Resource Management in Cognitive Radio Networks

by

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Abstract

In the last decade, the world has witnessed rapid increasing applications of wireless networks. However, with the fixed spectrum allocation policy that has been used since the beginning of the spectrum regulation to assign different spectrum bands to different wireless applications, it has been observed that most of the allocated spectrum bands are underutilized. Therefore, if these bands can be opportunistically used by new emerging wireless networks, the spectrum scarcity can be resolved. Cognitive Radio (CR) is a revolutionary and promising technology that can identify and then exploit the spectrum opportunities. In Cognitive Radio Networks (CRNs), the spectrum can be utilized by two kinds of users: Primary Users (PUs) having exclusive licenses to use certain spectrum bands for specific wireless applications, and Secondary Users (SUs) having no spectrum licenses but seeking for any spectrum opportunities. The SUs can make use of the licensed unused spectrum if they do not make any harmful interference to the PUs. However, the variation of the spectrum availability over the time and locations, due to the coexistence with the PUs, and the spread of the spectrum opportunities over wide spectrum bands create a unique trait of the CRNs. This key trait poses great challenges in different aspects of the radio resource management in CRNs such as the spectrum sensing, spectrum access, admission control, channel allocation, Quality-of-Service (QoS) provisioning, etc.

In this thesis, we study the resource management of both single-hop and multi-hop CRNs. Since most of the new challenges in CRNs can be tackled by designing an efficient Medium Access Control (MAC) framework, where the solutions of these challenges can be integrated for efficient resource management, we firstly propose a novel MAC framework that integrates a kind of cooperative spectrum sensing method at the physical layer into a cooperative MAC protocol considering the requirements of both the SUs and PUs. For spectrum identification, a computationally simple but efficient sensing algorithm is developed, based on an innovative deterministic sensing policy, to assist each sensing user for identifying the optimum number of channels to sense and the optimum sensing duration. We then develop an admission control scheme and channel allocation policy that can be integrated in the proposed MAC framework to regulate the number of sensing users and number of access users; therefore, the spectrum identification and exploitation can be efficiently balanced. Moreover, we propose a QoS-based spectrum allocation framework that jointly considers the QoS provisioning for heterogeneous secondary Real-Time (RT) and Non-Real Time (NRT) users with the spectrum sensing, spectrum access decision, and call admission control. We analyze the proposed QoS-based spectrum allocation framework and find the optimum numbers of the RT and NRT users that the network can support. Finally, we introduce an innovative user clustering scheme to efficiently manage the spectrum identification and exploitation in multi-hop ad hoc CRNs. We group the SUs into clusters based on their geographical locations and occurring times and use spread spectrum techniques to facilitate using one frequency for the Common Control Channels (CCCs) of the whole secondary network and to reduce the co-channel interference between adjacent clusters by assigning different spreading codes for different clusters.

The research results presented in this thesis contribute to realize the concept of the CRNs by developing a practical MAC framework, spectrum sensing, spectrum allocation, user admission control, and QoS provisioning for efficient resource management in these promising networks.

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List of Abbreviations

ACK	acknowledgment
AS	allocated-group sensing
ATIM	ad hoc traffic indicating message
AWGN	additive white Gaussian noise
BER	bit error rate
CAF	cyclic autocorrelation function
CCC	common control channel
CG	cluster gateway
CH	cluster head
CM	cluster member
CP	code pool
CR	cognitive radio
CRN	cognitive radio network
CSD	cyclic spectral density
CSMA/CA	carrier sense multiple access/ collision avoidance
CTMC	continuous time Markov chain
CTS	clear to send
D-OFDM	discontinuous orthogonal frequency division multiplexing
DRP	data-and-reserving phase
DS	deterministic-group sensing
DSA	dynamic spectrum access

DSN	dynamic spectrum-access network
FCC	federal communications commission
FFT	fast Fourier transform
IEEE	institute of electrical and electronics engineers
ISM	industrial, scientific, and medical (spectrum bands)
ITU	international telecommunication union
LP	linear programming
MAC	medium access control
MACA	multiple access with collision avoidance
MC-CDMA	multiple carrier- code division multiple access
MDP	Markov decision process
NIP	non-linear integer programming
NLP	non-linear programming
NRT	non-real time
OFDM	orthogonal frequency division multiplexing
OSA	opportunistic spectrum access
OSN	opportunistic spectrum-access network
PIWF	price-based iterative water filling
POMDP	partial observable Markov decision process
PU	primary user
QoS	quality of service
RF	radio frequency
RP	reporting phase
RS	random sensing
RT	real time
RTR	request to register
RTS	request to send

SDR	software defined radio
SIFS	short inter frame space
SRP	sensing-and-registration phase
SU	secondary user
TDCS	transform domain communication system
TV	television
UHF	ultra high frequency
VHF	very high frequency
WLAN	wireless local area network
WMN	wireless mesh network
VOIP	voice over Internet protocol
WSS	wide sense stationary
SINR	signal-to-interference-and-noise ratio
SNR	signal-to-noise ratio

List of Notations

α	probability that the channel transits from state ON to state OFF
β	probability that the channel transits from state OFF to state ON
$B(x, a, b)$	incomplete beta function
$\Gamma(a, b)$	upper incomplete gamma function
γ	received SNR
δ	activity of the PUs on the licensed channels
ϵ	indicator of the presence of a PU
ζ	threshold that the detector compares with its normalized outputs
η	spectrum utilization by the SUs
Θ	normalized average aggregate throughput of the SUs
λ	arrival rate of the SUs
λ_{ad}	admitted rate of the SUs
ν	cyclic frequency
ρ	area ratio
τ	sensing duration
Φ	average aggregate throughput of the SUs
χ^2_{2m}	Chi-square distribution with $2m$-degree of freedom
ψ	secondary traffic utilization
A_{rt}	number of the arriving RT calls
A_{rt}^{ad}	number of the admitted RT users
B	channel bandwidth

$\mathbf{c}$	vector indicating the available channels
C	number of the clusters
D	user waiting delay
$E[X]$	expectation of the random variable X
$F(k, n, p)$	cumulative distribution function of the binomial distribution
h	amplitude gain of the channel
H_0	hypothesis when the primary signal does not exist
H_1	hypothesis when the primary signal exists
k	cluster overlapping factor
K	number of the channels that a SU can access simultaneously
$\mathbf{I}^+$	set of positive integer numbers
I_{ji}	interference from user j to user i
l	average packet length
L	number of the sensed channels per user
m	sensing time-bandwidth product
M	number of the SUs in the secondary network
M_{aw}	number of the admitted winning users
M_{B1}	number of the SUs at beacon B1
M_{B2}	number of the SUs at beacon B2
M_C	number of the SUs in a cluster
M_s	number of the leaving users
M_{nrt}	number of the NRT users
M_r	number of the remaining users at the DRP
M_{res}	number of the reserving users
M_{rt}	number of the RT users
M_s	number of the sensing users
M_s^{max}	maximum number of the sensing users in a cluster

M_w	number of the winning users
$M_{w_{max}}$	maximum number of the winning users
n	number of the sensed channels by a user in a cluster
N	number of the licensed channels
N_0	background AWGN power
n_a	number of the allocated channels per user
N_a	number of the available channels
N_c	number of the channel sensed cooperatively
N_C	total number of the sensed channel in a cluster
N_d	number of the channel groups in the DS and AS policies
n^{max}	maximum number of the sensed channels by a user in a cluster
n_{nrt}	number of the allocated channels for each NRT user
N_{nrt}	number of the channels for NRT users
N_r	number of the channel group in the RS policy
N_{res}	number of the reserving slots
N_{rt}	number of the channels for RT users
$n(t)$	the AWGN at the receiver at time t
p	receiver responding probability to the reserving message
P_{aw}	probability of a user being admitted
P_B	blocking probability
P_B^{th}	blocking probability threshold
$P_{B_{bs}}$	blocking probability due to busy channel carrying other RT calls
$P_{B_{un}}$	blocking probability due to channel unavailability
P_d	probability of detection
P_d^{th}	probability of detection threshold
P_D	dropping probability
P_D^{th}	dropping probability threshold

P_f	probability of false alarm
P_f^{th}	probability of false alarm threshold
P_i	received power at user i
P_m	probability of miss-detection
P_{PU}	received power of a PU
P_{sens}	percentage of the sensed channels
Q	probability transition matrix of the Markov chain
$Q(\cdot)$	Q-function
Q_d	probability of detection in OR-rule cooperative sensing
Q_f	probability of false alarm in OR-rule cooperative sensing
q_{ij}	transition probability of the Markov chain from state i to state j
r	radius of the cluster
$R_x^{\nu}(\tau)$	CAF of the received signal
S	average aggregate throughput per SU
$S(f,\nu)$	CSD of the received signal
$s(t)$	transmitted primary signal
T	duration of each time slot
T_{B1}	duration of beacon B1
T_{B2}	duration of beacon B2
T_B	duration of beacons B1 and B2
T_c	duration of the control messages
T_{DRP}	duration of the DRP
T_{max}	maximum duration time slot
T_{ms}	mini-slot duration of the RP
t_r	time to report the sensing result for a sensing user
T_{res}	duration of the mini-slot reserving time
T_{RP}	duration of the RP

t_s	sensing time per channel
T_s	duration of the SRP and RP
T_{SIFS}	duration of the SIFS
T_{SRP}	duration of the SRP
U	normalized identified unused spectrum
u_c	number of the cooperative sensing users sensing the same channels
$\mathbf{w}$	vector indicating the reserving outputs
W	width of the communication area
$\overline{X}$	average value of the variable X
$x(t)$	received signal at time t
Y	decision metric of the energy detection
$Z_1(\cdot)$	first zero of the given polynomial
$\lceil x \rceil$	round up the real number x to the nearest integer
$\lfloor x \rfloor$	round down the real number x to the nearest integer
$[x]$	round up or down the real number x to the nearest integer

Chapter 1

Introduction

Most of the countries in the world have one or more radio spectrum regulation agencies that allocate and manage the local frequency spectrum bands, while the International Telecommunication Union (ITU), which is a United Nations agency, coordinates the shared global use of the radio spectrum. Based on the current and past frequency spectrum regulations, most of the spectrum bands are allocated exclusively to licensees regardless of their real spatiotemporal usage. As a result of this allocation procedure and with increasing demand for higher bandwidth to meet the requirements of the new emerging wireless communication applications, this precious natural resource is running out. However, it has been found that the apparent spectrum scarcity is due to the spectrum underutilization caused by the past and current fixed regulations rather than the physical scarcity. According to a study done by the Federal Communications Commission (FCC) [1], the spectrum utilization of the assigned bands is in the range of $15-85\%$ based on the spatiotemporal usage.

The spectrum scarcity and the increasing demand for new wireless applications have led the regulation agencies, such as FCC, to rethink in the spectrum allocation policy and consider opening up the underutilized bands by licensed users to be used by unlicensed users. Therefore, new concept of spectrum allocation called Dynamic Spectrum Access (DSA) has been proposed with different spectrum access models [2]. Recently, the Opportunistic Spectrum Access (OSA) model has gained a lot of attention due to its promising solution to the spectrum scarcity [2–5]. In OSA, there are two types of users: Primary Users (PUs) that own licenses to use the assigned spectrum bands, and Secondary Users (SUs) that do not have licenses but seek spectrum opportunities. The SUs can use the spectrum only when the PUs do not use it, which is known as overlay DSA. The spectrum band is considered as an opportunity for SUs when at a given time and a specific location this band is underutilized by the licensed PUs. Since the SUs are considered as lower priority users, they can benefit from spectrum opportunities spatiotemporally left over by PUs if these SUs do not make any harmful interference to the PUs. Moreover, the PUs are not required to change or modify their communication systems for the purpose of spectrum sharing with the SUs [2].

1.1 Cognitive Radio Networks

The concept of OSA sounds simple; however, the key question is how to implement this concept. Fortunately, with the advanced technologies in the Software Defined Radio (SDR) and the new evolution of the Cognitive Radios (CRs), implementation of the OSA can be envisioned. CRs are promising technologies that can be used by the SUs to identify and exploit the spectrum opportunities. The CR in the context of OSA can be defined as a radio that is aware of its surrounding spectrum environment and can adaptively change its transmitting parameters based on the spectrum availability. This definition implies that the CR has the ability to sense the spectrum, analyze which spectrum can be used, decide its transmitting parameters, and then access the selected available spectrum. These abilities interpret the cognition cycle of the CR [6–8]. By the spectrum sensing and analysis, the CR can identify the available unused spectrum, while by adjusting its transmitting parameters and spectrum access, the CR can exploit opportunistically the available spectrum without harmful interference to the PUs.

The wireless networks that use the CRs to identify and then exploit the underutilized spectrum are called Cognitive Radio Networks (CRNs). It is worth mentioning that CRNs, Dynamic Spectrum-access Networks (DSNs), and Opportunistic Spectrum access Networks (OSNs) are often used interchangeably in the literature. Throughout this thesis, we use the CRNs terminology.

1.2 Research Challenges and Motivations

The spectrum availability variation over the time and locations due to coexistence with the PUs and the spread of the spectrum opportunities over wide spectrum bands create a unique trait of the CRNs. This key trait poses great challenges in different aspects in the basic design of CRNs such as the spectrum sensing, spectrum access, admission control, channel allocation, and QoS provisioning [2, 6–10], which will be explained correspondingly when we study these challenges throughout this thesis. All these challenges should be tackled for efficient resource management in CRNs. The solutions of these challenges can be integrated in an efficient cognitive Medium Access Control (MAC) framework that manages the spectrum identification and exploitation.

Designing MAC frameworks for CRNs, similar to all other wireless networks, highly depends on the network architecture, i.e., either centralized or ad hoc networks. In fact, developing MAC frameworks for centralized CRNs, such as IEEE 802.22, is relatively easier that that of ad hoc CRNs [11–16]. However, due to the ease of deployment, the ad hoc CRNs are expected to attract the future applications of the secondary spectrum usage [10]. In this thesis, we are interested in the ad hoc CRNs.

Several MAC frameworks have been proposed for ad hoc CRNs to tackle one or more challenges. Most of these frameworks are discussed in two surveys presented in [10, 17]. Indeed, the MAC frameworks for CRNs can be considered in general as multichannel MAC protocols with special requirements. Reference [18] provides comprehensive comparison between these multichannel MAC protocols, while [19] compares between the opportunistic multichannel MAC protocols. In the following, we list the major challenges that should be considered while developing efficient MAC frameworks suitable for CRNs, and brief discussions on these challenges and their related works will be discussed in the next chapter. These challenges include: 1) designing efficient spectrum sensing and access schemes, 2) constraining the interference to the PUs, 3) fair spectrum sharing among the SUs, 4) hardware and computational costs, 5) hardware limitations, 6) utilizing the spectrum efficiently, 7) choosing the control channel, 8) spectrum heterogeneity seen by the SUs, 9) hidden/ exposed primary nodes problem, 10) multi-hop communications, and 11) QoS provisioning.

However, designing practical and effective MAC frameworks for efficient resource management in CRNs is still in its infancy. We believe that cooperation between the SUs can compensate for the need of complex hardware. Cooperation here implies that a group of SUs cooperate with each other to identify the spectrum opportunities and to exploit these opportunities. Therefore, integrating a cooperative spectrum sensing policy into a cooperative spectrum access scheme considering the admission control, channel allocation, and QoS provisioning for efficient spectrum exploitation can achieve the ultimate goal of the CRNs. Therefore, more research efforts are needed in these topics to realize the concept of these wireless networks.

1.3 Research Contributions

The main contributions of this thesis are listed in the following:

- Proposal of a novel cognitive MAC framework for distributed CRNs by integrating a cooperative spectrum sensing policy that manages the detection process of the primary signals at the physical layer into a cooperative MAC protocol considering the requirements of the primary and secondary users [20]. To identify the spectrum opportunities, an innovative deterministic sensing policy called Allocated-group Sensing (AS) policy is investigated and analyzed. The effectiveness of the AS policy is demonstrated by comparison with two random sensing policies. Then a computationally simple but efficient sensing algorithm is developed to assist each sensing user to identify online and distributively which channels to sense and for how long to sense each channel.

- Proposal and analysis of an admission control scheme and channel allocation policy for CRNs [21]. By dividing the SUs into sensing and accessing groups, they can cooperate to identify and then exploit as many unused channels as possible. However, the number of the sensing users and the number of the access users should be regulated to balance the spectrum identification and exploitation. The secondary network behavior is studied to give insight into the relation between the sensing and access users and to investigate the parameters that can be adjusted to control the number of the admitted users. The secondary network coordinator in each time slot admits only a number of new SUs that meet the QoS requirements. Furthermore, the admitted SUs use their dynamic IDs and the IDs of the available channels to determine distributively which channels can be allocated to each of them.

- Development and analysis of a QoS-based spectrum allocation framework that jointly considers the QoS provisioning for heterogeneous SUs with the spectrum sensing, spectrum access decision, and call admission control [22]. Giving priority to the secondary Real-Time (RT) users and considering their QoS requirements in terms of the dropping and blocking probabilities, it is proposed to allocate a number of available channels to the optimum number of the RT users that can be admitted to the secondary network, while the remaining available channels are allocated to the adaptive optimum number of the secondary Non-Real Time (NRT) users considering the spectrum sensing and utilization indispensability. The proposed QoS-based spectrum allocation framework is analyzed further to determine how many identified available channels can be allocated to each NRT user for different QoS satisfaction metrics.

- Proposal of a novel user clustering scheme to efficiently manage the spectrum identification and exploitation in multi-hop ad hoc CRNs [23]. The SUs are clustered based on their geographical locations and occurring orders. Using spread spectrum techniques with different spreading codes for different clusters, one Common Control Channel (CCC) for the whole secondary network can be facilitated and the co-channel interference between the adjacent clusters can be reduced. The proposed clustering scheme allows the SUs to initiate and maintain the clusters reliably with signaling inherent in the MAC protocol. Moreover, the SUs in each cluster can benefit from all the available spectrum for concurrent transmissions without affecting other users in the adjacent clusters.

1.4 Outline of the Thesis

The remainder of this thesis is organized as follows. Chapter 2 provides background and literature review. Chapter 3 describes the system model including the primary and secondary networks. In Chapter 4, the resource management in single-hop CRNs is studied including developing and analyzing the MAC framework, admission control and channel allocation, and QoS provisioning. Chapter 5 introduces a novel user clustering scheme for resource management in multi-hop CRNs. Finally, Chapter 6 gives concluding remarks of this thesis and outlines possible future research works.

Chapter 2

Background and Literature Review

Success of the CRNs mainly depends on the successful management of the spectrum identification and exploitation that mainly rely on the two key functions of the CRs: spectrum sensing and spectrum access. Spectrum identification and exploitation are jointly related and should be integrated in the MAC framework to realize the concept of CRNs. Since the spectrum sensing and designing a cognitive MAC framework are the foundations of resource management in CRNs, we first give an overview on them in this chapter and then provide a literature overview on the related works.

2.1 Spectrum Sensing

In order to adaptively change its output communication parameters, the SU has to identify spectrum opportunities in its vicinity. Spectrum identification depends on the ability of the CR to detect the unused spectrum, which is known as spectrum sensing. Ideally, the most efficient way to detect spectrum opportunities is to detect the primary receivers that are in the coverage area of the SU. However, without cooperation of the PU, it is difficult for the SU to obtain information about the channels between the primary transceivers and also between its transmitter and the primary receivers, which are passive terminals. Therefore, the most recent research efforts are focused on the detection of the primary transmitters [8].

2.1.1 Spectrum Sensing Considerations

The SUs are equipped with CRs that should be operated in an environment where there is no collaboration with the PUs, so the SUs may be required to monitor large bandwidth and efficiently detect the presence of the PUs and then determine the spectrum opportunities. This is not a trivial process where there are many considerations that should be taken into account. In the following, some of these considerations are briefly explained.

1) Fading and Shadowing Environments: Shadowing and multipath fading highly affect the detection process of the primary signals, and they may lead to incorrect results in determining the spectrum opportunities especially when the environment varies significantly based on the mobility and location of the primary and secondary users. The detection capability of the CRs should be more sensitive than the primary receivers to avoid the problem of hidden primary terminals. Because the SUs do not have direct measurements of the channels to the primary receivers, an additional margin of the Signal-to-Noise-Ratio (SNR) is required in the detection process of the CRs [7].

2) Sensing Duration: In the OSA model, the PU can claim its band anytime, so the SUs operated at that band should detect the occurrence of the PU in a very short time and vacate the band immediately. Another related issue is the sensing rate, i.e., should the CRs sense the required bands continuously or discontinuously and at which rate? The detection limit time and sensing rate create challenges in the implementation of the CR [24].

3) Types of the PUs: The SUs may be required to deal with different types of PUs with different modulation schemes that may require different detection sensitivity and sensing rate. For example, the spread spectrum modulations are known to be very difficult if not impossible to be detected in a reasonable time unless the hopping pattern of the frequency hopping scheme or the spreading code of the direct sequence scheme are known to the SUs.

4) Interference from other SUs: When there are other SUs competing for the same spectrum opportunities, the sensing process will be harder due to the additional mutual interference between the SUs [25].

5) Hardware and Software Constraints: Spectrum sensing for a large dynamic range necessitates a high degree of flexibility in the RF front end (hardware) and a high accuracy and speed of the signal processing computations (software) [7]. Although, technologies of the hardware and software are in rapid progress, implementation requirements of the CR make them more complex and hence costly. Therefore, tradeoffs between the complexity and the cost of the CR should be considered while seeking for an efficient spectrum sensing technique.

2.1.2 Spectrum Sensing Methods

In the available literature, there are different methods of spectrum sensing that can be categorized, in general, into four main approaches as shown in Figure 2.1. In the following subsections, each of them is briefly explained with emphases on its advantages and disadvantages.

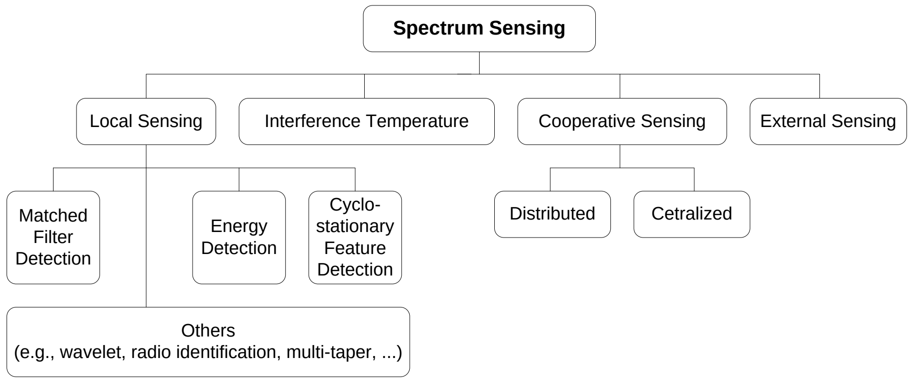

Figure 2.1: Spectrum sensing methods.

A. Local Sensing

In OSA, the SU should be able to distinguish between the presence and absence of the primary signals to avoid the interference with them, i.e., the SU should detect the transmitted primary signal even if it is very weak based on its local observations. Detection of the primary signal can be modeled as two hypotheses [26] as follows

$$x(t) = \begin{cases} n(t), & H_0 \\ hs(t) + n(t), & H_1, \end{cases} \tag{2.1}$$

where $x(t)$ is the received signal by the SU, $n(t)$ is the additive white Gaussian noise (AWGN), $s(t)$ is the transmitted primary signal, and h is the amplitude gain of the channel. Hypothesis H_0 is that when the primary signal does not exist in a certain band at a given time and location, while H_1 is the hypothesis when it exists.

There are three common techniques used for signal detection: matched filter detection, energy detection, and cyclostationary feature detection [24]. In addition, there are other alternative techniques that can be used for detecting the primary signals such as waveform based detection, radio identification, multi-taper spectral estimation, and wavelet transform-based estimation. In this subsection, however, the focus is on the three common techniques mentioned above, and the interested reader may refer to [9] and the references therein for more details about the alternative techniques.

Another point to be mentioned here is that two detection techniques can be combined to improve the detection process such as that proposed in IEEE 802.22, which is the first CRN's standard. Spectrum sensing in this standard has been proposed to be on two stages: fast sensing based on energy detection, and fine sensing based on a more powerful technique such as matched filtering or cyclostationary feature detection [11].

A1. Matched Filter Detection

It is well known that matched filtering is the optimal detection method if the receiver has sufficient information about the transmitted signal [27]. It requires only a number of O(1/SNR) samples from the received signal to achieve a certain probability of detection [24], i.e., it can detect the signal in a short time, which is a very important criterion in spectrum sensing. However, there are some significant drawbacks of using this technique in the CRs. The CR is firstly required to demodulate the received signal, so it needs prior knowledge about the primary signal, which may not be available for the CR, and even it is against the privacy of the PUs. Moreover, for each primary signal type, the CR requires a specific receiver, which implies implementation complexity and larger power consumption [9].

A2. Energy Detection

Energy detection is the most common technique used to detect unknown signals by comparing its output with a threshold that depends on the noise floor [28]. Therefore, it has attracted interest to be used in detecting the primary signal. Using the model for detecting the primary signal defined in (2.1), the decision metric of the energy detection can be written as

$$Y = \begin{cases} \chi^2_{2m}, & H_0 \\ \chi^2_{2m}(2m\gamma), & H_1, \end{cases} \tag{2.2}$$

where χ^2_{2m} is the central Chi-square distribution, and $\chi^2_{2m}(2m\gamma)$ is the non-central Chi-square distribution with parameter $2m\gamma$, each of them with $2m$-degree of freedom. The parameter m is the sensing time-bandwidth product and γ is the received signal-to-noise ratio (SNR) [28, 29].

Based on the real states of the primary signal and the spectrum sensing results, the decision metric of (2.2) has four possible outcomes, each defines a specific probability in the context of CRNs as follows:

- The PU is active and the sensing result is H_1, which is known as the probability of detection, P_d;
- The PU is active while the sensing result is H_0, which is known as the probability of miss-detection, $P_m = 1 - P_d$;
- The PU is idle while the sensing result is H_1, which is known as the probability of false alarm, P_f; and
- The PU is idle and the sensing result is H_0, which is the complement probability of false alarm, i.e., $1 - P_f$.

Practically, the P_d is constrained to be larger than a given threshold acceptable by the PUs to reduce the potential interference, and also the P_f is constrained to be smaller than a given value required by the SUs in order to utilize the spectrum efficiently [30]. Therefore, these two probabilities are key criteria in designing efficient spectrum sensing schemes. These two probabilities can be given, respectively, for the energy detector as

$$P_f = \Pr\{Y > \zeta | H_0\} = Q\left(\frac{\zeta - 2m}{\sqrt{4m}}\right) \tag{2.3}$$

and

$$P_d = \Pr\{Y > \zeta | H_1\} = Q\left(\frac{\zeta - 2m(\gamma+1)}{\sqrt{4m(2\gamma+1)}}\right), \tag{2.4}$$

where ζ is a threshold that the detector will compare its normalized output with, γ is the SNR detection sensitivity of the detector, i.e., it should be able to detect any primary signal greater than or equal to this value [31, 32]. $Q(\cdot)$ is the Q-function given by

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} exp(-t^2/2)dt. \tag{2.5}$$

Using (2.3) and (2.4), the probability of false alarm given a required probability of detection, and the probability of detection given a specific value of the probability of false alarm can be obtained, respectively, as

$$P_f = Q\left(\sqrt{2\gamma+1}Q^{-1}(P_d) + \sqrt{m}\gamma\right) \tag{2.6}$$

and

$$P_d = Q\left(\frac{1}{\sqrt{2\gamma+1}}Q^{-1}(P_f) - \sqrt{m}\gamma\right). \tag{2.7}$$

Energy detection can be implemented using the Fast Fourier Transform (FFT) and does not need any prior knowledge on the primary signals, i.e., lower in the computation and implementation complexity than the matched filter. Therefore, it is the most common attractable technique in spectrum sensing [9]. However, it requires O(1/SNR^2) samples (i.e., longer detection time) to meet a certain probability of detection due to the non-coherent detection compared to the coherent detection in matched filtering. Furthermore, its decision threshold is basically subjected to uncertainty in noise power. In addition, it cannot distinguish between the primary signal and any interference or noise signals. Finally, it does not work efficiently for detecting spread spectrum signals [7].

A3. Cyclostationary Feature Detection

Modulated signals have some specific features such as wave carriers, pulse trains, hopping sequences, or repeating codes. These signals, which can be modeled as stationary random processes, exhibit periodicity in their means and correlations, so they are characterized as cyclostationary random processes. Furthermore, their features can be identified by analyzing their Cyclic Spectral Density (CSD). On the other hand, the noise is a wide-sense stationary (WSS) process with no correlation [9]. The CSD of the received signal $x(t)$ in the second part of (2.1), i.e., in hypothesis H_1, can be written as

$$S(f,\nu) = \int_{-\infty}^{\infty} R_x^{\nu}(\tau) exp(-j2\pi f\tau) d\tau, \tag{2.8}$$

where

$$R_x^{\nu}(\tau) = E\left[x(t-\tau)x^*(t)e^{j2\pi\nu\tau}\right] \tag{2.9}$$

is the Cyclic Autocorrelation Function (CAF) of $x(t)$, $E[\cdot]$ is the expectation, and ν is the cyclic frequency. The CSD in (2.8) has its peak values when ν is equal to the fundamental frequencies of the transmitted signal $s(t)$; therefore, the transmitted signal can be detected. The value of ν for each modulated signal is assumed to be known by the receiver or can be extracted using some techniques such as neural networks [33].

The key advantage of cyclostationary feature detection is its ability to differentiate the primary signal from the noise and from other secondary signals, so this technique can outperform the energy detection technique. However, its computation is more complex, and it requires significantly longer observation time to give efficient results [8].

B. Interference Temperature

In the underlay DSA approach [2], the SU is allowed to transmit in the presence of the primary signal if it can maintain its transmitted power under a certain noise floor threshold of the PU. This threshold is known as the interference temperature threshold. The key idea of this approach is that, at a frequency band of interest, the SU is assumed to be able to measure the interference margin at the primary receiver. If this margin is sufficient for the secondary signal providing that it does not raise the interference above the temperature threshold of the primary receiver, the SU considers that band as an opportunity, and it can exploit it [34].

Although the concept of interference temperature is obvious, the key question is how to measure or estimate its level efficiently at the primary receiver and under which rules. Moreover, the SU may not be able to estimate its transmission effects on all possible nearby primary receivers. Recently, this sensing approach, which was proposed by FCC, has been dropped due to its implementation difficulty [5].

C. Cooperative Sensing

In the local sensing method, the SUs rely on their individual capabilities to detect the primary signals. However, in real situations, the SUs may experience severe shadowing and/or deep multipath fading, so they may not be able to detect very weak primary signals; furthermore, they cannot prevent the hidden terminal problem. If the SUs work together as a team to detect the spectrum opportunities, they can overcome these severe problems. This is what is known as collaborative or cooperative spectrum sensing [26, 29].

Cooperative sensing can be implemented in two ways depending on the network architecture. The first way is the centralized sensing, where a central unit, which can be a base station or a selected SU, collects the sensing information from all or some SUs, analyzes this information, determines the spectrum opportunities, and then broadcasts the final decision to all the nodes in the same network. The second way is the distributed sensing. In this way, the SUs share their sensing observations among each other, without need for a central unit, and then each SU decides which spectrum band can be considered as a spectrum opportunity.

Comparing to the local spectrum sensing, the cooperative spectrum sensing has some advantages and disadvantages summarized in the following, and the interested reader may refer to [9] and the references therein for further details. The advantages include: 1) significantly mitigate multi-path fading and shadowing, 2) alleviate the problem of primary hidden terminals, 3) reduce the required sensing time, and 4) obtain higher accuracy in detecting spectrum opportunities. While the disadvantages include: 1) require a common control channel to share the sensing information, 2) require an efficient algorithm for data fusing, 3) increase the overhead traffic, and 4) increase the implementation complexity.

D. External Sensing

In the cooperative sensing method, the spectrum sensing and transmission processes are both done by each SU. This architecture may lead to conflicts between sensing and transmission processes; furthermore, the spent time for sensing reduces the transmission time, which decreases the spectrum efficiency. These problems can be solved if these two processes are separated into two distinct networks: a sensing network for cooperative spectrum sensing, and an operational network for data transmission [8, 9].

External sensing can be performed by an external agency that broadcasts the spectrum opportunities to the SUs, and the later, in their turn, just use this information to adapt their transmissions [8]. However, this approach may disagree with the basic definition of the CR mentioned in Chapter 1, where the CR should be able to sense and then exploit the spectrum opportunities itself. Moreover, this approach increases the complexity of implementing two networks instead of one.

2.1.3 MAC Layer Oriented Sensing

The spectrum identification in CRNs actually does not depend only on the spectrum sensing at the physical layer. To efficiently identify the available spectrum, the SUs should be able to know which channels to sense and for how long to sense considering the requirements of the PUs. In other words, the spectrum sensing at the physical layer should be managed and integrated in the MAC layer. This necessitates the cross-layer design approach where there should be a sensing policy integrated into the MAC framework of the CRNs.

2.2 Cognitive MAC Framework

Once the spectrum opportunities are identified, the second step is to exploit these opportunities efficiently. Both the spectrum identification and exploitation are managed by the MAC framework that links the physical and MAC layers with the upper layers.

2.2.1 MAC Framework Considerations

It is difficult to develop a MAC framework that can be considered perfect to overcome all the new challenges in CRNs comprehensively; however, to develop a MAC framework suitable for CRNs, these challenges should be kept in mind. In the following, the main challenges that should be taken into considerations are briefly discussed. Most of these challenges are dependent on each other, so they should be tackled somehow jointly. Some related research works to these challenges are discussed later on in this chapter.

1) Designing efficient spectrum sensing and access schemes: The spectrum sensing and access processes should be integrated to make a wise spectrum access decision. Any theoretical decision algorithm, such as Markov Decision Process (MDP), or any other known access mechanism, such as the well-known Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA), can be used to perform intelligent spectrum access if they are designed jointly with the spectrum sensing results.

2) Constraining the interference to the PUs: The SUs should maintain their potential interference within the tolerable interference to the PUs; otherwise, the interference is considered harmful and will impact the performance of the PUs, which is not acceptable.

3) Fair spectrum sharing among the SUs: The SUs are supposed to seek for some spectrum opportunities, so they should get the same chance, and this can be achieved by maintaining fair competition.

4) Hardware and computational costs: As other ad hoc networks, the hardware costs, power consumption, and the computational complexity, which are related to each other, should be designed efficiently. However, in CRNs, there are more sensing and computational requirements that involve additional costs, so these costs should be considered.

5) Hardware limitations: Even technology is in rapid progress, there are technical limitations in the hardware. For example, it is not reasonable to assume that the CR is able to sense or access a very wideband spectrum in short time. These limitations should be also considered.

6) Utilizing the spectrum efficiently: The spectrum opportunities are the target of the CRNs; therefore, each available spectrum portion should be utilized efficiently, or the spectrum scarcity would not be alleviated.

7) Choosing the control channel: The SUs need to exchange information about their spectrum observations and the spectrum allocations. This necessitates a way to reliably exchange their control signaling, so a common control channel (CCC) or any alternative control method is imperative in designing the MAC framework.

8) Spectrum heterogeneity: It may happen that the secondary transmitter and receiver are under different communication coverage areas of PUs, so some or all of the available channels at each secondary link end may be different. How to overcome this problem is one of the new challenges in CRNs.

9) Hidden/ exposed primary nodes problem: This problem is related to the spectrum heterogeneity. At one or both of the secondary link ends, there may be some primary receivers either hidden or exposed to the communication carried on the secondary link. The interference to these primary nodes should be considered.

10) Multi-hop communications: In cases where some SUs cannot communicate with each other directly, i.e., they are out of the coverage of each other, there may be what so-called multi-hidden/exposed SUs due to the multichannel nature of the CRNs.

11) QoS provisioning: Once the SUs detect the presence of the PUs on some channels, they must cease their transmission and vacate these channels immediately. This will lead to decrease the throughput of the SUs and even to fully stop their transmission for random times, i.e., the queue buffer size of the secondary nodes may significantly increase, and the delay consequently increases. Therefore, the variation in the throughput of each secondary link and the delay time will highly affect the QoS provisioning in the CRNs. How to deal with this problem for different

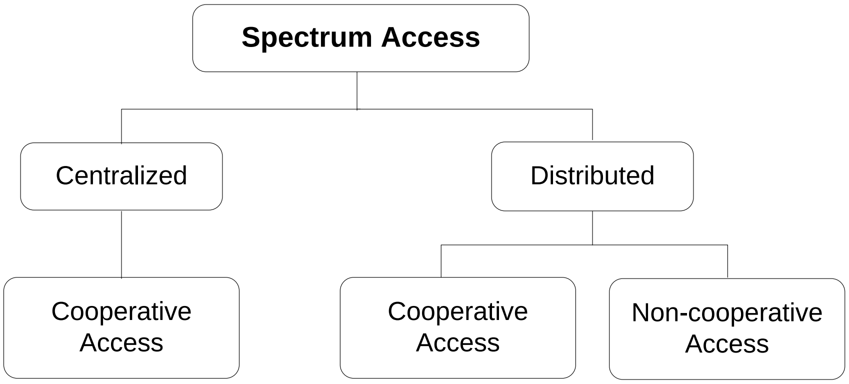

Figure 2.2: Spectrum access methods.

wireless applications (services) in CRNs is a question comes into the picture of the QoS provisioning in CRNs.

2.2.2 Spectrum Access Methods

Spectrum access can be classified into centralized or distributed access method based on the architecture of the networks as shown in Figure 2.2. In the centralized method, there is a central entity controls the spectrum allocation that each node can access, while each node is responsible for the spectrum allocation and access in the distributed method.

Moreover, the spectrum access can be considered as cooperative or non-cooperative access. In the distributed access method, the information of the spectrum allocation and access are shared between the nodes, while in the centralized architecture, the nodes share their information with the base station to manage the spectrum access efficiently. However, in non-cooperative access, which is known also as selfish access, each communicating pair works independently regardless what other pairs trying to do. It is reasonable to consider the centralized spectrum access as cooperative access since the base station cooperates with the SUs by allocating the available spectrum to them. While the distributed spectrum access can be either cooperative or non-cooperative access. The non-cooperative access may reduce the overall spectrum utilization; however, its implementation may be easier than that of the cooperative access [8].

2.3 Literature Overview

2.3.1 Spectrum Sensing

A survey of spectrum sensing and its challenges in CRs can be found in [35]. The energy detection has been considered as a promising technique to detect the primary signals since it does not need any knowledge about the PUs in addition to its computational and implementation simplicities. Therefore, we mainly focus on the energy detection throughout this thesis.

The performance of energy detection is studied in [36, 37, 39]. In [36], to estimate the prior probabilities of the activities of the PUs, the channel occupancy is modeled as a Markov chain, and the prior probabilities can be estimated using queuing theory. The cooperative sensing is also studied, and it is found that this sensing technique can reduce the probability of false alarm and the probability of miss-detection. In [37], the cooperation gain in spectrum sensing is quantified by introducing a diversity order for the single-user sensing and multi-user sensing with soft and hard information fusion strategies. While in [38], a utility loss function is proposed to set the threshold in spectrum sensing to solve the dilemma between detection the PUs and the interference from the SUs to the PUs due to the channel reciprocality. It is found that cooperative sensing between the SUs can efficiently solve this dilemma. In [39], the relations between the detection and false alarm probabilities of energy detection at the physical layer and the accessing probabilities at the MAC layer are provided as follows. The probability of successful transmission is equivalent to the product of the probability of no false alarm and the prior probability of the PU being idle, while the probability of colliding is equal to the probability of miss-detection.

The sensing time is a key parameter in the spectrum sensing; therefore, it should be optimized to obtain a reasonable sensing result that maintains acceptable potential interference to the PUs while maximizing the spectrum utilization. In [31, 32, 40], the sensing time is optimized based on some proposed models that use energy detection. Also the optimization of sensing time in cooperative sensing is studied in [41, 42]. Moreover, some different optimization techniques are used for different purposes in spectrum sensing. In [43], the difference of sensing capabilities among SUs is assumed in a distributed spectrum sensing scheme. A linear programming method is used to optimize the performance of the sensing process based on the number of sensing processes that each SU performs. In [44], the sensing process is modeled as an optimal stopping problem for a secondary network, and using a dynamic programming approach, the optimal sensing order is found. An optimal sensing schedule is investigated in [45] to maximize the channel efficiency under the constraint of interference period.

The activity of the PUs on the licensed channels are often modeled as a two-state Markov chain, i.e., ON/OFF model, and the SUs rely on the spectrum sensing to identify whether the channel is idle or occupied by a PU. In many papers, e.g., [61], the PUs activity is assumed as a fixed factor during the time slot the SUs exploit the available channels. In [80], the two-state Markov chain model is validated using some measurements, and then a stochastic approach is used to estimate the activity of the PUs. The PUs activity can be estimated using two metrics: the probability of being idle and the probability of successful transmission during a time slot. The authors proposed a CSMA-based protocol with a CCC and multiple data channels. Each SU has two radios: control and data radios. For each transmission, there are two steps. The first one is to sense the selected channels; if they are occupied by PUs, then the transmission will be ended; otherwise, if they are idle, the SU can transmit on them. However, before transmitting, the SU should decide which channel is the best for transmission. The quality of each channel from the occupancy by PUs point of view can be determined using two metrics: the probability of being idle and the probability of successful transmission during that time slot, where these two metrics can be estimated using Bayesian learning. Therefore, the activity of the PUs can be estimated slot by slot instead of assuming it as a given and fixed value.

2.3.2 MAC Framework Design

In the following, several research works related to the aforementioned considerations in designing the cognitive MAC framework will be discussed. Since each work almost deals with more than one challenge, it is difficult to sort all these research works according to what challenge is tackled; however, closer works are listed together under one point for more convenience. Comparison between most of these MAC frameworks can be found in [10, 17, 19].

1) Markov Model Approach

Some researchers proposed using Markov chains or Markov decision process to develop an analytical framework for CRNs [46–54]. In [46], each SU pair decides, without cooperation with other SUs, when to sense and when to access the spectrum based on the Partial Observable Markov Decision Process (POMDP) framework where optimal and suboptimal decision rules are discussed. The case of sensing errors and spectrum homogeneous/ heterogeneous are considered. Although this approach does not need a common control channel, one of the main issues is the synchronization between the secondary transmitter and receiver, even the handshaking between them is not provided. Moreover, the computational complexity of this approach may not be suitable for this kind of networks. However, the tradeoff between optimality and complexity of this approach is provided in [47] where a truncated Markov Decision Process (MDP) formulation for OSA is developed to reduce the complexity of this method. Moreover, in [48, 49], the separation principle is used in the proposed POMDP approach. This principle implies optimizing the spectrum sensing at the physical layer and then optimizing the spectrum access at the MAC layer to find optimal solution for unconstrained POMDP instead of constrained solution in order to reduce the computational complexity of this approach.

The scopes of [50, 51] are to design a cognitive MAC that assists SUs to access the spectrum in presence of a Wireless Local Area Network (WLAN), i.e., 802.11b, using the concept of the frequency hopping, except it requires spectrum sensing, taking the mutual interference between the SUs and the PUs into consideration. Continuous Time Markov Chain (CTMC) is used to predict the behavior of the WLAN based on empirical measurements. The problem of multiple access is modeled as Continuous Markov Decision Process (CMDP), and a Linear Programming (LP) technique is used to find the optimal policy of the spectrum access. Full and partial observations are also analyzed and evaluated. This study considers only one SU pair, so the problem of spectrum sharing with other SUs is not discussed; moreover, it does not discuss how to efficiently utilize the overall spectrum band. Another drawback of this study is that it depends on empirical measurements of the WLAN in 2.4GHz, so it may not be suitable for other spectrum bands since it is not always easy to get empirical measurements for every spectrum band.

In [52], a Markov chain approach is used to analyze the dynamic access of the

CRNs. Some performance metrics for SUs such as blocking probability, interrupted probability, forced termination probability, non-completion probability, and waiting time are developed. The interference to the PUs is considered by giving them higher priority while giving the SUs lower priority. This study models and analyzes the spectrum access in CRNs and does not provide any MAC protocol.

In [53, 54], the PUs behavior is modeled as two-state Markov chain, i.e., busy or idle state, and the actions of each SU are modeled as three-state Markov chain, i.e., sensing, transmission, or control state. The aim of [53] is to design a MAC protocol based on time cooperation of two SU pairs. The two pairs alternatively sense or access the spectrum, i.e., when a pair is in the sensing state, the other is in the access state, and if there is collision with the PUs, the collided pair will move to the control state; therefore, the time slot can be exploited for two functions at a time. However, each group of two pairs needs a common control channel to exchange their control messages, and for multiple groups, this approach may not be effective. Moreover, managing these groups in a network is not provided. Using the same models of the PUs and SUs as in [53], the authors of [54] proposed a Fair Opportunistic Spectrum Access (FOSA) scheme for distributed CRNs without using the Request-to-Send/Clear-to-Send (RTS/CTS) mechanism to improve the channel efficiency, and instead using another mechanism called fast catch-up strategy. However, the agreement between the two ends of the secondary link is not discussed since the analysis is based on the secondary links not on the individual nodes.

2) Statistical Approach

Statistical information about the existence of PUs on the intended channels is proposed in [55, 56] to design cognitive MAC protocols. The authors of [55] proposed statistical MAC (SCA-MAC) based on statistical sensing results at the previous time slots. The two ends of the secondary link negotiate the best data channels between them by exchanging CRTS/CCTS (where the extra C here means the control signaling is on the control channel). The receiver decides which are the best channels and includes their numbers in the CCTS, and then the transmitter will send on the selected channels. The proposed MAC in [56] is called Opportunistic Cognitive MAC (OC-MAC) and is almost the same concept of that in [55] except it uses a different handshake mechanism. The secondary transmitter and receiver exchange RTS/CTS/CRTS where CRTS means confirm-RTS and used to notify its neighbors about which channel are going to be used. Both of these two MAC protocols use statistical sensing about the PUs from the last time slot, so if the status of the PUs in the current time slot significantly changes for any reason, the decision taken by the secondary receiver may not be the best any more, and possibly the secondary transmission may increase the interference to the PUs to an unacceptable level.

3) Game Theory Approach

The game theory approach has been proposed by many researchers to model the dynamic spectrum sharing. The authors of [57] gave an overview about modeling OSNs using game theory. Three reasons behind using this approach in OSNs are explained. First, the behavior of the PUs and SUs and their interaction can be modeled efficiently. Second, game theory provides equilibrium criteria in optimizing the spectrum usage. Third, it enables each SU to take distributed decision based on local information.

A game-theoretic approach is used in [58] to model the competition spectrum sharing in CRNs. The SUs use this model to optimize their throughout based on a pricing function. The authors of [59] tried to fill the gap between the theoretical game approach and the design of the MAC protocols. They described how the game theoretic DSA can be embedded in the MAC protocol. However, the computational complexity and the required time to converge to equilibrium in order to take decision may be still higher than what are reasonable in CRNs.

In [60], using non-cooperative game theory to model the joint power/ channel allocation scheme, the authors tried to improve the network performance, i.e., decreasing the average transmitted power and increasing the average throughput. They used price-based iterative water filling (PIWF) algorithm to force the actions of the SUs to converge to the Nash equilibrium. The SUs exchange RTS/CTS/DTS, where DTS means Decide-to-Send, handshaking to negotiate the power and channel to be used. However, the spectrum sensing is not considered in this study and the proposed multiple SUs overlapping in the same spectrum is not explained. Finally, the computational complexity and the required time to converge may not be acceptable in CRNs, which are the general problems of using game theory in CRNs.

4) Slotted Time Approach

Dividing the MAC frame time into slots and sequential phases has been proposed by some authors. In [61] an opportunistic MAC protocol for CRNs is proposed based on a slotted time structure of the control and the data channels. The proposed protocol relies on the RTS/CTS accessing mechanism in addition to using two sensing policies. The first one is called random sensing policy where each SU randomly selects one of the channels for sensing, and the other is called negotiation-based sensing policy where the SUs exchange control messages to negotiate how they efficiently sense the channels, which needs many time slots to converge to the steady state. This protocol requires each SU to be equipped with two radios: a traditional radio is devoted for the control channel and an SDR to sense and transmit/receive data. Using the Markov chain and the bulk-service queuing models, the average throughput and delay of the SUs are analyzed for saturated and non-saturated network respectively. However, the hardware costs problem is a main drawback of this study. Moreover, when the number of the SUs is low, the average throughput of the secondary network is low too, and the available spectrum is not utilized efficiently.

In [62], a distributed multichannel MAC protocol for CRNs (MMAC-CR) is proposed. Although the power consumption is the main issue in this work, it considers the interference to the PUs and a practical sensing scheme. This MAC is almost similar to that of IEEE 802.11 PSM (Power Saving Mode), and the sensing scheme is similar to that proposed for IEEE 802.22, i.e., on two phases: fast sensing and fine sensing. The false alarm and miss detection probabilities are considered during the simulation. The evaluation of this protocol is mainly done by simulation, so analytical analysis is necessarily required.

In [63], an Opportunistic Spectrum Access MAC (OSA-MAC) is proposed. The main approach is to divide the CCC into three phases: channel selection using Ad hoc Traffic Indicating Message (ATIM) contention, selected-channel sensing, and channel access using the four-way RTS/CTS/DATA/ACK mechanism. The probability of collision with the PUs due to sensing errors (miss detection) is analyzed to maintain the interference to the PUs under a certain level. However, the proposed protocol uses two round contentions, which may lead to significant delay. Moreover, the protocol does not utilize the spectrum efficiently since some available channels may not be accessed.

5) Hardware Constraints

The hardware constraints are the main concern in [64]. Each SU node is assumed to be equipped with a single half-duplex CR. The pair that wins in the contention period will use the optimal stopping time theory to optimize when to stop sensing, based on the sensing and transmission constraints, and then access the identified channels. The protocol requires three handshaking mechanisms: contention RTS/CTS, sensing RTS/CTS, and transmission RTS/CTS. This approach deals well with the sensing and transmission constraints; however, the simultaneous transmission from faraway secondary nodes may lead to inaccurate detection of the PUs, this is called the sensing exposed terminal problem. Another issue is that the spectrum utilization is not optimized since there may be some available channels not exploited by any secondary users.

6) The Control Channel

The SUs have to exchange control information to coordinate the spectrum sensing and the spectrum allocation in the ad hoc CRNs. The intuitive way is to have a CCC. In the literature, there are two genral approaches for using a CCC to exchange the control information between the SUs. The first approach is an out-of-band CCC, which can be in a special spectrum band dedicated for this purpose or in the Industry, Scientific, and Medical (ISM) unlicensed spectrum bands. Dedicating a specific band for CCCs suffers from several drawbacks such as scalability, congestion, contention, failure, conflicts with the opportunistic nature of the CRNs, and subject to malicious jamming; while the ISM-band CCC has some drawbacks too such as unreliability due to the interference to other unlicensed services and the band is already over-crowded. The second approach is in-band CCC, which is subject to the PUs activities and has the problem of circular dependency, i.e., the SUs need a CCC to coordinate the spectrum identification, but having a CCC requires spectrum identification first. Instead of using a CCC for coordination, a rendezvous control scheme that does not need a CCC may be used; however, this method requires pre-assigned hopping sequences to rendezvous on channels that might be free of PUs; therefore, this scheme experiences the problem of limited static set of channels for the hopping sequences.

Instead of using a CCC dedicated for the SUs, some papers, such as [65, 68], propose alternative control methods similar to that proposed for the general ad hoc multichannel MAC protocols with some modifications. A comprehensive comparison between these multichannel MAC protocols can be found in [24]. In [65], a cognitive MAC (C-MAC) protocol for multichannel networks is proposed. Instead of using a fixed CCC, a rendezvous channel is chosen dynamically with a backup channel for the coordination among the secondary nodes. In this MAC protocol, each channel is divided logically into recurring super-frames, and each super-frame includes a slotted beaconing period to allow the nodes to negotiate their channels usage, and a data transfer period to send data. However, the low throughput of this protocol is a main problem since each node can exploit only one channel at a time if it is available.

In [66], a synchronized MAC protocol (SYN-MAC) is proposed without need for a CCC. This protocol requires using two radios: one dedicated to exchange the control messages and the other to sense and send/receive data. The time is slotted into a number equals the maximum number of the channels at each node. Using a common time slot, two nodes can communicate. Although this protocol avoids using a CCC and elevates the multi-hidden nodes problem, it needs a robust synchronization technique in addition to using two radios for low throughput.

In [67], a heterogeneous distributed MAC (HD-MAC) is proposed. Instead of using out-of-band CCC, SUs are divided into neighboring groups. Each group has its own in-band control channel to exchange the members' control packets. Then bridge nodes are used to link between the groups. The proposed protocol addresses the problem of spectrum heterogeneity and avoids using a CCC. However, the in-band control channels are subject to the occurrence of the PUs, which interrupt the control signaling; moreover, the spectrum utilization and the throughput are low since each secondary link uses only one channel at a time if it is available.

The transmission on the CCC is discussed in [126]. A novel transmission scheme that combines the Orthogonal Frequency Division Multiplexing (OFDM) with the Transform Domain Communication System (TDCS) is proposed to provide long transmission range with low emission power suitable for accessing the CCC. The OFDM-based TDCS scheme is a kind of spread spectrum that can facilitate to use one CCC for a large CRN whether the CCC is an in-band or out-of-band channel.

The TDCS was originally proposed for CRs in [127].

7) Spectrum Utilization

The authors of [69] discussed the concept of spectrum agility. They provided analytical models of two performance metrics: spectrum utilization and spectrum-access blocking time. Then they proposed three basic system entities namely Measurement Management Entity (MME) that is responsible of the spectrum sensing, Resource Management Entity (RME) to manage the spectrum access, and Group Coordination Entity (GCE) that coordinates the channel selection within a group. Using these entities, the performance metrics are simulated. In fact, this study provides general philosophy of modeling OSNs and does not give detailed MAC protocols; however, it discusses the spectrum utilization clearly.

Another spectrum utilization idea is provided in [70], where an opportunistic spectrum MAC (OS-MAC) is proposed. The main approach is to divide the SUs into groups; each group has a delegate SU (DSU) that periodically exchanges control messages and updates its information with other DSUs on a CCC and then comes back to its group on one of the data channels and broadcasts the new information to all the group members. The proposed approach provides good spectrum utilization in the sense that the data channel is always used by the SUs even when the DSU is exchanging the control packets. The main drawback of this study is that it does not consider the spectrum sensing at all. Moreover, it uses only one data channel for each group, which limits the throughput of the SUs; in addition, the group members exchange their control packets on the data channel, so if a PU occurs suddenly on that channel, the group will be fully disrupted and should be re-initiated, which affects the network reliability.

The objective of [71] is to find the optimal number of the SUs that maximizes the overall throughput of the primary and secondary networks. The authors tried to find the number of the SUs relative to the number of the PUs that maximizes the sum throughput in the system. They found that the optimal fraction of the PUs is very close to the duty cycle of the data traffic, and the sensitivity to sense the PUs decreases as the interference tolerance of the PUs increases. In [72], the objective is to compute lower and upper bounds for the throughput of a secondary network overlaid in a cellular network. While in [73], an analytical formulation of the throughput of prioritized contention access in a secondary network is provided.

8) Constraining the Interference to the PUs

Constraining the potential interference to the PUs is one of the most important requirements in designing the MAC frameworks for OSNs. Therefore, almost all researchers in this area have considered these constraints either implicitly or explicitly. In the following some research efforts are discussed. In [74], the throughput of the SUs is studied using three different random access schemes called virtual-xmit-if-busy (VX), vacation-if-busy (VAC), and keep-sensing-if-busy (KS). The interference to the PUs is considered using two constraints: collision probability and overlapping time with the PUs. This work provides good discussion about protecting the performance of the PUs; however, perfect sensing is assumed, i.e., the false alarm and miss-detection probabilities are assumed to be zero, and the proposed random access schemes are used just to evaluate the interference, so more practical sensing and accessing schemes are needed.

The authors of [75] proposed analytical and simulation approaches to maximize the SU throughput constrained by the interference to the PUs; however, they did not provide any MAC protocols. The key idea of [76] is that the requirements of spectrum utilization and controlling the interference to the PUs can benefit from the group testing of all the intended channels. False discovery Rate (FDR) based cooperative strategy is proposed to detect the existence of the PUs. However, in some situations, the sensing time is too short, so it may be better to sense each channel individually and decide to either access that channel or not.

9) Hidden PUs and Spectrum Heterogeneity

Hidden SUs or PUs complicate the design of efficient MAC protocols for CRNs. Most of the proposed protocols, such as [77], deal with the hidden SUs; however, dealing with the hidden PUs seems to be more difficult. To tackle the challenge of the hidden PUs, the authors of [78] proposed including the information of the neighboring PUs in the RTS and CTS control packets, and then they proposed a distributed CR MAC (DCR-MAC) protocol in [79]. This work aims to detect and protect the PUs around the two ends of the secondary link. When a secondary source node wants to transmit, it sends an RTS including a list of the available channels at that node. If the secondary neighbors of this source find that there is a PU on any of the chosen channel, they send tones on the associated mini-slots of the reporting period to notify the source node about the existence of that PU. Then the source node sends an RTS update (RTSu) including the new channel list. The destination node receives the RTS and waits for the RTSu, and then with the helping of its neighbors, which they do the same as what the source's neighbors do, it replies with a CTS including the best list that are available at the both ends. Finally the source node will send on these channels. This handshaking mechanism can be used to tackle the problem of spectrum heterogeneous in addition to solve the problem of hidden PU nodes. However, it needs time to successfully exchange all these control messages. Another drawback of this work is that the spectrum sensing is not considered, where each node just maintains a channel status table (CST) indicates the available channels at that node and updates it every received RTS, RTSu, or CTS; however, how these nodes sense the PUs in their vicinity is not discussed.

10) Extending the WLAN to Licensed Bands

The current WLANs are operated in the ISM-bands, which are unlicensed spectrum bands. However, some approaches have been proposed to extend the WLANs to work in some licensed bands using CRs. In [81], a MAC protocol is proposed to extend the IEEE 802.11s, i.e., Wireless Mesh Networks (WMNs), into licensed bands. Each mesh node is equipped with an additional CR to cover these licensed bands, while another conventional radio is used to cover the unlicensed band. One channel in the unlicensed band is used as the CCC. In [84], to support relay communications, instantaneous channel information at the relay nodes is included in modified RTS/CTS packets, and then the receiver node decides which relay nodes are the best to establish a communication link knowing that some of these nodes may be operated in the licensed bands.

In [85], the WLAN Multiple Access with Collision Avoidance (MACA) protocol is modified to support concurrent transmission in the unlicensed band using CRs. By modifying the handshaking mechanism, the exposed node can be discovered and then allowed to simultaneously transmit in the two-hop networks. In [86], to support the QoS in the unlicensed band, the CSMA/CA protocol is modified based on the general vision of the cognitive cycle in CRs, which consists of four stages: observe, plan, decide, and act stage. However, this approach gives a general view of modifying the existing WLAN MAC to be consistent with the general concept of CRs without any details of how the MAC protocol should work to support the required QoS.

2.3.3 Resource Allocation and QoS Provisioning

The multiuser Discontiguous OFDM (D-OFDM) technique has been appeared widely in the literature of CRNs as the spectrum access mechanism with different resource allocation schemes. In [88], a resource allocation algorithm that ensures proportional rates to predefined target rates for SUs using multiuser OFDM is proposed for non-real time services. While in [89], a spectrum assignment algorithm is proposed to utilize the disjoint spectrum bands using D-OFDM. The Multi-Carrier Code Division Multiple Access (MC-CDMA) is another promising technique to access the disjoint spectrum bands in CRNs [128] where the resource allocation and access can be controlled. A comparison between D-OFDM and the Non-Contiguous MC-CDMA for CRNs can be found in [129].

In [90–92], joint admission and power control schemes were proposed to meet certain QoS requirements of the SUs considering the interference to the PUs in CRNs. Moreover, queuing approaches are used in [93, 94] to study the secondary user throughput and delay and to develop admission control and channel allocation methods for CRNs. Different from call admission control of the traditional wireless networks such as cellular networks, which has been extensively studied in the literature [95], call admission control for CRNs must be spectrum aware, i.e., to admit a new SU into the network, there should be spectrum available and identified through spectrum sensing to guarantee the required QoS in terms of the blocking and dropping probabilities. A call admission control strategy integrated with a QoS-based spectrum handoff mechanism is proposed in [96] to improve the QoS and spectrum utilization in a centralized CRN, while user admission control with and without spectrum handover for the ongoing secondary transmissions is studied in [97]. Call admission control with opportunistic scheduling scheme is proposed in [98]. Moreover, class-based call admission control schemes are proposed in [99,100] to improve the blocking probability and the secondary throughput of specific CRNs. In [101], user admission and eviction control considering the user satisfaction is suggested to maximize the profit of a wireless service provider employing CRNs. Finally, a cross-layer optimization framework that integrates spectrum sensing and call admission control is proposed in [102] for centralized CRNs to minimize the secondary dropping rate taking the secondary blocking rate and the interference to the PUs into consideration.

In general, the QoS provisioning approaches that have been proposed in CRNs can be classified into four categories. The first category investigates the MAC protocol and opportunistic scheduling design, which can provide QoS for the SUs in different secondary network models [14, 61, 103]. The second category proposes power allocation schemes that are aware of QoS for different scenarios of CRNs [90–92, 104–106]. The third category suggestes different call admission control and channel allocation schemes that maintain certain secondary QoS requirements [13, 96–102]. Finally, the fourth category studies the QoS provisioning considering the services and applications carried out by CRNs [107–112].

2.3.4 Clustering for Multi-Hop CRNs

Network clustering can be used to overcome the spectrum heterogeneity in multi-hop CRNs by grouping the nearby nodes that may experience the same activities of the same set of PUs; moreover, the clustering can help to reduce the signaling overhead required for operating the network and maintaining its connectivity. Almost all the existing clustering approaches in CRNs aim to avoid using a global CCC and instead rely on in-band CCCs to coordinate their processes, and form clusters based on the local similarity of the available spectrum [67, 117–122]. However, the in-band CCCs are subject to the activity of the PUs, so with the frequent occurring of the PUs on these channels, re-clustering and maintaining the clusters become inevitable annoying functions that waste the time and network resources. In [123–125], cluster-based cooperative spectrum sensing schemes have been proposed; however, forming the clusters are not considered and assumed to be done by a base station or by a higher network layer.

Chapter 3

System Model

In CRNs, there are two types of networks: primary and secondary networks. The primary networks consist of PUs that have licenses to exclusively use one or more spectrum bands; however, they do not use the spectrum all the time and all places, so some channels in these bands are spatiotemporally underutilized. In order to efficiently utilize the frequency spectrum, the spectrum regulators coordinate with the primary network holders to open up these bands to be utilized by a secondary network that consists of SUs seeking for spectrum opportunities. Moreover, the PUs have the priority to use the spectrum, and can reclaim the channel(s) at any time without notifying the SUs. Furthermore, the PUs are not required to make any modifications on their legacy systems for the purpose of spectrum sharing with the SUs.

Figure 3.1 illustrates possible environments in which CRNs can be operated. There are different types of PUs such as TV monitors receiving from TV base stations, cellular phones within the coverage of their base stations, and walkie-talkies operated in centralized or ad hoc modes. Each type of the PUs is operated in its own allocated spectrum bands that are different from that of the other types,

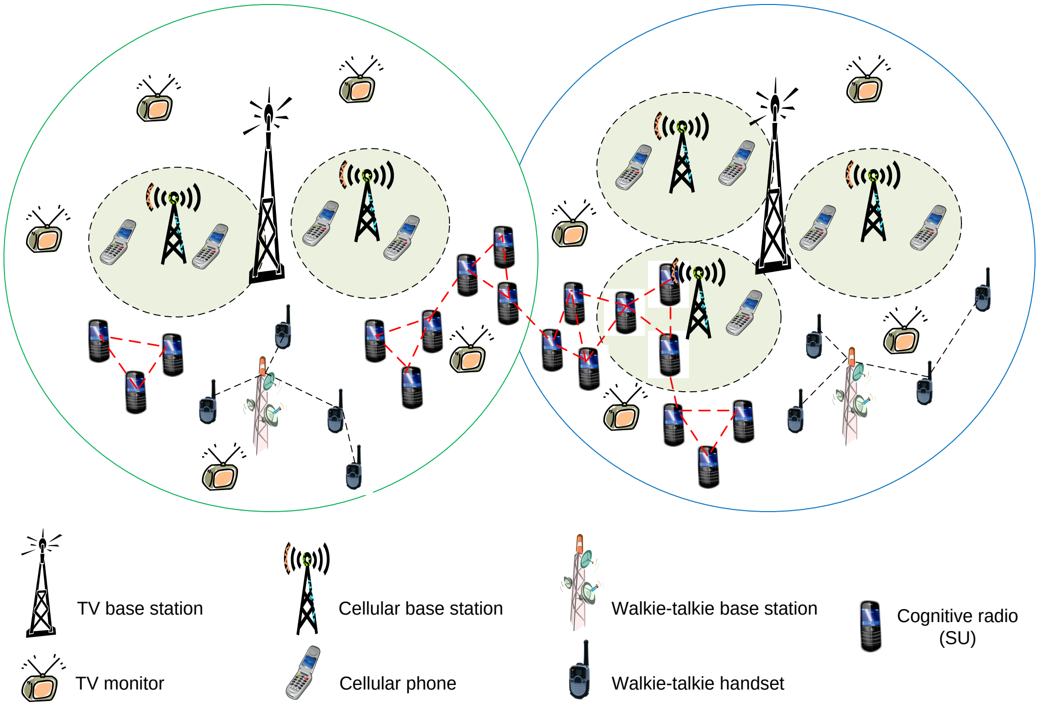

Figure 3.1: Operating environments for ad hoc CRNs.

so all types can be deployed in the same geographical region at the same time. The PUs are legacy systems providing communications with relatively large coverage range. On the other hand, the communication range of the SUs are small comparing to that of the PUs. The SUs are supposed to communicate with each other in an ad hoc network. Therefore, the SUs that are in the communication range of each other can form a single-hop ad hoc network covering a relatively small area; however, the CRN can cover larger area in a multi-hop ad hoc manner. Moreover, any SU in the CRN may access any other network such as the Internet through a gateway.

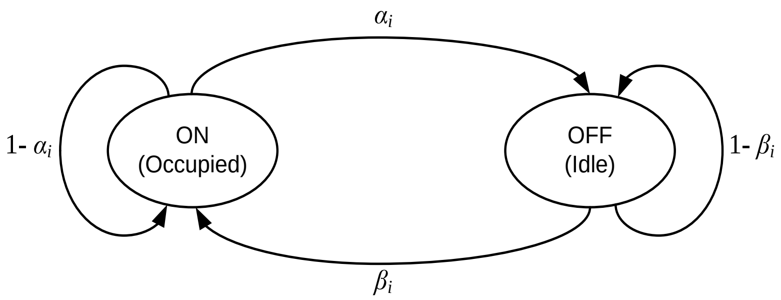

Figure 3.2: Model of the licensed channels.

3.1 Primary Network Model

Regardless of the types of the PUs, the primary networks are considered to consist of N non-overlapped channels, each with bandwidth B_i, where $1 \leq i \leq N$, and the channels are numbered from 1 to N based on their sequences in the spectrum. Each channel of the N licensed channels can be modeled at any time as an ON/OFF source, i.e., either occupied by a PU or idle with exponentially distributed periods. Therefore, the states of each channel can be modeled as a two-state Markov chain as shown in Figure 3.2. The occupancy of the i-th channel can be given as

$$\delta_i = \frac{\beta_i}{\beta_i + \alpha_i}, \qquad i = 1, 2, ..., N \tag{3.1}$$

where, α_i is the probability that channel i transits from state ON to state OFF, and β_i is the probability that this channel transits from state OFF to state ON.

3.2 Secondary Network Model

The network architecture of CRNs can be centralized (infrastructure) or ad hoc (infrastructureless). In centralized network, there is a base station that monitors and controls the whole network, while each node is responsible to maintain its communications with the other nodes in the ad hoc network. Since we believe that ad hoc networks will be the practical architecture that attracts the future secondary usage of the spectrum due to their ease of deployment, we will focus on ad hoc CRNs throughout this thesis. Moreover, we consider the single-hop and multi-hop scenarios in deploying the SUs in ad hoc CRNs.

3.2.1 Single-Hop Secondary Network

In the single-hop CRNs, the secondary network consists of a total of M SUs seeking for spectrum opportunities over the N licensed channels. Any SU is equipped with a single half-duplex CR transceiver that has the ability to sense at most L channels in sequence and access at most K channels simultaneously based on its hardware and technology constraints, where $1 \leq L \leq N$ and $1 \leq K \leq N$.

The SUs that are in the range of each other form a single-hop ad hoc network covering a relatively small area, while the communication range of the legacy primary systems is larger than that of the SUs, so each single-hop SU group can be considered to be almost under the same coverage of the PUs set. The SUs use a local CCC to exchange their control messages.

3.2.2 Multi-Hop Secondary Network

The SUs may cover larger area in a multi-hop network scenario. The secondary network consists of a number of SUs distributed over a region that is under different types of PUs with different activities operated on specific spectrum bands. These spectrum bands are divided into N non-overlapped channels. The PUs are legacy systems that are expected to cover larger communication range than that of the SUs, so each group of nearby SUs is expected to be almost under the coverage of the same set of PUs.

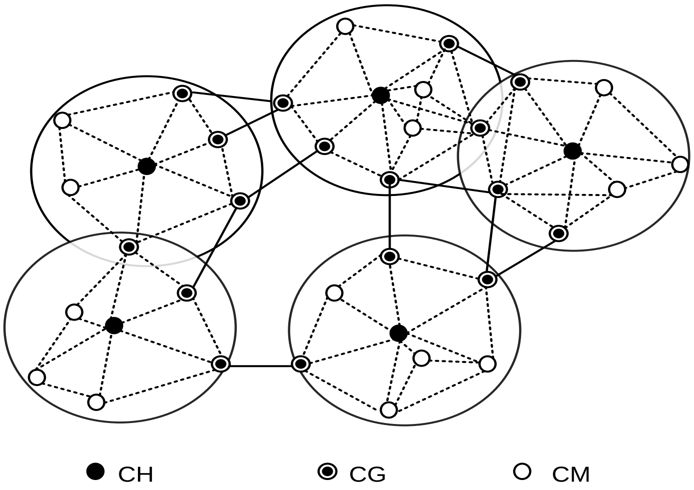

Figure 3.3: Multi-hop secondary network architecture.

The nearby SUs are clustered with 1-hop from a central SU based on the geographical locations of the SUs and their joining time to the network. Therefore, each cluster of SUs covers a geographical part of the whole communication region. The SUs in each cluster cooperate to sense the spectrum in their vicinity and then access the available channels. As shown in Figure 3.3, each cluster consists of a Cluster Head (CH) user that initiates the cluster, Cluster Member (CM) users, and Cluster Gateway (CG) users that join the cluster with its neighboring clusters. We assume that the SUs rarely move, and when they do, they move slowly, so the topology of the network is dynamic with stable status. Any SU may become a CH that is responsible to initiate and maintain the cluster and coordinate the communications within the cluster and with the neighboring clusters in addition to performing its own communications. Moreover, the routing in the multi-hop scenario much complicates the network. Therefore, to enable the CHs to do these tasks in reasonable time and to reduce the latency between the SUs due to packet routing, each SU is assumed to be equipped with two radios: a control radio, which is a traditional and simple radio for exchanging the control signaling, and a CR for sensing and data exchanging.

In order to enable using only one frequency spectrum for all the local CCCs of the clusters in the whole secondary network, which can be in-band or out-of-band channels, and to manage the co-channel interference between the SUs in the adjacent clusters, spread spectrum is used to access the channels in the physical layer. Each cluster is assigned a unique pseudo-noise spreading code chosen by the cluster initiator from a code pool (CP), where the codes are assumed to be orthogonal and numbered with specific IDs.

Chapter 4

Resource Management in Single-Hop CRNs

In this chapter, a novel MAC framework that integrates a kind of cooperative spectrum sensing method at the physical layer into a cooperative MAC protocol is proposed for single-hop distributed CRNs considering the requirements of both the primary and secondary users. For spectrum identification, a computationally simple but efficient sensing algorithm is developed based on an innovative deterministic sensing policy called Allocated-group Sensing (AS) Policy. Moreover, we study how to balance the spectrum identification and exploitation and propose an admission control scheme and channel allocation policy that can be integrated in the MAC framework. The parameters that can be adjusted to regulate the number of the admitted users are also studied. Furthermore, we propose and analyze a QoS-based spectrum allocation framework that jointly considers the QoS provisioning for heterogeneous secondary Real-Time (RT) and Non-Real Time (NRT) users with the spectrum sensing, spectrum access decision, and call admission control in CRNs.

4.1 MAC Framework

Although several MAC frameworks have been proposed to tackle some of the new challenges in the distributed CRNs, designing practical and efficient such protocols is still in its infancy, so more research efforts are needed to realize the concept of this emerging wireless networks. Cooperation between the SUs can compensate for the need of complex hardware. Cooperation here implies that the SUs cooperate with each other to identify the spectrum opportunities and also to exploit these opportunities. To the best of our knowledge, there is no such study that provides this twofold cooperation in distributed CRNs considering the hardware limitations and costs in addition to the requirements of both the primary and secondary users. In this section, we propose to divide the SUs into two cooperative groups: sensing users and access users and develop a MAC framework that can handle the cooperation between the two groups to achieve the ultimate goals of the CRNs without need for complex hardware. Since each SU is equipped with a single transceiver, the SU can be either a sensing or an access user but not both in a time slot, where there are at least one sensing user and one access user in each time slot. In order to control the spectrum identification and exploitation distributively, we propose a novel dynamic ID numbering approach that helps out to order the SUs in a distributed manner. Furthermore, we investigate a computationally simple but efficient sensing algorithm that relies on an innovative sensing policy to assist the SUs to optimally identify the spectrum opportunities.

4.1.1 MAC Protocol

A. MAC Time Structure and Protocol Overview

The system model under consideration is presented in Chapter 3, where the primary network is discussed in Section 3.1, while the single-hop secondary network is discussed in Section 3.2.1. To manage the spectrum identification and exploitation, we propose a cooperative MAC framework based on the slotted time MAC structure shown in Figure 4.1. All the licensed channels and the CCC are slotted into time slots each with T time duration. The SUs sense the spectrum at the beginning of the time slot, and once each licensed channel is identified whether idle or occupied by a PU, the channel is considered to stay at the identified state during the remaining time of the time slot. The duration of the time slot [1] must be chosen to be large enough for the SUs to exchange their control and data packets; however, it should not exceed a threshold that maintains the potential interference to be tolerable to the PUs as will be discussed later on in this section. The CCC is further divided into three phases. The first phase is called Sensing-and-Registration Phase (SRP), the second phase is the Reporting Phase (RP) that is divided into N mini-slots corresponding to the N licensed channels, and the third phase is the Data-and-Reserving Phase (DRP). In addition to these phases, there are two beacons named B1 and B2. The purposes of these phases and beacons are discussed below. Figure 4.2 illustrates the operating flowchart of the proposed MAC framework.

A1. Sensing-and-Registration Phase (SRP)

- At the beginning of each time slot, the first winner from the last DRP becomes the network coordinator at the current time slot, so it broadcasts beacon B1 to synchronize the network and to inform the other SUs about the new total

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[1] In the IEEE 802.22 standard, the MAC time slot is 160 ms [115].

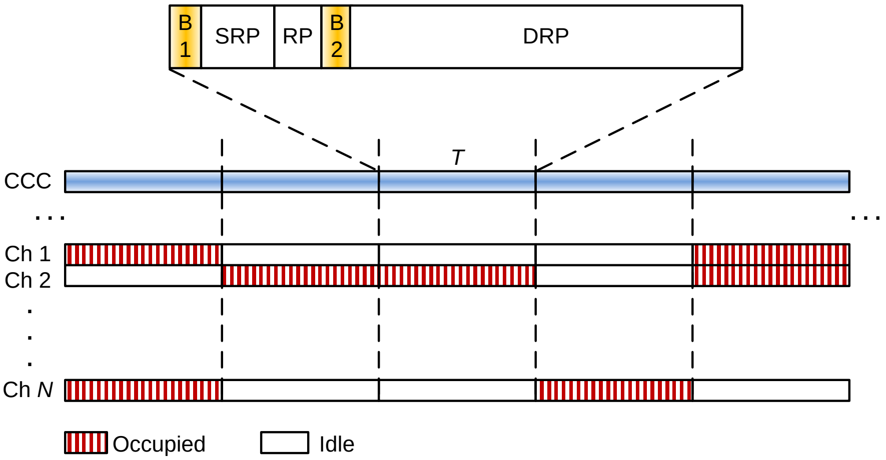

Figure 4.1: The MAC structure.

number of the SUs in the network, M, the number of the winning users, M_w, and the number of the leaving users, M_l, in the last DRP, and the old dynamic IDs of the winning and leaving users.

- The other SUs use this information to calculate the new number of the sensing users, i.e., $M_s = M - M_w$, and to update their dynamic IDs as will be discussed in the dynamic ID updating algorithms in Section 4.1.1-B.
- The sensing users sense the N channels based on a sensing algorithm, which will be discussed in Section 4.1.3-D.
- Any new SU that wants to join this network have to exchange request-to-register (RTR) and RTR-acknowledgment (RTR-ACK) with the network coordinator at the current time slot and get its dynamic ID based on a distributed algorithm that will be discussed in Section 4.1.1-B.

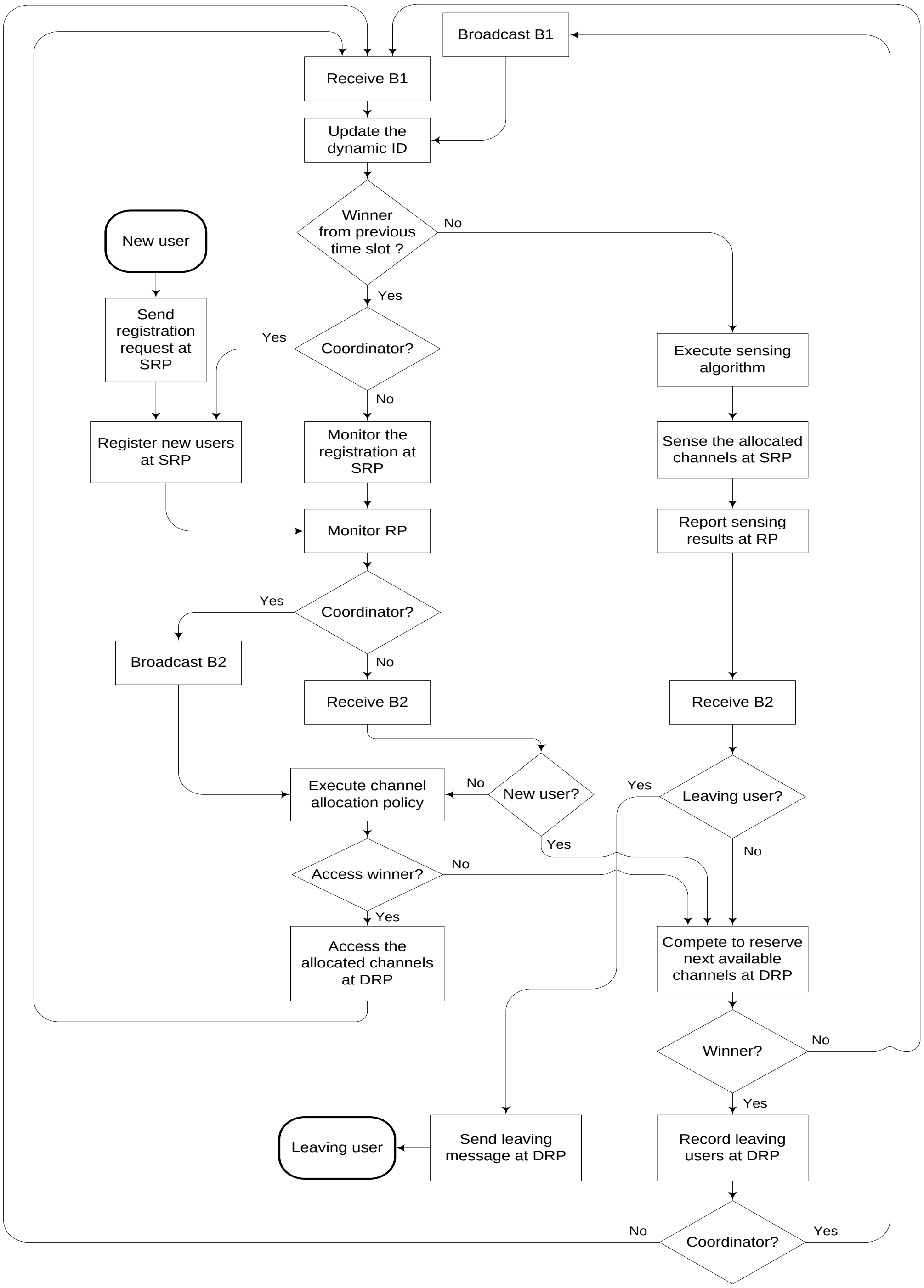

Figure 4.2: Flowchart of the proposed MAC framework.

A2. Reporting Phase (RP)

- Each sensing user sends tones at the mini-slots only if it detects primary signals on the corresponding sensed channels to inform the winning users about the existence of some PUs on these channels.

- All the winning users monitor the CCC at this phase and figure out the available channels.

- At the end of this phase, the first winner broadcasts the updating beacon B2. This beacon has twofold. The first is to tighten the network synchronization, and the second is to inform the SUs about the new value of M since there may be new SUs have joined the network at the SRP.

A3. Data-and-Reserving Phase (DRP)

- Based on the number of the identified available channels, N_a, some or all of the winning users access these channels based on a channel-allocation policy that will be discussed in Section 4.2.2.

- In the first part of the DRP, all the remaining SUs try to reserve the potential identified available channels at the next time slot using a fair access mechanism on the CCC, such as RTS/CTS, and record their winning orders, i.e., the first, second, and so on.

- In the second part of the DRP, the SUs that want to leave the network send short messages on the CCC indicating that they are leaving.

- The new first winning user, which will be the network coordinator at the next time slot, records the number of the leaving users and their dynamic IDs to broadcast them in the coming beacon B1.

B. Dynamic ID Numbering

The SUs can cooperate efficiently to sense and access the spectrum if each has a unique ID that can be changed dynamically each time slot. As mentioned before, the network coordinator broadcasts beacon B1 that includes the new values of M, M_w, and M_l in addition to the old IDs of the winning pairs and the leaving users where these IDs are ordered from low to high; moreover, it broadcasts beacon B2 to update the value of M. In the following, all distributed algorithms used in obtaining or updating the dynamic IDs of the SUs in the network are provided.

- The winning users update their dynamic IDs based on their winning order using Algorithm 4.1 as:
  Algorithm 4.1:
  i-th winning user ID $\leftarrow M - i + 1$, where $1 \leq i \leq M_w$.

- The sensing users having old dynamic IDs less than or equal to the number of the new sensing users, i.e., M_s , do nothing, while the sensing users having old IDs greater than the new number of M_s must update their dynamic IDs using Algorithm 4.2 as:
  Algorithm 4.2:
  For each sensing user, if its old ID $>$ new M_s, then
  i-th last sensing user ID $\leftarrow$ i-th last ID on B1, where i=1, 2,... .

  Using the above two steps, we have M_s sensing users with new dynamic IDs ordered from 1 to M_s and M_w winning users with new dynamic IDs ordered from $M_s + 1$ to M.

- During the SRP, each new SU exchanges registering packets with the current network coordinator and gets its dynamic ID based on its joining time using Algorithm 4.3 as:

Algorithm 4.3:

i-th new user ID $\leftarrow M + i$, where i= 1, 2, ...

C. General Notes

- Since the first winning user is the secondary network coordinator that has the key function of broadcasting B1 and B2 in the MAC protocol, there should be a backup user to do this function in case the first winner fails to do it for any reason. The other winning users can do the same job; therefore, they monitor the first winner, and if it fails, the second winner will replace it and if not the third one and so on. The failure user will realize this and should become the last winner.

- In case there are only two SUs in the network wanting to communicate with each other, the one that wants to transmit broadcasts beacon B1, and the receiver senses the channels while the transmitter registers any new SU, if any, then the receiver reports its observation on the RP and the transmitter figures out which channels are available to be used in the DRP. If there will be new SUs registered at the SRP, the network will become with many SUs and everything works as discussed previously, and if not, the procedure of two SUs will be repeated.

- To establish a secondary network, any SU want to communicate with other SUs scans the intended CCC for a time longer than T. If it does not find control packets on this CCC, then it will realize that it may be the first SU that should establish the network and broadcasts beacon B1. If there is a collision with other SU trying to establish the network too, both of them will realize that the network is still empty of users, so they have to try to broadcasts beacon B1 again using random back-off time.

4.1.2 Spectrum Sensing

A spectrum sensing policy is required to manage the identification of the spectrum opportunities. This policy should assist to identify which and how many channels are available to be used by the SUs. Therefore, when the percentage of the sensed channels out of the N licensed channels increases, the throughput of the secondary network is expected to increase.

The channel is said to be available at a specific time when it is not used by any PU at that time; however, the channel status is unknown to the SUs; therefore, they should rely on their ability to identify the channel availability. Let N_a be the random number of the available channels at time slot t. Knowing that the channels that can be exploited are just that sensed by the SUs, the average number of the available and sensed channels at time slot t can be calculated as

$$\overline{N_a} = \sum_{n=0}^{NP_{sens}} n\Pr\{N_a = n, \text{sensed}\}, \tag{4.1}$$

where P_{sens} is the percentage of the sensed channels out of the N channels. The average activity of the PUs on the intended channels can be estimated by collecting the statistical observations on the channels, i.e., δ_i in (3.1), during the previous time slots and then using a technique such as Bayesian learning [87]. Distinguishing a channel as occupied by a PU or not at any time slot is determined by the spectrum sensing. Since the total number of the available channels at any time slot depends on the overall activity of the PUs on the N channels regardless of the details of the occupancy of each channel, it is sufficient to know the average overall activity of the PUs to estimate the total number of the available channels; therefore, without loss of generality, we can assume that $\delta_i = \delta \ \forall i$, where δ is the average overall activity of the PUs. Since the channels are independent, $\Pr\{N_a = n,\text{sensed}\}$ can be modeled as binomial distribution and (4.1) can be rewritten as

$$\begin{aligned}\overline{N_a} &= \sum_{n=0}^{NP_{sens}} n \begin{pmatrix} NP_{sens} \\ n \end{pmatrix} (1-\delta)^n \delta^{(NP_{sens}-n)} \\ &= (1-\delta)NP_{sens}.\end{aligned} \tag{4.2}$$

Therefore, if P_{sens} can be increased by investigating a proper sensing policy, more spectrum opportunities can be identified.

A. Sensing Policies

A sensing policy is considered to be ideal if all the N licensed channels can be sensed, i.e., $P_{sens} = 1$. Based on the system model, each SU can sense L channels, where $1 \leq L \leq N$; therefore, P_{sens} highly depends on the number of the sensing users, M_s, and the number of sensed channels per each sensing user, L. In the following, three sensing policies namely Random-Sensing (RS) Policy, Distinct-group-Sensing (DS) Policy, and Allocated-group-Sensing (AS) Policy are proposed and discussed. Eventually, the best of them comparing to the ideal sensing case will be chosen as the sensing policy that can be integrated in the proposed MAC framework.

A1. Random-Sensing (RS) Policy

In the RS policy, each sensing user chooses independently and uniformly L consecutive channels out of the N channels as shown in Figure 4.3. Therefore, there is a number of possible channel groups given by

$$N_r = N - L + 1. \tag{4.3}$$

Similar to [61], the probability mass function (pmf) of the sensed channels can be modeled as $(N_r + 1)$-state Markov chain. However, each SU is assumed to be able

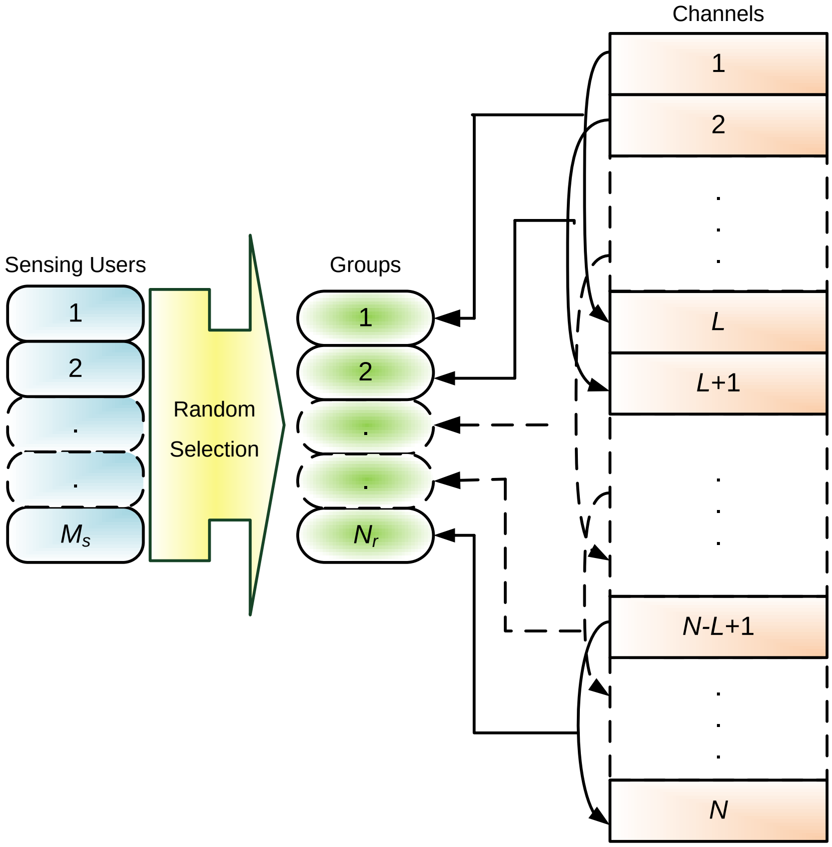

Figure 4.3: Channel group selection in the RS policy.

to sense only one channel in [61], while each SU can sense L channels in sequence in our policy. This Markov chain can be written mathematically as

$$q_{ij} = \begin{cases} i/N_r, & j = i \\ 1 - i/N_r, & j = i+1 \\ 0, & \text{o.w.}, \end{cases} \tag{4.4}$$

and the probability transition matrix of this chain can be given by

$$Q = \{q_{ij}\}, \qquad 0 \le i \le N_r, \qquad 0 \le j \le N_r. \tag{4.5}$$

The probability of C channel groups are sensed by M_s sensing users can be evaluated by calculating the M_s-step transition probability from state 0 to state c as

$$\Pr\left\{C = c\right\} = Q^{M_s}_{(0,c)}, \tag{4.6}$$

where the right hand side of (4.6) means the element in row 0 column c of the M_s-step transition matrix [61]. Therefore, the probability of the sensed channels can be given as

$$P_{sens} = \frac{1}{N_r} \sum_{c=0}^{N_r} c Q^{M_s}_{(0,c)}. \tag{4.7}$$

A2. Distinct-group-Sensing (DS) Policy

For the DS policy, the N channels are divided, as shown in Figure 4.4, into distinct non-overlapped channel groups given by

$$N_d = \left\lceil \frac{N}{L} \right\rceil, \tag{4.8}$$

where$\lceil x \rceil$ means the real number x is rounded up to the nearest integer number. Each sensing user chooses independently and uniformly one of the groups and starts to sense L channels beginning by the first channel of the chosen group. When N/L is not an integer number, the last group will contain some channels overlapped with the previous group. Similar to what have been done in the RS policy, $(N_d + 1)$-state Markov chain is used to find the pmf of the sensed channels. Therefore, the probability of the sensed channels in this policy can be given as

$$P_{sens} = \frac{1}{N_d} \sum_{c=0}^{N_d} c Q^{M_s}_{(0,c)}. \tag{4.9}$$

A3. Allocated-group-Sensing (AS) Policy

The randomness in both RS and DS policies is expected to decrease the average number of the sensed channels and consequently to decrease the average aggregate

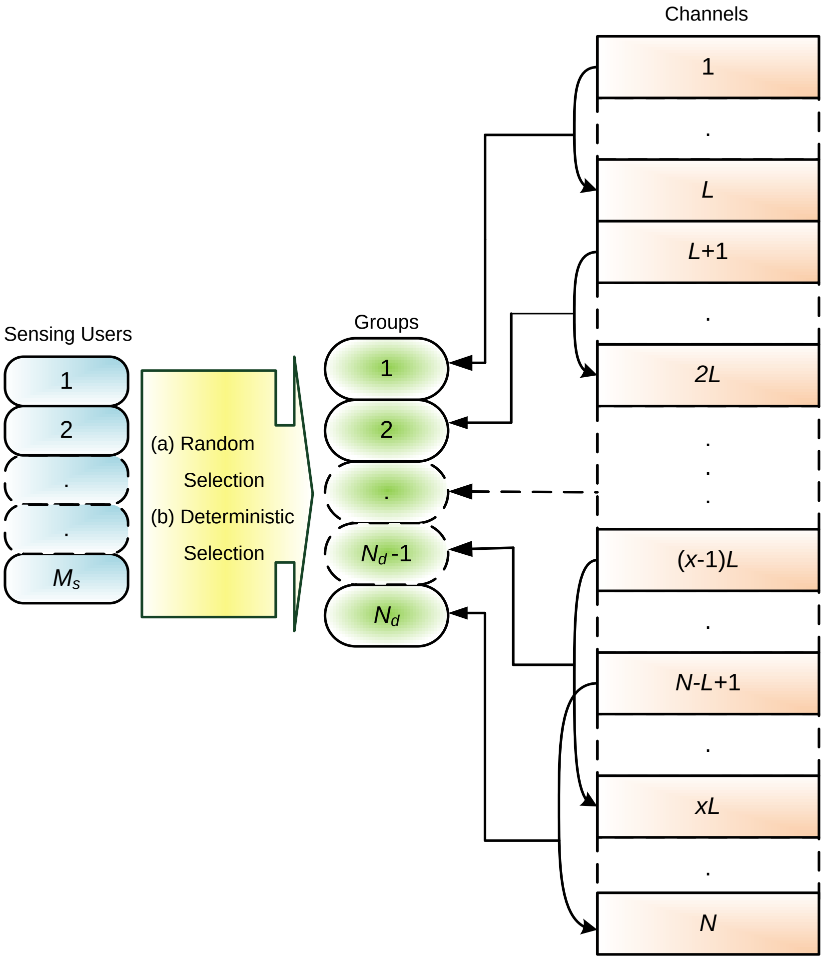

Figure 4.4: Channel group selection in: (a) the DS policy and (b) the AS policy.

throughput of the secondary network. The main purpose of AS policy is to ensure that each sensing user will sense different channel group from any other group sensed by any other sensing user when the number of the sensing users is less than or equal to the number of the channel groups. Using the same channel grouping of DS policy shown in Figure 4.4, each sensing user chooses a group deterministically instead of a random selection as follows. After updating the dynamic IDs of all the SUs and before starting the sensing process at the SRP duration, each sensing user calculates how many channel groups based on (4.8) and chooses a specific group using Algorithm 4.4 as follows:

Algorithm 4.4:

```
Calculate: $num = \text{mod}(\text{user-dynamic-ID}, N_d)$
If $num = 0$, choose channel group # $N_d$.
Otherwise, choose channel group # $num$.
```

Therefore, the percentage of the sensed channels in this policy can be given as

$$P_{sens} = \begin{cases} \frac{LM_s}{N}, & M_s < N_d \\ 1, & M_s \geq N_d. \end{cases} \tag{4.10}$$

B. Performance Evaluation

The performance of the proposed sensing policies discussed above is evaluated in this subsection. The performance here means the percentage of the sensed channels out of the N licensed channels, i.e., P_{sens}. Since the channel group in RS and DS policies are chosen randomly, we use simulation to validate the analytical results.

Figure 4.5 shows the performance comparison of the three proposed sensing policies with respect to the number of the sensing users. It can be seen that the AS policy, which is the deterministic sensing method, outperforms the other two random policies, where it needs only $M_s = N/L$ sensing users to achieve the ideal sensing case. However, due to the randomness of the other sensing policies, more sensing users are required to achieve the ideal sensing case, e.g., around 40 sensing users are required for the DS policy while more and more sensing users are required for the RS policy. Moreover, the DS policy is better than that of the RS policy since the number of the channel groups in the DS policy is less than that of the RSP policy. It is obvious that the simulation and analytical results are almost identical for both DS and RS policies, which verifies the used analytical expressions.

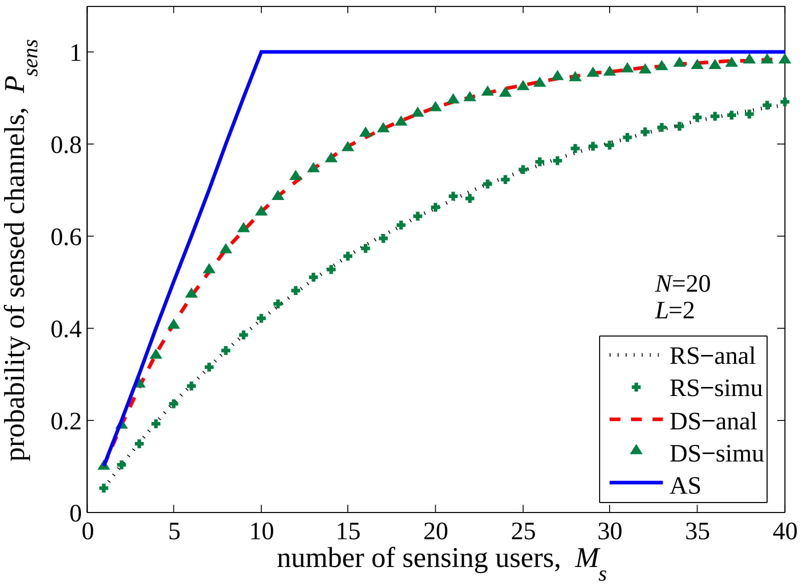

Figure 4.5: Performance comparison between the proposed sensing policies with respect to the number of the sensing users.

It is desirable also to examine the performance of these sensing policies with respect to the number of the sensed channels per user. As shown in Figure 4.6, the performance of the AS policy increases sharply with increasing L until saturates at the ideal sensing case once the number of the sensed channels per user becomes $L = \text{ceil}(N/M_s)$. However, using this number of sensing users, the performance of the RS policy reaches the ideal sensing case only when each sensing user can sense all the licensed channels. Moreover, the performance of the DS policy increases in steps based on the number of the channel groups and the overlapped channels between the last two channel groups if N/L is not an integer number. The simulation results in this figure are also consistent with the analytical results.

From Figures 4.5 and 4.6, the AS is able to sense higher number of the licensed channels, i.e., more spectrum opportunities can be identified even with lower number of sensing users. Therefore, the AS policy is chosen to be integrated into the

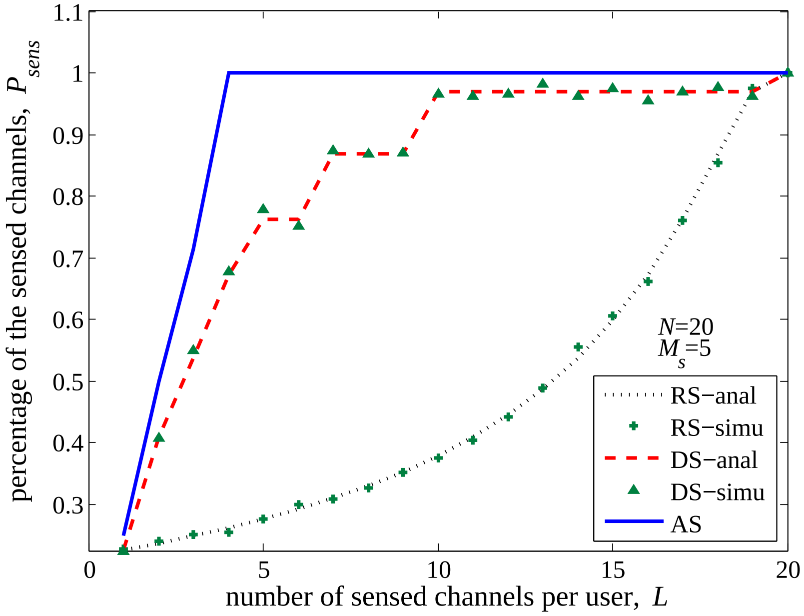

Figure 4.6: Performance comparison between the proposed sensing policies with respect to the number of the sensed channels.

proposed MAC framework to manage the spectrum identification.

4.1.3 Spectrum Access

The required duration for spectrum sensing is related to two key issues in CRNs: the spectrum utilization and the interference to the PUs. One of the principles of CRNs is to maximize the spectrum usage by utilizing efficiently the available unused channels, so the SUs are required to detect the spectrum opportunities as fast as possible to exploit these opportunities as long as possible for transmitting. However, the SUs must maintain its potential interference to the PUs under a predetermined level acceptable by the PUs; therefore, the SUs must sense the spectrum for enough time to meet this interference constraint. These two contrary requirements necessitate optimizing the MAC frame time shown in Figure 4.7.

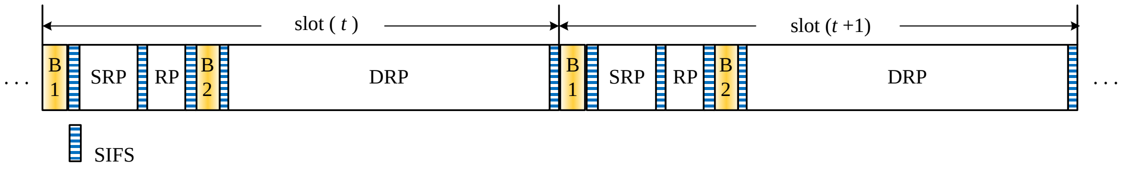

Figure 4.7: The MAC frame time.

A. Spectrum Utilization

The spectrum utilization can be defined as the percentage of the time that the identified available channels are utilized; in other words, it is the actual usage of the identified unused spectrum. Therefore, the required spectrum utilization is related to the sensing policy and the frame time of the proposed MAC protocol as

$$\eta = \frac{T - T_c - \tau}{T} P_{sens}, \tag{4.11}$$

where T is the overall time slot duration, and τ is the sensing duration during the sensing phase. T_c is the time duration for the control messages, which can be given by

$$T_c = T_{B1} + T_{B2} + NT_{ms} + 5T_{SIFS}, \tag{4.12}$$

where T_{B1} and T_{B2} are the time duration for beacon B1 and B2, respectively, and T_{ms} is the time duration of each mini-slot corresponding to the N licensed channels. Moreover, a Short Inter Frame Space (SIFS) time is used to give time for the propagation delay and for tuning the transceiver to the next phase.

B. Interference to the PUs

The potential harmful interference to the PUs may happen when the SUs transmit for longer time than the tolerable interference duration acceptable by the PUs. Moreover, the potential interference may happen due to sensing errors made by the

SUs. When the SUs identify some licensed channels as idle and send packets on them while they are occupied, there will be collisions with the PUs. The acceptable sensing error level of the SUs can be interpreted in terms of the required detection probability of the PUs.

In the spectrum sensing at the physical layer, there are two related hypothetic parameters: the probability of detection, P_d, and the probability of false alarm, P_f. The probability of detection is a measure of the ability of the SUs to detect the presence of the primary signals, and it is desirable to be maximized to protect the PUs from the interference of secondary signals. However, the probability of false alarm is the probability of announcing a primary signal is present while it is not, and it is required to be minimized in order to increase the spectrum opportunities. Using a simple energy detector, these two probabilities are related as shown in (2.6) and for the i-th licensed channel, their relation can be given as

$$P_f^{(i)} = Q\left(\sqrt{2\gamma+1}Q^{-1}\left(P_d^{(i)}\right) + \sqrt{t_s^{(i)}B^{(i)}\gamma}\right), \tag{4.13}$$

where γ is the SNR detection sensitivity of the detector, B is the bandwidth of the sensed channel, and t_s is the required sensing time for channel i.

C. Average Aggregate Throughput

In order to obtain higher throughput for the secondary network, it is important to optimize the parameters of the sensing duration. Since the data packets are sent during the DRP, the average number of the available sensed channels given by (4.2) can be exploited only during this phase. Suppose that the intended spectrum band is divided into N channels with equal bandwidth, B, so without considering the sensing error, the average aggregate throughput of the secondary network can be given as

$$\overline{\Phi} = \frac{T - T_c - \tau}{T}(1-\delta)NBP_{sens}. \tag{4.14}$$

Let us define the normalized average aggregate throughput of the secondary network as

$$\overline{\Theta} = \frac{\overline{\Phi}}{(1-\delta)NB} = \frac{T - T_c - \tau}{T} P_{sens}, \tag{4.15}$$

which is equivalent to the spectrum utilization. Now, considering the sensing error and using the AS policy, (4.15) can be rewritten as

$$\overline{\Theta} = \begin{cases} \frac{1}{N} \sum\limits_{j=1}^{M_S} \sum\limits_{i=1}^{L_j} \frac{T-T_c-\tau}{T} \left(1 - P_{f_j}^{(i)}\right), & M_s L_j \leq N \\ \frac{1}{N} \sum\limits_{i=1}^{N} \frac{T-T_c-\tau}{T} \left(1 - Q_f^{(i)}\right), & M_s L_j > N, \end{cases} \tag{4.16}$$

where τ is the sensing duration, $P_{f_j}^{(i)}$ is the probability of false alarm by user j for channel i, and $Q_f^{(i)}$ is the probability of false alarm in the cooperative sensing of channel i, which is a kind of OR-rule cooperative sensing. Since the single-hop SUs are almost under the same set of PUs, the OR-rule sensing is sufficient to identify the available spectrum; moreover, this sensing rule is easier to be implemented in a distributed network. The values of the aforementioned parameters in (4.16) can be given, respectively, as

$$\tau = \max_j \sum_{i=1}^{L_j} t_{s_j}^{(i)}, \quad 1 \leq j \leq M_s, \tag{4.17}$$

$$P_{f_j}^{(i)} = Q\left(\sqrt{2\gamma_j + 1} Q^{-1}\left(P_{d_j}^{(i)}\right) + \sqrt{t_{s_j}^{(i)} B} \gamma_j\right), \tag{4.18}$$

and

$$Q_f^{(i)} = 1 - \prod_{j=1}^{u_i} \left(1 - P_{f_j}^{(i)}\right), \tag{4.19}$$

where u_i in (4.19) is the number of the sensing users that are supposed to cooperate to sense channel i.

From (4.15), it is clear that maximizing the average aggregate throughput leads to the maximization of the spectrum utilization. The design of the spectrum sensing duration now becomes an optimization problem that can be defined as

$$\begin{aligned} \max_{\tau>0} \quad & \overline{\Theta} \\ \text{s.t.} \quad & P_d^{(i)} \geq P_d^{th} \\ & T \leq T_{max}, \end{aligned} \tag{4.20}$$

where P_d^{th} is the probability-of-detection threshold and T_{max} is the maximum-time-slot duration. These two parameters should be chosen to maintain the interference to the PUs under a specific level. It is obvious that these two parameters depend on the traffic type of the PUs, and for each PU, there may be different requirements of these parameters. However, considering the values of these parameters for different typs of PUs in an adaptive MAC framework is beyond this research work at this time. Their values can be chosen to be that of the most conservative PU, so the MAC framework can work for any type of the PUs.

The solution of (4.20) can be simplified based on the proposed system model. All the SUs are equipped with identical CRs that have the same SNR detection sensitivity, i.e., they have the same ability of the spectrum sensing, so $\gamma_j = \gamma \ \forall i$. Moreover, according to the proposed AS policy each sensing user is required to sense the same number of channels, so (4.16) can be rewritten as

$$\overline{\Theta} = \begin{cases} \frac{M_s L}{N} \frac{(T-T_c-Lt_s)}{T} \left(1-P_f\right), & M_s L \leq N \\ \frac{T-T_c-Lt_s}{T} \left(1-Q_f\right), & M_s L > N. \end{cases} \tag{4.21}$$

In the OR-rule cooperative sensing, the probability of false alarm, Q_f, can be found as

$$Q_f = 1 - \left(1-P_f\right)^{u_c}, \tag{4.22}$$

where P_f is the individual probability of false alarm made by each cooperative sensing user and u_c is the number of the cooperative sensing users. However, according to the AS sensing policy, some channels may be sensed by different numbers of sensing users, so we have to find these numbers first. In the AS policy, the number of the cooperative sensing users, u_c, and the number of the channels sensed cooperatively, N_c, when the number of the sensing users is greater than the number of the channel group, i.e., $M_s > N_d$, where $N_d = \lceil N/L \rceil$, can be found as

$$u_c = \begin{cases} u_{c1} = \lfloor M_s/N_d \rfloor \\ u_{c2} = u_{c1} + 1 \\ u_{c3} = 2u_{c1} \end{cases} ; N_c = \begin{cases} N_{c1} = N - N_{c2} - N_{c3} \\ N_{c2} = \mathrm{mod}(M_s, N_d)L \\ N_{c3} = L - \mathrm{mod}(N, L). \end{cases} \tag{4.23}$$

Therefore, the average value of the probability of cooperative false alarm given in (4.22) can be obtained as

$$Q_f = 1 - \left(\frac{N_{c1}}{N}(1 - P_{f1})^{u_{c1}} + \frac{N_{c2}}{N}(1 - P_{f2})^{u_{c2}} + \frac{N_{c3}}{N}(1 - P_{f3})^{u_{c3}} \right). \tag{4.24}$$

However, it is known that in the OR-rule cooperative sensing, the probability of detection increases as well as the probability of false alarm [29], but increasing the probability of false alarm is not desirable in CRNs. In order to balance between these two probabilities, each cooperative sensing user is required to recalculate its requisite individual probability of detection based on the number of the cooperative sensing users. The probability of detection in OR-rule cooperative sensing is given by

$$Q_d = 1 - (1 - P_d)^{u_c}. \tag{4.25}$$

Now, for a given value of Q_d, which maintains the potential interference of the SUs to the PUs under a specific level, the individual detection probability that each sensing user should meet can be found as

$$P_d = 1 - (1 - Q_d)^{1/u_c}. \tag{4.26}$$

Therefore, the individual false alarm probabilities P_{f1}, P_{f2}, and P_{f3} in (4.24) can be obtained as

$$P_{fi} = Q\left(\sqrt{2\gamma + 1} Q^{-1}(1 - (1 - Q_d)^{1/u_{ci}}) + \sqrt{t_s B} \gamma \right), \qquad i = 1, 2, 3. \tag{4.27}$$

Finally, the normalized average throughput given by (4.21) can be rewritten as

$$\overline{\Theta} = \begin{cases} A\frac{M_s L}{N}\left(1 - Q\left(\sqrt{2\gamma+1}Q^{-1}(Q_d) + \sqrt{t_s B}\gamma\right)\right), & M_s L \leq N \\ A\sum_{i=1}^{3}\frac{N_{ci}}{N}\left(1 - Q\left(\sqrt{2\gamma+1}Q^{-1}(1-(1-Q_d)^{1/U_{ci}}) + \sqrt{t_s B}\gamma\right)\right)^{u_{ci}}, & M_s L > N, \end{cases} \tag{4.28}$$

where $A = \frac{T - T_c - Lt_s}{T}$.

Thus, the optimization problem in (4.20) can be solved using (4.28) subject to $Q_d \geq P_d^{th}$ and $T \leq T_{max}$. By this optimization problem, we want to find the optimal sensing duration, i.e., $\tau = Lt_s$, which depends on two values: the required sensing time for each channel, t_s, and the number of the sensed channels that each SU can sense, L. Our ultimate goal is to develop a simple yet efficient sensing algorithm that can be executed online by each sensing user to determine distributively which channels and for how long to sense each of them.

D. Sensing Algorithm

The time required to sense each channel, t_s, is expected to be small for practical threshold values of the required probability of detection and the probability of false alarm, say 0.95 and 0.01 respectively. That means, even if we want to find the optimal value of the sensing time, its acceptable range will be small and does not affect the sensing duration significantly. Therefore, the sensing duration mainly depends on the number of the sensed channels rather than the sensing time for each channel. The minimum required sensing time for any channel given the threshold values of the detection probability, P_d^{th}, and the probability of false alarm, P_f^{th}, can be found from (4.13) as

$$t_s = \left(\frac{\sqrt{2\gamma+1}Q^{-1}(P_d^{th}) - Q^{-1}(P_f^{th})}{\gamma\sqrt{B}}\right)^2. \tag{4.29}$$

Using this value, the optimal number of the sensed channels per each sensing user can be found by maximizing the throughput given in (4.28). The first constraint mentioned in (4.20), i.e., $Q_d \geq P_d^{th}$, is implied in calculating the minimum required sensing time in (4.29). Therefore, the optimization problem in (4.20) can be simplified to

$$\begin{aligned} L^* = \arg\max_{L} \quad & \overline{\Theta} \\ \text{s.t.} \quad & T \leq T_{max} \\ & 1 \leq L \leq N \\ & L \in \mathbf{I}^+, \end{aligned} \tag{4.30}$$

where $\mathbf{I}^+$ means a set of positive integer numbers.

This optimization problem is Nonlinear Integer Programming (NIP). Since the value of the variable L is not binary, one approach to solve this problem is to relax the value of L to be a real number, then solve the problem as a standard Non-Linear Programming (NLP) problem, and finally round the output value of L up to the nearest integer number. However, solving an optimization problem online may not be possible in distributed CRNs due to the time limitation.

Fortunately, much simpler and intuitive value of the optimal number of the sensed channels per each sensing user can be guessed. When there are M_s of identical users trying to sense N channels, the intuitive value of L is just $\lceil N/M_s \rceil$. However, when the number of the sensing users is small compared to the N channels, and each of them is required to sense a large number of channels, this will increase the time of spectrum identification at the cost of decreasing the time of spectrum exploitation and consequently decreasing the specrtum utilization; therefore, the value of L should not exceed its maximum value that maximizes the throughput when $M_s L \leq N$, which can be found from the first part of (4.28) as

$$\begin{aligned} \frac{\partial \overline{\Theta}}{\partial L} &= 0 \\ \Rightarrow L &= \frac{T - T_c}{2t_s}. \end{aligned} \tag{4.31}$$

Therefore, the optimal number of the sensed channels per each sensing user can be found as

$$L^* = \min\left(\left\lceil \frac{N}{M_s} \right\rceil, \left\lceil \frac{T_{max} - T_c}{2t_s} \right\rceil \right). \tag{4.32}$$

Finally, in order to set up the MAC frame time, each SU calculates the optimal sensing duration as $\tau = L^* t_s$. Thus, each SU should be preloaded by a sensing algorithm that determines how long to sense each channel, how many channels to sense, and which channels to sense. This algorithm, which is computationally simple and can be implemented online, is summarized in the following Sensing Algorithm.

Sensing Algorithm: For each sensing user, after receiving the beacon B1 on the CCC channel, do the following:

```
1: extract the content information,
2: update the dynamic ID using Algorithm 4.2,
3: calculate how many sensing users using: $M_s = M - M_w$,
4: calculate how long to sense each channel using (4.29),
5: calculate how many channels to sense using (4.32),
6: calculate how many channel groups using (4.8),
7: determine which channel group to sense using Algorithm 4.4, and
8: start to sense.
```

4.1.4 Numerical Results

In this subsection, some numerical results are presented to illustrate the findings of this section. The numerical parameters are summarized in Table 4.1 unless any of them is stated elsewhere with different values.

Table 4.1: Numerical parameters for performance evaluation of the MAC framework.

Parameter	**Value**	**Description**
B	6 MHz	bandwidth of each licensed channel
T_{max}	100 ms	duration of each time slot
P_d^{th}	0.95	probability of detection threshold
P_f^{th}	0.01	probability of false alarm threshold
γ	-15 dB	SNR detection sensitivity of the SU's detector
δ	0.3	the activity of the PUs
T_{B1}	100 μs	duration of beacon B1
T_{B2}	100 μs	duration of beacon B2
T_{ms}	10 μs	mini-slot duration of the RP
T_{SIFS}	15 μs	short inter-frame space duration

Figure 4.8 shows the minimum sensing time required to identify any spectrum opportunity on a sensed channel for given values of the probability of detection and the probability of false alarm. It is clear that the required sensing time slightly increases with increasing the probability of detection. This means, when the PUs need higher protection from the potential interference of the SUs, the SUs are required to sense each channel for longer time. On the other hand, when the SUs need smaller probability of false alarm, the SUs are required to spend more time to sense each channel. For example, in practical situations, the PUs may need the

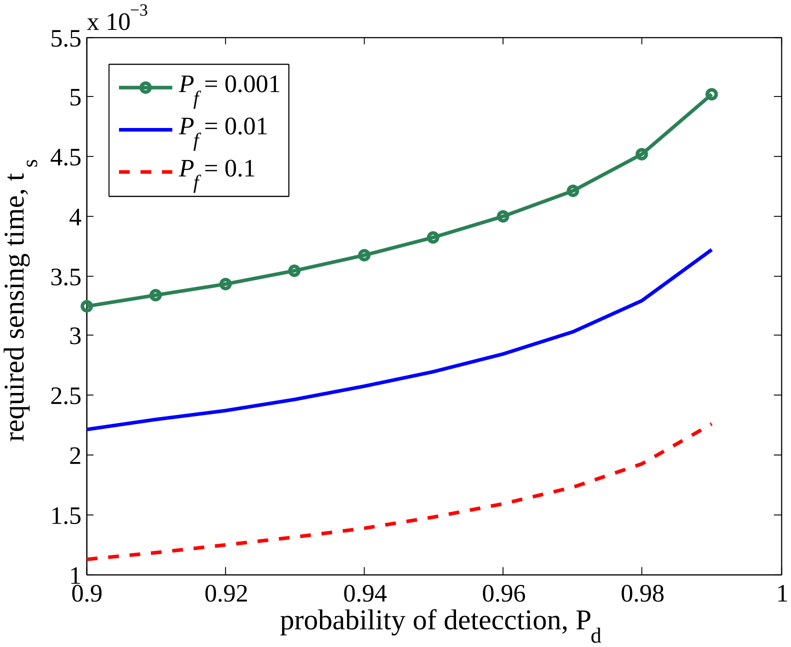

Figure 4.8: The required sensing time with respect to the probabilities of detection and false alarm.

probability of detection to be 0.95, while the SUs may require the false alarm to be 0.01, so each SU should sense each channel for 2.7ms.

The normalized average aggregate throughput is plotted versus the number of the sensed channels for different numbers of sensing users in Figure 4.9. Obviously, for each number of the sensing users, there is an optimal number of the channels that should be sensed by each sensing user to maximize the secondary throughput. This optimal value is consistent with the closed form obtained in (4.32). In general, the average aggregate throughput increases with increasing L until all the N channels are sensed, i.e., when $M_s L = N$, where the optimal number of L appears, then the average aggregate throughput decrease beyond the optimal L. This behavior can be explained as follows. Before the optimal value of L, there are some channels are not sensed, so this will lower the average aggregate throughput; however, after the optimal L, there are some channels over-sensed that comes at the cost of increasing

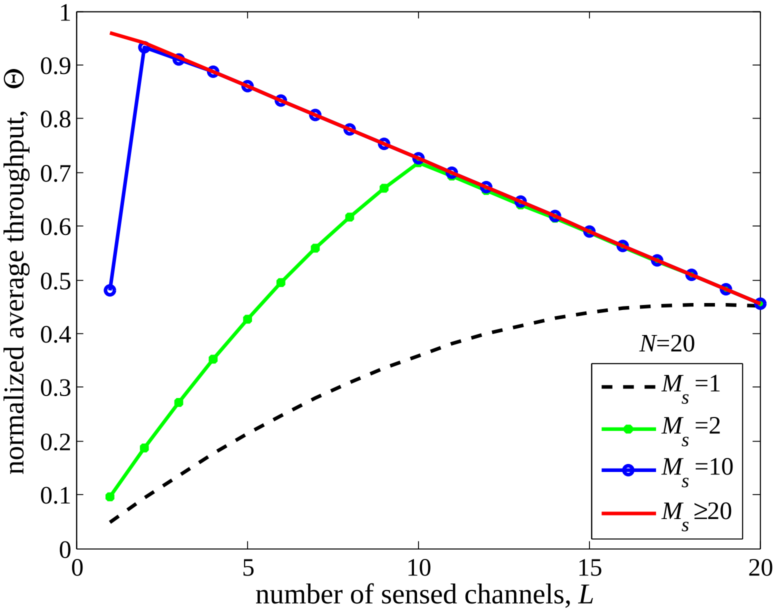

Figure 4.9: The secondary normalized average aggregate throughput with respect to the number of the sensed channels.

the sensing duration, so the remaining time that is supposed to be credit for data transmitting will be decreased. The average aggregate throughput improves with increasing the number of the sensing users until this number is equal to the number of the licensed channels and then saturates.

In order to verify the closed form of obtaining the optimal number of the sensed channels, Figure 4.10 compares the optimal number of the sensed channels obtained from the solution to the optimization problem defined in (4.30) and the direct closed form in (4.32) for different numbers of sensing users. There are small differences at some points between the two methods due to the approximation used in solving the optimization problem when relaxing the L to be real number and then rounding it up to the nearest integer number; however, we can conclude that the two methods are equivalent.

Figure 4.11 shows the maximum normalized average aggregate throughput and

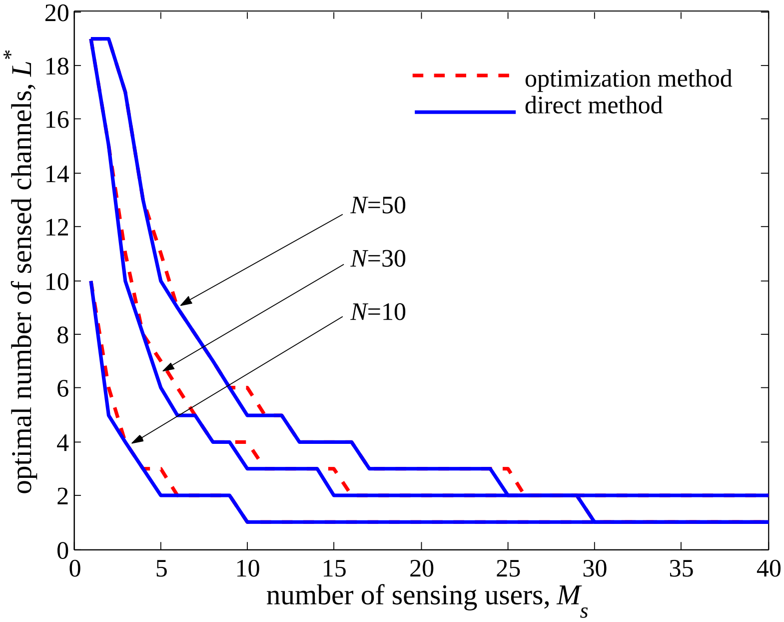

Figure 4.10: The optimal number of the sensed channels using two methods.

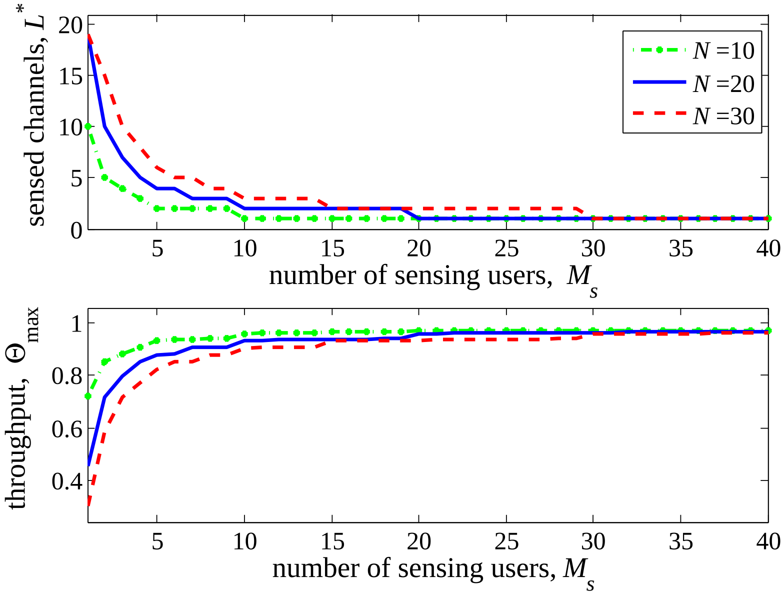

Figure 4.11: Optimal number of the sensed channels and the corresponding throughput.

the optimal number of the sensed channels per user for different numbers of the licensed channels. Some intuitive observations can be drawn from this figure. First, more sensing users are required to improve the average aggregate throughput when the number of the licensed channels are high, which is intuitive since more licensed channels means the spectrum opportunities are expected to be high, so more users are required to identify them. Second, when the number of the sensing users is relatively low, each one of them is required to sense more channels to maximize the throughput; however, with increasing the number of the sensing users, the optimal number of the sensed channels per user decreases until reaches one channel when $M_s \geq N$ and the throughput saturates. Therefore, in the situations when the power is concern, the AS policy can include a rule that allows just N users to sense the spectrum and the others do nothing or even turn to sleep mode to save their power.

In Figure 4.12, the optimal sensing duration is plotted with respect to the number of the sensing users for different values of the probability of detection threshold. As expected, the optimal sensing duration decreases with increasing the number of the sensing users when the other parameters are fixed. In fact, decreasing the sensing duration is desirable; however, this decreasing almost saturates when $M_s \geq N$ as discussed before. Another observation can be drawn from this figure. The required sensing duration increases when the required probability of detection threshold increases, which is intuitive since more primary network protection requires more sensing time to achieve this protection level.

A higher value of the maximum slot time, i.e., T_{max}, is desirable by the SUs, but the opposite is true for the PUs. In fact, the exact threshold of the time slot should be governed by the PUs' requirements according to some spectrum secondary usage regulations. Figure 4.13 shows the influence of T_{max} on the performance. The optimal sensing duration is the same for all the values of T_{max} except when there is only one sensing user, which can be explained easily by referring to (4.32).

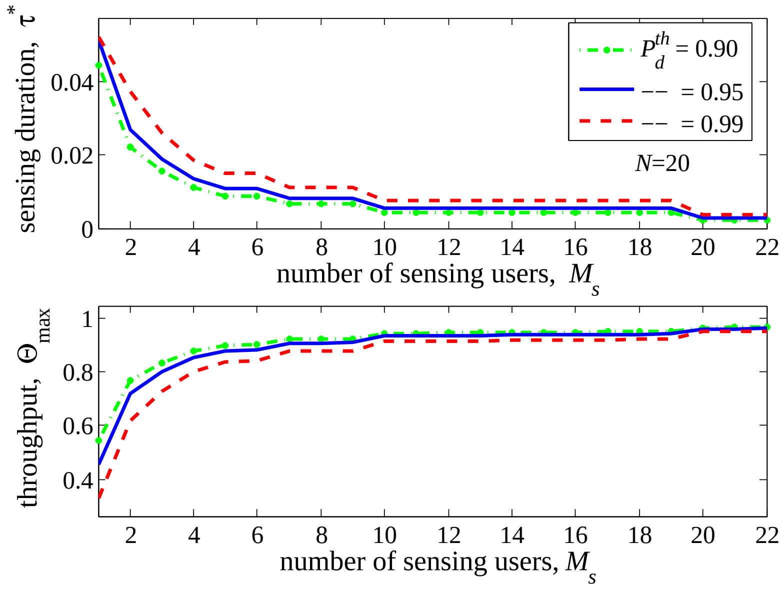

Figure 4.12: Optimal sensing duration for different levels of required probability of detection and the corresponding throughput.

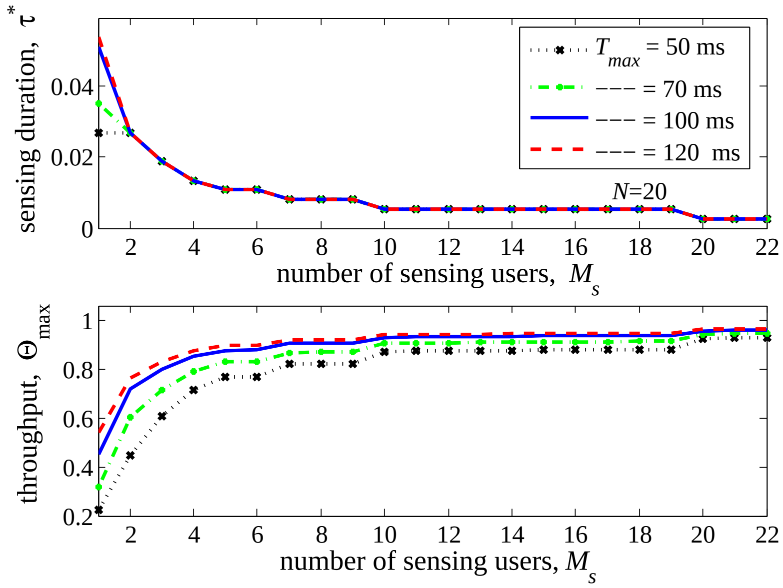

Figure 4.13: Optimal sensing duration for different levels of the maximum-slot time and the corresponding throughput.

On the other hand, the average aggregate throughput is affected by the value of T_{max}. When T_{max} is small and the number of the sensing users is also relatively small compared to the N channels, the average aggregate throughput becomes low; however, the difference between the throughput curves becomes smaller until almost finishes with increasing the number of the sensing users. This is because larger part of the slot time is used to sense more channels when the number of the sensing users is small, while when each user senses fewer number of channels, the average aggregate throughput improves.

4.2 Admission Control and Channel Allocation

In this section, we propose to regulate the spectrum access of the cooperative distributed CRNs based on the user dynamic IDs and the slotted time MAC structure developed in the previous section. With the help of the secondary network coordinator at each time slot, the admitted users use their dynamic IDs and the IDs of the identified available channels to determine which channels can be allocated to each of them; moreover, the secondary network coordinator at each time slot admits only a number of new SUs that maintains the QoS requirements of the SUs in the secondary network. We study the dynamic behavior of the secondary network to investigate the system design parameters that can be adjusted to control the number of the admitted users.

4.2.1 Dynamic Behavior of the System

Since the system behavior varies dynamically over a number of dependent consecutive time slots, studying the instantaneous behavior of the secondary network is important to understand how the network resources are shared by the SUs in each time slot. On the other hand, the steady state behavior of the secondary network is important to design the system parameters in an efficient way. Based on the MAC framework, the SUs try to reserve the potential available channels in the next time slot at the current time slot; moreover, the number of the reserving users should be related to the number of the sensing users in such a way to balance between the spectrum sensing and spectrum access that together should maximize the spectrum utilization and maintain tolerable interference to the PUs.

A. Instantaneous System Behavior

Using Figure 4.7, at beacon B1 in time slot t, the network coordinator at the current time slot, which is the first winner from time slot (t-1), broadcasts the new number of the SUs in the network, M_{B1}, which can be given mathematically as

$$M_{B1}^{(t)} = M_{B2}^{(t-1)} - M_{aw}^{(t-1)}, \tag{4.33}$$

where $M_{B2}^{(t-1)}$ is the number of the SUs in the network broadcast on beacon B2 at time slot (t-1), and $M_{aw}^{(t-1)}$ is the number of the access winning users at time slot (t-1). Moreover, the network coordinator broadcasts the dynamic IDs of the $M_{aw}^{(t-1)}$ users and the number of the winning users, so the remaining users update their dynamic IDs based on whether they are sensing or winning users using the algorithms in Section 4.1.1-B.

All the SUs calculate the number of the sensing users in order to set up the time duration of the phases in the MAC frame time. The number of these sensing users can be found as

$$M_{s}^{(t)} = M_{B1}^{(t)} - M_{w}^{(t-1)}, \tag{4.34}$$

where $M_{w}^{(t-1)}$ is the number of the winning users at the DRP of time slot (t-1). Therefore, the time duration of the SRP, which reflects the sensing duration, can be calculated as

$$\begin{aligned}\tau^{(t)} &= L^{(t)} t_s \\ &= \min\left(\left\lceil \frac{N}{M_s^{(t)}} \right\rceil, \left\lceil \frac{T-T_c}{2t_s} \right\rceil\right) t_s.\end{aligned} \tag{4.35}$$

Since the time durations of the SRP and the DRP are inversely proportional, the duration of the DRP is given by

$$T_{DRP}^{(t)} = T - \tau^{(t)} - T_c. \tag{4.36}$$

The sensing users sense the intended N licensed channels based on the sensing algorithm developed in Section 4.1.3-D and report their observations on the RP, while the winning users monitor the RP to get the information about how many channels available at the current time slot, $N_a^{(t)}$, and their IDs in the spectrum chart. In other words, each winning user has a vector indicating the available channels as

$$\mathbf{c}^T = \{c_i\}; \quad c_i \in \{0,1\}, \quad i = 1,2,...,N, \tag{4.37}$$

where $c_i = 0$ means the channel with ID indicating c_i is not available, while it is available when $c_i = 1$. It is clear that

$$N_a^{(t)} = \sum_{i=1}^{N} c_i, \tag{4.38}$$

which is a random number that depends on the activities of the PUs on the N licensed channels given in (3.1).

The SUs that are registered in the network stay in the network until they transmit there packets. Since there may be new SUs joining the network, the number of the SUs in the network is updated by the current network coordinator on beacon B2, so the new number can be given as

$$M_{B2}^{(t)} = M_{B1}^{(t)} + \left\lfloor \lambda \tau^{(t)} \right\rfloor, \tag{4.39}$$

where $\lfloor x \rfloor$ is the floor operator that rounds down the real number x into the nearest integer number, λ is the arrival rate of the users joining the network during the SRP, and $\tau^{(t)}$ is the duration of the SRP given in (4.35).

Some or all of the winning users can access the identified available spectrum based on how many channels are identified as available ones by the sensing users in the current time slot. The number of the access winners can be given as

$$\begin{aligned} M_{aw}^{(t)} &= \begin{cases} M_w^{(t-1)}, & M_w^{(t-1)} < N_a^{(t)} \\ N_a^{(t)}, & M_w^{(t-1)} \geq N_a^{(t)} \end{cases} \\ &= \begin{cases} M_{B1}^{(t)} - M_s^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} < N_a^{(t)} \\ N_a^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} \geq N_a^{(t)}, \end{cases} \end{aligned} \tag{4.40}$$

where $M_w^{(t-1)}$ is the number of the winning users at the DRP of time slot (t-1) and $N_a^{(t)}$ is the number of the identified available channels at time slot t. The number of the remaining users is given by

$$M_r^{(t)} = M_{B2}^{(t)} - M_{aw}^{(t)}. \tag{4.41}$$

These remaining users will try to reserve the next time slot.

In order to support concurrent transmissions, a number of SUs should be allowed to reserve the next time slot. Any transmitting user registered in the network can reserve the next time slot for transmission if it successfully exchanges reserving messages with its intended receiver during the DRP. These messages can be seen as exchanging the de facto RTS/CTS control packets. However, when the number of the competing users is high, the probability of collision increases; therefore, the SUs may use their dynamic IDs sequence to enter the reserving process instead. Since each user in the network has a unique dynamic ID updated each time slot, and this ID reflects the sequence order of that user in the network, each user knows which user is the first, second, and so on in the network that can enter the reserving process at the DRP; therefore, the SUs can reserve based on the first-in first-out concept. The reserving user is considered as winner when it successfully exchanges the reserving messages with its receiver. Let each reserving pair exchange these messages during a reserving time denoted as T_{res}, then the number of the reserving slots can be given by

$$\begin{aligned} N_{res}^{(t)} &= \left\lfloor \frac{T_{DRP}^{(t)}}{T_{res}} \right\rfloor \\ &= \left\lfloor \frac{T - \tau^{(t)} - T_c}{T_{res}} \right\rfloor . \end{aligned} \tag{4.42}$$

However, the number of the winning users should be chosen carefully in such a way that they do not affect the sensing process, i.e., the number of the winning users and the number of the sensing users should be balanced to efficiently utilize the unused spectrum. All the N licensed channels can be identified when $M_s L \geq N$, where from (4.32), L should not exceed $\left\lceil \frac{T-T_c}{2t_s} \right\rceil$; therefore, $M_s \geq \left\lceil \frac{2t_s N}{T-T_c} \right\rceil$, and the minimum number of the sensing users that can sense all the N licensed channels is given by

$$M_s = \left\lceil \frac{2t_s N}{T - T_c} \right\rceil , \tag{4.43}$$

and the maximum number of the winning users is give by

$$M_{w_{max}}^{(t)} = M_r^{(t)} - \left\lceil \frac{2t_s N}{T - T_c} \right\rceil . \tag{4.44}$$

Since the winning users are scheduled deterministically to exchange their reserving messages on the CCC based on their dynamic IDs, there are no collisions between the winning users during this process. Therefore, the successful exchange of the reservation messages mainly depends on the ability or even the willing of the intended receiver to respond to the sender. The outputs of the reserving process are random, and they can be written in a vector as

$$\mathbf{w} = \{w_i\}; \quad w_i \in \{0, 1\}, \quad i = 1, 2, ..., \tag{4.45}$$

where $w_i = 1$ indicates that a user successfully exchanged the reserving messages with its intended receiver, and it is considered as a winner. The first non-zero element of $\mathbf{w}$ indicates which user is the first and so on. The order of the winning users is important in allocating the identified available channels to them, as will be discussed in the channel allocation policy. Obviously, the number of the reserving users can be obtained as

$$M_{res}^{(t)} = \sum_{i=1}^{N_{res}^{(t)}} w_i. \tag{4.46}$$

Finally, the number of the winning users for the next time slot can be found as

$$M_{w}^{(t)} = \begin{cases} M_{res}^{(t)}, & M_{res}^{(t)} < M_{w_{max}}^{(t)} \\ M_{w_{max}}^{(t)}, & M_{res}^{(t)} \geq M_{w_{max}}^{(t)}. \end{cases} \tag{4.47}$$

B. Steady-State System Behavior

It is desirable to find the closed form solutions of the difference equations that describe the system at any time slot and help to study the steady state of the system. The two main quantities in the set of these equations are the dynamic number of the users at beacon B1 given in (4.33), and the dynamic number of the sensing users given in (4.34). Once the solutions of these two equations are found, any other quantity in the system can be found. Substituting (4.39) and (4.40) in (4.33), we get

$$M_{B1}^{(t)} = \begin{cases} \lfloor \lambda \tau^{(t-1)} \rfloor + M_s^{(t-1)}, & M_{B1}^{(t-1)} - M_s^{(t-1)} < N_a^{(t-1)} \\ M_{B1}^{(t-1)} + \lfloor \lambda \tau^{(t-1)} \rfloor - N_a^{(t-1)}, & M_{B1}^{(t-1)} - M_s^{(t-1)} \geq N_a^{(t-1)}, \end{cases} \tag{4.48}$$

where $\tau^{(t-1)}$ and $N_a^{(t-1)}$ depend on $M_s^{(t-1)}$ that can be found from (4.34) as

$$M_s^{(t-1)} = M_{B1}^{(t-1)} - M_w^{(t-2)}, \tag{4.49}$$

and $M_w^{(t-2)}$ can be found from (4.47).

However, finding closed form solutions of these equations is very difficult; moreover, the randomness of the number of the available channels and the number of the reserving users each time slot add another difficulty dimension; therefore, numerical analysis will be used instead.

4.2.2 Channel Allocation Policy

Since the identified available channels may be disjoint due to the spectrum fragmentation, the admitted winning users should use the D-OFDMA or MC-CDMA technique as the channel physical access mechanism to overcome the spectrum fragmentation. Based on the identified available channels, each admitted user can access at least a number of channels given by

$$n_a^{(t)} = \left\lfloor \frac{N_a^{(t)}}{M_{aw}^{(t)}} \right\rfloor . \tag{4.50}$$

The identified available channels are allocated to the admitted users based on the users' dynamic IDs and the IDs of the $n_a^{(t)}$ channels in the spectrum. Substituting (4.40) in (4.50), we obtain

$$n_a^{(t)} = \begin{cases} \left\lfloor \frac{N_a^{(t)}}{M_{B1}^{(t)} - M_s^{(t)}} \right\rfloor, & M_{B1}^{(t)} - M_s^{(t)} < N_a^{(t)} \\ 1, & M_{B1}^{(t)} - M_s^{(t)} \geq N_a^{(t)}. \end{cases} \tag{4.51}$$

To efficiently utilize the spectrum, all the identified available channels should be used. However, when $N_a^{(t)}/M_{aw}^{(t)}$ is not an integer number, there may be a considerable number of available channels that should be allocated to some access users to efficiently utilize the unused spectrum. In general, there are three possible channel allocating methods:

1. allocating $\left\lfloor n_a^{(t)} \right\rfloor + 1$ to some of the first winning users and $\left\lfloor n_a^{(t)} \right\rfloor$ to the others based on the first-come first-service rule;

2. allocating $\left\lfloor n_a^{(t)} \right\rfloor$ to all the winning users, and allocating the remaining unallocated channels as extra channels to the network coordinator. This can be seen as a reward for the network coordinator since it wastes some of its own resources to manage the secondary network at the current time slot; and
3. allocating just $\left\lfloor n_a^{(t)} \right\rfloor$ channels to all the winning users if the user fairness is more important than the spectrum utilization efficiency.

In fact, choosing one of these three allocating methods should depend on the QoS satisfaction of the SUs since different secondary network operators may have different satisfaction metrics.

4.2.3 Admission Control

From the channel allocation policy, the SUs share the identified available channels based on their IDs and the IDs of the identified available channels. To maintain certain QoS (e.g., average aggregate throughput and delay) levels in the secondary network, the number of the SUs that can be admitted to access the identified available channels should be controlled. In the system, there are many parameters that affect the number of the admitted users; however, not all these parameters can be flexibly controlled. The two most important flexible parameters that can be adjusted are the mini-slot reserving time, T_{res}, and the admitted user rate, λ_{ad}.

Based on the average number of the identified available channels and the required QoS level, the network coordinator at each time slot, determines the acceptable number of the arrivals that can be registered in the network at the SRP. This number is given by $\lambda_{ad}\tau^{(t)}$. Since $\tau^{(t)}$ varies from time slot to time slot depending on the number of the sensing users in each time slot as appears from (4.35), the network coordinator should adjust λ_{ad} to maintain the required QoS level; therefore,

λ_{ad} can be used as an admission control parameter. It can be adjusted each time slot by registering only the intended acceptable number of users, i.e., responding to the request-to-register messages from the acceptable number of the new SUs and assigning dynamic IDs to them. In other words, the network coordinator sharps the user arrival rate by admitting only a portion of the arrivals. Moreover, the network coordinator determines the mini-slot reserving time that meets the required QoS level and broadcasts it at beacon B2. Based on their IDs order, the reserving users exchange the reserving messages with the intended receivers during this mini-slot reserving time.

Let the required QoS level in the secondary network be denoted as a utility function given by $U(\lambda_{ad}, T_{res})$. The optimal admission parameters can be found by solving the following optimization problem

$$\begin{aligned} \max_{\lambda_{ad}, T_{res}} \quad & U(\lambda_{ad}, T_{res}) \\ \text{s.t.} \quad & 0 < T_{res} < T_{DRP}^{(t)} \\ & \lambda_{ad} > 0, \end{aligned} \tag{4.52}$$

where maximizing the utility function implies maximizing the average aggregate throughput, minimizing the average delay, minimizing the blocking probability of the rejected SUs, or minimizing the dropping rate of the handover users. In this section, we are interested in studying the effects of the controlling parameters on the average aggregate throughput and waiting delay of the SUs in the network rather than finding their optimal values.

4.2.4 Performance Analysis

The average aggregate throughput and user waiting delay in the secondary network are analyzed in this section. Considering the proposed channel allocation policy, the effects of the admitted control parameters as well as other system parameters on the network performance can be assessed.

A. Average Aggregate Throughput

Considering the interference to the PUs, the spectrum sensing in CRNs is related to the probability of detection required by the PUs and also the probability of false alarm required by the SUs. The average aggregate throughput of the SUs is affected by the probability of false alarm by a factor (1-P_f^{th}) as shown in (4.21), where P_f^{th} is the probability of false alarm threshold, which should be very small (e.g., 0.01) to efficiently utilize the identified available channels. To simplify the derivation in this section without loss of generality, we neglect this small factor. Each admitted user can access either $n_a^{(t)}$ or $n_a^{(t)}+1$ as mentioned in Section 4.2.2, so the average aggregate throughput of the SU (in channels/user) can be simply found from the expectation of the $n_a^{(t)}$ in (4.51) without the floor operator as

$$\begin{aligned}\overline{S}^{(t)} &= E[n_a^{(t)}] \\ &= \begin{cases} \frac{E[N_a^{(t)}]}{M_{B1}^{(t)}-M_s^{(t)}}, & M_{B1}^{(t)}-M_s^{(t)} < E[N_a^{(t)}] \\ 1, & M_{B1}^{(t)}-M_s^{(t)} \geq E[N_a^{(t)}]. \end{cases}\end{aligned} \tag{4.53}$$

The average number of the identified available channels using the AS policy developed in Section 4.1.2-A can be given as

$$E[N_a^{(t)}] = \begin{cases} (1-\delta)L^{(t)}M_s^{(t)}, & L^{(t)}M_s^{(t)} < N \\ (1-\delta)N, & L^{(t)}M_s^{(t)} \geq N. \end{cases} \tag{4.54}$$

Let $\overline{N}_a^{(t)} = E[N_a^{(t)}]$, the average aggregate throughput of the secondary user (in channels/user) can be given as

$$\overline{S}^{(t)} = \begin{cases} \frac{\overline{N}_a^{(t)}}{M_{B1}^{(t)}-M_s^{(t)}}, & M_{B1}^{(t)}-M_s^{(t)} < \overline{N}_a^{(t)} \\ 1, & M_{B1}^{(t)}-M_s^{(t)} \geq \overline{N}_a^{(t)}, \end{cases} \tag{4.55}$$

and the steady-state average aggregate throughput of each SU can be found from

$$\overline{S} = \lim_{t\to\infty} \overline{S}^{(t)}. \tag{4.56}$$

It is desirable to find the normalized average aggregate throughput of the secondary network, which reflects the actual usage of the licensed channels by the SUs. The normalized average aggregate throughput can be found as

$$\overline{\Theta}^{(t)} = M_{aw}^{(t)} \frac{\overline{S}^{(t)}}{\overline{N}_a^{(t)}} \frac{(T - \tau^{(t)} - T_c)}{T}. \tag{4.57}$$

By substituting the values of $M_{aw}^{(t)}$, $\overline{S}(t)$, and $\overline{N}_a^{(t)}$, (4.57) can be rewritten as

$$\overline{\Theta}^{(t)} = \begin{cases} \frac{L^{(t)} M_s^{(t)}}{N} \frac{(T-\tau^{(t)}-T_c)}{T}, & L^{(t)} M_s^{(t)} < N \\ \frac{T-\tau^{(t)}-T_c}{T}, & L^{(t)} M_s^{(t)} \geq N, \end{cases} \tag{4.58}$$

and the steady state normalized average aggregate throughput of the secondary network can be obtained from

$$\overline{\Theta} = \lim_{t\to\infty} \overline{\Theta}^{(t)}. \tag{4.59}$$

B. User Average Waiting Delay

The average SU waiting delay can be defined as the average time spent by a SU registered in the network to be admitted to transmit its packets on the allocated available channels. Based on the system model, the secondary network always has SUs that want to transmit their packets, so the delay evaluation depends on the saturated network analysis.

The winning users have to wait $T_{DRP}^{(t)} + T_c + \tau^{(t+1)}$ time duration to know how many of them are allowed to access the identified available channels at time slot $(t+1)$, while the remaining users have to try again to be winners in the coming time slots. Therefore, from Figure 4.7, the time a user has to wait to get a chance to transmit its packets can be given as

$$D^{(t)} = 3\text{SIFS} + T_{RP} + T_{B2} + \frac{1}{P_{aw}^{(t)}} \left(T_{DRP}^{(t)} + T_c + \tau^{(t+1)} \right), \tag{4.60}$$

where $T_{RP} = NT_{ms}$ is the time duration of the RP, $T_{DRP}^{(t)} = T - \tau^{(t)} - T_c$ is the time duration of the DRP at time slot t, and $P_{aw}^{(t)}$ is the probability of being admitted winner, which can be found as

$$P_{aw}^{(t)} = \frac{M_{aw}^{(t+1)}}{M_r^{(t)}}, \tag{4.61}$$

so (4.60) can be rewritten as

$$D^{(t)} = 3\text{SIFS} + NT_{ms} + T_{B2} + \frac{M_r^{(t)}}{M_{aw}^{(t+1)}} \left(T - \tau^{(t)} + \tau^{(t+1)} \right), \tag{4.62}$$

where $M_r^{(t)}$ can be given from (4.39) and (4.41) as

$$\begin{aligned} M_r^{(t)} &= M_{B2}^{(t)} - M_{aw}^{(t)} \\ &= M_{B1}^{(t)} + \lambda_{ad}\tau^{(t)} - M_{aw}^{(t)} \\ &= \begin{cases} \lambda_{ad}\tau^{(t)} + M_s^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} < N_a^{(t)} \\ M_{B1}^{(t)} + \lambda_{ad}\tau^{(t)} - N_a^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} \geq N_a^{(t)}, \end{cases} \end{aligned} \tag{4.63}$$

where the floor operator used in (4.39) is removed here since we are calculating the average value. From (4.40), $M_{aw}^{(t+1)}$ can be given as

$$M_{aw}^{(t+1)} = \begin{cases} M_w^{(t)}, & M_w^{(t)} < N_a^{(t+1)} \\ N_a^{(t+1)}, & M_w^{(t)} \geq N_a^{(t+1)}. \end{cases} \tag{4.64}$$

Therefore, the average user delay can be found as

$$\overline{D}^{(t)} = 3\text{SIFS} + NT_{ms} + T_{B2} + \frac{E[M_r^{(t)}]}{E[M_{aw}^{(t+1)}]} \left(T - \tau^{(t)} + E[\tau^{(t+1)}] \right), \tag{4.65}$$

where $E[M_r^{(t)}]$ can be found from (4.64) as

$$E[M_r^{(t)}] = \begin{cases} \lambda_{ad}\tau^{(t)} + M_s^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} < \overline{N}_a^{(t)} \\ M_{B1}^{(t)} + \lambda_{ad}\tau^{(t)} - \overline{N}_a^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} \geq \overline{N}_a^{(t)}, \end{cases} \tag{4.66}$$

and $E[M_{aw}^{(t+1)}]$ can be found from (4.64) as

$$E[M_{aw}^{(t+1)}] = \begin{cases} E[M_w^{(t)}], & E[M_w^{(t)}] < E[N_a^{(t+1)}] \\ E[N_a^{(t+1)}], & E[M_w^{(t)}] \geq E[N_a^{(t+1)}], \end{cases} \tag{4.67}$$

where $E[M_w^{(t)}]$ can be found from (4.47) as

$$E[M_w^{(t)}] = \begin{cases} E[M_{res}^{(t)}], & E[M_{res}^{(t)}] < E[M_{w_{max}}^{(t)}] \\ E[M_{w_{max}}^{(t)}], & E[M_{res}^{(t)}] \geq E[M_{w_{max}}^{(t)}]. \end{cases} \tag{4.68}$$

As mentioned in Section 4.2.1, the reserving at the DRP is a random process. Let receiver i respond to the reserving message sent by transmitter i with certain probability p_i. To simplify the analysis without loss of generality, assume $p_i = p$ for all i, then the reserving process can be modeled as a binomial distribution. From (4.46), $E[M_{res}^{(t)}] = pN_{res}^{(t)}$, and from (4.44), $E[M_{w_{max}}^{(t)}]$ can be found as

$$E[M_{w_{max}}^{(t)}] = E[M_r^{(t)}] - \frac{2t_s N}{T - T_c}, \tag{4.69}$$

where $E[M_r^{(t)}]$ is given by (4.66). By denoting $E[M_{w_{max}}^{(t)}]$ as $\overline{M}_{w_{max}}^{(t)}$, (4.68) can be rewritten as

$$E[M_w^{(t)}] = \begin{cases} pN_{res}^{(t)}, & pN_{res}^{(t)} < \overline{M}_{w_{max}}^{(t)} \\ \overline{M}_{w_{max}}^{(t)}, & pN_{res}^{(t)} \geq \overline{M}_{w_{max}}^{(t)}. \end{cases} \tag{4.70}$$

Similar to finding $E[N_a^{(t)}]$ in (4,54), $E[N_a^{(t+1)}]$ in (4.67) can be found, which depends on $M_s^{(t+1)}$ given from (4.34) as

$$\begin{aligned} M_s^{(t+1)} &= M_{B1}^{(t+1)} - M_w^{(t)} \\ &= M_{B2}^{(t)} - M_{aw}^{(t)} - M_w^{(t)} \\ &= M_{B1}^{(t)} + \lambda_{ad}\tau^{(t)} - M_{aw}^{(t)} - M_w^{(t)}, \end{aligned} \tag{4.71}$$

and

$$E[M_s^{(t+1)}] = M_{B1}^{(t)} + \lambda_{ad}\tau^{(t)} - E[M_{aw}^{(t)}] - E[M_w^{(t)}], \tag{4.72}$$

where $E[M_w^{(t)}]$ is given in (4.70), and $E[M_{aw}^{(t)}]$ can be given from (4.40) as

$$E[M_{aw}^{(t)}] = \begin{cases} M_{B1}^{(t)} - M_s^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} < \overline{N}_a^{(t)} \\ \overline{N}_a^{(t)}, & M_{B1}^{(t)} - M_s^{(t)} \geq \overline{N}_a^{(t)}. \end{cases} \tag{4.73}$$

Finally, $E[\tau^{(t+1)}]$ can be found from (4.35) but with time slot $(t{+}1)$ instead of t, i.e., it depends on $E[M_s^{(t+1)}]$, which is given by (4.72). By substituting $E[M_r^{(t)}]$, $E[M_{aw}^{(t)}]$, and $E[\tau^{(t+1)}]$ into (4.65), the average user waiting delay can be found. Last, the steady state average user waiting delay in the secondary network until it is admitted to transmit can be found from

$$\overline{D} = \lim_{t\to\infty} \overline{D}^{(t)}. \tag{4.74}$$

4.2.5 Numerical and Simulation Results

The numerical and simulation evaluation of the system behavior and the proposed admission control and channel allocation policy are presented in this section. The numerical parameters used in the performance evaluation are listed in Table 4.2. The evaluation is performed on two levels: on the time slot level that describes the interaction activities of the SUs in one time slot and on the steady state level that describes the capability of the secondary network.

A. One Time Slot Level

For each time slot, a number of sensing users should identify the available licensed channels, so this number is expected to affect the whole performance of the system.

Table 4.2: Numerical parameters for the system behavior analysis and the admission control and channel allocation policy evaluation.

Parameter	**Value**	**Description**
B	6 MHz	bandwidth of each licensed channel
T	50 ms	duration of each time slot
P_d^{th}	0.95	probability of detection threshold
P_f^{th}	0.01	probability of false alarm threshold
γ	-15 dB	SNR detection sensitivity of the SU's detector
δ	0.3	the activity of the PUs
N	30	the number of the licensed channels
T_{B1}	100 μs	duration of beacon B1
T_{B2}	100 μs	duration of beacon B2
T_{ms}	10 μs	mini-slot duration of the RP
T_{SIFS}	15 μs	short inter-frame space duration

In the following three figures, we will show the relations between the number of the sensing users and different important quantities in the secondary network.

Figure 4.14 shows the relation between the number of the winning and admitted users with respect to the number of the sensing users in a time slot when $M_{B1} = 50$ (users), $\lambda_{ad} = 1$ (user/ms), and $T_{res} = 2$ (ms). It can be seen that the sensing and winning users are inversely related. This is because for each time slot the total number of the SUs is divided into sensing and winning users, so increasing one type will decrease the other linearly. On the other hand, the number of the admitted users is related to the number of the identified available channels. When the number of the sensing users is small, i.e., $M_s \leq 3$ users, the number of the identified channels is small, so the number of the admitted users is small too, and it increases until it equals the average number of the identified channels, where each

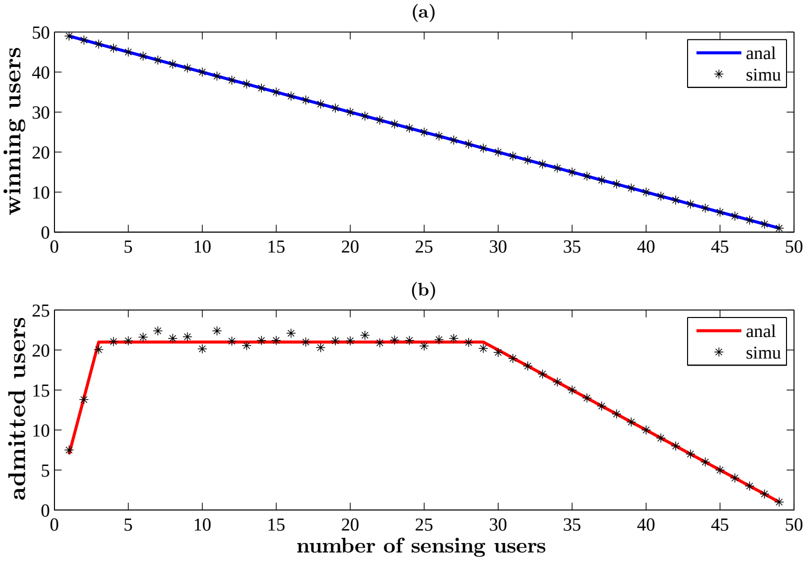

Figure 4.14: Relation between the number of the sensing users and: (a) number of the winning users, and (b) number of the admitted users in a time slot.

admitted user will access only one channel. When the number of the sensing users is greater than the number of the licensed channels, i.e. $M_s \geq N$, the number of the remaining users is less than the N channels, so the number of the admitted users decreases. The simulation results are consistent with the analytical results.

Figure 4.15 shows the number of the identified licensed channels and the network normalized average aggregate throughput with respect to the number of the sensing users in a time slot when $M_{B1} = 50$ (users), $\lambda_{ad} = 1$ (user/ms), and $T_{res} = 2$ (ms). The analytical and simulation results of this figure illustrate that when there is a sufficient number of sensing users, they can identify the number of the average available licensed channels. However, when the number of the sensing users is relatively small comparing to the number of the N channels, each sensing user is required to sense more channels to identify all these channels; consequently, the sensing duration increases, which is at the cost of the remaining time that should

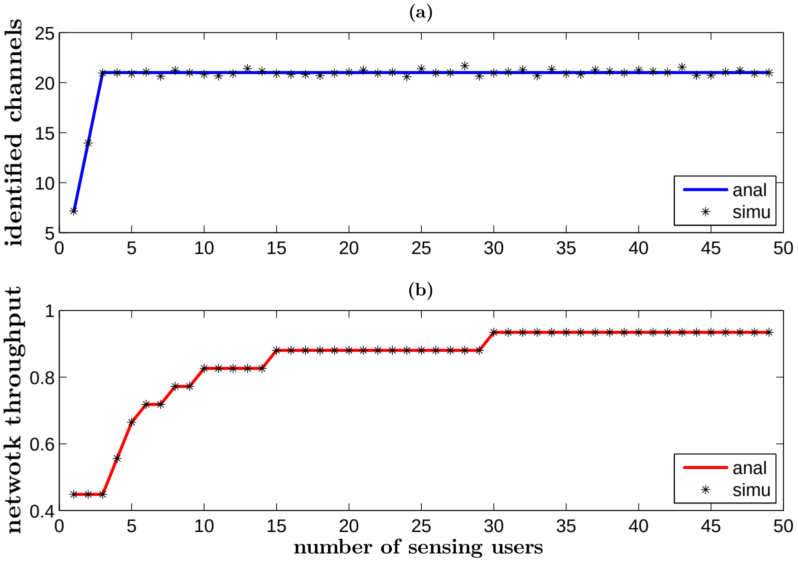

Figure 4.15: Relation between the number of the sensing users and: (a) number of the identified licensed channels, and (b) network normalized average aggregate throughput in a time slot.

be used for data transmission by the admitted users at the DRP. This is what makes the network throughput increases in steps until it saturates when the number of the sensing users is equal to the number of the licensed channels, where each sensing user senses only one channel. It can be seen that the SUs can utilize up to 0.95 of the available spectrum, while the remaining 0.05 is the cost of the signaling overheads and the sensing time, which reflects the effectiveness of the used MAC framework.

Figure 4.16 shows the SU average aggregate throughput (channels/user) and average waiting delay (time slots) with respect to the number of the sensing users at a time slot when $M_{B1} = 50$ (users), $\lambda_{ad} = 1$ (user/ms), and $T_{res} = 2$ (ms). The admitted users decreases with increasing the number of the sensing users when $M_s \geq N$ as can be seen from Figure 4.14(b), so each admitted user has the chance to obtain more allocated channels; consequently, its average aggregate throughput

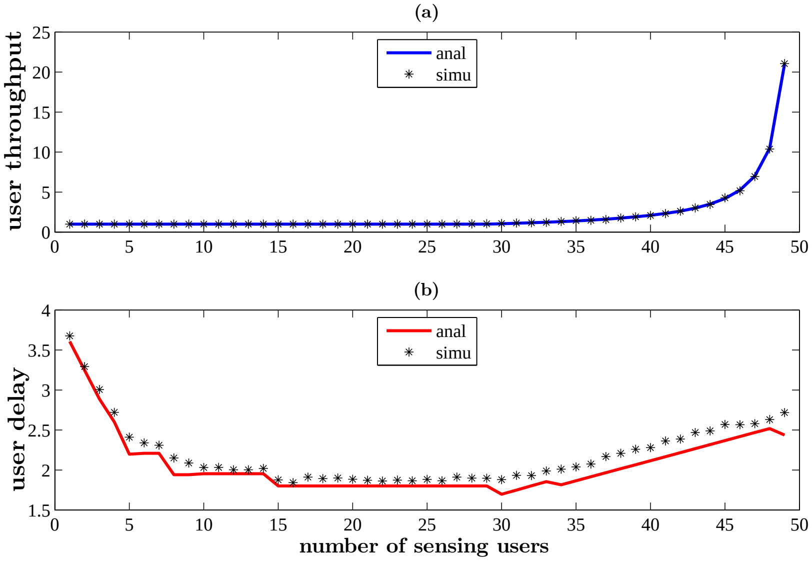

Figure 4.16: Effects of the number of the sensing users on: (a) average aggregate throughput of the SU, and (b) average waiting delay in the network.

increases. However, the cost of allocating more channels to fewer users is that of increasing the average waiting delay of the user in the network. Therefore, there is a QoS tradeoff between the average aggregate throughput and the average delay of the SU in the network. It can be seen that the minimum waiting delay in the network is when the number of the sensing users is equal to the number of the licensed channels, which is always the case since each sensing user senses only one channel, i.e., the sensing duration is minimum, and the number of the access users is maximum, so the users get the chance to access the available channels faster; consequently, the user delay is the minimum.

B. Steady State Level

In the long run of the network, the network performance quantities are in the steady state; therefore, the network capability in terms of the number of the admitted

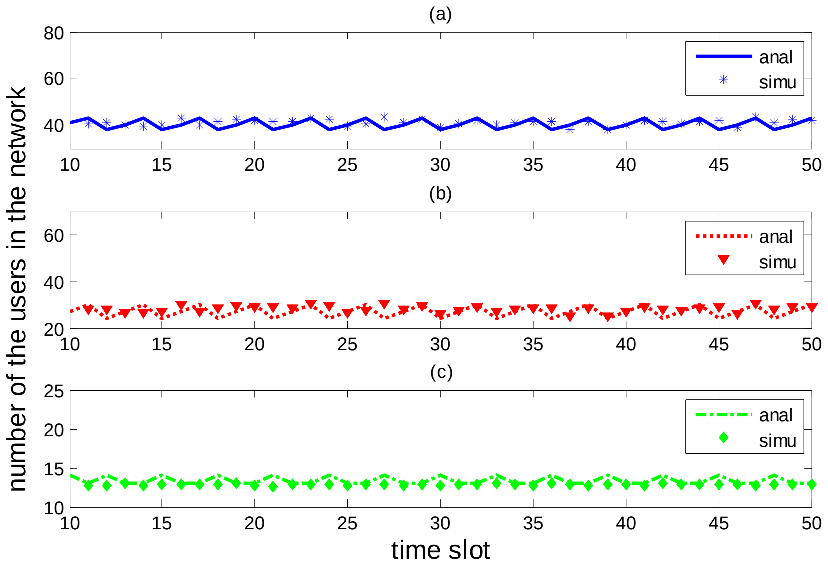

Figure 4.17: Number of: (a) users at beacon B1, (b) sensing users, and (c) admitted winning users, in the secondary network for a number of time slots.

users, the average aggregate throughput, and the average delay can be studied. Figure 4.17 shows the number of the (a) users at beacon B1, (b) sensing users, and (c) admitted winning users in the secondary network for a number of time slots when $T_{res} = 3$ (ms), and $\lambda_{ad} = 3$ (user/ms). While Figure 4.18 shows the average (a) user aggregate throughput (channels/user), (b) network normalized aggregate throughput, and (c) user delay (time slots) for the same time slots. From these two figures, it can be seen that the aforementioned quantities converge to specific values based on the system parameters regardless of the initial start of the network. The ripples on the curves indicate the relations between the system parameters that reflects the mathematical coefficients of the random difference equations discussed in Section 4.2.1-B. Since the simulation results of Figures 4.17 and 4.18 verify the analytical results in the steady state case, we will consider only the analytical results in the following figures.

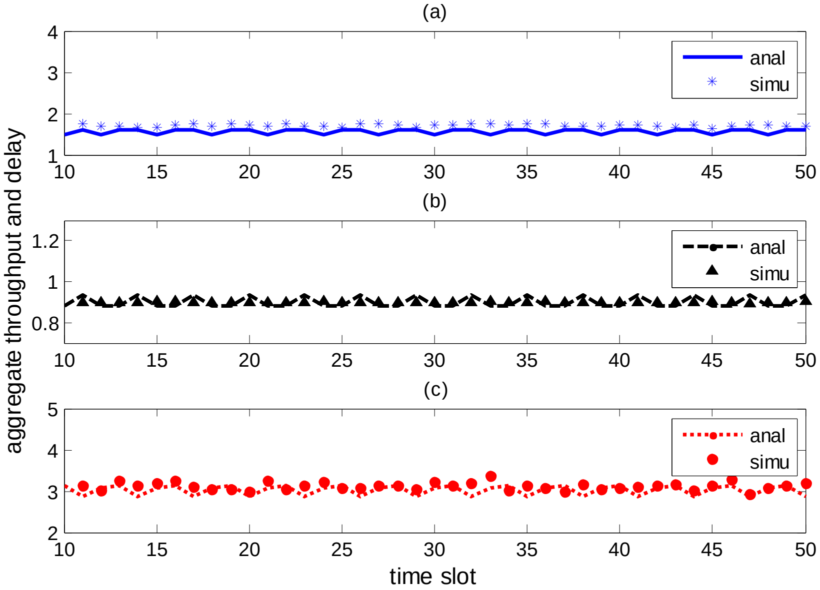

Figure 4.18: Average values of: (a) user aggregate throughput, (b) network normalized aggregate throughput, and (c) user delay for a number of time slots.

One of the main design parameters in the system is the mini-slot reserving time duration at the DRP, T_{res}. Based on this parameter, the number of the SUs that can win to reserve the next time slot can be controlled. Figure 4.19 shows the effects of the mini-slot reserving time duration, on the network capability: (a) average number of admitted users, (b) user average aggregate throughput (channels/user), and (c) user average delay (time slots). When this parameter increases, the number of the winning users can be decreased; consequently, the expected number of the admitted users at the next time slot decreases. When the number of the admitted users decreases, the admitted users get higher chance to access more identified channels, so their average aggregate throughput increases; however, the average delay increases too because the number of the users accumulates in the network due to decreasing the number of the admitted users. In this figure, the effect of increasing the admitted user rate is also shown. Increasing the admitting rate will

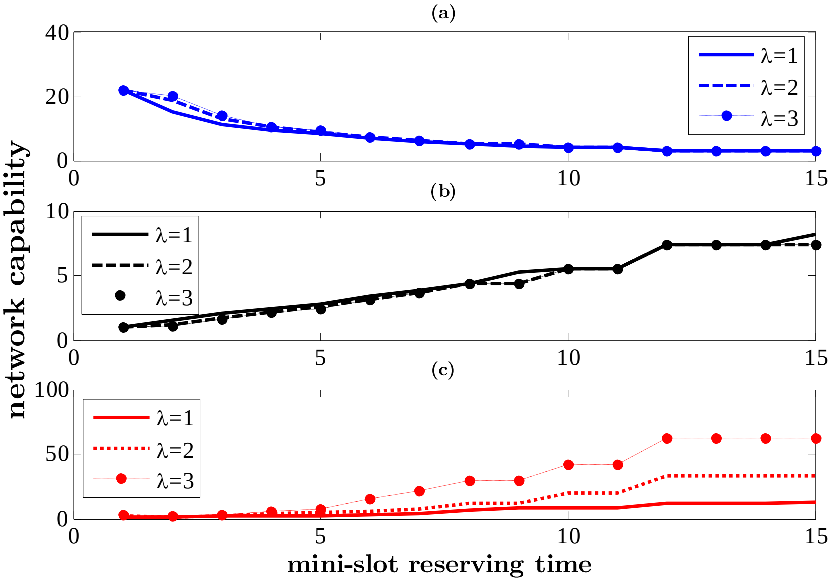

Figure 4.19: Effects of the mini-slot reserving time on the network capability: (a) average number of admitted users, (b) user average aggregate throughput, and (c) user average delay.

increase the waiting delay in the network when the other parameters are fixed, but almost it will not affect the number of the admitted users or the average aggregate throughput.

The second important design parameter is the admitted user rate, λ_{ad}. To meet certain QoS levels in the secondary network, the network coordinator admits only a number of new SUs. Figure 4.20 shows the effects of the admitted user rate (user/ms) on the network capability: (a) average number of admitted users, (b) user average aggregate throughput, and (c) user average delay (time slots). In general, admitting more SUs increases the average delay in the network. It can be seen from the figure that increasing the mini-slot reserving time duration affects the network capability as well.

Figure 4.21 shows the effects of the receiver responding probability, p, on the

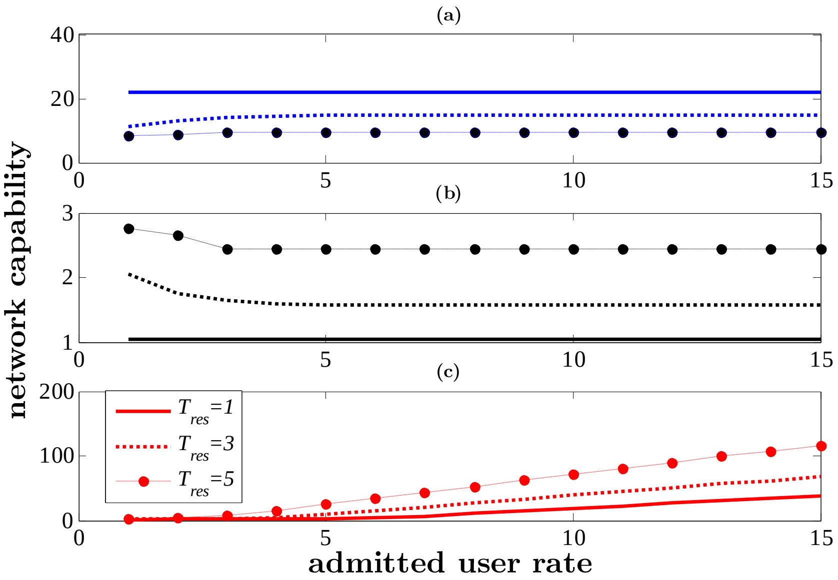

Figure 4.20: Effects of the admitted user rate on the network capability: (a) average number of admitted users, (b) user average aggregate throughput, and (c) user average delay.

network capability: (a) average number of admitted users, (b) user average aggregate throughput (channels/user), and (c) user average delay (time slots) when $T_{res} = 3$ (ms) and $\lambda_{ad} = 2$ (user/ms). This parameter cannot be controlled as a system design parameter; however, its influences on the network capability should be considered while designing the other parameters. When this probability increases, the successful exchange of the reserving messages increases. Since more winning users can assigned, more admitted users can be accepted on the next time slot; however, this will decrease the user average aggregate throughput but decrease the delay too. Based on the information of the probability of the receiver response, which can be learned over the time, the mini-slot reserving time should be chosen properly.

Choosing the time slot duration, T, is related to the tolerable interference to the

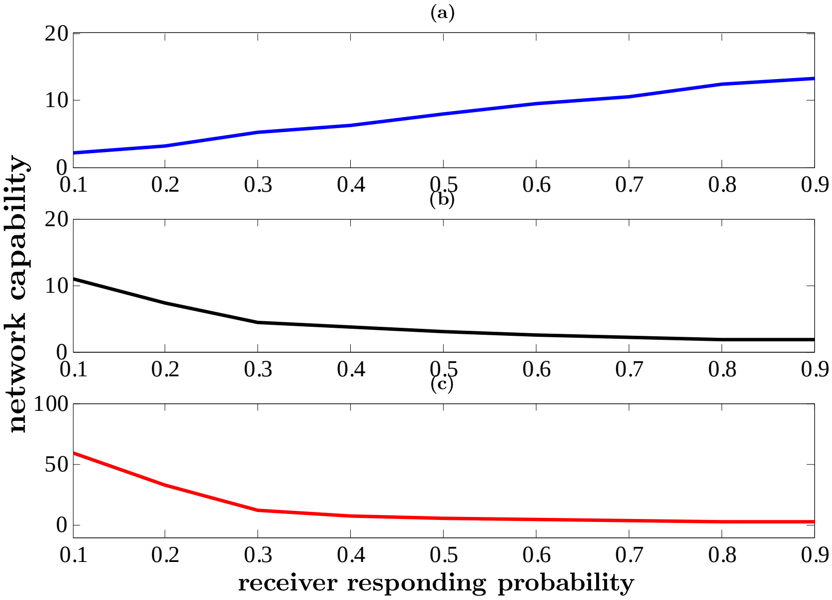

Figure 4.21: Effects of the receiver responding probability on the network capability: (a) average number of admitted users, (b) user average aggregate throughput, and (c) user average delay.

PUs, i.e., for different PU, there may be different interference requirement. Increasing this time duration is expected to increase the secondary network throughput; however, this will increase the interference to the PUs. Therefore, its effects on the secondary network capability should be studied. Figure 4.22 shows the effects of the slot time duration on the network capability: (a) average number of admitted users, (b) user average aggregate throughput (channels/user), and (c) user average delay (time slots) when $T_{res} = 3$ (ms) and $\lambda_{ad} = 2$ (user/ms). These effects are almost similar to what have been shown in Figure 4.21 but with different values; however, when the number of the admitted winning users saturates, the average user delay starts to increase slightly with increasing the time slot duration because in this case the users are required to wait longer time until they probably get the chance to access the available channels in the coming time slots; moreover, for the

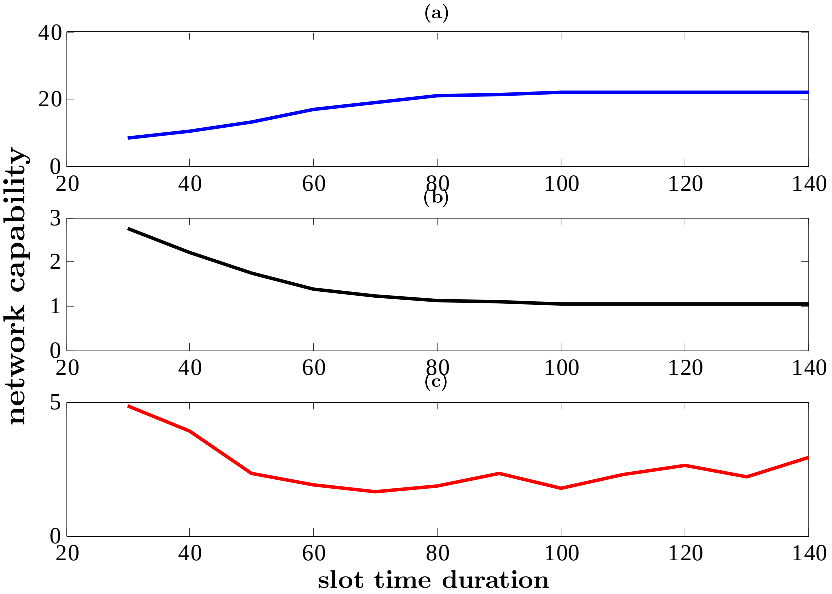

Figure 4.22: Effects of the slot time duration on the network capability: (a) average number of admitted users, (b) user average aggregate throughput, and (c) user average delay.

given set of parameters, there are some ripples on the average delay curve due to the calculation averaging.

The availability of the licensed channels is dependent on the activity of the PUs on that channels, δ, which cannot be controlled but should be considered. Figure 4.23 shows the effects of the PU activity on the network capability: (a) average number of admitted users, (b) user average aggregate throughput (channels/user), and (c) user average delay (time slots) when $T_{res} = 3$ (ms) and $\lambda_{ad} = 2$ (user/ms). The average number of the identified channels is $(1-\delta)N$; however, the maximum number of the admitted users is 13 based on the given values of T_{res} and λ_{ad}; therefore, only 13 of the identified channels can be exploited. When δ increases above 0.5, the number of the admitted users decreases linearly since the average number of the identified channels decreases linearly. Moreover, the average aggregate

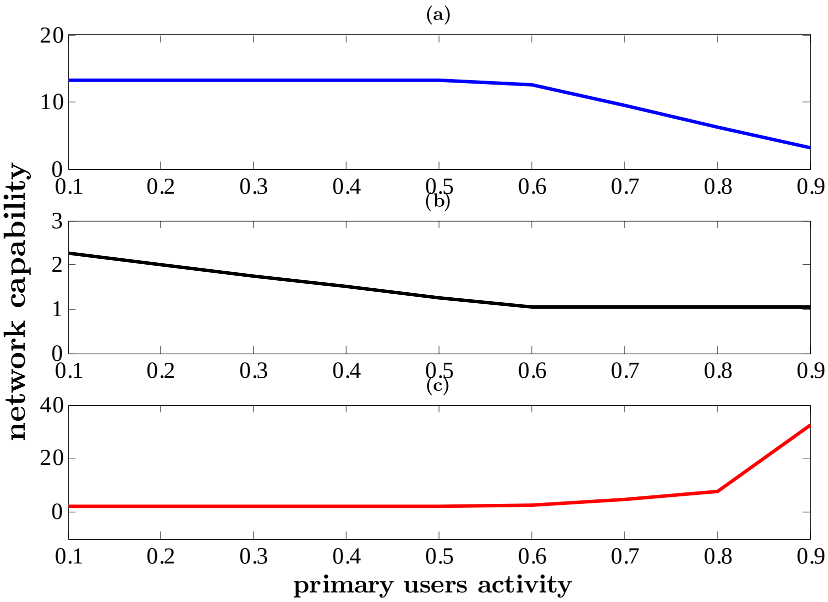

Figure 4.23: Effects of the PU activity on the network capability: (a) average number of admitted users, (b) user average aggregate throughput, and (c) user average delay.

throughput decreases linearly with decreasing the average number of the identified channels, while the average delay is constant until each admitted user accesses only one channel, where the delay increases with decreasing the average number of the available channels.

4.3 QoS Provisioning

The availability fluctuation of the licensed channels poses serious difficulties in providing QoS for the SUs. When the channel availability varies depending on the PUs activities on the licensed channels, the secondary traffic flows should be regulated accordingly to guarantee the QoS requirements of the SUs. Therefore, unlike the traditional QoS provisioning that mainly depends on the traffic statistics, providing

QoS for the SUs should be realized through the spectrum sensing, spectrum access decision and allocation, and the admission control. In CRNs, when a PU appears on a channel used by a SU, the SU must vacate that channel and try to find another available channel to complete its ongoing call, which is known as spectrum handover; however, there is a possibility of dropping the call due to having unavailable channels. Moreover, the probability of blocking the incoming calls increases when the activities of the PUs are high on the licensed channels. Therefore, the dropping and blocking probabilities are related to the aggregate throughput and service waiting time of the SUs. Furthermore, the underutilized spectrum should be used efficiently by the SUs.

In this section, we propose to jointly consider the QoS provisioning of heterogeneous secondary Real Time (RT) and Non-Real Time (NRT) users, with the spectrum sensing, spectrum access decision, channel allocation and call admission control in distributed cooperative CRNs. Based on the statistical information of the available channels that can be learned over the time by the CRs, we allocate a number of the available channels that are identified by spectrum sensing to the optimum number of the RT users, which guarantees their dropping and blocking probability QoS requirements. These users are allowed to access the available channels in consecutive time slots until they successfully transmit their packets. The remaining available channels in each time slot are allocated to the adaptive optimum number of the NRT users with variable data rate to efficiently utilize the unused spectrum.

4.3.1 QoS Provisioning Model

A. Hybrid RT and NRT Users

The MAC framework proposed in Section 4.1 can support secondary RT and NRT users to concurrently access the spectrum in CRNs. The RT user, e.g., voice over Internet protocol (VOIP), requires constant data rate and acceptable average packet delay; moreover, it is annoying to drop an RT user once it is established, so the RT user dropping probability should not exceed a certain threshold; furthermore, blocking the RT user from accessing the network is not desired, so the blocking probability should also be within an acceptable threshold. For the NRT user, e.g., Data transferring, the most important QoS requirement in the context of CRNs is the throughput. Considering both RT and NRT users, the spectrum utilization is an ultimate goal in employing the secondary network. Figure 4.24 illustrates the proposed QoS provisioning model. Since the RT user is delay sensitive, the RT users are given priority to access the available channels once they are admitted in the network using spectrum handover. Spectrum handover in this context implies that whenever an RT user is allowed to access an allocated channel at the current time slot, this user will be allowed to access an allocated available channel, if any, in the coming consecutive time slots until it completes its transmission. The remaining available channels in each time slot are utilized by NRT users.

B. Channel Allocation and Call Admission Control

Since there are two user classes in the network, the dynamic IDs of the SUs, which are obtained during the registration process at the SRP in the MAC framework, reflect their sequences in their classes. Using these dynamic IDs, each user in the network can decide distributively which channels to access as follows. For the RT users, an RT admitted user will access an available channel from the total identified

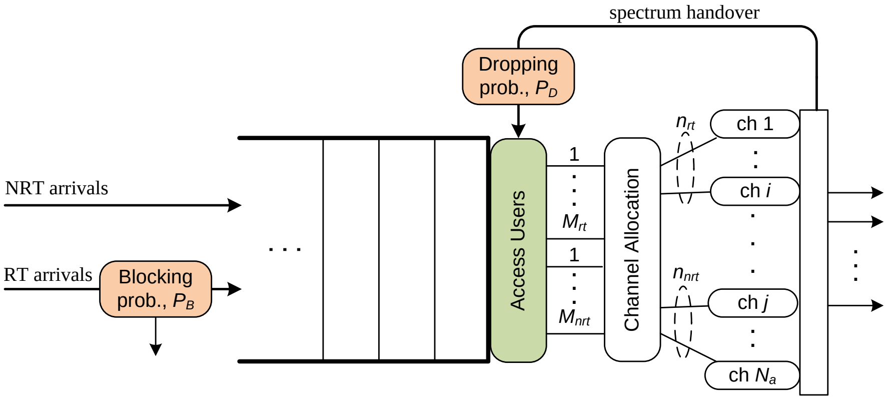

Figure 4.24: The RT and NRT QoS provisioning model.

available channels based on the ID sequence of the RT admitted user in its class and the ID sequences of the available channels, e.g., the first RT admitted user will access the first available channel and so on. The remaining available channels, if any, will be utilized by the NRT users similarly, i.e., each NRT access user will access one or more available channels based on its ID sequence in its class and the ID sequences of the remaining available channels. Moreover, based on the statistical distribution of the number of the available channels, the network coordinator in each time slot admits only the number of the RT users that guarantees their QoS requirements. Furthermore, to support as many as possible NRT users, the adaptive optimum number of them are allowed to access the remaining available channels considering the balance between the number of the sensing users and the number of the access users. The NRT users may access more than one available channel to efficiently utilize the unused spectrum.

4.3.2 Analysis of the QoS-Based Spectrum Allocation

We develop analytical models for the QoS requirements of the RT and NRT users. By using the proposed QoS-based spectrum resource allocation framework, we can find the optimal numbers of the RT and NRT users that can be admitted to access the available channels.

A. The RT User

It is expected that dropping the ongoing RT user is more annoying than blocking the user from the beginning. Therefore, the user dropping probability should not exceed a certain threshold to guarantee the users' satisfactions. The dropping probability in this context can be defined as the probability of having an unavailable channel for the ongoing user due to the occurrence of a PU on the licensed channel. Suppose that there are N_{rt} channels carrying ongoing RT users, where each user requires one channel from the available N_a channels. The dropping probability of the ongoing RT user can be defined as

$$P_D = \Pr(N_a \leq N_{rt} - 1). \tag{4.75}$$

The distribution of the number of the available channels can be learned by the CRs over the time based on historical statistical information about the activity of the PUs. Although any statistical distribution can be used, binomial distribution is the most appropriate one as discussed in the beginning of Section 4.1.2; therefore, without loss of generality, let the N_a available channels follow binomial distribution with parameters N and $(1-\delta)$, where the first is the number of the licensed channels and the second is the availability of the channels, then (4.75) can be rewritten as

$$P_D = F\left(N_{rt} - 1; N, 1 - \delta\right), \tag{4.76}$$

where $F(k;n,p)$ is the cumulative distribution function (cdf) of the binomial distribution, which can be given in terms of regularized incomplete beta function as

$$\begin{aligned} F(k;n,p) &= \sum_{i=0}^{k} \begin{pmatrix} n \\ i \end{pmatrix} p^{i}(1-p)^{(n-i)} \\ &= (n-k) \begin{pmatrix} n \\ k \end{pmatrix} B(1-p;n-k,k+1) \\ &= I_{1-p}\left(n-k,k+1\right), \end{aligned} \tag{4.77}$$

where $B(x;a,b) = \int_0^x t^{a-1}(1-t)^{b-1}dt$ is the incomplete beta function. From (4.76), the number of the channels that maintain the dropping probability of the RT user within a certain threshold can be found as

$$N_{rt} = 1 + F^{-1}\left(P_D; N, 1-\delta\right), \tag{4.78}$$

where $F^{-1}(p_k;n,p)$ is the inverse cdf of the binomial distribution that returns the smallest integer k evaluated at the cdf value of p_k.

The RT user dropping probability should be very small. However, when the number of the licensed channels is relatively small (say $N < 5$) and the activity of the PUs is high (say $\delta > 0.5$), the RT user blocking probability due to the channel unavailability (i.e., because of active PUs) may increase up to 100%, i.e., there will be no any RT user allowed to access the available channels. Therefore, there should be balance between these two contrary requirements. The blocking probability due to the channel unavailability can be found as

$$\begin{aligned} P_{B_{un}} &= \Pr(A_{rt} > N_{rt}) \\ &= 1 - \Pr(A_{rt} \leq N_{rt}), \end{aligned} \tag{4.79}$$

where A_{rt} is the number of the RT users arriving in each time slot, which can be naturally assumed to be a Poisson process, so (4.79) can be rewritten as

$$\begin{aligned} P_{B_{un}} &= 1 - \sum_{j=0}^{N_{rt}} \frac{A_{rt}^{j}}{j!} \exp(-A_{rt}) \\ &= 1 - \frac{\Gamma(N_{rt}+1, A_{rt})}{N_{rt}!}, \end{aligned} \tag{4.80}$$

where $\Gamma(s,x) = \int_x^\infty t^{s-1}e^{-t}dt$ is the upper incomplete gamma function.

In addition to the user blocking probability due to the channel unavailability, the RT user will be blocked also when the N_{rt} channels are busy carrying N_{rt} ongoing RT users (i.e., because of other SUs). For practical acceptable dropping probability, e.g., around 0.01, the probability of having a number of available channels less than N_{rt} is very small comparing to the probability of having at least N_{rt} channels, so this probability can be neglected. Therefore, the blocking probability due to busy channels carrying other RT users can be modeled as an M/G/N_{rt}/N_{rt} queuing system. In [113], it is proven that the blocking probability of this system can be given by the Erlang B formula as

$$P_{B_{bs}} = \frac{(A_{rt}E[X])^{N_{rt}}/N_{rt}!}{\sum_{j=0}^{N_{rt}}(A_{rt}E[X])^{j}/j!}, \tag{4.81}$$

where $E[X]$ is the expected service time of the RT user. In order to find the average service time of the RT user, it is necessary to know how the RT packets are sent. These packets are actually sent during the DRP in the MAC framework; however, the winning users cannot start sending until they get information about the available channels during the SRP and RP as discussed in the MAC protocol in Section 4.1.1, so the packets require one time slot to be successively transmitted. From Figure 4.7, the duration of the DRP can be given as $T_{DRP} = T - Tc - T_{SRP}$, where T_{SRP} is the duration of the SRP phase that depends on the sensing policy and can be given from (4.32) as

$$T_{SRP} = \begin{cases} \min\left(\left\lceil \frac{N}{M_s} \right\rceil, \left\lceil \frac{T-T_c}{2t_s} \right\rceil\right) t_s, & LM_s < N \\ \left\lceil \frac{N}{M_s} \right\rceil t_s, & LM_s \geq N, \end{cases} \tag{4.82}$$

where t_s is the required time to sense each channel given in (4.29). Since T_{SRP} may vary from time slot to time slot depending on the number of the sensing users, T_{DRP} varies accordingly. To efficiently utilize the T_{DRP}, the packet size varies, which can be determined in the transportation layer [114]. However, this is out of the scope of this thesis. Let the arrival RT users have i.i.d. number of packets to transmit with an arbitrary distribution that has an average of l packets, and each packet is sent on an available channel at each time slot, so the traffic utilization (in Erlang) is just $\psi = E[X]A_{rt} = lTA_{rt}$, and (4.81) can be rewritten as

$$P_{B_{bs}} = \frac{\psi^{N_{rt}}/N_{rt}!}{\sum_{j=0}^{N_{rt}} \psi^j/j!}. \tag{4.83}$$

Using the relation $\sum_{j=0}^{s-1} \frac{x^j}{j!} = \frac{\Gamma(s,x)\exp(x)}{(s-1)!}$, (4.83) can be rewritten in terms of Gamma function as

$$P_{B_{bs}} = \frac{\psi^{N_{rt}}\exp(-\psi)}{\Gamma(N_{rt}+1,\psi)}. \tag{4.84}$$

Therefore, the overall blocking probability of the arrival RT users can be given as

$$\begin{aligned} P_B &= 1-(1-P_{B_{un}})(1-P_{B_{bs}}) \\ &= 1-\frac{\Gamma(N_{rt}+1,A_{rt})}{N_{rt}!}\left(1-\frac{(lTA_{rt})^{N_{rt}}\exp(-lTA_{rt})}{\Gamma(N_{rt}+1,lTA_{rt})}\right). \end{aligned} \tag{4.85}$$

Since the actual RT user serving rate is $A_{rt}(1-P_B)$, the average number of the RT users in the secondary network can be found from Little's formula as

$$\begin{aligned} \overline{M}_{rt} &= lTA_{rt}(1-P_B) \\ &= \frac{lTA_{rt}\Gamma(N_{rt}+1,A_{rt})}{N_{rt}!}\left(1-\frac{(lTA_{rt})^{N_{rt}}\exp(-lTA_{rt})}{\Gamma(N_{rt}+1,lTA_{rt})}\right). \end{aligned} \tag{4.86}$$

To maximize the average number of the RT users, the network coordinator in each time slot decides how many RT users can be admitted into the network to guarantee the dropping and blocking probabilities of the RT user to be within certain values. Therefore, we define the following optimization problem

$$\begin{aligned} A_{rt}^{*} = \arg\max_{A_{rt}} \quad & \overline{M}_{rt} \\ \text{s.t.} \quad & P_B \le P_B^{th} \\ & P_D \le P_D^{th} \\ & A_{rt} \in \mathbf{I}^{+}, \end{aligned} \tag{4.87}$$

where P_B^{th} and P_D^{th} are the blocking probability threshold and dropping probability threshold, respectively, and $\mathbf{I}^{+}$ means the set of positive integer numbers. It is obvious that this optimization problem is nonlinear integer programming. In fact, since the secondary network is a distributed ad hoc network, it is desirable to find a simple computational yet accurate expression for the spectrum access decision rather than using an optimization algorithm that requires more time to get results. Fortunately, for practical values of the quantities in (4.87), the solution of his optimization problem is always the one that satisfies the first constraint, as will be seen in Figures 4.27–4.30. Therefore, A_{rt}^{*} can be found by first finding the zeros of the first constraint and then choosing the one that is in the appropriate range, i.e., $0 \le A_{rt} \le N_{rt}$. Furthermore, the overall blocking probability is due to that when the available channels are busy carrying other RT users (see Figure 4.26), so the blocking probability can be approximated as $P_B \approx P_{B_{bs}}$. Therefore, it can be inferred that the number of the admitted RT users is mainly affected by the probability of having the available channels busy carrying other RT users. From (4.84), the first constraint of (4.87) can be approximated as

$$\frac{(lTA_{rt})^{N_{rt}}\exp(-lTA_{rt})}{\Gamma(N_{rt}+1, lTA_{rt})} \le P_B^{th}. \tag{4.88}$$

Define the following polynomial

$$f\left(A_{rt}\right) = (lTA_{rt})^{N_{rt}}\exp(-lTA_{rt}) - P_B^{th}\Gamma(N_{rt}+1, lTA_{rt}), \tag{4.89}$$

then the solution of (4.87) can be approximated as $A_{rt}^{*} \approx Z_1\left(f(A_{rt})\right)$, where the operator $Z_1(\cdot)$ means the first zero of the given polynomial. Since the actual number of the RT arrivals may be less than A_{rt}^*, the number of the RT users that can be admitted by the network coordinator is given by

$$A_{rt}^{ad} = \min(A_{rt}, A_{rt}^*). \tag{4.90}$$

Finally, the average number of the RT calls in the system can be approximated as

$$\overline{M}_{rt} \approx lTA_{rt}^{ad}\left(1 - \frac{(lTA_{rt}^{ad})^{N_{rt}}\exp(-lTA_{rt}^{ad})}{\Gamma(N_{rt}+1, lTA_{rt}^{ad})}\right). \tag{4.91}$$

B. The NRT User

To efficiently utilize the unused spectrum, all the remaining available channels should be used by the NRT users. In this subsection, we will determine the optimal number of the NRT users that can access the spectrum simultaneously at each time slot and study how to allocate the remaining available channels to them considering the spectrum sensing and utilization indispensability.

Dependent upon the used spectrum sensing policy and the MAC time structure, the normalized identified unused spectrum that can be exploited by the SUs can be given as

$$U = \begin{cases} \frac{(T-T_c-T_{SRP})}{T}\frac{LM_s}{N}(1-P_f), & LM_s < N \\ \frac{(T-T_c-T_{SRP})}{T}(1-Q_f), & LM_s \geq N, \end{cases} \tag{4.92}$$

where P_f is the probability of false alarm of each sensing user, and Q_f is the probability of false alarm of cooperative sensing users since in case of $LM_s \geq N$ each channel may be sensed by more than one sensing user. Since the probability of false alarm increases in the case of OR-rule cooperative sensing, the sensing users can adjust their detection capabilities to maintain the probability of the false alarm of the cooperative sensing to be equal to that of the individual sensing case, i.e., $Q_f = P_f$, as discussed in Section 4.1.3.

The available channels that are not used by the RT users should be utilized by a number of NRT users. Since the goal is to support as many NRT users as possible to access the available channels simultaneously, we initially assume that each NRT user can access one available channel. Therefore, considering the number of the RT and NRT access users, the normalized aggregate throughput of the secondary network can be given as

$$\Theta = \begin{cases} \frac{(T-T_c-T_{SRP})}{T}\frac{LM_s}{N}\frac{(M_{rt}+M_{nrt})}{N_a}(1-P_f), & LM_s < N \\ \frac{(T-T_c-T_{SRP})}{T}\frac{(M_{rt}+M_{nrt})}{N_a}(1-P_f), & LM_s \geq N, \end{cases} \tag{4.93}$$

where M_{rt} is the number of the RT users that access some of the available channels and M_{nrt} is the number of the NRT users that can access the remaining available channels. The number of the sensing users can be found as

$$M_S = M_{B2} - M_n - M_{rt} - M_{nrt}, \tag{4.94}$$

where M_{B2} is the total number of the SUs in the network at beacon B2, and M_n is the average number of the new SUs registered in the network with the help of the network coordinator at each time slot. By substituting (4.82) in (4.93) and considering (4,94), the normalized aggregate throughput can be rewritten as

$$\Theta = \begin{cases} \frac{(1-P_f)LM_s}{TNN_a}\left(T - T_c - \min(\left\lceil \frac{N}{M_s} \right\rceil, \left\lceil \frac{T-T_c}{2t_s} \right\rceil)t_s\right)(M_{rt}+M_{nrt}), & LM_s < N \\ \frac{(1-P_f)}{TN_a}\left(T - T_c - \left\lceil \frac{N}{M_s} \right\rceil t_s\right)(M_{rt}+M_{nrt}), & LM_s \geq N. \end{cases} \tag{4.95}$$

The optimal number of the NRT users that can access the remaining available channels concurrently in each time slot can be found by maximizing (4.95) with respect to M_{nrt} using any appropriate optimization technique. However, the computational time is a key issue for this kind of network. Therefore, we are trying to find a closed form expression for the optimal value of M_{nrt} rather than using an optimization algorithm. Using the closed form, the secondary nodes can decide almost immediately how many NRT users can access the available channels. By choosing the design parameters carefully, we can maintain $\frac{N}{M_S} < \frac{T-T_c}{2t_s}$, e.g., the duration of the time slot[2] can be chosen as $T > \frac{2Nt_s}{M_s} + T_c$, so the number of the sensed channels always greater than or equal to the N channels, i.e., $LM_s \geq N$, and (4.95) can be reduced to be

$$\Theta = \frac{(1-P_f)}{TN_a}\left(T - T_c - \left\lceil \frac{N}{M_{B2} - M_n - M_{rt} - M_{nrt}} \right\rceil t_s\right)(M_{rt} + M_{nrt}). \quad (4.96)$$

For all the feasible values of M_{nrt} and the other parameters, (4.96) is always increasing or concave function, so the optimal value of M_{nrt} in each time slot can be found using $\frac{\partial \Theta}{\partial M_{nrt}} = 0$ to get

$$M_{nrt}^{*} = \min\left(\left[M_{B2} - M_n - M_{rt} - \sqrt{\frac{(M_{B2} - M_n)Nt_s}{T - T_c}}\right], N_a - M_{rt}\right), \quad (4.97)$$

where $[x]$ means rounding the real number x to the nearest integer number. Since M_{B2} and N_a may vary from time slot to time slot, M_{nrt}^{*} is changed accordingly; therefore, it is an adaptive optimal value.

With the adaptive optimal number of the NRT access users, the unused spectrum may not be efficiently utilized since there may be some available channels not occupied due to the balance between the number of the sensing users and the number of the access users. To efficiently utilize the spectrum, the NRT access users are allowed to access more than one channel, if there are still available channels, in each time slot. In this way, it can be guaranteed that all the available channels are utilized, i.e.

$$M_{rt} + n_{nrt}M_{nrt}^{*} = N_a, \quad (4.98)$$

where n_{nrt} is the number of the available channels that each NRT access user can occupy in each time slot. Substituting (4.97) and arranging (4.98), n_{nrt} can be

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[2] In the IEEE 802.22 standard, the MAC time slot is 160 ms [115].

given as

$$n_{nrt} = \frac{N_a - M_{rt}}{\min\left(\left\lceil M_{B2} - M_n - M_{rt} - \sqrt{\frac{(M_{B2}-M_n)Nt_s}{T-T_c}}\right\rceil, N_a - M_{rt}\right)}. \tag{4.99}$$

For homogeneous demand NRT users, the n_{nrt} will be allocated equally to the NRT access users if it is an integer number; however, if n_{nrt} is not an integer number, there may be a considerable number of available channels not allocated to access users. These channels should be allocated to some access users to efficiently utilize the unused spectrum. Similar to the channel allocation policy discussed in Section 4.2.2, there are three possible channel allocating scenarios:

1. allocating $\lfloor n_{nrt} \rfloor + 1$ to some of the first NRT access users and $\lfloor n_{nrt} \rfloor$ to the others based on the first-come first-service rule;
2. allocating $\lfloor n_{nrt} \rfloor$ to all the NRT users, and allocating the remaining unallocated channels as extra channels to the network coordinator. This can be seen as a reward for the network coordinator since it wastes some of its own resources to manage the secondary network at the current time slot; and
3. allocating just $\lfloor n_{nrt} \rfloor$ channels to all the NRT access users if the user fairness is more important than the spectrum utilization efficiency.

Since different secondary network operators may have different QoS satisfaction levels, choosing one of these three allocating scenarios should be changed accordingly. Allocating the available channels to NRT users with heterogeneous demands is out of the scope of this thesis.

Since the N_a available channels follow binomial distribution, their average can be given as

$$N_a = \begin{cases} (1-\delta)LM_s, & LM_s < N \\ (1-\delta)N, & LM_s \geq N. \end{cases} \tag{4.100}$$

The average of the adaptive optimal number of the NRT access users and their average number of allocated channels can be given, respectively, as

$$\overline{M}_{nrt} = \min\left(M_{B2} - M_n - \overline{M}_{rt} - \sqrt{\frac{(M_{B2}-M_n)Nt_s}{T-T_c}}, (1-\delta)N - \overline{M}_{rt}\right), \tag{4.101}$$

and

$$\overline{n}_{nrt} = \frac{(1-\delta)N - \overline{M}_{rt}}{\min\left(M_{B2} - M_n - \overline{M}_{rt} - \sqrt{\frac{(M_{B2}-M_n)Nt_s}{T-T_c}}, (1-\delta)N - \overline{M}_{rt}\right)}, \tag{4.102}$$

where $\overline{M}_{rt}$ is given in (4,91). Finally, the average normalized aggregate throughput can be given as

$$\overline{\Theta} = \frac{(1-P_f)}{(1-\delta)NT}\left(T - T_c - \frac{Nt_s}{M_{B2} - M_n - \overline{M}_{rt} - \overline{M}_{nrt}}\right)(\overline{M}_{rt} + \overline{n}_{nrt}\overline{M}_{nrt}). \tag{4.103}$$

4.3.3 Numerical and Simulation Results

In this subsection, we first show how the average number of the identified available channels is used to allocate the channels for both RT and NRT users, and validate the relation between the admitted and access RT users with simulation results. We then illustrate the accuracy of the approximation of the blocking probability used to find the average number of the RT users in the network. Finally, we evaluate the average aggregate throughput, average number of RT and NRT users in the network, and the number of the allocated channels to the NRT users. All the parameters used for the evaluation are summarized in Table 4.3.

Figure 4.25 shows the fluctuation in the number of the available channels for different time slots using the distribution in (4.76). Based on the distribution of the number of the available channels and the acceptable level of the dropping probability threshold, there are N_{rt} identified available channels can support RT

Table 4.3: The parameters for performance evaluation of the QoS provisioning.

Parameter	**Value**	**Description**
P_d	0.95	probability of detection threshold
P_f	0.01	probability of false alarm threshold
B	6 MHz	bandwidth of each licensed channel
T	100 ms	duration of each time slot
γ	-15 dB	SNR detection sensitivity of the SU's detector
N	20	the number of the licensed channels
δ	0.3	the activity of the PUs
T_{B1}	100 μs	duration of beacon B1
T_{B2}	100 μs	duration of beacon B2
T_{ms}	10 μs	mini-slot duration of the RP
T_{SIFS}	15 μs	short inter-frame space duration
P_D	0.01	dropping probability threshold
P_B	0.1	blocking probability threshold
l	20	the average number of the packets that the RT user has

users, and the remaining identified available channels can be used by NRT users in each time slot. It is clear that at most of the time, the number of the channels that can support the RT users are available; however, at time slots 30 and 50 some users are dropped. Moreover, at time slot 96, there is no any available channel left for the NRT users. Distinguishing which channels are available at each time slot is determined by the spectrum sensing.

In Figure 4.26, the average number of the RT users that can be supported by the network and their blocking probability are illustrated with respect to the number of the RT admitted users. With the increase of the number of the RT admitted users, their blocking probability increases gradually until all of them are blocked.

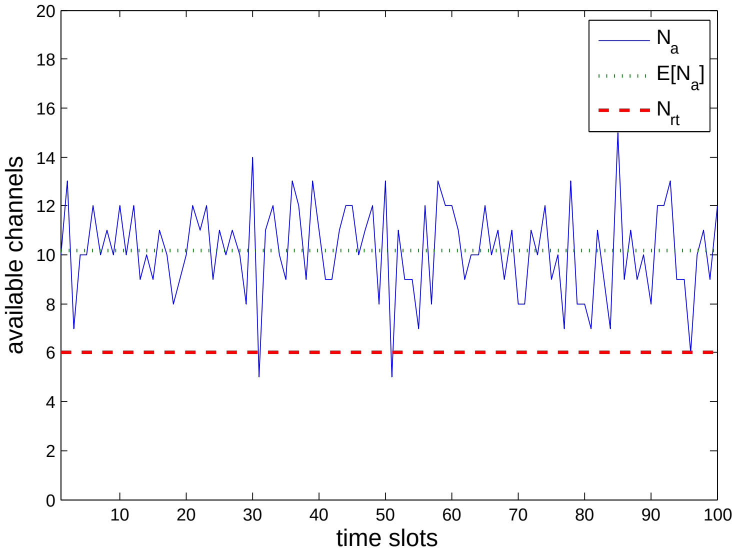

Figure 4.25: Fluctuation of the available channels, N_a, their mean, $E[N_a]$, and the number of the channels that can support the RT users, N_{rt}; for $N = 20$ channels, $\delta = 0.5$, and $P_D = 0.01$.

The blocking probability due to other RT access users, i.e., $P_{B_{bs}}$, increases faster than the blocking probability due to the PUs, i.e., $P_{B_{un}}$, until the number of the admitted RT users is above the average number of the available channels, where $P_{B_{un}}$ becomes faster since there are no any more available channels. Moreover, for a desired level of the blocking probability (e.g., < 0.15), the blocking is due to serving other RT users. This explains why the overall blocking probability is approximated as $P_B \approx P_{B_{bs}}$ in the analysis, which is true for all practical values of the used parameters as can be calculated using (4.81) and (4,84) for $P_{B_{un}}$ and $P_{B_{bs}}$, respectively. Furthermore, there is an optimum number of the admitted RT users that maximizes the average number of the served RT users considering the required blocking probability threshold, which necessitates integrating the QoS provisioning with the call admission control. Finally, the good match of the simulation results validates the analytical analysis.

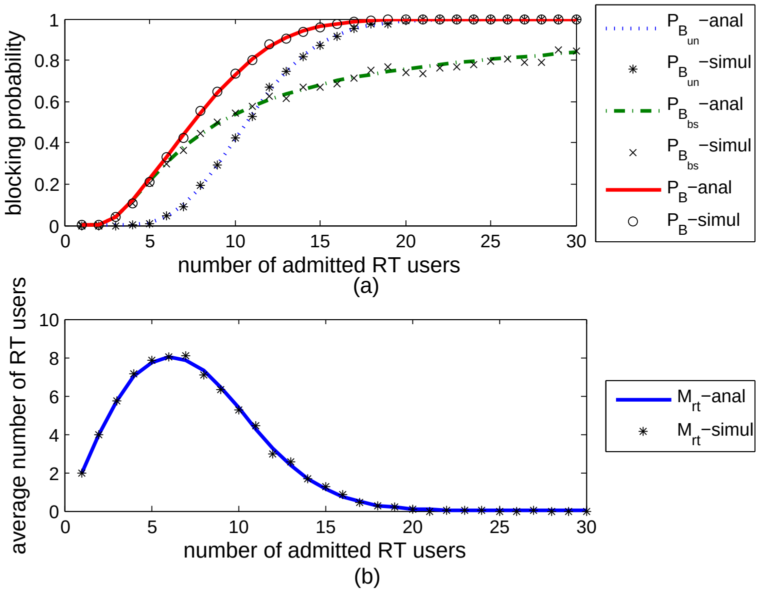

Figure 4.26: Relation between the number of the admitted RT users and: (a) blocking probabilities, and (b) average number of the RT users in the network.

For given dropping and blocking probability thresholds, the optimal number of the admitted and average number of the access RT users are shown in Figure 4.27 for different average number of packets that the RT user has. When the RT user has few numbers of packets to send, more RT users can be admitted in the network; however, when the RT user has many number of packets to send, the number of the RT users decreases because each RT user needs more time to send its packets, while the average number of the RT access users in the network increases with the increase of the number of the packets until it saturates at the number that guarantees the required dropping and blocking probability thresholds. Actually, this figure demonstrates the interaction between the numbers of the admitted and access RT users, so for the acceptable QoS levels, admission control has to be applied. Moreover, it can be seen that the approximation of the blocking probability, i.e., $P_B \approx P_{B_{bs}}$, which is used in the analysis is very accurate and even exact for the

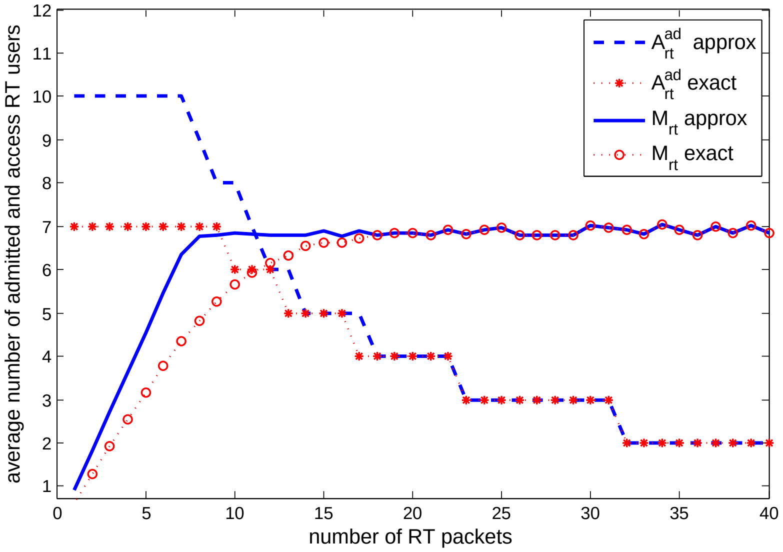

Figure 4.27: Approximated and exact number of admitted RT users and access RT users for different number of RT packets.

practical case when the RT users have many packets to send.

Figure 4.28 shows the optimal numbers of the admitted and access RT users for different threshold values of the blocking probability. As expected, more RT users can be admitted and hence more RT users can access the available channels if the blocking threshold is acceptably increased. It is shown also that the approximation of $P_B \approx P_{B_{bs}}$ is precise and even exact when $P_B < 0.15$, which reflects the practical acceptable blocking level. The same behavior can be seen in Figure 4.29 for the dropping probability threshold. Since the number of the available channels that support the RT users increases with increasing the dropping probability threshold, the average number of the access RT users increases in steps. Moreover, the exact and approximated values of the number of the admitted and access RT users are the same, which validates the used blocking probability approximation.

The availability of the channels is dependent on the activity of the PUs. Figure

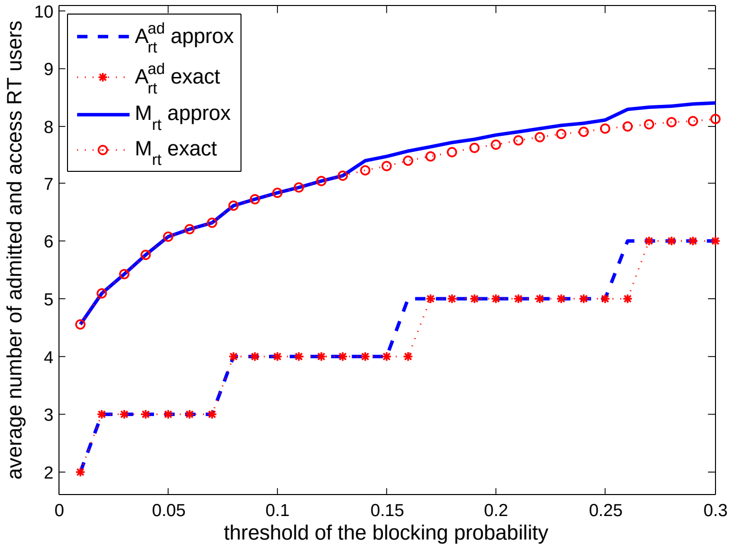

Figure 4.28: Approximated and exact number of admitted RT users and access RT users for different threshold values of the blocking probability.

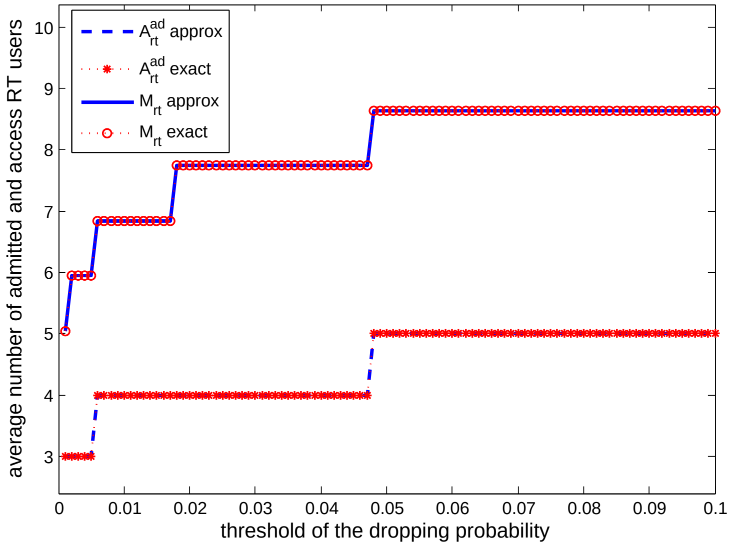

Figure 4.29: Approximated and exact number of admitted RT users and access RT users for different threshold values of the dropping probability.

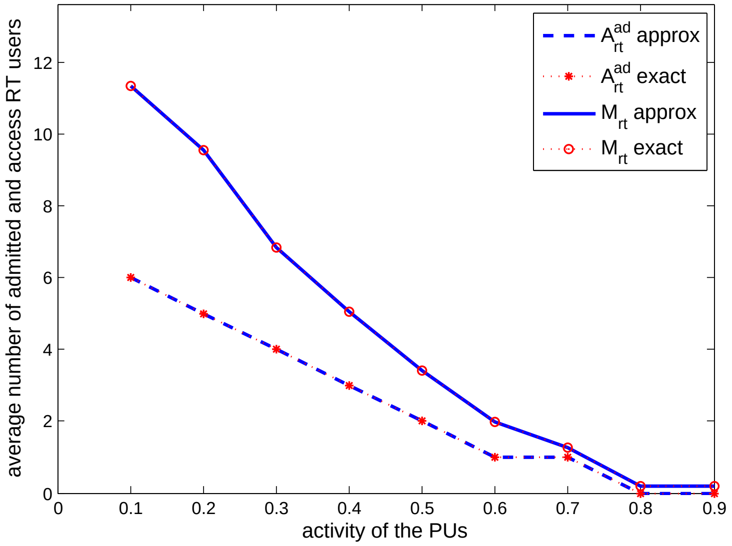

Figure 4.30: Approximated and exact number of admitted RT users and access RT users for different values of the activity of the PUs.

4.30 shows the effects of this dependency on the number of the admitted and access RT users. When the PUs increase their activities in using the licensed channels, the blocking probability of the RT users increases until all of them are blocked. The blocking probability approximation is validated also here since the exact and approximated values of the number of the admitted and access RT users are identical.

Figure 4.31 shows the relation between the number of the NRT access users and the aggregate throughput for different total numbers of the SUs in the network, i.e., M_{B2}. For given dropping and blocking probability thresholds, the optimal number of the RT access users are admitted to utilize their allocated channels considering their acceptable QoS levels, and the remaining available channels are used by some NRT access users. When the total number of the users in the network is relatively small, only a few number of the NRT users can access the remaining available

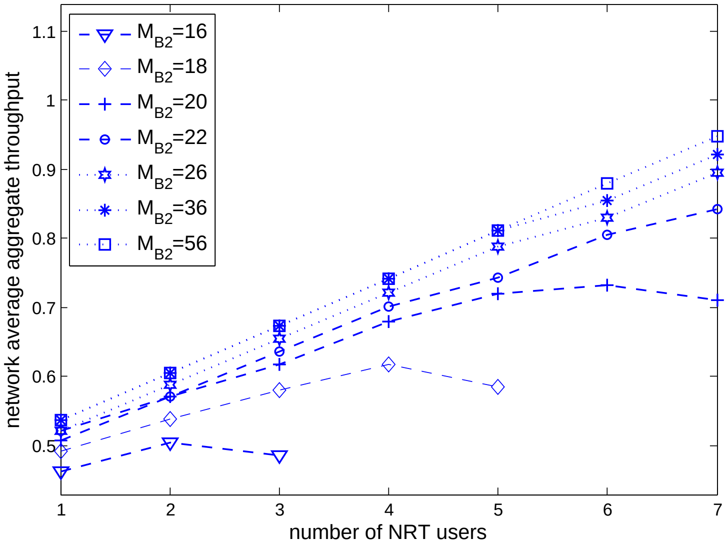

Figure 4.31: The network aggregate throughput with respect to the number of the NRT access users for different numbers of the SUs in the network.

channels, and there is always an optimum number of them maximizing the aggregate throughput. However, even at the optimal number of the NRT access users, the aggregate throughput is relatively low. This is because there is balance between the number of the sensing users and the number of the access users in the MAC framework, i.e., balancing between identifying the available channels and exploiting these channels. On the other hand, when the total number of the SUs is high, the aggregate throughput always increases with the increase of the number of the NRT access users since there are enough number of sensing users that can identify all the available channels. The aggregate throughput can be efficiently utilized by allowing each NRT access users to access more than one available channel as will be discussed in the following figure.

Figure 4.32 illustrates the average number of the RT access users, NRT access users, allocated channels to each NRT access user, and the average aggregate throughput of the network with respect to the total number of the SUs in the net-

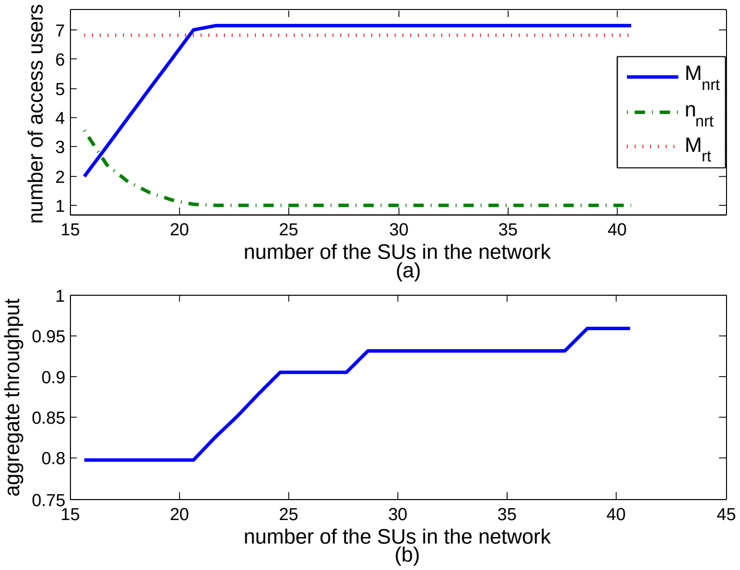

Figure 4.32: Relation between the number of the SUs in the network and: (a) the average number of the RT access users, NRT access users, and NRT allocated channels; and (b) the network average aggregate throughput.

work. Since the RT users have priority to access the available channels, a number of RT users, which guarantees the acceptable dropping and blocking probabilities, access the available channels regardless of the total number of the users in the network, while a few NRT users can access the remaining available channels when the total number of the users in the network is small, as shown in Figure 4.31; however, to utilize the remaining available channels, more than one channel are allocated to each NRT access user, where the average number of the allocated channels decreases until it reaches only one channel per each NRT access user with increasing the total number of the users in the network. Moreover, the average aggregate throughput of the network increases with the increase of the total number of the users in the network since there are enough number of sensing and access users.

Figure 4.33 and Figure 4.34 show that the average number of the RT access users increases if the dropping and blocking probability thresholds are acceptably

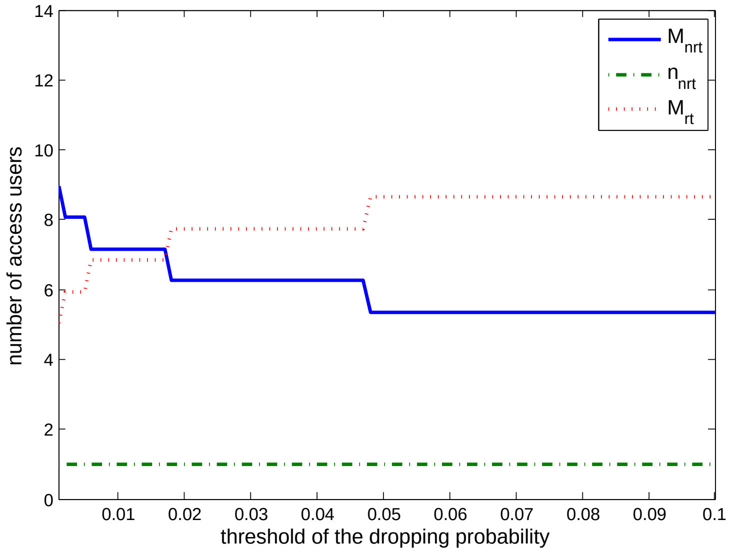

Figure 4.33: Average number of the RT access users, NRT access users, and NRT allocated channels for different threshold values of the dropping probability.

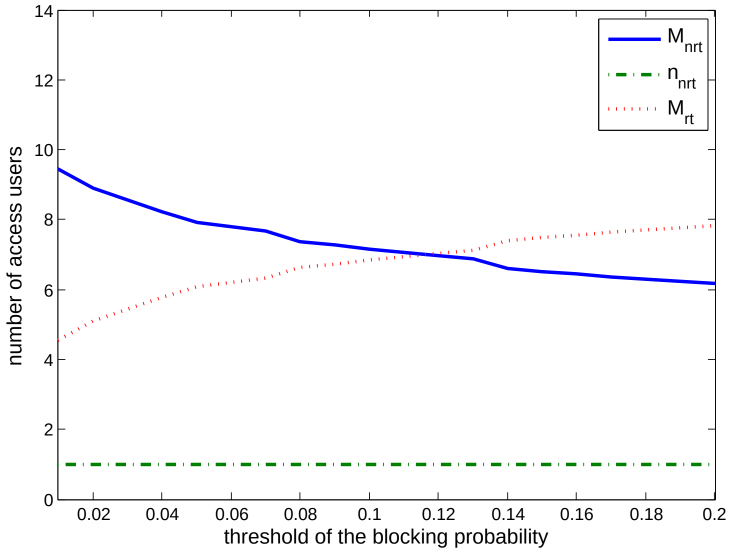

Figure 4.34: Average number of the RT access users, NRT access users, and NRT allocated channels for different threshold values of the blocking probability.

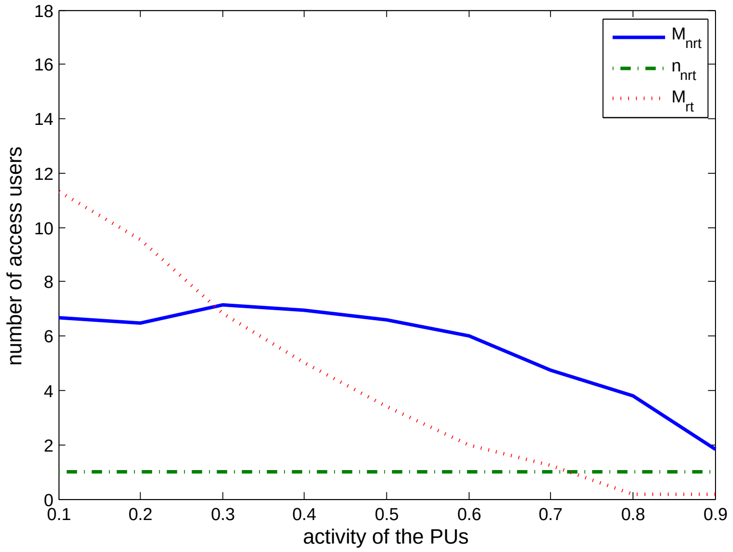

Figure 4.35: Average number of the RT access users, NRT access users, and NRT allocated channels for different values of the activity of the PUs.

increased; however this is at the cost of reducing the average number of the NRT access users. If the average number of the NRT and RT access users are required to be equal, there are specific values of the dropping and blocking probability thresholds that can be chosen, e.g., for the given set of parameters, the dropping probability threshold is around 0.018 and blocking probability threshold is around 0.12 as shown in Figure 4.33 and Figure 4.34, respectively.

Finally, Figure 4.35 shows how the activity of the PUs affects the average numbers of the RT and NRT access users. Both of them decrease with the increase of the activity of the PUs; however, the average number of the RT access users decreases faster since the RT users require strict dropping and blocking QoS levels that are highly dependent on the number of the available channels, while the NRT users only send their packets whenever there are available channels.

4.4 Summary

In this chapter, we have analytically studied the resource management in distributed single-hop CRNs. First, we have proposed a novel cooperative MAC framework for distributed CRNs considering the requirements of both the primary and secondary users. Moreover, we have investigated and analyzed an innovative deterministic spectrum sensing policy, and then we developed a simple computational but efficient spectrum sensing algorithm. This algorithm assists each SU to identify distributively and online which channels, how many channels, and for how long to sense. Second, we have proposed and analyzed an admission control scheme and channel allocation policy that can be integrated into the proposed MAC framework. We studied the relation between the sensing and access users to balance the spectrum identification and exploitation and to investigate the system parameters that can be adjusted to regulate the number of the SUs that can be admitted to the secondary network. Finally, we have proposed and analyzed a QoS-based spectrum allocation framework that supports heterogeneous secondary RT and NRT users in the distributed CRNs. This framework jointly considers the QoS provisioning with the spectrum sensing, spectrum access decision, channel allocation, and call admission control. Depending on the rigorousness of the PUs and using the proposed QoS-provisioning framework, the SUs in the network can distributively decide how many RT and NRT users can access the available spectrum and which channels to access.

Chapter 5

Resource Management in Multi-Hop CRNs

In this chapter, we introduce a novel user clustering scheme to efficiently manage the spectrum identification and exploitation in multi-hop ad hoc CRNs. We cluster the SUs based on their geographical locations and occurring time and use spread spectrum to facilitate using one frequency for the CCCs in the whole secondary network and to reduce the co-channel interference (on the data channels) between the adjacent clusters by assigning different spreading codes for different clusters. The proposed clustering scheme assists the SUs to initiate and maintain the clusters reliably with signaling inherent in the MAC framework; moreover, the SUs in each cluster can benefit from all the available spectrum without affecting other SUs in the adjacent clusters.

5.1 Introduction

The spectrum availability variation over time and locations creates serious challenges in different aspects in the basic design of ad hoc CRNs. In some situations, the SUs may be deployed in a communication area where they are out of the range of each other such as a large communication area or an area with some partitioning obstacles or shadowing regions. Therefore, the SUs should communicate in a multi-hop network. To improve the spectrum identification and exploitation in the multi-hop CRNs, we propose to cluster the SUs into adjacent clusters as discussed in the system model in Section 3.2.2. In the multi-hop ad hoc CRNs, one of the major challenges is how the SUs can exchange their control signaling to coordinate their spectrum sensing, spectrum allocation and access, and traffic routing. The intuitive way is to have a CCC, which can be in-band or out-of-band channel. However, the spectrum heterogeneity seen by the SUs in multi-hop ad hoc CRNs makes using a CCC an embarrassing challenge.

Spread spectrum can facilitate the use of one CCC for the whole secondary network if the adjacent clusters are assigned different spreading codes, so the same frequency can be used for the CCC of each cluster. If the CCC is required to be in-band channel, the OFDM-based TDCS [126], which is a spread spectrum technique, has some attractive features motivating to use it to access the CCC including:

- it is able to overcome the interference whether from PUs or other SUs using the same frequency channel since it works in the background noise level; therefore, it can be used for in-band CCC and can guarantee the tolerable interference to the PUs if they occur frequently on the CCC;
- it provides secure communication in the form of transmission security against malicious jamming;

- it provides multiple access if needed; and
- the transmitted power can be adjusted for short, medium, or long distance communication coverage.

The main drawback of this technique is its low data rate if it is required for long distance communication with very low power emission. However, the control packets sent on the CCC normally contain small size of information about the spectrum sensing and allocation especially within a small area, so its low data rate is not a concern. On the other hand, if the CCC can be a dedicated out-of-band channel, the traditional CDMA can be used to access the CCC.

The SUs in each cluster can use D-OFDM technique [129] to access the identified available channels, i.e., the data channels; however, the interference between neighboring SUs that may be allocated incidentally same available channels in adjacent clusters must be managed, which is a complicated process when using the D-OFDM access technique. Therefore, to reduce the co-channel interference between the SUs in adjacent clusters, we propose to use the MC-CDMA technique [129] to access the identified available data channels. By using different spreading codes for the adjacent clusters, the co-channel interference between the neighboring SUs of adjacent clusters assigned incidentally the same available data channels can be reduced.

In summary, to manage the spectrum identification and exploitation in the multi-hop ad hoc CRNs, we propose to group the SUs into clusters based on their geographical locations and their occurring time; moreover, by assigning different spreading codes for the adjacent clusters, we propose to use spread spectrum to facilitate using one frequency for the CCCs of the clusters in the whole secondary network and to reduce the co-channel interference (on the data channels) between the adjacent clusters.

5.2 MAC Framework

The system model of the multi-hop ad hoc CRNs is explained in Section 3.2.2. Since the CH of each cluster works as a central user that can assign the spectrum sensing task and allocate the available channels to the SUs, we modify the cooperative MAC framework proposed in Section 4.1, which is originally proposed for single-hop distributed CRNs, to manage the spectrum identification and exploitation in the multi-hop situation. In general, the two MAC frameworks have the same time structure shown in Figure 4.7; however, the tasks in each phase are slightly changed in addition to assuming each SU in the multi-hop case is equipped with two radios as discussed in Section 3.2.2.

The modified MAC framework is explained briefly as follows. At beacon B1, the CH broadcasts the sensing assignment vector that tells the CMs and CGs in the cluster which channels each user is required to sense. At the SRP, the sensing users start to sense the assigned channels using the CR and use the control radio to recognize the new registering SUs by listening to the registration signaling between the new SUs and the CH; while the CH registers the new SUs that want to joint this cluster using the control radio, and it can also sense its assigned channels using the CR. Then the sensing users report their spectrum observations at the RP to the CH, and the CH in its turn combines the cooperative sensing information about the available channels and broadcasts the spectrum allocation vector in beacon B2. Finally, at the DRP, the winning users from the previous time slot start to access their allocated channels using the CR, and all the SUs use their control radios to try to reserve the next time slot following a mechanism similar to the RTC/CTS method.

5.3 Clustering Scheme

5.3.1 Neighbor Discovery and Cluster Formation

The proposed clustering scheme is based on the geographical locations and the occurring orders of the SUs. The SUs first discover their neighboring SUs and then either join an existing cluster, if they can, or form new clusters. The neighbor discovery and cluster formation, which are jointly related, are explained in the following steps.

- Any new SU that wants to join the network monitors the predefined spectrum of the CCCs of the secondary network for a time longer than the time slot of the MAC framework and detects the activities of the SUs for all the spreading codes in the code pool, CP. In the performance analysis, we will prove that 7 spreading cods are sufficient for the whole CRN.
- If the new SU detects beacon(s) of CH(s): 1) it chooses the CH with the strongest signal as its home CH and records the ID(s) of the other clusters (if any) as neighboring clusters; 2) it sends a request-to-register (RTR) packet, using the codes of the identified clusters to the chosen CH piggybacking its observations about its neighboring clusters at the SRP of the MAC framework; therefore, any nearby CH hearing this RTR packet records this new user as a CG to the intended cluster, and the chosen CH updates its members and neighboring CH lists; and 3) once the new SU is registered in the intended cluster, it follows the MAC framework that manages the spectrum identification and exploitation in that cluster.
- If the new SU detects signals of CMs or CGs but not CH(s): 1) it recognizes that it is 2-hop form nearby CH(s), so it records the ID(s) of the used

spreading code(s) and picks a different code from the CP and elects itself as a new CH; 2) it forms a new cluster and sends beacons at B1 and B2 of the MAC framework using combination of its code and the recorded code(s) of the adjacent cluster(s); and 3) any CM or CG hearing this beacons updates its neighboring cluster information and informs its home CH and neighboring CH (if any) about the new cluster.

- If the new SU does not detect any activity on the CCC for any spreading code, it picks any code from the CP forming a new separated cluster and sends beacons at B1 and B2 frequently until some SUs join this cluster and may connect it to the other clusters.

The connected clusters work synchronously, and once the separated clusters become connected to each other, the SUs in each cluster update their synchronization using any technique used in the traditional ad hoc networks [130]. The synchronization between the clusters is important to unify the sensing duration and consequently the whole MAC frame time, so the SUs can detect the PUs without confusing with other SUs.

5.3.2 Inter-cluster Communication

As shown in Figure 3.3, two adjacent clusters may have more than one CG to reduce the congestion at the CGs; consequently, the problem of bottleneck connection between the clusters can be alleviated. The CGs use store-forward delivery mechanism to connect between two clusters. In general, there are two types of CGs: a CG that is 1-hop from its home CH and also from a CH of a partially overlapping cluster, and a CG that is 1-hop from its home CH and 2-hop from a CH of an adjacent cluster. In the first type, the CG uses its home code to coordinate with the members of its home cluster, then it shift to the code of its neighboring cluster, so it can hear the coordination signaling on the CCC of the two clusters one at a time.

In the second type of CGs, the CG needs a peer CG from the neighboring cluster to deliver the packets from its home cluster to the adjacent cluster. Therefore, the peer CGs of this type require a kind of extra coordination to make an agreement on the data channels. This coordination can be made following these steps:

- the CG, which wants to deliver packets to a neighboring cluster, sends an RTS on the CCC using a combination of its code and the code of its neighboring cluster including its preference group of licensed channels;
- the peer CG reply to the RTS by a CTS using the two codes including the chosen preference channel group;
- since the home CH hears the RTS and the neighboring CH hears the CTS, both of them assign the available channels of the preferred channel group after the spectrum sensing to these peer CGs; and
- the sending CG starts to send the data on its allocated channels since the chance of having the same available channels at the peer CG is high because both of them are close to each other and expected to be under the same set of PUs' activities.

To guarantee common available data channels, an alternative mechanism for the last step is to let the receiving CG to send its list of available channels to the sending CG, and then the sending CG chooses the common available channels and send on them; however, this mechanism requires one more control signaling between the peer CGs. This mechanism can be an option in the case of severe spectrum heterogeneity.

5.4 Resource Allocation and Admission Control

Using the MAC framework in Section 5.2, three main processes can be controlled: the spectrum identification, spectrum allocation, and user admission. Based on the number of the SUs in each cluster, the CH can decide how many licensed channels each user should sense and which channels should be sensed cooperatively, and then the CH broadcasts the sensing assignment vector on the CCC. Therefore, the spectrum sensing is decided by the CH in this framework instead of the distributed individual sensing decision in the sensing policy of the MAC framework in Chapter 4. Moreover, the proposed spectrum allocation and user admission control schemes for single-hop CRNs in Chapter 4 can be used here for multi-hop CRNs with two main differences: 1) the CH in each cluster is always the network coordinator in the multi-hop case instead of a different network coordinator at each time slot in the single-hop case, 2) having two radios for each SU in the multi-hop case instead of a single radio in the single-hop case to assist the SUs in the multi-hop case to perform two functions at the same time such as sensing the licensed channels and monitoring the CCC at the SRP, and transmitting and negotiating with other SUs at the DRP.

5.5 Performance Analysis

5.5.1 Interference Reduction

The main advantage of using the spread spectrum techniques in our clustering scheme is to reduce the interference from other SUs using the same frequency bands. In case of in-band CCC, the OFDM-based TDCS technique allows using the same frequency for the CCC in each cluster when the adjacent clusters are assigned different orthogonal spreading codes; moreover, this technique can overcome the interference from PUs partially use the same frequency of the CCC, i.e., the SUs are still able to use the CCC without need to change it when the PUs occur on this channel. On the other hand, the MC-CDMA technique is used to access the identified available channels, i.e., the data channels, in each cluster to reduce the co-channel interference between neighboring SUs in adjacent clusters incidentally transmitting on the same channels. Based on the MAC protocol, in each cluster, only one SU can transmit on the CCC in a given time, and a number of SUs can send concurrently on different identified available channels, i.e., the SUs of each cluster are scheduled properly to prevent their mutual interference within their cluster. Therefore, the interference that should be reduced comes from the neighboring SUs in the adjacent clusters. The general form of the signal-to-interference-and-noise ratio (SINR) at receiving user i using spread spectrum can be given as

$$\mathrm{SINR}_i = \frac{P_i}{N_o + \sum_{j \neq i} I_{ji} + \epsilon P_{PU}}, \tag{5.1}$$

where P_i is the received power at user i from the intended transmitter, N_o is the background AWGN power, and I_{ji} is the received interference from user j at user i. In case of using in-band CCC, $\epsilon \in \{0, 1\}$ that indicates the presence of a PU on the used channel with $\epsilon = 0$ means there is no PU, while $\epsilon = 1$ means there is a PU on the channel, and P_{PU} is the received power of a PU. The transmitting user uses the OFDM-based TDCS technique and should adjust its transmitting power to accommodate the presence/absence of the PU by sending with P_0 when $\epsilon = 0$ and with P_1 when $\epsilon = 1$, so the SINR is maintained almost the same at the receiving user within each cluster. In case of using out-of-band CCC, (5.1) with $\epsilon = 0$ is valid for both the control and data channels since the control channel is dedicated for the SUs as a CCC and each data channel is accessed only when it is vacant assuming perfect sensing.

Considering the omni-directional transceiving of identical users, the clustering theoretically forms a combination of overlapped and non-overlapped circles. From circle packing problem, the maximum number of identical adjacent circles with non-overlapped centers is 6, where the maximum interference occurs from hexagonal packing with 6 circles in the first-tier and $6k$ circles in the k-th tier of circles [131]. Normally, the first-tier co-channel interference is sufficient to calculate the bit-error rate (BER) performance of the system. In fact, the BER performance of the TDCS and MC-CDMA have many details to deal with, which are out of the scope of this thesis; however, for completeness, we give a simple example on the performance of these two techniques that can fit to our system model in this chapter. In [126], it was proven that a BER of 10^{-3} for around 10 access users can be achieved using OFDM-based TDCS at SINR less than -12 dB; while in [128], the same BER performance can be achieved using MC-CDMA at SINR around 12 dB. The very low SINR of the TDCS reflects its ability of working in the background noise of the PUs, while the relatively higher SINR of the MC-CDMA indicates the need of spectrum sensing before using the data channels.

The number of the maximum interfering clusters also important to determine the size of the code pool, CP, i.e., the number of the required spreading codes. To reduce the time and computations of joining or initiating a cluster, it is desirable to have a small size of CP by reusing the codes in cluster constellations that do not interfere with each other similar to the systematic method of reusing spectrum frequencies in the cellular system. From the maximum interference discussed above, 7 spreading codes are enough for the whole network considering the interference from the first-tier clusters.

5.5.2 Number and Size of Clusters

From the nature occurrence and deployment of the SUs, the secondary network has a random number of clusters with random topology; consequently, it is very

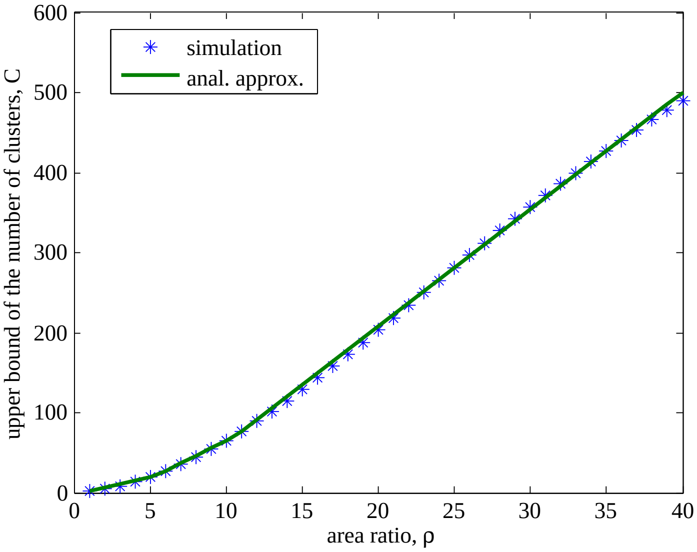

Figure 5.1: Upper bound of the number of the clusters in the network.

complicated to estimate or find the distributions of the number of the clusters and the number of the SUs in each cluster. Even an upper bound of the number of the clusters is very hard to be obtained analytically; however, it can be estimated using simulation. For large number of SUs in an W x W area, the relation $W^2/(\pi r^2) = kC$ should be held, where r is the radius of the cluster, C is the number of the clusters, and k is a factor indicating the overlapping between the clusters. Therefore, the number of the clusters is proportional to the area ratio $\rho = W/r$. By conducting extensive simulation with different combinations of W and r for practical values of ρ, e.g., $1 \leq \rho \leq 40$, Figure 5.1 can be obtained, and the results can be approximated analytically as

$$C = \begin{cases} 04.60\rho - 02.98 & 01 \leq \rho \leq 05 \\ 09.52\rho - 29.81 & 06 \leq \rho \leq 10 \\ 14.59\rho - 83.49 & 11 \leq \rho \leq 40. \end{cases} \tag{5.2}$$

Now, the upper bound of C in an W x W area can be estimated for practical ρ

using (5.2) and the lower bound is intuitively equal to one. The values of C between these bounds and the average number of the SUs in the clusters can be found by simulation.

5.5.3 Spectrum Sensing Ability and Utilization

The SUs in each cluster identify and exploit the available spectrum independently on the other clusters. That means the whole intended licensed channels can be exploited in each cluster if there are enough sensing and accessing users that can identify the available channels and then access them. Therefore, it is expected that the spectrum utilization will be improved in the whole secondary network with increasing the number of the clusters, which is similar to the spectrum reuse in the cellular network system.

The spectrum identification has two phases: spectrum sensing at the SRP and spectrum reporting at the RP in the MAC framework. The duration of these two phases together, T_s, is fixed for the whole secondary network, so the synchronization between the clusters in the whole secondary network is maintained; however, the sensing duration, T_{SRP}, and the reporting duration, T_{RP}, can be adaptively changed in each cluster by the CH based on the number of the SUs in each cluster. The relation between these durations is given as

$$\begin{aligned} T_s &= T_{SRP} + T_{RP} \\ &= nt_s + (M_s - 1)t_r, \end{aligned} \tag{5.3}$$

where t_s is the time required to sense each licensed channel, which can be given by (4.29), M_s is the number of the sensing users, and n and t_r are the number of the sensed channels and the time to report the sensing results per each sensing user, respectively. Using (5.3), the total number of the sensed channels in the cluster is given by

$$\begin{aligned} N_C &= nM_s \\ &= \lfloor (M_s T_s - M_s(M_s - 1)t_r)/t_s \rfloor , \end{aligned} \tag{5.4}$$

where $\lfloor \cdot \rfloor$ is the floor operator.

Now, we want to study the sensing capability of the SUs in each cluster. From (5.3), the number of the sensing users is given as

$$M_s = \lfloor (T_s - nt_s + t_r)/t_r \rfloor . \tag{5.5}$$

The maximum number of the sensing users is when $n = 1$, i.e., $M_s^{max} = (T_s - t_s + t_r)/t_r$. Moreover, from (5.3), the number of the sensed channels per user is given as

$$n = \lfloor (T_s - (M_s - 1)t_r)/t_s \rfloor \tag{5.6}$$

with maximum value when $M_s = 1$, i.e., $n^{max} = T_s/t_s$, where there is no need to report sensing results since the CH is the only user that senses in this case. Therefore, the number of the sensing users and the number of the sensed channels per user are bounded as $1 \leq M_s \leq M_s^{max}$ and $1 \leq n \leq n^{max}$, respectively, with optimum values obtained by maximizing (5.4) to get

$$M_s^* = (T_s + t_r)/(2t_r) \tag{5.7a}$$

$$n^* = (T_s + t_r)/(2t_s); \tag{5.7b}$$

consequently, the maximum number of the channels that can be sensed in each cluster is $N_C^* = n^* M_s^* = (T_s + t_r)^2/(4t_r t_s)$.

Considering the number of the SUs in each cluster, M_C, when $M_C > M_s^*$, the CH calculates M_s^* and n^* as above and then decides which users sense which channels, and the remaining users, i.e., $M_C - M_s^*$, are given rest at this time slot and will be assigned channels to sense in the coming slots; however, when $M_C < M_s^*$, the CH calculates n using (5.6) with $M_s = M_C$ and then assigns the sensing task among these sensing users. In general, when $N_C > N$, more sophisticated cooperative sensing can be decided by the CHs, e.g., using the m-out-of-M_s rule with $m = 1$ (OR rule) means at least one sensing user and $m = M_s$ (AND rule) means all the sensing users, respectively, must observe the presence of a PU on the intended channel to announce that channel as an unavailable one. In this chapter, we use the OR-rule sensing decision. Moreover, the CHs may assign the same channel group to be sensed by the transmitting and receiving nodes to allocate the common available channels to them. This sensing assignment is important especially when the two SUs are in different clusters as mentioned in Section 5.3.2.

The spectrum utilization can be defined as the percentage of the actual usage of the available spectrum. From the MAC frame time shown in Figure 4.7 and without considering the sensing errors, the spectrum utilization in cluster i can be given as

$$\begin{aligned}\eta_i &= \frac{(T - T_s - T_B)}{T}\frac{\min(N_{C_i}, N)}{N} \\ &= \frac{(T - T_s - T_B)}{TN}\min\left(\left\lfloor \frac{M_{s_i}T_s - (M_{s_i}^2 - M_{s_i})t_r}{t_s}\right\rfloor, N\right),\end{aligned} \tag{5.8}$$

where T is the time slot duration of the MAC, N is the number of the licensed channels, and $T_B = T_{B1} + T_{B2}$ is the time duration of beacons B1 and B2. Finally, the average spectrum utilization of the secondary network is given by

$$\eta = \frac{1}{C}\sum_{i=1}^{C}\eta_i. \tag{5.9}$$

5.6 Simulation Results

In this section, we evaluate the performance of the proposed spectrum management scheme. Different numbers of SUs are randomly deployed in 1000 m x 1000 m area, where each SU has a 200 m communication range. The time parameters of the MAC framework are set up (in ms) as: T =100, T_B =0.2, T_s =10, t_r =0.1, and t_s =2; and the number of the licensed channels is 50 channels. Each value of the simulation results is averaged over 50 random network topologies.

Figure 5.2 shows the relation between the number of the SUs in the whole secondary network with the number of the formed clusters and the average number of the SUs in each cluster. As expected, with increasing the number of the SUs, the number of the clusters increases fast and then saturates at the maximum number of the clusters that can be formed in the area, where the chance of the new SUs to find existing clusters to join increases with increasing the number of the SUs. Moreover, the average number of the SUs in the clusters increases linearly with increasing the number of the SUs in the secondary network, i.e., more SUs are accommodated in each cluster based on their locations.

In Figure 5.3, the number of the sensed channels in each cluster increases linearly with increasing the number of the SUs in the network since the average number of the SUs in each cluster increases, while the spectrum utilization increases linearly until it reaches the maximum value that can be achieved using this MAC framework, where almost 5% of the MAC time is used for sensing and exchanging the control signaling.

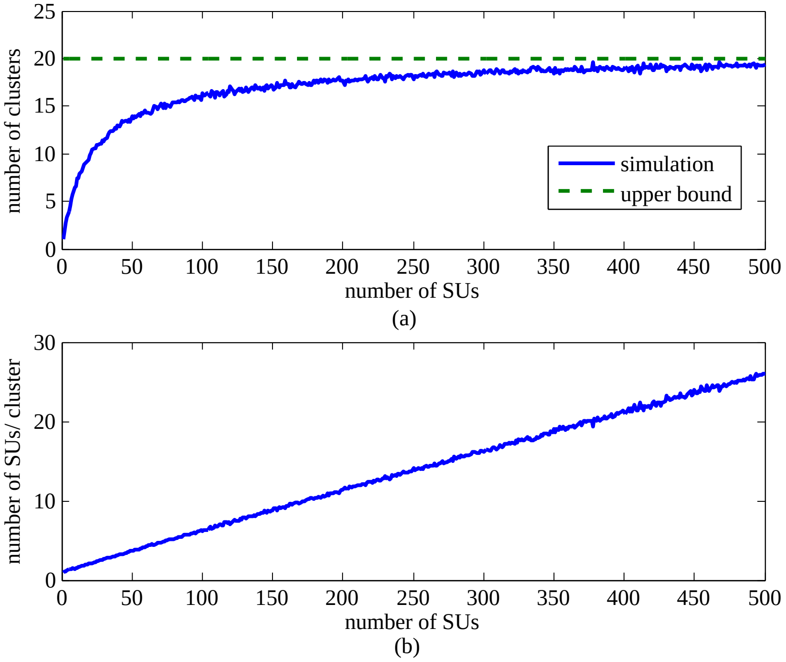

Figure 5.2: Number of the clusters and average number of the SUs in each cluster.

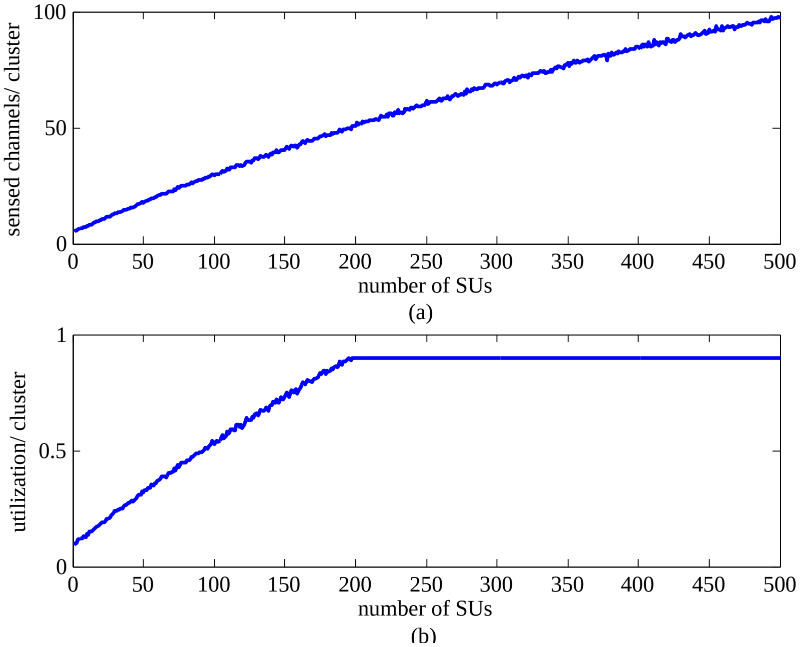

Figure 5.3: Number of the sensed channels and spectrum utilization in each cluster.

5.7 Summary

In this chapter, we have analytically studied the resource management in multi-hop CRNs. First, we have modified the cooperative MAC framework proposed in Section 4.1, which originally deals with the single-hop distributed CRNs, to manage the spectrum identification and exploitation in the multi-hop situation. We then proposed a novel clustering scheme for spectrum management in multi-hop ad hoc CRNs. In addition to addressing the challenge of using one frequency for all the CCCs of the clusters, we have treated the co-channel interference between the SUs in adjacent clusters. The proposed clustering scheme allows the SUs in each cluster to cooperatively identify the available spectrum and then make use of all the available channels for multiple concurrent transmissions.

Chapter 6

Conclusions and Further Works

Although cognitive radio networks, CRNs, have a potential solution to the spectrum scarcity by introducing a novel paradigm of wireless networking, the new challenges accompanying the CRNs should be tackled first to visualize the revolution of this kind of wireless networks. The spectrum availability variation over time and locations due to the coexistence with the primary users, PUs, and the spread of the spectrum opportunities over wide spectrum bands create great challenges in different aspects in the resource management of these networks. The aim of this thesis is to study the resource management in cooperative CRNs. In this chapter, we summarize the achieved research contributions of this thesis and propose some future research works.

6.1 Major Research Contributions

The major contributions of this thesis are summarized as follows:

- We have proposed a novel cooperative MAC framework for distributed CRNs considering the requirements of both the primary and secondary users. By dividing the secondary users, SUs, into sensing and accessing groups, they can cooperate to identify and then exploit as many unused channels as possible. We then investigated and analyzed a simple computational but efficient spectrum sensing algorithm that relies on an innovative deterministic spectrum sensing policy. This algorithm assists each SU to identify online and distributively which channels, how many channels, and for how long to sense. We have found that using the proposed MAC framework with this sensing algorithm, the spectrum opportunities can be identified efficiently even with only a few number of SUs each equipped with a CR transceiver. Consequently, the secondary throughput and hence the spectrum utilization can be maximized while constraining the interference to the PUs.

- We have proposed and analyzed an admission control scheme and channel allocation policy that can be integrated in the proposed MAC framework. We studied the dynamic relation between the sensing and access users in the network to balance the spectrum identification and exploitation and then to determine the number of the new SUs that can be admitted into the secondary network. With the help of the secondary network coordinator in each time slot, the admitted SUs use their dynamic IDs and the IDs of the identified available channels to distributively decide which available channels can be allocated to each of them.

- We have proposed and analyzed a QoS-based spectrum allocation framework that supports heterogeneous secondary RT and NRT users in CRNs. This framework jointly considers the QoS provisioning with the spectrum sensing, spectrum access decision, channel allocation, and call admission control. Based on the statistical information of the available licensed channels, a number of the available channels, which are identified after spectrum sensing, are allocated to the optimum number of real-time, RT, users considering their acceptable dropping and blocking probability requirements. The remaining available channels are allocated to the adaptive optimum number of non-real-time, NRT, users considering the spectrum sensing and utilization essentiality. Depending on the rigorousness of the PUs and using the proposed QoS-based spectrum resource allocation framework, the SUs in the cooperative CRNs can efficiently utilize the unused spectrum and guarantee the QoS levels of both the RT and NRT users served concurrently in the network.

- We have proposed to partition the secondary network into adjacent clusters of SUs to overcome the problem of spectrum heterogeneity, so the available spectrum can be efficiently managed. Since there is a central user in each cluster that can manage the spectrum sensing assignment and spectrum access allocation, we have slightly modified the cooperative MAC framework that we have proposed for the single-hop distributed CRNs to manage the spectrum identification and exploitation in the multi-hop situation. We then proposed a novel clustering scheme for spectrum management in the multi-hop ad hoc CRNs. Emulating the natural deployment of the users, the SUs are clustered based on their geographical locations and occurring times. In addition to addressing the challenge of using one frequency for all the common control channels, CCCs, of the clusters, we have treated the co-channel interference between the SUs in adjacent clusters using spread spectrum techniques. The proposed clustering scheme allows the SUs in each cluster to cooperatively identify the available spectrum and then make use of all the available channels for multiple concurrent transmissions.

6.2 Further Research Works

Our research work in this thesis focuses on the resource management in CRNs to provide opportunistic communications. The following relevant research topics are of importance and deserve further investigation:

- The licensed channel occupancy is modeled as a two-state Markov chain (i.e., ON/OFF source model) in Section 3.1, which is a common model widely used in CRNs. Although this model simplifies the analysis due to the memoryless feature of the distribution of the two-state periods, more sophisticated model that can catch accurately the practical situations of the activities of the PUs on the licensed channels is sought. The states of the PUs during each time slot of the MAC framework are considered constant in Section 4.1.1 since the PUs are legacy systems that usually last for long time in the ON or OFF state. In case the PUs change their states within the time slot frequently, their performance should not be affected significantly since the interference from the SUs will be tolerable. However, the collision between the SUs and the recurrent PUs after sensing period may affect the performance of the SUs in some degree; moreover, the absence of the PUs after the sensing period also may affect the spectrum utilization. Therefore, modeling the effects of the occurrence/absence of the PUs within the time slot of the MAC framework and including these effects in the analysis of the system performance is worth more investigation.

- In analyzing the average aggregate throughput of the SUs considering the spectrum errors in Section 4.1.3, we considered the threshold-value requirements of the most conservative PUs; therefore, any less conserving PU will not be affected. However, to efficiently utilize the unused spectrum, these threshold values should be adaptive to the variant types of the PUs, which may requires some information about the behavior of the PUs. Considering adaptive threshold values for variant PUs' requirements is of our interest in the future work.

- In the distributed channel allocation policy in Section 4.2.2, the SUs are allocated some identified available channels regardless of the local environments of the SUs. In the distributed networks, it is very hard to find a resource allocation scheme considering the channel preference of each user with reasonable overhead signaling. This problem is open for future research.

- In the multi-hop CRNs, traffic routing is very challenging, where choosing the route should be spectrum aware. Developing a routing protocol for the multi-hop CRNs with the clustering scheme proposed in Chapter 5 and then analyzing the secondary traffic delay in the secondary network are of our interest in the future work.

- In the literature, there is little attention in studying the effects of the spectrum variation on the transportation layer of the CRNs. Packetizing the traffic with variable packet size at the transport layer and the traffic rate should be spectrum aware. Studying this topic is worth insight investigation.

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