC scheme for single-radio DCRNs, following the same reservation-based rationale adopted in the single-channel approach. The proposed MAC scheme adopted a distributed non-preemptive MaxWeight scheduling policy based on the opportunistic service time of each channel, derived in the first part of this chapter, and on the size of the queue backlog of each SU. Results showed that the spectrum utilization ratio under the MC-C2RMAC is considerably high for any number of available licensed data channels.

6.2 Future Work

The CR technology is still an emerging technology and therefore the models and the results of this thesis can be used for future work on the development and benchmark of novel PHY-MAC frameworks for DCRNs.

The EBS parameterization criteria evaluated in Chapter 3 can be used to select the best parameterization strategy of new spectrum sensing frameworks. Based on the primary and secondary networks' requirements, such as the secondary network goodput or the interference caused to the primary network, the proposed model is able to provide the optimal values for the sensing duration and the energy threshold for the EBS technique. In addition, the network's goodput and the primary's interference analytical models can be used to evaluate new parameterization strategies. Regarding the interference model of a realistic PU's behavior it can be extended to embrace the existence of more than one PU transmitter, or even a different distribution to represent the change in the PU's activity state. Nevertheless, it is important to notice that this model has already been used in the evaluation of a new CR MAC protocol [Rei+15].

The opportunistic service time model can also be extended/reformulated for various scenarios. For example, the model assumes that the PU activity may be represented by a geometric distribution, which has been proved with real traces of cellular users when small periods of PU's inactivity are considered. However, when large period of PU's inactivity are considered, the same study shows that the primary activity can be fitted by a lognormal distribution. Therefore, it would be interesting to understand how accurate is the proposed model under the assumption of large periods of PU's inactivity. The proposed model can also be extended to consider different SU's packet length distributions.

Finally, the MC-C2RMAC scheme could be optimized to operate in the absence of a dedicated CC. As discussed in Chapter 2, there are some situations where a dedicated CC is not possible to implement. Therefore, it would be interesting to adapt a philosophy of channel hopping between the available data channels, giving the opportunity to the SUs of selecting the channel with the most availability to be used as CC, always keeping the decentralized nature of the protocol.

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APPENDIX A

PMF OF THE NUMBER OF SUs SELECTED TO THE SECOND STAGE

Consider a CRN formed by n SUs competing in the first contention stage where each SU will select one of the cw_1 mini-slots with probability $1/cw_1$ to transmit its mini-packet. The C2RMAC protocol defines that only the SUs accessing in the busy mini-slot of the frame implementing the first contention stage will be selected to compete in the second stage. Therefore, when n SUs compete for the medium, one of the frame's mini-slots will be occupied (busy) by the SU's transmission. The required PMF is obtained through an analysis of all events included in the probability set, *i.e.*, all cases when $m \in \{0, cw_1 - 1\}$ slots are found idle before the occurrence of the busy mini-slot.

When $m = cw_1 - 1$, the n competing nodes transmit together in the last slot of the frame. Since this is one of the cw_1 slots where $k = n$ SUs may transmit together, the probability of observing $k = n$ SUs transmitting in the same slot is

$$cw_1/cw_1^n, \tag{A.1}$$

where cw_1^n represents the number of different ways to distribute the nodes in the slots. Next we derive the probabilities to the cases when $m \in \{0, cw_1 - 2\}$ and $1 \leq k < n$.

For $m = 0$, *i.e.*, when the first mini-slot of the frame is busy due to k SUs' transmissions, the probability of k SUs transmit in the first busy slot, with $1 \leq k < n$, is given by $\binom{n}{k}\left(\frac{1}{cw_1}\right)^k\left(1-\frac{1}{cw_1}\right)^{(n-k)}$, since the number of nodes competing in the first mini-slot follows a binomial distribution. Following the same rationale, when the first mini-slot is idle and the second mini-slot is found busy, *i.e.* $m = 1$, only the $1 \leq k < n$ SUs accessing in the second mini-slot will compete in the second stage, which occurs with probability

$$\binom{n}{k}\left(\frac{1}{cw_1 - m}\right)^k\left(1-\frac{1}{cw_1 - m}\right)^{(n-k)}\left(\frac{cw_1 - m}{cw_1}\right)^n, \tag{A.2}$$

where $\binom{n}{k}\left(\frac{1}{cw_1 - m}\right)^k\left(1-\frac{1}{cw_1 - m}\right)^{(n-k)}$ denotes the probability of finding $1 \leq k < n$

SUs transmitting in the second mini-slot $(m = 1)$, and $\left(\frac{cw_1 - m}{cw_1}\right)^n$ represents the probability of none of the SUs have transmitted in the m mini-slots before.

Defining N_{St2} as a random variable representing the number of SUs selected to compete in the second stage, the PMF of N_{St2} is given by combining (A.1) and (A.2), which after several simplifications can be represented as follows

$$Pr\left\{N_{St2} = k\right\} = \begin{cases} \binom{n}{k} \frac{1}{{cw_1}^n} \sum_{m=0}^{cw_1-2} (cw_1 - m - 1)^{(n-k)}, & 1 \leq k < n \\ \frac{cw_1}{{cw_1}^n}, & k = n \end{cases} . \tag{A.3}$$

APPENDIX B

PMF OF THE NUMBER OF BUSY MINI-SLOTS IN THE RESERVATION PHASE

When n SUs are distributed in cw_2 mini-slots, without exclusion, there are ${cw_2}^n$ different ways to distribute the nodes. Being CW_{2B} a random variable representing the number of busy mini-slots, with $x \in \{1, 2, ..., min(n, cw_2)\}$, the number of possible ways to distribute n SUs leading to x busy mini-slots is given by [Fel50]

$$\binom{x}{0}(x-0)^n - \binom{x}{1}(x-1)^n + \binom{x}{2}(x-2)^n - ... + (-1)^{x-1}\binom{x}{x-1}(1)^n = \sum_{k=0}^{x-1}(-1)^k\binom{x}{k}(x-k)^n. \quad \text{(B.1)}$$

Moreover, the number of different cases where $CW_{2B} = x$ mini-slots can be found busy in cw_2 mini-slots is given by the combination $\binom{cw_2}{x}$, for $x \leq cw_2$. Thus, the probability of finding $CW_{2B} = x$ mini-slots busy is given by

$$Pr\{CW_{2B} = x\} = \begin{cases} \frac{1}{{cw_2}^n}\binom{cw_2}{x}\sum_{k=0}^{x-1}(-1)^k\binom{x}{k}(x-k)^n, & 1 \leq x \leq \min(cw_2, n) \\ 0, & \text{otherwise.} \end{cases} \quad \text{(B.2)}$$

APPENDIX C

Regenerative time from a DTMC's stationary distribution

Let $\{X_n\}_{n \geq 0}, n \in \mathbb{N}_0$ be an independent and identically distributed sequence of random variables in the time-homogeneous DTMC state space $\mathcal{D}$. Admitting that for any initial state $d \in \mathcal{D}$ the average time between two successive visits of state d (return time) is finite, and being T_d a random variable representing the return time of state d, the successive times of visits to state d, $T_d^0 = 0, T_d^1, T_d^2, ...$ occur in the pieces of trajectory $\{X_{T_d^k}, X_{T_d^{k+1}, ...}\}, k \geq 0$. These pieces of trajectory are called the regenerative cycles of the chain between visits to state d, and each random time T_d^k is denoted as regenerative time, being the sequence $\{T_d^k - T_d^{k-1}\}_{k \geq 1}$ independent and identically distributed [Bre98, Theo. 7.4].

Lemma 1: Denoting π as the stationary distribution of a positive recurrent DTMC, for any state $d \in \mathcal{D}$, the expected regeneration time of state d is given by

$$E_d [T_d] = [\pi_d]^{-1} . \tag{C.1}$$

Proof. The proof follows directly from the proof given in [Bre98, p. 118] for the Regeneration Form of the Stationary Distribution. □

APPENDIX

D

PMF OF THE DURATION OF THE SU TRANSMISSION'S CONTENTION

The duration of the transmission's contention of each SU is expressed by the amout of frames spent by the SU to go from state $\mathbf{St2_{SU}}$ to state $\mathbf{Tx_{SU}}$ (see Figure 4.12). Considering T_{Tx}^{SU} a random variable representing the duration of the transmission's contention, we can write the distribution of $T_{Tx}^{SU} = k$ when $V = v$ idle frames are observed during the same period k as follows

$$Pr\left\{T_{Tx}^{SU} = k|V = v\right\} = \frac{1}{CW_{2B}}\binom{k-1}{v-1}{P_{I,i}}^{v}\left(1-P_{I,i}\right)^{(k-v)}, \tag{D.1}$$

where $1/CW_{2B}$ represents the probability of transmitting in one of the CW_{2B} idle frames, $\binom{k-1}{v-1}$ represent the combination of all the sequences of states that lead the SU to transmit, excluding the sequences without a final idle frame, and $(1-P_{I,i})^{(k-v)}$ represents the probability of observing $k-v$ busy frames during the transmission's contention with duration k.

Since a SU can only observe $v = min\{k, CW_{2B}\}$ idle frames during the same transmission's contention period, the distribution of T_{Tx}^{SU} can be writen as follows

$$Pr\left\{T_{Tx}^{SU} = k\right\} = \frac{1}{CW_{2B}}\sum_{v=1}^{min(k,CW_{2B})}\binom{k-1}{v-1}{P_{I,i}}^{v}\left(1-P_{I,i}\right)^{(k-v)}. \tag{D.2}$$