Cognitive MAC Protocols for Mobile Ad-Hoc Networks

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Abstract

The term of Cognitive Radio (CR) used to indicate that spectrum radio could be accessed dynamically and opportunistically by unlicensed users. In CR Networks, Interference between nodes, hidden terminal problem, and spectrum sensing errors are big issues to be widely discussed in the research field nowadays. To improve the performance of such kind of networks, this thesis proposes Cognitive Medium Access Control (MAC) protocols for Mobile Ad-Hoc Networks (MANETs).

From the concept of CR, this thesis has been able to develop a cognitive MAC framework in which a cognitive process consisting of cognitive elements is considered, which can make efficient decisions to optimise the CR network. In this context, three different scenarios to maximize the secondary user's throughput have been proposed. We found that the throughput improvement depends on the transition probabilities. However, considering the past information state of the spectrum can dramatically increases the secondary user's throughput by up to 40%. Moreover, by increasing the number of channels, the throughput of the network can be improved about 25%.

Furthermore, to study the impact of Physical (PHY) Layer errors on cognitive MAC layer in MANETs, in this thesis, a Sensing Error-Aware MAC protocols for MANETs has been proposed. The developed model has been able to improve the MAC layer performance under the challenge of sensing errors. In this context, the proposed model examined two sensing error probabilities: the false alarm probability and the missed detection probability. The simulation results have shown that both probabilities could be adapted to maintain the false alarm probability at certain values to achieve good results.

Finally, in this thesis, a cooperative sensing scheme with interference mitigation for Cognitive Wireless Mesh Networks (CogMesh) has been proposed. Moreover, a priority-based traffic scenario to analyze the problem of packet delay and a novel technique for dynamic channel allocation in CogMesh is presented. Considering each channel in the system as a sub-server, the average delay of the users' packets is reduced and the cooperative sensing scenario dramatically increases the network throughput 50% more as the number of arrival rate is increased.

To My Parents

Acknowledgments

I would like to thank my supervisor, Professor Hamed Al-Raweshidy, for his valuable advices, encouragement and guidance during my PhD study. He has been very kind, helpful, and supportive throughout the whole work.

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List of Abbreviations

ACK	Acknowledgement
AMRCC	Adaptive Multiple Rendezvous Control Channel
AP	Access Point
API	Application Programming Interface
BS	Base Station
BSS	Basic Service Set
CCC	Common Control Channel
CDMA	Code Division Multiple Access
CFP	Contention Free Period
CFSR	Channel Filtering Sender Receiver
CogMC	Cognitive Mesh Client
CogMesh	Cognitive Wireless Mesh Network
CogMR	Cognitive Mesh Router
CPC	Cognition enabling Pilot Channel
CR	Cognitive Radio
CRAHN	Cognitive Radio Ad-Hoc Networks
CS	Carrier Sensing
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CT2	second generation of Cordless Telephone
CTS	Clear To Send
CW	Contention Window
DAB	Digital Audio Broadcasting
DCF	Distributed Coordination Function
DIFS	Distributed Coordination Function Inter-Frame Space
DS	Distributed System
DSP	Digital Signal Processing
DSSS	Direct Sequence Spread Spectrum
DVB-T	Terrestrial Digital Video Broadcasting
EIFS	Extended Inter-Frame Space
EKBR	Extended Knowledge-Based Reasoning

EME	Energy with Minimum Eigenvalue
EU	European Union
FC	Fusion Centre
FCC	Federal Communications Commission
FCS	Frame Check Sequence
FDD	Frequency-Division Duplexing
FDM	Frequency-Division Multiplexing
FDMA	Frequency Division Multiple Access
FSA	Fixed Spectrum Access
GPRS	General Packets Radio Service
GSM	Global System for Mobile Communications
HDL	Hardware Description Language
HMM	Hidden Markov Models
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronic Engineering
IETF	Internet Engineering Task Force
IFS	Inter-Frame Space
IP	Internet Protocol
ISI	Inter-Symbol Interference
ITM	Interference Temperature Model
LAN	Local Area Network
LLC	Logical Link Control
LNA	Low Noise Amplifier
LTE	Long Term Evolution
MAC	Medium Access Control
MACA	Multiple Access Collision Avoidance
MAI	Multiple Access Interference
MANET	Mobile Ad-Hoc Network
MC	Mesh Client
MDP	Markov Decision Process
MF	Matched Filter
MME	Maximum-Minimum Eigenvalue

MR	Mesh Router
NAV	Network Allocation Vector
Ofcom	Office of communications
OFDM	Orthogonal Frequency Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
OSI	Open System Interconnection
PA	Power Amplifier
PC	Point Coordinator
PCF	Point Coordination Function
PHY	Physical
PIFS	Point Coordination Function Inter-Frame Space
POMDP	Partially Observed Markov Decision Process
PU	Primary User
QoS	Quality of Service
RCC	Radio Common Carriers
RF	Radio Frequency
RTS	Request To Send
SDR	Software Defined Radio
SE	State Estimator
SIFS	Short Inter-Frame Space
SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise Ratio
SPTF	Spectrum Policy Task Force
SS	Spread Spectrum
STBC	Space-Time Block Coding
SU	Secondary User
TDMA	Time-Division Multiple Access
UHF	Ultra High Frequency
UK	United Kingdom
UMTS	Universal Mobile Telecommunications System
US	United States

WiMAX	Worldwide interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMN	Wireless Mesh Network
WPAN	Wireless Personal Area Network
WWAN	Wireless Wide Area Network

Author's Declaration

The work described in this thesis has not been previously submitted for a degree in this or any other university and unless otherwise referenced it is the author's own work.

Statement of Copyright

Chapter 1

Introduction

1.1 Motivations

The rapid development in wireless communication applications has made data communications as well as multimedia communications have significant importance of interest and increasing need in our life nowadays. However, several challenges such as traffic congestion, spectrum scarcity, power efficiency, interference between multiple users and environment fading still stand obstacle in the way of widespread use of the wireless communications technology. Therefore, wireless networks elements including nodes, protocol layers, policies and behaviors, are limited and unable to make intelligent adaptations to overcome such mentioned problems and offer a new featured services such as providing ubiquitous wireless access or increasing the data rate of current systems. Although a huge amount of the spectrum sits idle at a specific time, one of the main reasons, which limit the ability of these elements of providing new featured services, is that we suffer from a lack of spectrum. This is because system designers usually give each system exclusive access to a certain block of spectrum in order to prevent interference between adjacent systems. Thus, there is a fundamental need to understand how to design and control the wireless applications that lies beyond what the current theory and science can provide.

The motivation of this research thesis can be summarized as follows:

1. In order to deal with such mentioned challenging demands, wireless networking has received a considerable importance in the field of research. Improving the existing protocols as well as developing new standards and technologies is the most approaches followed by many researchers and scientists from academia as well as industrial sector. Therefore, designing and developing models that allow different wireless systems share the spectrum to exploit the huge amount of the idle spectrum without causing excessive harmful interference to each other is needed. The key feature of such approaches that allowing a huge of data communications to take place in a given amount of spectrum, which would definitely lead to a revolution in the world of wireless services and technology.

2. In order to advance the idea of Cognitive Radio (CR) technology [1]-[2], which has the promise to remove the mentioned limitations and impediments, developing the Medium Access Control (MAC) and the Physical (PHY) layers design to allow more flexibility for the radio system is needed. This trend is capable to allow the network elements observe, learn, detect, and act to adapt their system legacy and optimize their network performance.

1.2 Aims and Objectives

This thesis aims at the following:

- Designing and developing a Partially Observed Markov Decision Process (POMDP) theory based CR Network model, with dividing the spectrum radio into multi channels and multi time slots. The objective of this design is to increase the chance of opportunistic spectrum access and improving the network performance.

- Introducing a time slotted MAC protocol Improves the performance of MAC layer by enhancing the throughput of the secondary user. The introduced mechanism must enable the user to manage the access decision process and select the appropriate channel and time slot to avoid any harmful interference with the licensed user.

- Examining the access decision process and the performance of MAC layer under constrain of some defaults by developing the proposed model considering the sensing errors. The objective is to enable users to adapt some sensing and access parameters to improve the throughput with respect of low Signal-to-Noise-Ratio (SNR).

- Addressing the problem of time delay and hidden terminal problem by designing a MAC protocol that choose the right channel at the right time, eliminating the handoff latency and reducing the handshake mechanism in heterogeneous wireless networks. The objective is firstly to reduce interference between users to maintain the primary network legacy, and secondly to enable more data rate to increase the capacity of the secondary user network.

1.3 Contribution

This thesis contributes to knowledge by designing a POMDP based cognitive MAC model for mobile nodes with multiple channel access, aiming at: firstly, increasing the network capacity of the secondary network, and secondly, mitigating the interference with the primary network at the same time.

Furthermore, the thesis presents a novel pre-sensing mechanism reducing the unnecessary handovers by controlling the handoff decision process by applying the pre-sensing strategy with packet fragmentation scenario for both resource allocation and priority based cooperative access in Wireless Mesh Networks.

The key contributions of this work are summarized as follows:

1. POMDP-based framework, specifically designed for CR MANETs. This design is specified by a finite set of states S, set of control actions A, a transition probability P, and a reward function R. The main goal behind using this strategy is to find sensing and access policies to optimize the CR network and to maximize the throughput of unlicensed users by maximizing the expected sum of rewards R.

2. POMDP-based cognitive MAC protocols (CogMAC) specifically designed for multiple channel access networks. CogMAC uses also time-slotted approach to manage the sensing period and the access process between different secondary users and primary users.

3. A spectrum sensing strategy to mitigate the Interference between CR users and primary users under the constraint of sensing errors. Both false-alarm and missed-detection probabilities are considered and adaptive parameters scenario is proposed.

4. A message fragmentation strategy to address the problem of fairness and the problem of packet loss. As the proposed model is time slotted based, we propose that each packet does not exceed certain length that match the slot size. Thus, all users are allowed to access the medium fairly and we insure retransmitting a small-lost packet instead of retransmitting the whole message.

5. A cooperative sensing strategy to be done between mesh nodes to enable efficient access to the available spectrum by exchanging prior sensing scenario between the mesh routers and clients. A pre-sensing counter is defined between secondary users who will be responsible of maintaining the available channels and accordingly fair share between secondary users can be calculated.

6. A priority-based traffic scenario to analyze the problem of packet delay and measure the effect of using multiple channel access scheme on reducing the average waiting time under different secondary and primary arrival rates.

1.4 Research Methodology

The research methodology used for conducting the research presented in this thesis is summarized as follows:

1. The initial phase of this research focuses on a literature review including: books, conference proceedings and journal papers, different relevant research articles and different white papers on spectrum sensing, spectrum access, spectrum sharing, channel assignment and resource allocation in CR Network. In particular, in this work, basic definitions and classifications of Cognitive MAC and PHY protocols for Mobile Ad-Hoc Networks (MANETs) [3] and Wireless Mesh Networks [4] were investigated and developed.

2. In order to advance and develop our study, a POMDP framework composed of different components and interactions represent the core network architecture is

designed. The POMDP framework is a dynamic system can be used to achieve a cognitive process leading to automated decision-making.

3. To create a transmission scenario based on efficient sensing and access strategies, a cognitive MAC protocol is proposed. The proposed scheme employs POMDP approach, which is specified by a finite set of states and actions to find transmission policies to optimize the CR network. To make our research easy and clarify our idea, a literature review was followed by mathematical study and analysis for each proposed scenario and different parameter settings and strategies were carried out according to the need of each individual case.

4. To validate the proposed schemes and the developed models, the simulation results are presented and the performance of the network is investigated. The simulation environment was based on MATLAB simulator, which provides easy interactive environment and fast numerical algorithms. It allows matrix manipulation, Implementation of algorithms, creation of user interfaces, interfacing with programs in other languages and plotting of functions and data.

1.5 Thesis Structure

This thesis consists of seven chapters. Following the introductory Chapter 1, Chapter 2 introduces the MANETs with presenting its advantages and characteristics. In addition, the MAC and PHY layers are introduced and the principles of multiple access technology are overviewed in brief. Beside, the basic concepts and definitions of cognitive radio networks and SDF technology are given in Chapter 2. The aim is to provide sufficient information to understand the CR technology and its role in developing the wireless communications services and applications.

Chapter 3 provides a detailed description with mathematical analysis of different components of POMDP-based multi-channel and time slotted cognitive MAC protocol for MANETs. The proposed model is designed for unlicensed user, which can be enabled to access the large amount of unused spectrum allocated for a licensed user, in an intelligent way, without causing any harmful interference. In addition, the mechanism of the proposed model is to sense the radio spectrum, detect the occupancy state of different primary channels, and then opportunistically communicate over unused channels (spectrum holes). In this chapter, different scenarios are introduced and the output of the comparative analysis of the proposed scenarios is investigated.

By developing the model proposed in chapter 3, chapter 4 address the problem of interference between the unlicensed and the licensed users which can be occurred when some free bands are further used by the licensed users. To alleviate such a problem, we present the joint sensing and scheduling scheme. Considering the sensing errors, we first investigate the impact of *false-alarm* and *missed-detection* probabilities on the MAC layer performance. We also, based on the proposed sensing strategy, investigate how the unlicensed users can access to the medium in an intelligent way to mitigate any harmful interference with the licensed users. Accordingly, the licensed users have to decide which and when that bands can be used. In particular, an optimal cross-layer design, spectrum sensing at PHY layer and spectrum access at MAC layer, is described.

Chapter 5 focuses more on the impact of sensing errors on the MAC layer performance, but this time in Cognitive Wireless Mesh Networks (CogMesh). In this chapter, a cooperative sensing scheme with interference mitigation for CogMesh is presented. A sensing strategy in which the mesh nodes (unlicensed users) can use the available licensed spectrum without causing harmful interference with the licensed users is presented. This chapter investigates the most important challenges such as Interference between simultaneous transmissions, fading and environmental noise that have been discussed widely in the research field.

Moreover, chapter 5 studies the queuing system delay in CogMesh, and a novel technique for dynamic channel allocation in CR networks is presented in this chapter. A priority-based traffic scenario to analyze the problem of packet delay and measure the effect of using multiple channel access scheme on reducing the average waiting time under different secondary and primary arrival rates is also presented. The aim is to determine the available channels priory and then allocate the arrival packets in a scenario such that the average delay of the mesh users' packets is reduced and high throughput can be achieved.

Finally, this thesis is summarized in chapter 6 and some ideas for future proposals are included based on the research carried out in this work.

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Chapter 2

Resource Allocation and Channel Assignment

2.1 Introduction

In contrast to wired networks where data as well as multimedia messages are exchanged from one host to another through a finite set of physical cables, wireless signal transmission occurs in the open air to be enabled within a given coverage range. This advantage offers to the mobile devices an unrestricted movement within a given coverage area where data is transferred using electromagnetic waves, most commonly via radio or infrared signals. In fact, wireless networks technology come to provide the power and freedom of mobility.

In general, the transmission in wireless networks can be done in one of two modes, ad-hoc or infrastructure mode. The ad-hoc mode is also defined as Independent Basic Service Set (IBSS) and the infrastructure mode as Basic Service Set (BSS). In infrastructure mode, a wireless node requires a central control unit, Access Point (AP), in order to connect to the network and provide the access control to the medium, see Figure 2-1. Each node sends and receives its communications via the access points. An access point is often a hub or router that has an antenna built in to transmit and receive the radio frequency and bridges a wireless network to appropriate network either wired or wireless network. A simple example of infrastructure networks is the cellular networks.

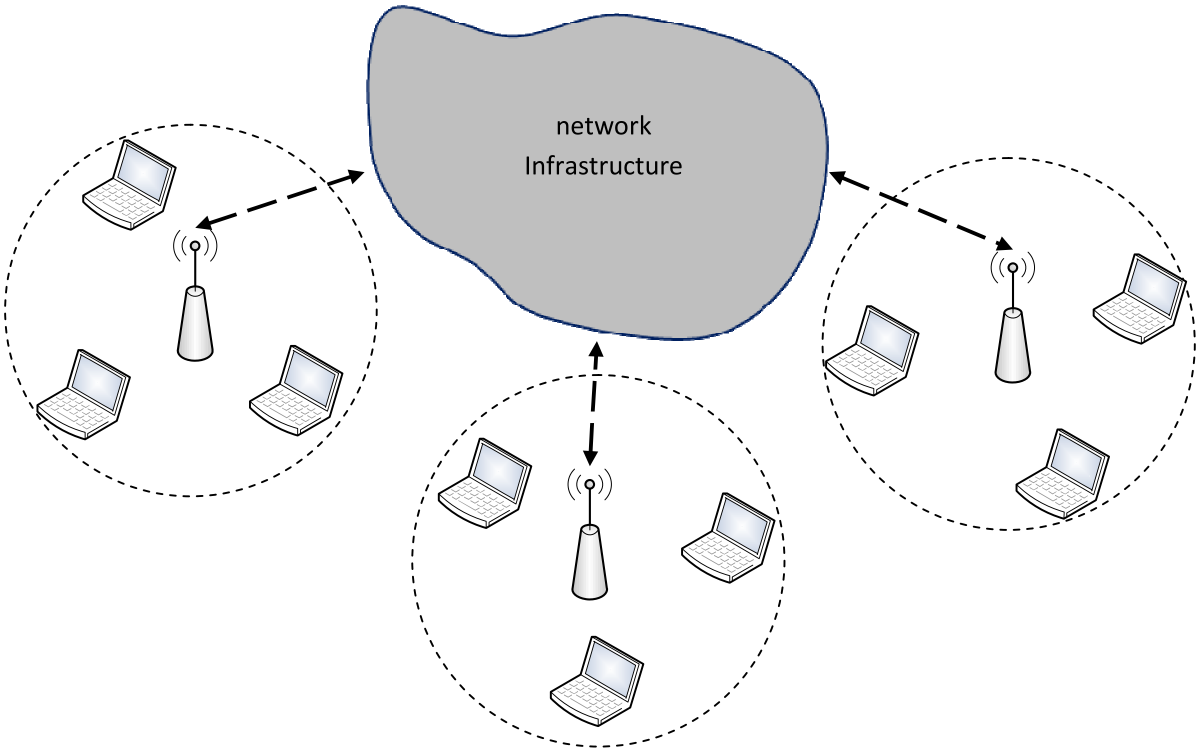


Figure 2-1: Infrastructure based wireless network

In contrast to infrastructure-based networks, in ad-hoc mode wireless nodes assist each other in transmitting and receiving packets across the network, see Figure 2-2. Mobile Ad-hoc Networks (MANETs) are a collection of mobile devices (nodes) moving within a geographical area to form a self-organizing, self-healing, self-configuring wireless networks. Nodes within the same transmission range can discover and communicate with each other directly without involving any central access points. Moreover, a node may join or leave the network at any time. In ad-hoc networks, all nodes have equal right to access the medium. To be able to establish communication with each other, each node must be able to see the others and send request a priory. The communication between the wireless nodes depends on whether they are within the radio range of each other. If a node wishes to communicate outside its range, i.e. the destination is beyond the source node coverage, another node within the same transmission range operates as a gateway to forward the contact as a multi-hop fashion to successfully relay the data traffic to the destination.

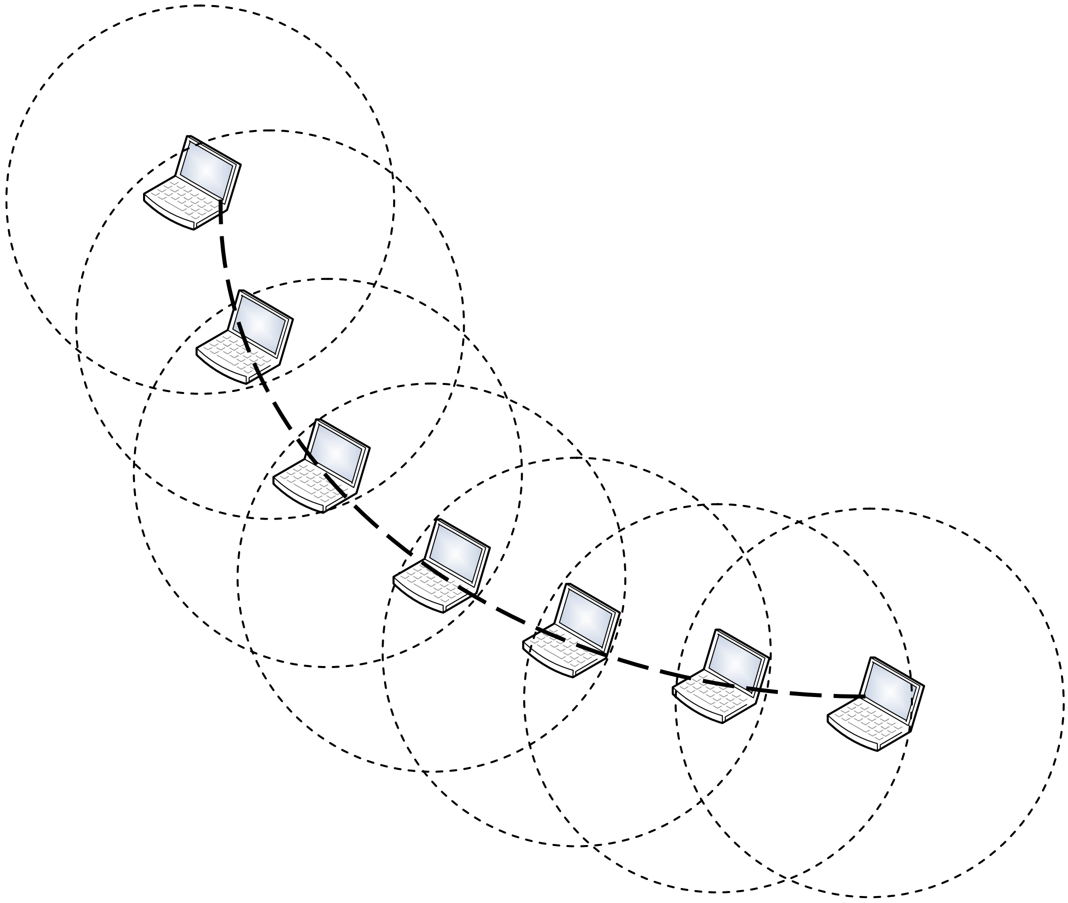


Figure 2-2: Mobile ad-hoc network

In multi-hop mode, the network consists of mobile radio repeaters, wireless terminals and dedicated mobile stations. The data packets are relayed from one hop to the other until data reached its destination. Beside to the multi-hop communication capability, the mobility support is another principal feature that a multi-hop network provides, allowing the wireless nodes to move within the defined area. Hence, data from the source needs to travel through several other intermediate nodes before it reaches the destination. Meeting rooms, sport stadiums, rescue and disaster recovery, battle-field and other applications that require rapid deployment and self-organizing fashion are some of the environments where MANETs can be applied.

The recent work related to ad hoc networks focus on many issues such as network architecture and network capacity. The problem of capacity is widely investigated and most researchers showed that the capacity could be increased as the size of the network is increased. In fact, the capacity of wireless ad hoc networks is based on the traffic behaviour at the Medium Access Control (MAC) layer. As each node in wireless ad hoc networks has to transmit relayed data as well as its own, so we need to discuss the issue of fairness. In addition, in wireless ad hoc networks as the traffic might be directed to the gateways, e.g. Wireless Mesh and Sensor Networks which are connected to external networks, these gateways would pose a bottleneck problem. In this case, we need to reduce the bottleneck wireless links along the path to the gateway. Other factors that influence the capacity of the network such as interference between simultaneous transmissions, fading, and environmental noise can also be considered. Therefore, the majority of MANETs' research work has been developed based on the specifications of MAC and Physical (PHY) layers.

2.1.1 Characteristics and Advantages

Mobile Ad-hoc Network (MANET) shares some common characteristics with wireless networks and preserves for itself some others that distinguish it as a special

- ***Wireless medium***: The MANET nodes communicate with each other wirelessly by sharing the same medium.
- ***Multi-hop communications***: The multi-hop feature of MANET allows the MANET node to communicate with any destination in the network, regardless whether the destination is within its radio range or not. Therefore, each node acts as a router to enable information routing between the source and destination.
- ***Autonomous and infrastructure-less****:* MANET does not rely on any sort of infrastructure. Hence, the network administration and control are performed in a distributed manner, where each node acts as an independent router.
- ***Mobility and dynamic topology****:* The mobility support in MANET permits the node to move around without interrupting the active communications. The mobility causes link breakage and topology variation, which in turns changes the connection patterns between the mobile nodes.

The above mentioned characteristics give MANETs important advantages over the other types of wireless networks in terms of moving while communicating, multi-hop communication ... etc. On the other hand, several challenges in the protocol design may rise, especially in developing routing protocols that has to cope with the nodes' mobility and the dynamic topology of the network.

2.2 Wireless Networking

In wireless networking, information is exchanged between nodes using radio frequency signals. The various types of wireless networks can be grouped in different ways depending on the criteria chosen for its classification. Such criteria include:

❶ The network architecture (Infrastructure or Infrastructure-less Networks).

❷ The network coverage (Wireless Personal Area Networks (WPAN), Wireless Local Area Networks (WLAN), Wireless Metropolitan Area Networks (WMAN) or Wireless Wide Area Networks (WWAN)).

❸ The network applications (home, sensor, vehicular, cellular networks ... etc).

2.2.1 OSI Model

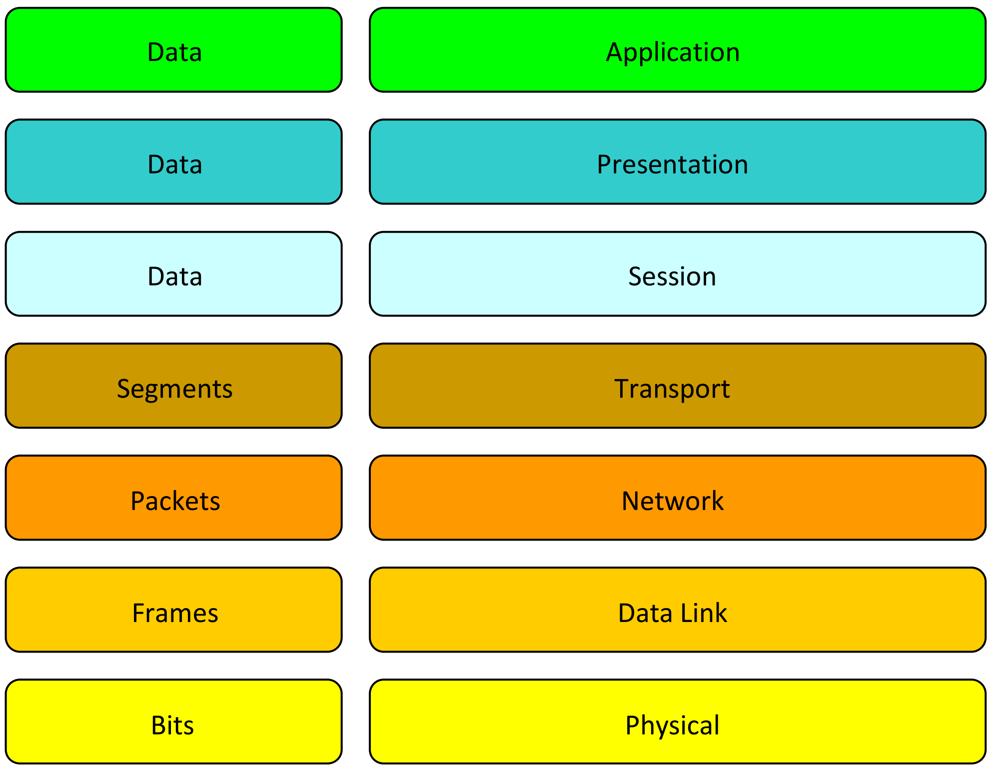


Figure 2-3: The seven layers of the OSI reference model

The *Open System Interconnection (OSI) reference model* describes how information from a software application in one computer moves through a network medium to a software application in another computer. The OSI reference model is a conceptual model composed of seven layers, each specifying particular network functions. The OSI model divides the tasks involved with moving information between networked computers into seven smaller, more manageable task groups. A task or group of tasks is then assigned to each of the seven OSI layers. Each layer is reasonably self-contained so that the tasks assigned to each layer can be implemented independently. This enables the solutions offered by one layer to be updated without adversely affecting the other layers. The following figure shows the seven layers of the OSI reference model.

2.2.2 The Physical Layer

The physical layer is the level one in the seven level OSI model of computer networking. This layer performs services requested by the data link layer. This level refers to network hardware physical cabling or a wireless electromagnetic connection. It also deals with electrical specifications, collision control and other low-level functions.

The physical layer is considered as the most basic network layer, providing only the means of transmitting raw bits. An analogy of this layer in a physical mail network would be a specification for various kinds of paper and ink, for example.

The major functions and services performed by the physical layer are:

❶ Establishment and termination of a connection to communication medium.

❷ Participation in the process whereby the communication resources are effectively shared among multiple users e.g. contention resolution and flow control.

❸ Conversion between the representations of digital data in user equipment and the corresponding signals transmitted over a communications channel.

2.2.3 The MAC Layer

The Medium Access Control (MAC) layer (also called MAC level) is the lower sub-layer of the Data Link layer (layer 2 of the OSI model) and sits directly on the top of the Physical layer (layer 1 of the OSI model). The upper sub-layer of MAC layer is the Logical Link Control

(LLC) layer, which presents a uniform interface to the user of the data link service, usually the network layer. Figure 2-4 illustrates MAC and LLC sub-layers.

<table>
<tr><td rowspan="2">Data Link Layer</td><td>Logical Link Control
(LLC)</td></tr>
<tr><td>Media Access Control
(MAC)</td></tr>
<tr><td>Physical Layer</td><td>Physical signalling
(PHY)</td></tr>
</table>

Figure 2-4: The MAC and PHY layers structure

MAC layer is the responsible to guarantee the communication operation between two nodes. In a wireless environment, the communication between the nodes is done via a radio, so we need a protocol to regulate the use of the medium, this task done through the channel access mechanism. The channel access mechanism is a way to divide main resource between nodes. The responsibility of this mechanism is to determine which node can access the medium and at what time, it tells each node when it can transmit and when it is expected to receive data.

We refer to this protocol, which regulates the usage of the medium as MAC protocol. The MAC protocol determines the state of the radio on a node. In wireless networks, the radio can be in one of two states, either in active (busy) state (sending or receiving data) or idle (free) state.

The MAC sub-layer is primarily concerned with recognizing the beginning and the end of frames in the bit-stream received from the physical layer (when receiving) or delimiting the frames (when sending) i.e. inserting information (e.g. some extra bits) into or among the frames being sent. Accordingly, the receivers are able to recognize the start and the end of the frames. Detection of transmission errors by means of e.g. inserting a checksum into every frame sent and recalculating and comparing them on the receiver side, inserting the source and destination MAC addresses into every frame transmitted filtering out the frames intended for the station by verifying the destination address in the received frames.

2.2.4 Service Primitives

The MAC primitives included in the software package MAC/PHY software layers could be classified in four categories as depicted in Figure 2-5, which under take the MAC interfacing. Services are specified by describing the service primitives that characterize it. A service may have one or more related primitives that constitute the activity, which is related to the particular service. The service may have zero or more parameters that convey the information required to provide the service [1].

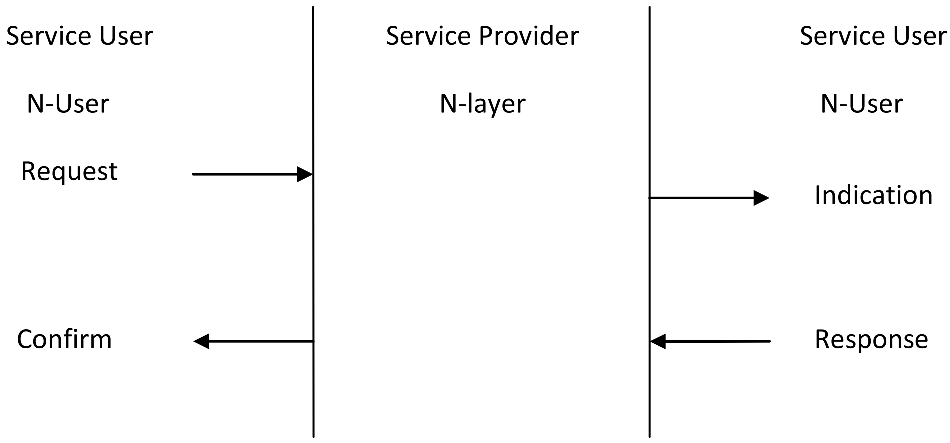


Figure 2-5: The service primitives

The service primitives could be classified as follows:

- **Requests:** The request primitive is passed to the MAC sub-layer from the upper layer to request that a service is initiated.
- **Confirms:** They are generated by the MAC sub-layer to the upper layer to convey the result of an associated previous service requests. Some functions will return the confirm value directly from the request.
- **Indication:** The indication primitive is passed from the MAC sub-layer from the upper layer to indicate an internal event that is significant to the upper layer. The indication primitives are generated as function calls called by the MAC layer.
- **Responses:** The response primitive is passed to the MAC sub-layer from the upper layer to complete a procedure invoked by an indication primitive.

2.3 Multiple Access

In ad hoc networks, generally, each node can only be a transmitter (source node) or a receiver (destination node) at a time. Communication among mobile nodes is limited within a certain transmission range. Nodes within the same communication range share the same frequency domain to communicate. Within such range, only one transmission channel is used covering the entire bandwidth. In the previous section, two-party of communications were concerned where a sender transmitting a coded message and a receiver receiving a decoded message. However, in most real environments, many users are simultaneously trying to establish connection with each other, which impose considerable challenges in wireless networking. The common challenge in wireless networks is interference, resulting from two nodes sending data at the same time over the same transmission medium or channel. Note that the source and destination nodes could be far away from each other and each time packets need to be relayed from one node to another in multi hop fashion. Accessing medium properly requires only informing the nodes within the vicinity of transmission. Therefore, MAC protocols deals only with per-link communications, not with the end-to-end communications [2].

Therefore, many MAC protocols have been developed in traditional areas of wireless voice and data communication networks to assist each node to decide when and how to access the channel. This problem is also known as channel allocation or multiple-access problem. In order to support everyone demand, there must be a way to share the communication medium. To achieve such mechanism, a multiple access scheme for multiplexing users' communications is used. This multiplexing, usually, can be done in time, frequency, or code, see Figure 2-6. MAC protocols are designed to control access to the transmission medium. Their aim is to provide an orderly and efficient use of the common communication medium. MAC protocols are responsible for per-link connection establishment, i.e. acquiring the medium, and per-link connection cancellation, i.e. releasing the medium free.

Generally, MAC protocols can be classified into two categories: *synchronous* protocols and *asynchronous* protocols. The synchronous MAC protocols (also referred to as Schedule-based protocols) are widely used in modern cellular communication systems. They are the preferred choice for cellular phone systems (e.g. GSM) and wireless networks supporting a mix of data and real-time traffic (e.g. Bluetooth). Their basic idea is to avoid interference by scheduling nodes onto different sub-channels. In synchronous MAC protocols, transmission capacity is divided into slots (i.e. time slots in TDMA and Slotted ALOHA, frequency bands in FDMA, time and frequency slots in FDMA/TDMA in GSM, and spreading codes in UMTS) and each node is only supposed to use one slot at a time to get access to the transmission medium. Since these channels do not interfere with each other, MAC protocols in this type are largely collision-free. The synchronized slots are assigned to nodes by a central control unit or AP in the system, i.e. Base Stations (BS) in GSM and UMTS systems.

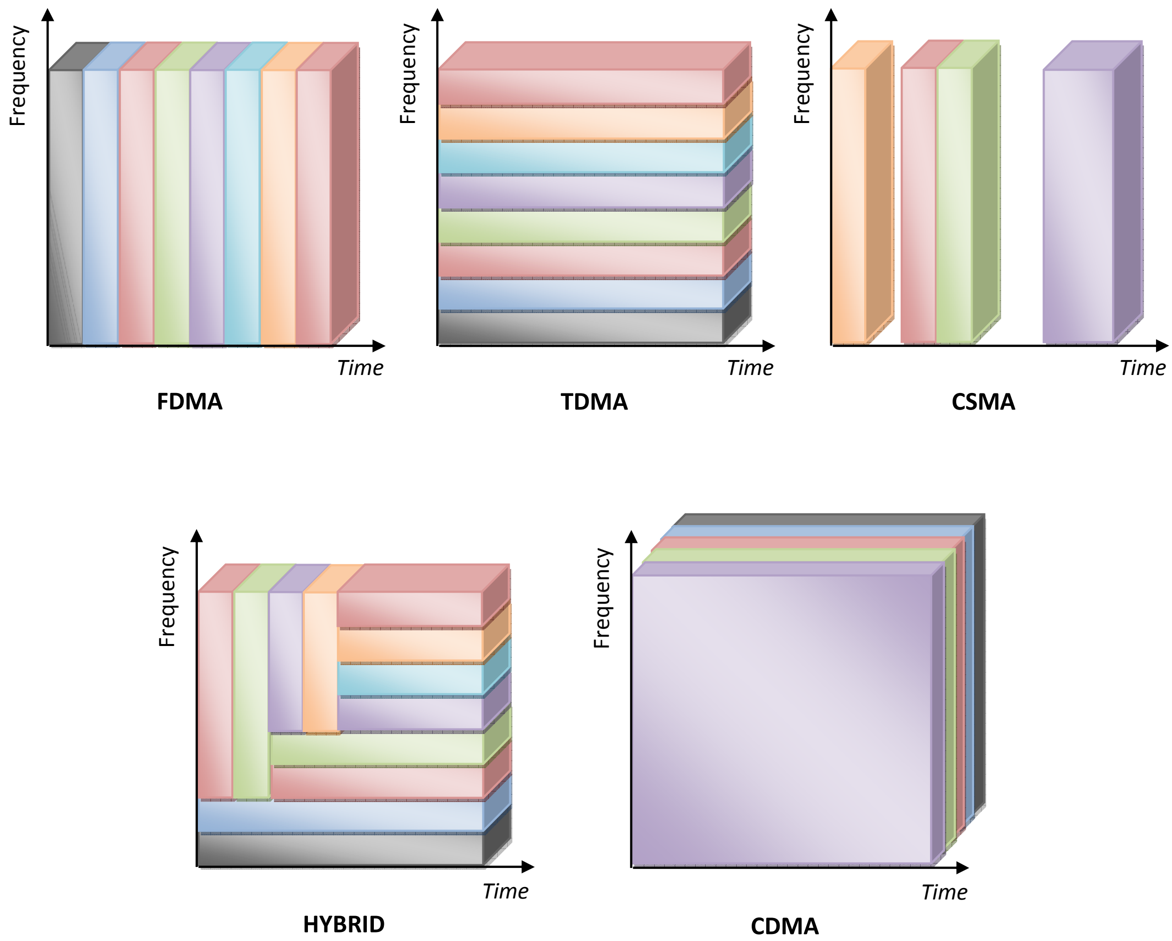


Figure 2-6: Multiple access schemes

However, due to the infrastructure-less property of ad-hoc networks, synchronization is not possible, leaving out asynchronous MAC protocols being the only option. The basic idea of the *synchronous MAC* protocols (also referred to as contention-based or scheduled protocols) is to avoid the collision by sensing the medium before transmitting a packet. Contention-based protocols also introduce the concept of back-off to allow nodes to control their access probabilities. Figure 2-6 shows a short comparison between some of multiple access schemes, and we describe each in detail below.

2.3.1 ALOHA Protocol

ALOHA protocol [3] uses a shared medium for transmissions. In ALOHA protocol all nodes communicate on the same frequency where some sort of mechanism is needed to control who could transmit at what time. The ALOHA solution allows each node to send its data without controlling when it was sent. An acknowledgment/retransmission scheme used to deal with collisions. Nodes also use the outgoing hub channel to broadcast packets directly to all clients on a second shared frequency, using an address in each packet to allow selective receipt at each client node. There are two types of ALOHA protocol, pure and slotted ALOHA.

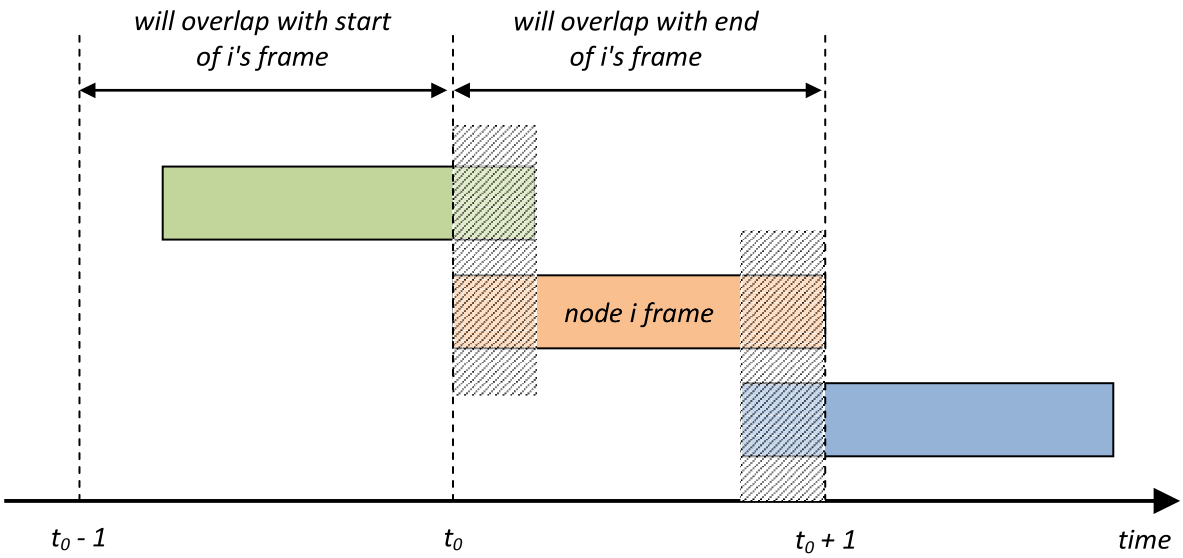


Figure 2-7: Overlapping frames problem in the pure ALOHA

In pure ALOHA, the mechanism implies that nodes do not check whether the channel is busy or idle before transmitting. Instead, nodes are allowed to send their data simply in the form of packets when it is generated. However, more than one node may transmit at the same time, causing interference among nodes or overlapping frames. Two overlapping frames will cause collision, resulting in damage to both frames. If a message collides with another transmission, nodes are allowed to try resending their data later. On the case of collision, sender waits random time before trying sending again. However, the resending data later concept where the back-off scheme chosen might significantly influences the efficiency of the protocol, the channel capacity, and the predictability of its behaviour. Figure 2-7 shows overlapping frames problem in the pure ALOHA.

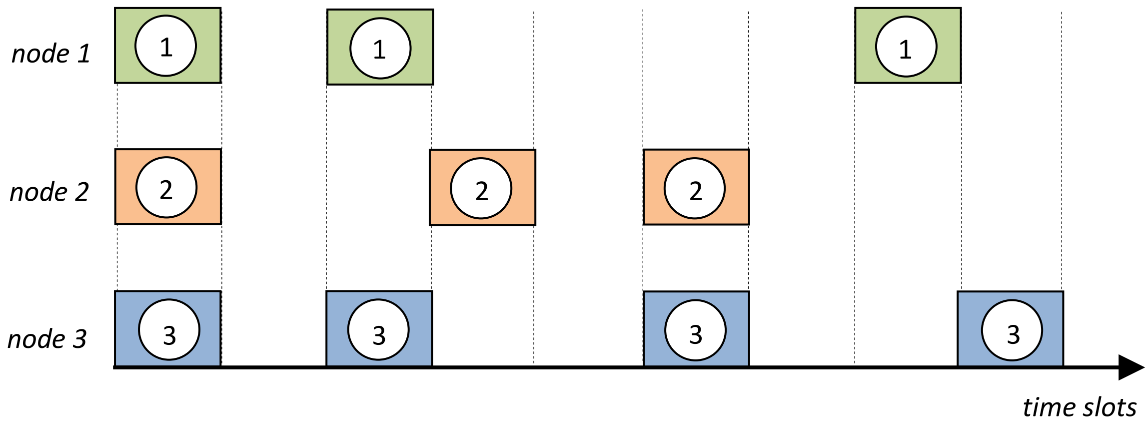


Figure 2-8: Time slots in slotted ALOHA

An improvement to the original ALOHA protocol is the Slotted ALOHA. It introduces discrete time slots, illustrated in Figure 2-8, and increases the maximum throughput. Slotted ALOHA comes to reduce the chance of interference by dividing the channel into equal time slots. To decrease the probability of collision, the node sends only at the beginning of a timeslot. In this case, we only need to worry about the transmission-attempts within one frame-time and not two consecutive frame-times, since collisions can only occur during each timeslot. If two or more nodes transmit in the same slot, all nodes detect collision. Packets that collide are discarded and will be retransmitted later. If no collision detected, node can send new data in the next time slot.

2.3.2 CSMA

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol is a collision avoidance protocol originally introduced in 1975 [4]. CSMA/CA comes to address the problem of collision by using a dialogue of three steps, RTS-CTS-DATA. The basic idea of CSMA that is when a node wants to send data to another node, it must firstly sense the medium whether it is idle or busy by sending a Request-To-Send (RTS) packet. Upon receiving the RTS packet, the receiving node responds with a Clear-To-Send (CTS) packet. Due to the broadcast nature of the message, all the neighbours of the sender and the receiver will be informed that the medium will be busy. As a result, neighbours will be prevented from transmitting any message to avoid any collisions. Figure 2-9 depicts this process. In turn, on receipt of the CTS, the sending node sends its queued data packets. If the sending node does not receive CTS after a timeout, it retransmits its RTS again and waits a little longer for a reply. Thus, the node only transmits its data when the medium is idle, i.e. no other nodes are transmitting. If it detected the medium is busy, it defers its own transmission and waits for a period of time to prevent a collision with the existing signal and retries later until the channel is idle. The advantage of CSMA protocol is that no centralized controller is needed.

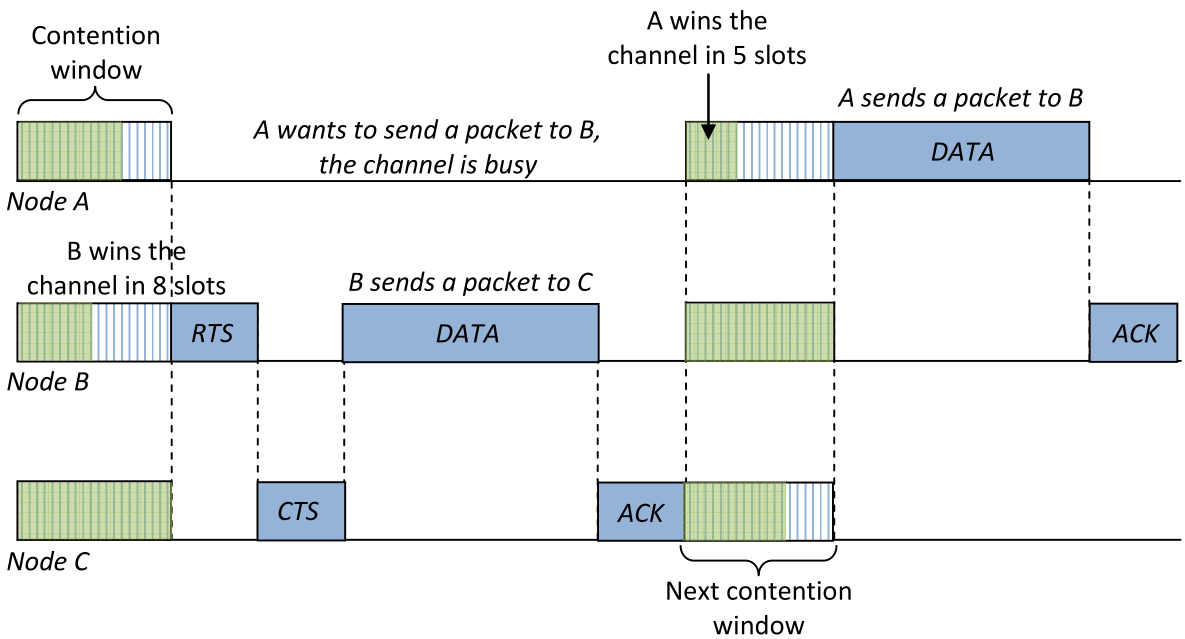


Figure 2-9: CSMA/CA channel access mechanism

However, a major problem in this scenario is that nodes transmitting simultaneously, causing interference, and data loss. Moreover, transmissions out of range cannot be detected. Thus, a transmission could still collide at the receiver with another transmission from an out of range nodes. This phenomenon is often referred to as the Hidden Terminal. Therefore, the Hidden Terminal Problem occurs where two or more nodes may share a communication with a common neighbor node while being out of each other's range. As illustrated in Figure 2-10, node B is within the range of nodes A and C, but nodes A and C are not in each other's range. If node A is transmitting to node B, node C, who is being out of A's range, cannot detect node A's transmission and may therefore send data to B, thus causing a collision at node B [5].

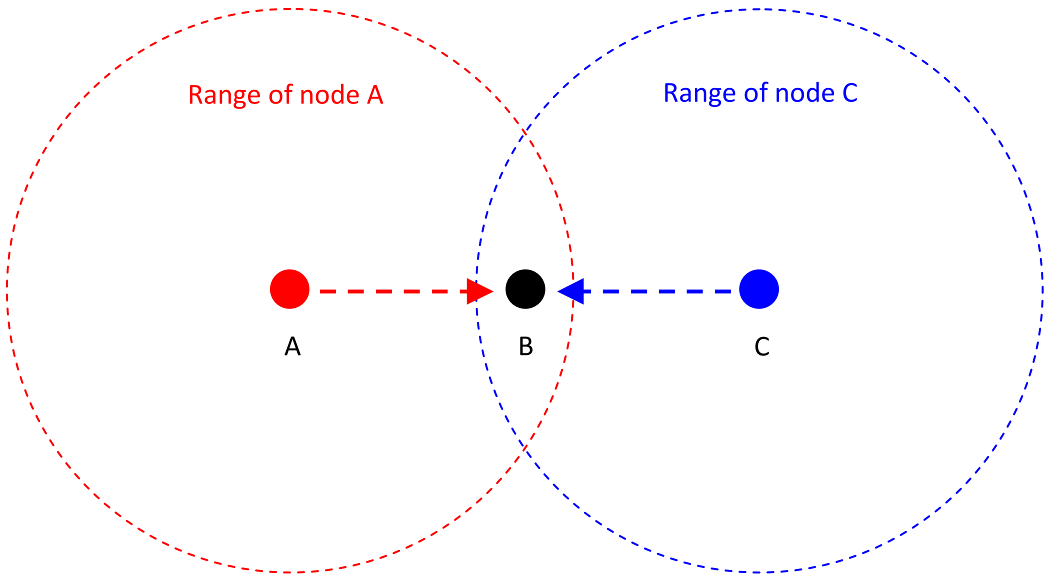


Figure 2-10: The hidden terminal problem

In addition, another case can be observed where the transmission range is not large enough. As shown in Figure 2-11, node B is transmitting to node A, since C is within B's range, it would hear the RTS sent by B, but not the CTS sent by A. Therefore, C will decide to defer its own transmission until nodes A and B finish their communication. However, this is unnecessary because C's transmission can cause any collision at receiver A. This is referred to as the Exposed Terminal Problem, since B being exposed to C caused the latter to needlessly defer its transmission [5].

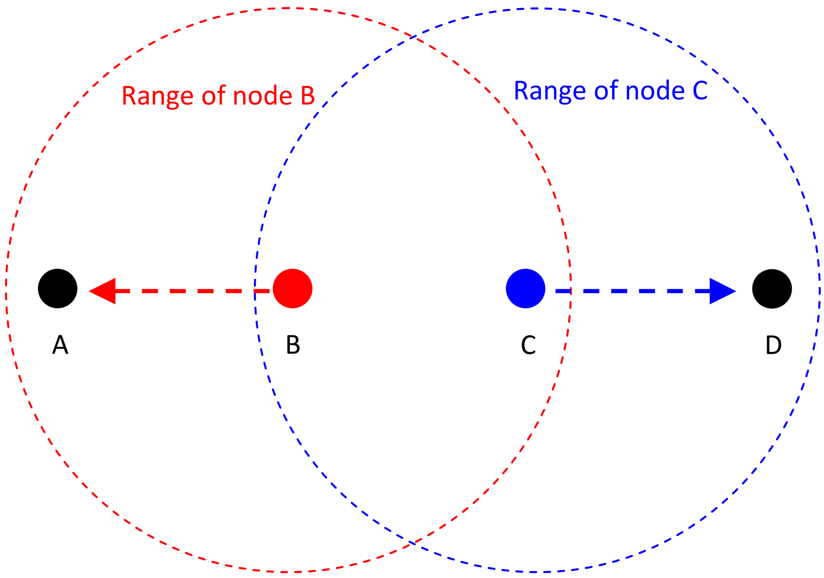


Figure 2-11: The exposed terminal problem

Both, the hidden and the exposed terminal problems cause the pure CSMA scheme to be inefficient for ad-hoc networks. To solve the hidden and exposed terminal problems in CSMA, the Multiple Access Collision Avoidance (MACA) [6] protocol was proposed. In this technique, when a node wishes to transmit a packet, it first sends an RTS packet indicating the length of the data to be transmitted. If the receiving node receives this RTS, it returns a CTS packet to the sending node that also contains the expected length of the data to be transmitted. On receipt of the CTS, the sending node immediately starts transmitting its data packet. The MACA scheme also presents the idea of that any node overhears an RTS packet has to defer its own transmissions until the associated CTS packet would have finished, and that any node overhearing a CTS packet would defer for the length of the expected data transmission. After waiting for the end of the current transmission, a node then starts the contention (random amount of time), if the channel is still idle, the node sends its data packets. The node that has chosen the shortest contention delay wins the access to the channel and transmits its data packet. The other nodes wait for the next contention. After that, to guarantee the packet delivery, MACAW [1] protocol is introduced to adds a fourth packet to the control sequence. The new scheme implies that when the data packet is received correctly at the receiving node, an explicit Acknowledgement (ACK) packet is sent back to the sender as soon as data reception is completed. If the sender does not receive the ACK packet in due time, it initiates a retransmission sequence to account for the corrupted or lost data. It has shown that MACAW achieves significantly higher throughput compared to MACA scheme. It however does not fully solve the hidden and exposed terminal problems.

2.3.3 IEEE 802.11 standard

The IEEE 802.11 standard [7] published in 1999 by the computer society. It consists of different elements that interact to provide a WLAN. These elements are the Basic Service Set (BSS), Distributed System (DS) and Independent Basic Service Set (IBSS). The BSS represents a group of wireless stations controlled by a Coordination Function (CF). The coordination function is a logical set of rules that manage the stations' access to the wireless medium. IEEE 802.11 specifies as Distributed Coordination Function (DCF) mode and Point Coordination Function (PCF) mode. The DCF is used by the stations as the basic coordination function, while PCF is optional and can be used to support Quality of Service (QoS) traffic. A BSS that operates without a DS is called an Independent Basic Service Set (IBSS). The mode of operation in the IBSS involves direct communication between the stations. According to PCF the stations are assigned priorities in accessing the medium coordinated by the Point Coordinator (PC), which usually resides in the Access Point (AP).

The IEEE 802.11 DCF is based on CSMA/CA technique where the concept of listen-before-talk is followed. It uses the RTS–CTS–DATA–ACK handshake scenario for data transmission. Its purpose is to prevent mobile nodes from accessing the wireless medium simultaneously. By using this mechanism, it eliminates the interference caused by the hidden nodes and decreases the packet collisions, and hence the network throughput is improved. The RTS/CTS packets are exchanged between mobile nodes prior to data transmission to make sure that the wireless medium is idle and a channel reservation for the sending node can be made. The process is initiated by the sending node, which senses the channel and sends RTS packet to the receiver. If it finds the channel idle, waits for a CTS packet from the receiver before it starts the effective data transmission. In turn, upon receiving the RTS packet, the receiver replies by sending a CTS packet to the sender and waits for the upcoming data.

IEEE 802.11 DCF also introduces the novel concept of virtual carrier sensing. This concept is implemented in the form of a Network Allocation Vector (NAV). In IEEE 802.11 network, every node should maintain a NAV to manage its access to the medium. The NAV contains a time value that represents the duration up to which the medium is expected to be busy. Due to simultaneous transmissions by other nodes, NAV is introduced as a solution to reduce collisions between multiple transmissions. If a node senses the medium busy, it starts random back-off time. Otherwise, it starts transmitting data via the wireless medium. After finishing its transmission, if no ACK message received by the sender node, the random back-off interval is increased, and the node must repeat new sensing scenario once again to check the availability of the medium. Since every packet contains the duration period for the remainder of the current transmission, every node overhearing a packet continuously updates its own NAV.

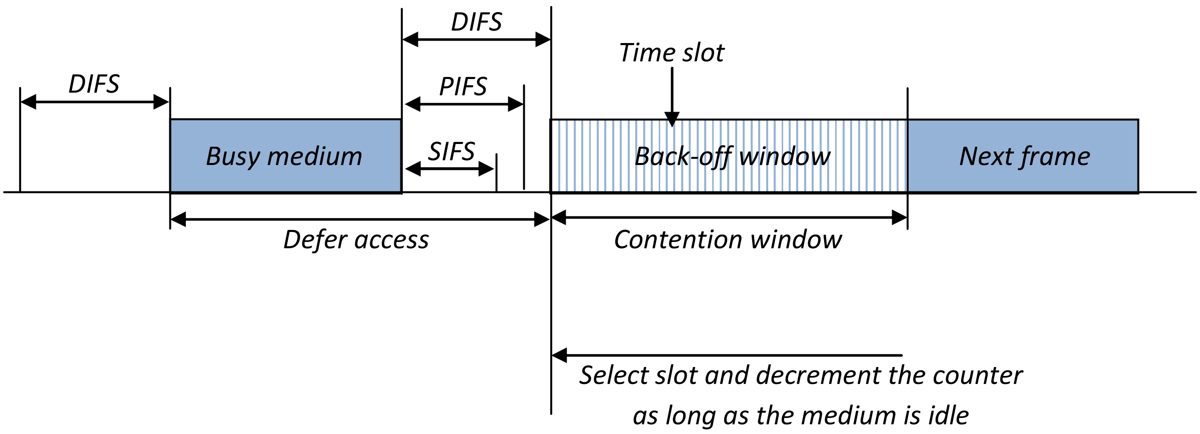


Figure 2-12: The different inter-frame spaces defined by the IEEE 802.11 MAC

In IEEE 802.11, time slots are divided into multiple frames. The time interval between adjacent frames is called Inter-Frame Space (IFS). There are several types of IFS are employed to provide different priorities to the frames. Four IFSs have been specified in the IEEE 802.11 standard as illustrated in Figure 2-12, which can be listed from the shortest to the longest as follows:

- Short IFS (SIFS) is used before the transmission of the following frames. It is also used before responding to any polling in PCF mode and before any frames from the Access point during the Contention Free Period (CFP).
- PCF IFS (PIFS) is used to provide the stations, operating under PCF mode, with the highest priority for gaining the medium access.
- DCF IFS (DIFS) is used by the stations, operating under DCF mode, to transmit data when the medium is determined as idle.
- Extended IFS (EIFS) is used by the DCF station whenever the PHY layer indicates that the frame reception contained an error or the MAC Frame Check Sequence (FCS) value was not correct. Therefore, the receiving stations should wait for a longer period of time before attempting to access the medium.

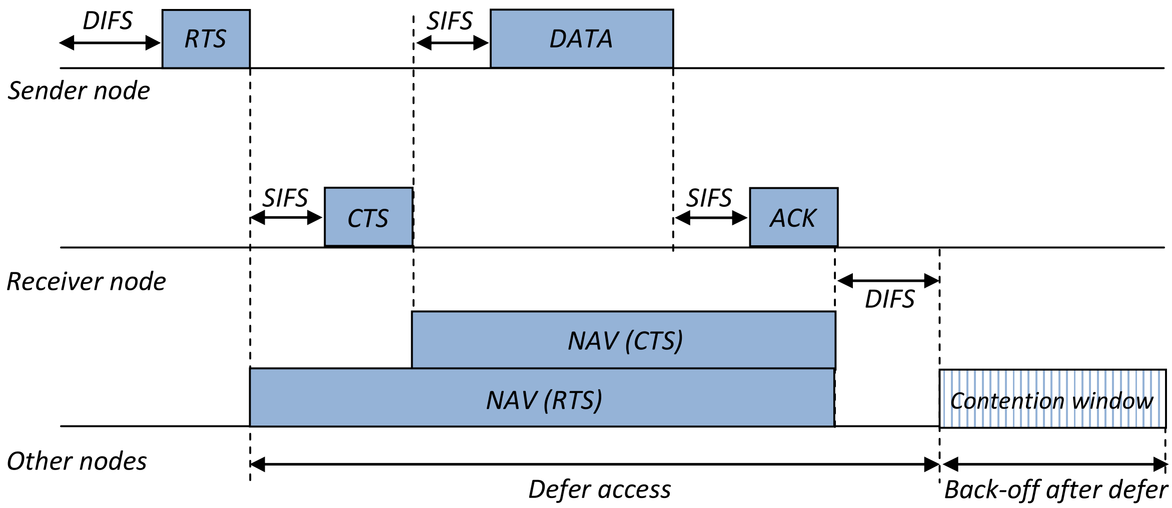


Figure 2-13: Virtual carrier sense procedure

As shown in Figure 2-13, node ***A*** wants to transmit a packet to node ***B***. Node ***A*** must first sense the radio channel to check if it is free for a specified DIFS time. If it senses the medium free, it can transmit its packet. Otherwise, if the medium is sensed busy, a back-off timer is initiated immediately. The initial back-off value of the timer is chosen randomly between 0 and CW-1 where CW is the width of the contention window. Unsuccessful transmission attempt will followed by another back-off which is performed with a doubled size of CW. After receiving the DATA packet, node ***B*** waits a SIFS time before confirming the reception of data by sending an ACK packet. Since the SIFS interval is set shorter than the DIFS interval, the receiver node takes precedence over any other node attempting to transmit data.

In addition, the IEEE 802.11 standard includes a power-saving mechanism. It is designed to preserve the energy of mobile nodes. It allows nodes to go into sleep mode for long periods of time when they have not data to send. However, this mode of operation requires the presence of an access point that records the status of each node. The access point is required to buffer any data addressed to a sleeping node. To let nodes in update situation, the access point regularly broadcasts beacon packets indicating which nodes have buffered packets. If a node knows that there is a data directed to it, it switches back from sleep mode to active mode and sends a poll request to the access point to retrieve the buffered data. However, the standard does not include a provision for power saving in multi-hop networks.

2.3.4 TDMA

In time-division multiple access (TDMA), users are multiplexed in the time domain, each being allocated a certain window in which to communicate. Time is typically divided into small segments (short windows), and each node in the network is assigned recurring time slots when they are scheduled to transmit. This scheduling typically requires a centralized controller in the network with knowledge of the capacity needs of each node. Therefore, TDMA is a schedule-based approach that controls the access to a single channel being divided into N time slots, generally of fixed size. In each slot, only one node is allowed to transmit, however, each node in the network may be allocated a certain number of slots where it can transmit. The N slots are usually organized in a frame, as shown in Figure 2-14, which is repeated on a regular basis.

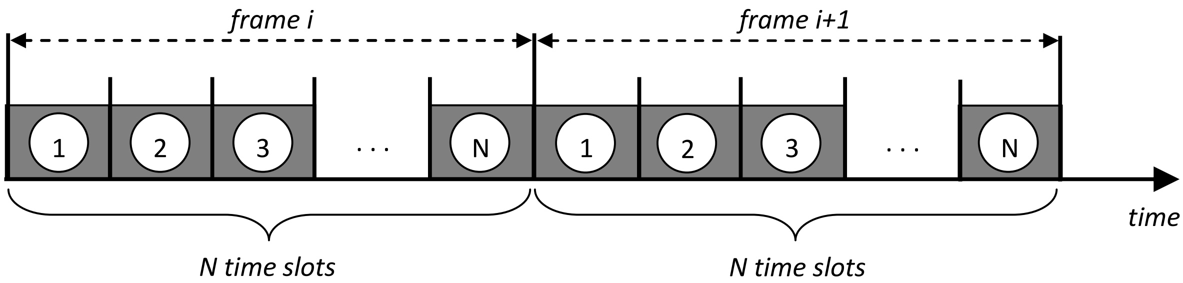


Figure 2-14: Time slots in TDMA

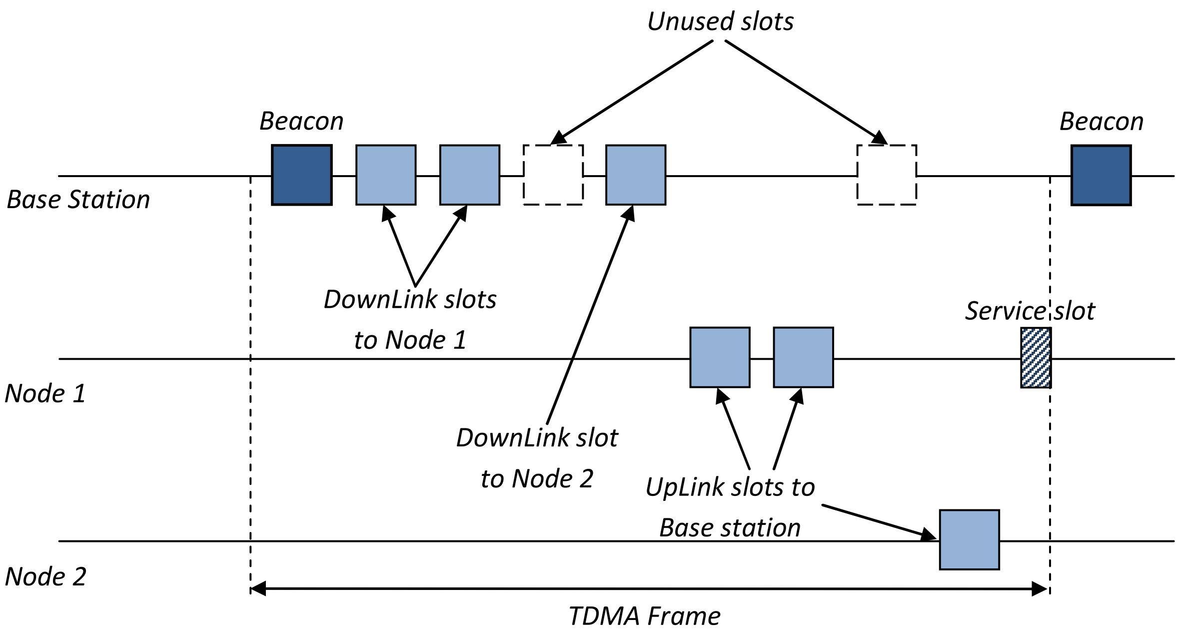


Figure 2-15: Channel access mechanism in TDMA system

In TDMA, the nodes are also organized into clusters. One of the nodes within the cluster is selected as the cluster head, and acts as the base station. This hierarchical organization restricts nodes to communicate with the cluster head within a cluster. TDMA is frequently used in cellular wireless communication systems, such as GSM. In such systems, within each cell, a base station acts as access point and allocates time slots to all mobile nodes. As there is no direct peer-to-peer communications between mobile nodes, nodes are provided timing and synchronization information. Each node just needs to follow the instruction of the base station. Very often, the frame is organised as downlink (base station to node) and uplink (node to base station) slots, and all the communications goes through the base station as shown in Figure 2-15. In TDMA technique, a service slot is used to indicate nodes to send a connection request message to the base station. In some standards, uplink and downlink frames are different frequencies, and the service slots might also be a separate channel.

2.3.5 FDMA

Moving on to the frequency domain, Frequency Division Multiple Access (FDMA) is another schedule-based approach that implemented at the MAC layer to controls the access to a single channel. FDMA is based on the Frequency-Division Multiplexing (FDM) technique used in wireless networking. It is one of the earliest multiple-access techniques for cellular systems when continuous transmission is required for analog services. In FDMA, the spectrum frequency is divided into a number of frequency bands or channels distributed among users. Each user in the network is assigned a specific frequency band for communication as illustrated in Figure 2-16, and during a call each user is only has the right to access its specific band. Thus, odes cannot share the same frequency band at the same time, but many nodes can transmit at the same time.

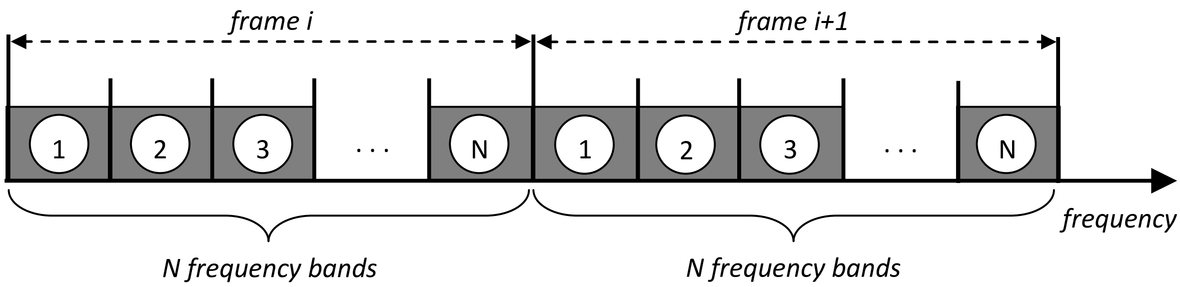


Figure 2-16: Frequency bands in FDMA

For example, in the satellite system, FDMA allows multiple carriers to share a single satellite transponder or range of frequencies. The transponder bandwidth is divided into sub-channels, each one is allocated to a particular earth station (carrier). The earth stations transmit continuously and the transponder conveys several carriers simultaneously at different frequencies. In wireless communications, FDMA achieves simultaneous transmission and reception by using Frequency Division Duplexing (FDD). In order for both the transmitter and the receiver to operate at the same time, FDD requires duplexers. However, the requirement of duplexers in the FDMA system makes it expensive. FDMA technique also suffers from inefficiency, since users typically cannot switch frequencies to use idle channels if they have many data to send.

2.3.6 CDMA

Code Division Multiple Access (CDMA) is a digital wireless technology different from the traditional ways (TDMA and FDMA). It multiplexes neither in time nor in frequency domain (i.e. nodes are not allocated the entire spectrum for part of the time or part of the frequency for all of the time). Instead, it allows all nodes to be allocated the entire spectrum all the time (i.e. all nodes are allowed to use both time and frequency simultaneously). This technology is based on a technique known as *Spread Spectrum (SS)* [8]. Spread Spectrum is a mean of transmission where the data occupies a larger bandwidth than necessary. To do this, it uses the Direct Sequence Spread Spectrum (DSSS) technique. In DSSS, before being transmitted, analog signals are multiplied by a high frequency pattern called a spreading code. The spreading code is a binary sequence that statistically satisfies the requirement of a random sequence, which can be exactly reproduced at the intended receiver through precise mathematical rules. Thus, only using the right spreading code, the receiving node can recover the spread signal, Figure 2-17, into the original information. This technique of spectrum access technology in which each sender-receiver pair has a distinct spreading code for transmitting and receiving over a common channel is known as CDMA [9].

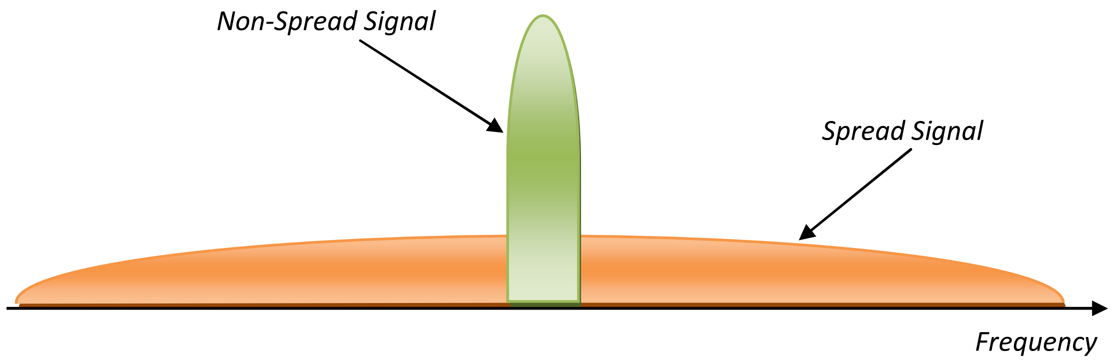


Figure 2-17: The spread signal in CDMA

Therefore, due to its superior characteristics, CDMA has been the spectrum access technology of choice in cellular systems, including the Third Generation (3G) systems [10]. In such systems, CDMA provides capacity six times greater than the capacity achieved by TDMA-based or FDMA-based systems [11]. Thus, CDMA is interference limited multiple access system. Because all users transmit simultaneously on the same frequency, internal interference generated by the system is the most significant factor in determining system capacity and call quality. Even though, the power should be enough to maintain the required Signal-to-Noise-Ratio (SNR) for a satisfactory call quality, the transmit power for each user must be reduced to limit interference. Moreover, it has shown that CDMA allows for interference-limited simultaneous transmissions to take place in the neighbourhood nodes of a receiving node and the near-far problem that undermines the throughput performance in MANETs can be solved. These advantages of CDMA come along with other desirable features including multipath resistance, inherent frequency diversity, and interference rejection to make CDMA to be also strongly considered for Ad Hoc networks [12].

However, one implementation issue for CDMA involves receivers knowing which spreading code to use to recover the coded signal. In most communication systems today, all wireless devices communicate only with a centralized controller, which must has the capability to access to all the spreading codes. In the research field, there has been much research approaches for dispreading DSSS signals without knowledge of the original spreading code [13]-[14]. Such approaches generally require short, repeating spreading codes and cyclostationary channels.

2.3.7 OFDMA

There are several hybrid approaches that combine TDMA and FDMA approaches to establish their communication. In such approaches, a centralized controller schedules data transmissions in both the frequency and time domain. A common example of this is called Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA technique is based on Orthogonal Frequency Division Multiplexing (OFDM), which has been applied widely in wireless communication systems due to its high data rate transmission capability with high bandwidth efficiency and its robustness to multi-path delay. Since there is a strong interest in extending the OFDM concept to multiuser communication scenarios, the OFDMA approach is resulted from a combination of OFDM with FDMA protocol. While OFDM system allows converting a single spectrum into many narrower subcarriers and transmitting the data in parallel streams, OFDMA is the multiplexing scheme for OFDM, i.e. it is a multi-user version of the popular OFDM digital modulation scheme. Multiple access scenarios are achieved in OFDMA by assigning subsets of subcarriers to individual users as illustration in Figure 2-18. This allows simultaneous low data rate transmission from several users.

In OFDMA systems, the available subcarriers are separated into several mutually exclusive clusters (subchannels or subbands) that are assigned to different users for simultaneous transmission. The orthogonality among subcarriers guarantees essential protection against Multiple Access Interference (MAI) while the adoption of a dynamic subcarrier assignment strategy provides the system with high flexibility in resource management. Furthermore, OFDMA technique has the ability to compensate channel distortions in the frequency domain without the need of computationally demanding time domain equalizers. Typically, in an OFDMA system, a burst will consist of several clusters or OFDM symbols. Hence, multiple users are allocated different slots in the time and frequency domain, i.e. different groups of subcarriers and/or OFDM symbols are used for transmitting signals to and from multiple users. As shown in Figure 2-18, the subcarriers in an OFDM symbol are represented by arrows and the lines shown at different times represent the different OFDM symbols. Six users presented by six different colours have been considered which show how resource can be allocated by using the different subcarriers and OFDM symbols.

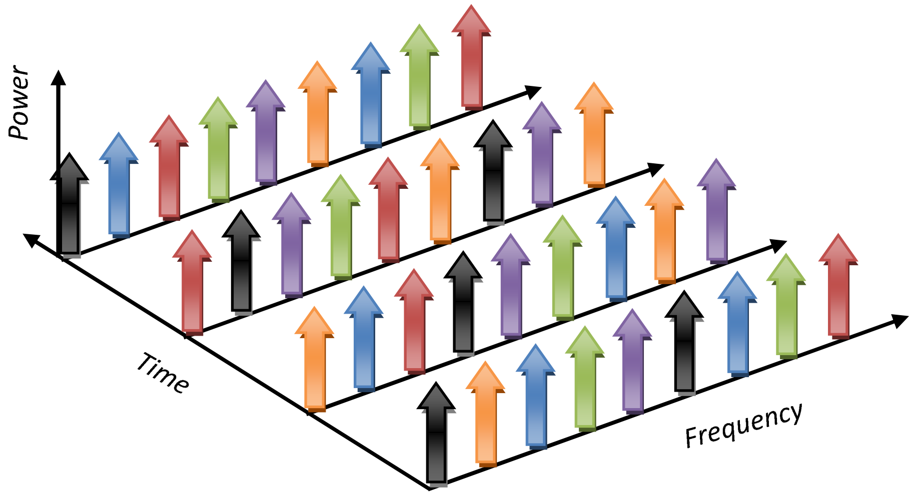


Figure 2-18: Multiple access scenarios in OFDMA system

In order to be able to provide high data rate services, OFDMA is considered one of the most favoured schemes for use in broadband transmission systems as it is capable of overcoming Inter-Symbol-Interference (ISI) and utilizing the given radio spectrum efficiently by dividing it into a large number of small subbands [15], [16]. Due to its favourable features, OFDMA has also been adopted in the emerging IEEE 802.16 standards for Wireless Metropolitan Area Networks (WMANs) [17] and some commercial systems such as Digital Audio Broadcasting (DAB) [18], Terrestrial Digital Video Broadcasting (DVB-T) [19], and the IEEE 802.11a Wireless Local Area Network (WLAN) [20]. It is currently attracting vast research attention from both academia and industry as a promising candidate for next generation broadband wireless networks.

2.4 Cognitive Radio

In order to define Cognitive Radio (CR) technology, firstly understanding the term Software Defined Radio (SDR) [21] is needed. Moreover, in this section, the goals of presenting the CR technology are studied and an overview on how a spectrum can be shared is given.

2.4.1 Software Defined Radio (SDR)

Obviously, new notions about radio systems have been invented in the recent decades differentiating from the pure hardware-based radios. The new radios involve a combination of both hardware and software to accommodate a significant range of Radio Frequency (RF) bands and air interface modes through software [22]. In the early 1990s, for example, Joseph Mitola introduced the idea of SDR. SDR is a developed technology that is strongly changing radio system engineering to be more flexible in its operation. A SDR system contains the same basic functionality components as any other digital communication system, which is implemented in software rather than hardware. Hence, the SDR technology combine software and hardware architecture together in order to be able to provide multiple band access, multiple mode operation, global seamless connectivity, and reconfigurability. A SDR system is a radio communication in which its operating parameters including detectors, amplifiers, transmission frequency, modulation scheme and transmission power are implemented in such way that the radio can be altered to transmit and receive widely different radio protocols without making any hardware changes. To achieve such flexibility for a radio system, the boundary of digital processing should be moved as close as possible to the antenna system. The application specific integrated circuits, which are traditionally used for baseband signal processing, should also be replaced with programmable implementations [23].

The best example of a potential real-world SDR application is the cellular networks, where the software embedded in a cellular phone could define the parameters under which the phone should operate in real time as it moves from one cell to another continuously. Obviously, SDR technology makes communication systems more flexible than those systems in which the operating frequency band and the communication protocols are fixed and limited by strict policies [24]. Compared to hardware radio in which the radio can perform only a single or a very limited set of radio functionality, SDR is built around software-based Digital Signal Processing (DSP) along with software adjustable radio frequency components. Such characteristics make SDR represents a very flexible and generic radio platform that is capable of operating with different bandwidths over a wide range of frequency bands and using many different modulation and waveform formats. As a result, SDR can support multiple standards such as GSM, GPRS, UMTS, LTE, WiFi, WiMAX and multiple access technologies such as TDMA, FDMA, CDMA, and OFDMA systems [25].

In general, an ideal SDR architecture consists of three main units: (i) reconfigurable digital baseband radio, (ii) software adjustable analog front-end along with embedded impedance synthesizer, and (iii) software tunable antenna systems. The reconfigurable digital baseband radio performs digital radio functionalities such as different waveform generation, optimization algorithms for software tunable radio and antenna units, with the potential of controlling these units. The software adjustable analog front-end system is limited to the components that cannot be performed digitally using current technology such as RF filters, Power Amplifier (PA), Low Noise Amplifiers (LNA), and data converters. The impedance synthesizer is used to optimize the performance of software tunable antenna systems for an arbitrary frequency plan specified by the cognitive engine. However, due to the current limitations (size, cost, power, performance, processing time, data converters ... etc), ideal SDR architectures are still costly [25].

2.4.2 Concept and Definition

With the rapid development as well as the efforts of the scientific research field, the development of many communication technologies such as wireless communication systems, DSP as well as the simulation industry used in the radio technology have guided us into new fabulous communication tools, which have facilitated our daily life [26]-[30]. In the meantime, industry was not only practical, but also resulted in improved radio communication performance, reliability, flexibility and increased value to the user [31]-[34]. In fact, one of the most highlighted topics of the developed systems nowadays is emerged as an extension of SDR technology in 2000, where Mitola developed the SDR concept one further step introducing the term Cognitive Radio (CR) [35]. CRs are essentially developed SDRs with artificial intelligence, capable of sensing and reacting to their environment efficiently. The work introduced by Mitola can be considered one of the novel idea, which presented CR technology and one of the novel approaches in wireless communications. The presented approach was based on the situation in which wireless nodes and the related networks are sufficiently computationally intelligent about radio resources and related device-to-device communication to detect the user communication needs as a function of use context and to provide resources fairly to multiple and different users [35].

In other words, a CR is a radio that has the ability to sense its environment and adapt its parameters according to the sensing outcomes. Accordingly, two basic characteristics of any CR device can be defined, which have cognitive capability and reconfigurability. In order to detect and adjust the spectrum parameters, a device should be able to interact with its environment. The spectrum parameters that needed to be analysed are spectrum concentration, power level, extent and nature of temporal and spatial variations, modulation scheme, and existence of any other network operating in the same environment or in the neighbourhood. Hence, the CR device should be capable to adopt itself to meet the spectrum needs in the optional methods. The recent developments in the communication systems such as the concept of software radios DSP techniques and antenna technology helped in this flexibility in CR devices design. Moreover, the intelligent support of CR's to the user arises by sophisticated networking of many radios to achieve the end behaviour, which provides added capability and other benefits to the user.

A comparison between software radio and cognitive radio can be illustrated in Figure 2-19. Although, definitions of the CR differentiate from other radio definitions, most radio experts agree with the fact that a CR device must have the following characteristics in order to be distinguished from others:

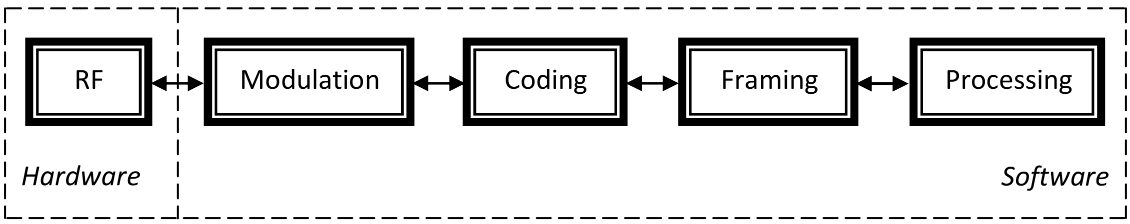
❶ CR device should be aware of its environment.

❷ CR device must be able to change its physical behaviour in order to adapt to the changes of its current environment.

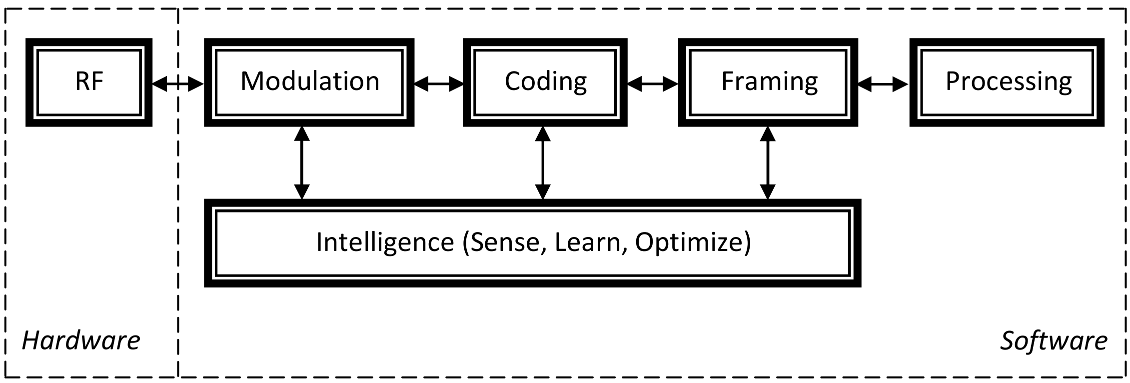
❸ CR device must be able to learn from its previous experience.

❹ Finally, CR device should be able to deal with situations unknown at the time of the device design, i.e. the device should be able to deal with any unexpected situations in the covered area.

In addition, as discussed earlier, one of the main characteristics of cognitive radio is its adaptability so that the radio parameters (such as carrier frequency, power level, modulation type, bandwidth, packet length) can be changed depending on the radio environment. Since SDR can provide very flexible radio functionality, it can be considered a core enabling technology for cognitive radio.



(a) Software Radio



(b) Cognitive Radio

Figure 2-19: A comparison between software radio and cognitive radio

2.4.3 Goals and Evolution

Different interpretations about the term "cognitive radio" have been developed in the research field in the past few years. Some of the more extreme definitions might be, for example, a military radio that can sense the urgency in the operator's voice, and adjust QoS guarantees proportionally. Another example is a mobile phone that could listen to your conversations, and if you mentioned to a friend that you are going to hail a cab and ride across town, it would preemptively establish the necessary cell tower handoffs [36]. However, more representative of Mitola's original research direction, these interpretations are becoming a bit too futuristic for today's technology. A CR system may be able to sense the current spectral environment, and memorize some of the past activity, which have done in its surrounded environment. However, a more common regulation restricts the radio's cognition to more practical sensing actions that are aligned with typical radio operation. To guarantee better functionality, it can make better decisions about how to best optimize for some overall goal. Possible goals could include achieving an optimal network capacity, minimizing interference to other signals, or providing robust security or jamming protection.

Another controversial difference in interpretation has to do with drawing the line between SDR and CR. Often times, frequency agile SDRs with some level of intelligence are called CRs. However, others believe that SDRs are just a tool in a larger CR infrastructure. For example, remote computers can analyse SDR performance and reprogram them to decide none of the SDRs' modulation schemes are sufficient for their current environment. It could create a new scheme generate Hardware Description Language (HDL) and new FPGA loads, and reload them over the network to add this new functionality.

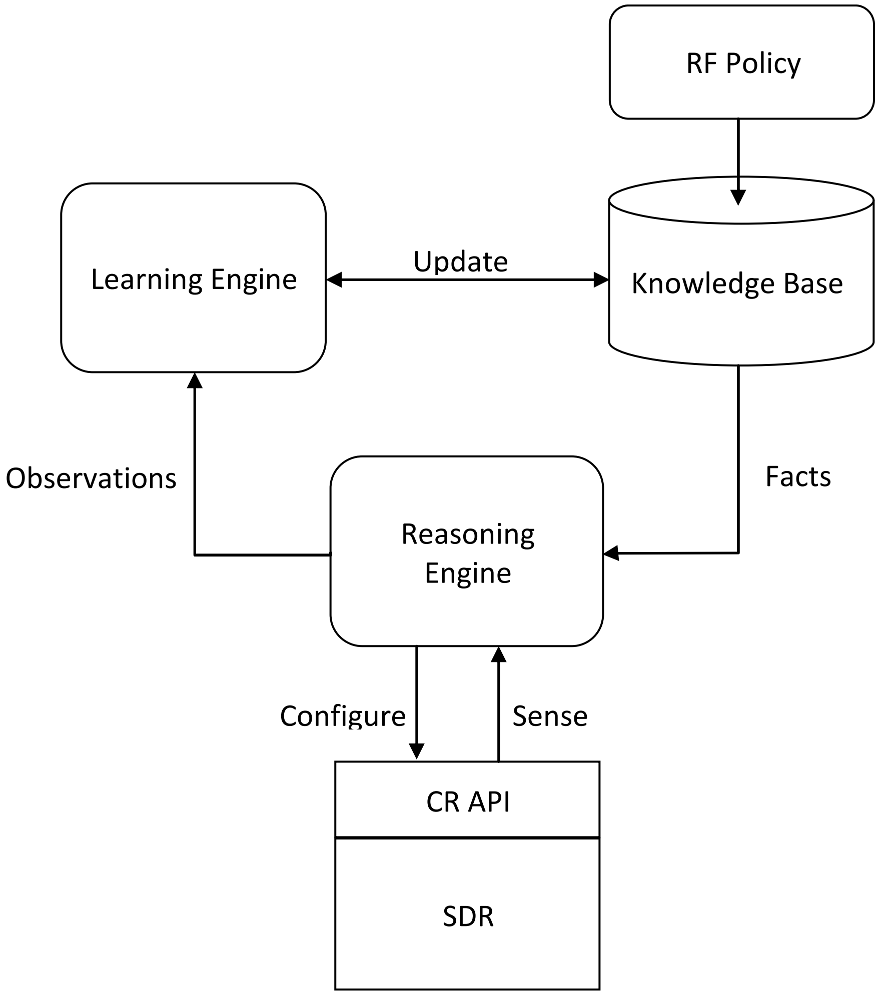


Figure 2-20: Functional portions of a cognitive radio

Figure 2-20 shows functional components of more concrete CR architecture. The SDR is accessed via a CR Application Programming Interface (API) that allows the CR engine to configure the radio according to its sensed environment. The role of the policy-based reasoning engine is to take facts from the knowledge base and information from the CR environment to form judgements about RF spectrum accessing opportunities. In addition to a simple policy-based reasoning engine, a learning engine observes the radio's behaviour and resulting performance, and adjusts facts in the knowledge base, which used to form judgements. However, a fundamental problem with such system is its complexity. The question is: Can the proposed learning and reasoning processes be done in near real time, to keep up with an ever changing RF environment? Can we come up with a simple set of metrics that can achieve the required performance without being overly computationally complex? Such questions and more development models related to CR functionality and its control algorithms are discussed deeply in the next chapter.

2.4.4 Reasons and Facts

One of the main reasons behind the concurrent increase in the demand for and congestion of RF spectrum is the rapid development of radio networks of all kinds in our modern life, which has defiantly changed the public feeling about radio. Nowadays, almost everybody has a mobile phone and radio stations are literary everywhere. Someone can argue that our world is becoming a radio world where waves are weaving everywhere around the Earth. What's more, this congestion has created a battle between the public, private and military sectors over frequency ownership and has put a premium on the cost of spectrum. In addition, the flexibility of an SDR and its capability to make an adaptive radio operates with many different bandwidths over a wide range of frequencies and using many different modulation and waveform formats has now reached the level where a radio can possibly perform beneficial tasks in the communication domain. It can help the user and the network to minimize the spectral congestion. In order to raise an SDR's capabilities to make it known as a CR, it must support applications to be capable to Interface with a wide range of wireless networks leading to management and optimization of network resources [37].

Therefore, with the rapid growth in wireless applications and the rapid advances in smart radio technology, the radio spectrum becomes of fundamental importance. According to a recent research introduced by the Federal Communications Commission (FCC) in the United States (US) and Office of communications (Ofcom) in the United Kingdom (UK), it was found that most of the frequency spectrum was inefficiently utilized [38]-[39]. The existing spectrum allocation process, denoted as Fixed Spectrum Access (FSA), headed for static long-term exclusive rights of spectrum usage and shown to be inflexible [40]-[41]. Other studies have shown, however, that spectral utilization is relatively low when examined not just by frequency domain, but also across the spatial and temporal domains [42]. Thus, an intelligent device aware of its surroundings and able to adapt to the existing RF environment in consideration of all three domains, may be able to utilize spectrum more efficiently by dynamically sharing spectral resources [43].

Although reports made by the mentioned spectrum regulators have shown that almost all the available spectrum has been allocated, extensive measurements made by Spectrum Policy Task Force (SPTF) in the US and Ofcom in the UK indicate that a large amount of licensed spectrum remains unused at a specific time or slot level [38]-[39]. As a result, the FCC began researching ways in which unlicensed users could use licensed bands, on condition that they do not interfere with existing licensees. In the resent years, the FCC has considered more flexibility and comprehensively usage of the available spectrum [44]. This phenomenon accelerated the emergence of Opportunistic Spectrum Access (OSA) concepts and cognitive radios are allowed to operate in certain frequency bands with respect to the system legacy. In the same context, the FCC also proposed the interference temperature model [45] in 2003 as a way to dynamically manage and allocate spectrum resources.

In CR Networks, licensed (primary) users have high priority to use their spectrum. Meanwhile, to mitigate the spectrum scarcity and improve their service quality, unlicensed (secondary) users are allowed to opportunistically access the spectrum and use temporarily the spectrum spaces unused by the licensed users, which are also known as spectrum holes or white spaces as illustrated in Figure 2-21. If the licensed users further use these bands, CR users should have the ability to vacate the bands and move dynamically to other spectrum holes or they might stay in the same band but change the transmission power level to avoid interference. To ensure robust system, spectrum management has to be done efficiently in CR Networks. Spectrum management can be composed of four major steps: sensing, decision making, sharing, and mobility [46]. Basically, cognitive radios have the ability to perform spectrum sensing continuously to recognize the status of the radio spectrum environment. Once white spaces (unused spectrum) are identified, the cognitive radio can change its transmission parameters, such as carrier frequency, bandwidth, power efficiency, and modulation schemes, according to the interactions with the environment in which it operates.

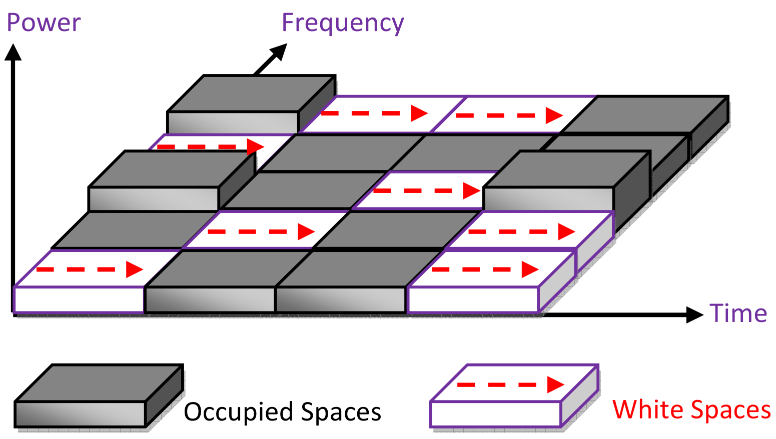


Figure 2-21: Illustration of occupied and white spaces in CR Networks

2.4.5 Opportunities and Sharing

Obviously, shared medium approach has been applied from the beginning of wireless technology. Maritime radio systems, for example, have always used shared channels in order to establish a connection to communicate with each other. In that era, 2,182 KHz is specified to be used as a calling frequency as well as emergency signalling frequency between different maritime radio systems where other frequencies are used as working frequencies. When two ships want to communicate, one should identify a working frequency and then make a call on the calling frequency. By using this technique, a working channel can be identified and then a communication between the two ships can be hold. Moreover, by specifying a channel (or channels), that ships keep watch on facilitates both emergency signalling and establishing connections between ships. In fact, channel sharing was necessary and effective due to the lack of communication medium offered to every single ship and due to the fact that, the typical ship required far less than a full channel of capacity [37].

The use of shared channels was long authorized by the FCC. In 1960's, for example, a single channel was covering a whole city where simple protocols (listen before talking) and short messages are used to allow efficient sharing of the single channel using the single-channel FM technology of the time. In order to expand the communication services, the FCC permitted land mobile operation on some of the lower Ultra High Frequency (UHF) channels in several large cities in the mid of 1970's. In that time, one group of channels was made available to Radio Common Carriers (RCCs) to provide mobile service on a common carrier basis. Moreover, the FCC adopted rules permitting open entry for these channels and requiring carriers to monitor the channels and select unused channel to carry each conversation. In essence, exclusivity was provided on a first-come-first-served mechanism basis one conversation at a time. Another example of medium sharing is the second generation of Cordless Telephone (CT2), developed by the British industry sector in the mid of 1980's. CT2 was designed to be used in both home and public. A pool of 40 channels was used at time. To establish a call, a device will automatically identify a vacant channel or a channel with the minimum interference and start the conversation on that channel [37].

It is fair to say no one can ignore the advantages of the radio. It can be used anywhere, at any time, and capable of establishing short links at very short distances as well as on a vast scale. Radio can be considered as a unique tool to connect things together without any material medium. It is a wonderful tool for social progress. Hence, all these facts about radio sharing guide us to the fact that spectrum management is a major goal for telecommunications efficiency. However, the situation regarding spectrum sharing is rather complex, as today's applications are using a great number of frequency bands. It is notable that there arises demand on spectrum access across the usable and unusable spectrum. As a result, sharing techniques are also becoming more complex. Even if the legal environment indicates that the spectrum sharing approach falls under the non-interference/non-protection regime, the requests for more protection and better QoS are major trends. In addition, even if there is no obvious need for new spectrum to be made available, there is a clear request to provide better QoS to certain category. As some spectrum frequency (e.g. spectrum above 40 GHz) is rather underutilised, development of technologies in this part of the spectrum should also be encouraged. Therefore, there is increasing trend for new sharing techniques to regulate the spectrum usage. Spectrum sharing approaches are also becoming more important in many countries nowadays. For example, in most of European Union (EU), the current European spectrum regulation allows different shared access to spectrum in a number of frequency bands. Other approaches, such as cognitive radio, spectrum sensing, and spectrum access, are also under development, aimed at increasing spectrum sharing opportunities. More aspects concerning these technologies will be discussed in details in the following chapters.

2.5 Conclusion

This chapter gives an overview on the multiple access techniques in Wireless Networks and spectrum sharing in Cognitive Radio Technology. The main objectives are to outline the fundamentals of the wireless communications technology by highlighting the basic operations of its MAC and PHY layers, and to explain the principles and the characteristics of MANETs. A detailed study on spectrum sensing and spectrum access in the Cognitive Radio Networks is then presented in the following chapters.

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Chapter 3

Multi-Channel Time Slotted Cognitive MAC Protocols for MANETs

3.1 Introduction

In wireless ad hoc networks, all nodes have equal right to access the medium. Hence, the performance of this mode is mostly limited by traffic congestion. To alleviate such a problem, Cognitive Radio (CR) technology can be used. Recent researches show that a large amount of licensed spectrum remains unused at a specific time. The contribution of this chapter is to investigate a CR-based Medium Access Control (MAC) layer for wireless ad hoc networks. We aim to focus on a Cognitive MAC protocols for unlicensed user, which can be enabled to access the large amount of unused spectrum allocated for a licensed user, in an intelligent way, without causing any harmful interference. We propose a cognitive MAC protocols based on the theory of the Partially Observed Markov Decision Process (POMDP), which sense the radio spectrum, detect the occupancy state of different primary channels, and then opportunistically communicate over unused channels (spectrum holes). The objective is to make efficient decisions on which channels to sense and access, that ensure maximization of the throughput of the secondary user.

Cognitive radio has been proposed as a solution to overcome spectrum scarcity in wireless communication. It has two important functionalities: spectrum sensing and adaptation. Initially, a secondary terminal senses the spectrum environment in order to learn the frequency spectrum unoccupied by PUs. Once unoccupied spectrum (spectrum hole) is found, the secondary user adapts its transmission power, frequency band, modulation, etc., so that it minimizes the interference to the PUs. Even after starting the transmission, SU should be able to detect or predict the appearance of PU so that it makes the spectrum available for PU.

3.2 Development of MAC Design

In the past few decades, the research in wireless networks has become one of the hot spot in emerging technologies. With the appearance of increasingly large scale size of the networks, wireless networks become more and more complex and difficult to describe complex phenomenon due to lack of dynamic and effective methods. In wireless communication networks, there are several common challenges for most MAC protocol designs. The challenges of hardware capability and software complexity make the sensing ability, adaptability, and intelligence degree of CRs to be a big challenge, which gives considerable intention for MAC design flexibility in CR networks. Depending on the application scenario and the network structure, the challenges for MAC protocol design in CR networks can be quite diverse on other networks. In CR networks, two aspects of coexistence issue can be described: one is the coexistence of licensed users and CR users in the licensed bands, and the other is the coexistence of CR users in the unlicensed bands. For the coexistence of primary and CR users, it is required that transmission by CR users does not interfere with the communication. In this section, many issues related to the wireless nature are discussed.

3.2.1 Common Control Channel (CCC)

The capacity of signalling information exchanged in a CR network is significantly larger as compare to other wireless networks. Therefore, many CR solutions either centralized or distributed uses explicit or out of band channels to exchange the control information. These channels are physically separated from the data channels to be responsible for transferring the control information, and known as common control channels (CCC). In CR networks, users share the common control channels to exchange the signalling, synchronisation, sensing, and decision information about the spectrum environment.

In fact, the CCC issue arises when a CR network operates in a licensed spectrum. As spectrum availability for CR users fluctuates over time and location, it is hard to find a common channel to exchange information on the scale of the entire network. Various MAC design and solutions are proposed for the CCC problem. For example a possible solution: is to assign the CCC locally. As nodes in a given neighbourhood, it can observe the same spectrum activities. Other solution is to allow the control messages to be exchanged in any channel across the network.

In [1], common control channel design for CR wireless ad hoc networks (CRAHNs) is proposed. The design is an adaptive frequency hopping CCC, called as adaptive multiple rendezvous control channel (AMRCC). The proposed scheme allows continuous connectivity between the CR users under dynamic PU activity. Author has also compared the performance of AMRCC to classical CCC schemes. Based on an Ultra Wideband pulse shaped signal, an out of band CCC design is proposed by author in [2]. A distributed spectrum sharing scheme, which is based on individual spectrum decisions, priority and messaging mechanism between CR users is also proposed in the literature [3]. Thus, a MAC protocol for CR networks would properly need to handle the issue of CCC in order to percolate control messages throughout the network.

3.2.2 Multichannel Hidden Terminal Problem

The multichannel hidden terminal problem arises when multiple users attempt to access one of multiple channels. Due to simultaneous transmissions directed to the same destination by different nodes that are within the direct transmission range of the receiver, collision of packets can be happen at the destination. In fact, the hidden terminal problem can significantly reduce the performance of the CR networks. As each user with a single transceiver can use only one channel in each sensing period, a control message on one channel between a transmitter and a receiver may collide with other data packets on the same channel. Such problem needs to be undertaken at the MAC layer level by applying an appropriate synchronization and signalling schemes. It has also shown that such problem can be addressed better in a multi-transceiver MAC design [4]-[5]. However, the presence of multiple transceivers at each node makes it expensive and the CR network more complex. In practical, the single transceiver cognitive MAC seems to be an ideal solution to keep the network complexity lower in wireless networks. Current single transceiver MAC solutions for the hidden terminal problem seem to be inefficient due to high control overhead.

3.2.3 Interference Temperature Measurement

The most important aspect in CR networks is the broadcast nature of the radio channel, i.e. transmission by any CR user will affect always the primary network by causing interference to the primary users within the radio range. In CR networks, minimizing the interference, packet drops, and error rate are always needed in the early of the development process [6]. To overcome the interference problem caused by the CR users, over the past few years, the Interference Temperature Model (ITM) has been recognized by the FCC in 2003 as a possible solution to dynamically manage and allocate the spectrum resources. In ITM, CR users would be capable of measuring the current interference environment, and allowed to adjust their transmission parameters in such a way that their transmissions avoid raising the interference temperature over certain threshold. However, the difficulty of the receiver detection model lies in effectively measuring the interference temperature, which poses a considerable challenge for the MAC design in CR networks.

Furthermore, as there have been no real schemes for actually using the interference temperature model and without a concrete technique, it is difficult to say whether it will be a practical solution. Hence, problems such as collision of packets, packet drop, and failure of transmission, still cause degradation in the performance of CR systems. Nevertheless, various solutions are suggested to reduce such factors for the CR systems. For example, in [7], authors have examined the capacity of CR MAC over the dynamic fading environment. Nash equilibrium game based algorithm for Signal-to-Interference Ratio (SIR) based power control was adopted. Based on a Space-Time Block Coding (STBC) MC-CDMA system, a novel adaptive algorithm was also proposed in [8], where authors of [9] describe signal processing aspects of cognitive radio.

3.2.4 Mobility of the users

Similar to other wireless systems, in CR networks, mobility is considered as one of the most important factors. It affects numerous network characteristics, such as capacity [10], connectivity [11], coverage [12], routing [13], which affects the performance of CR systems. Despite its importance, however, mobility is still largely unexplored in the context of CR and dynamic spectrum access. This will result in multiple challenges, making it necessary to review the MAC design and protocols in CR systems, such as mechanisms for spectrum sensing, interference management and routing. Meanwhile, various studies and different solutions are proposed for the mobility issue. The channel assigning agent at the mobile Internet Protocol (IP) layer can be used, for example, to allow CR mobile users to use the channel as long as possible. This strategy aims at avoiding additional interruption loss due to unnecessary channel adaptations. In [14], spectrum mobility management architecture, requirements, and solutions for the heterogeneous CR networks are also investigated. Solutions for the Long Term Evolution (LTE) networks were provided by the authors of [15] where they preferred to propose cross-layer protocol of spectrum mobility at the data link layer and handover at the network layer in cognitive LTE networks.

3.2.5 Multi-user Sensing

The sensing phase is one of the important processes, which is necessary to be achieved by the CR users efficiently to deny any harmful interference to the licensed users. The existence of CR users and the primary users in the same environment let the sensing process more complex. Moreover, joining new primary or secondary users to the network always has big impact on the performance of the CR system. Consequently, multiuser environment impose difficult behaviour to a CR user to sense the licensed users and to estimate the actual interference. Many articles discussed the problem of multiuser and proposed different solutions to solve this problem. For example, multi-carrier DS CDMA modulation over a frequency-selective fading channel was proposed in [16] to solve the multiuser problem in CRAHNs. An efficient multiuser based algorithm is also proposed in [17] to maximize the sum capacity of the cognitive OFDM systems while maintain the proportional rate. In [18], authors have examined the effects of multi-user diversity in a spectrum sharing system. However, cooperative sensing is the most popular approach which discussed widely to solve such a problem. Cooperative solution is discussed in chapter Five.

3.3 Background and Related Work

Cognitive radio has been proposed as a solution to overcome spectrum scarcity in wireless communication. It has two important functionalities: spectrum sensing and adaptation. Initially, a secondary terminal senses the spectrum environment in order to learn the frequency spectrum unoccupied by PUs. Once unoccupied spectrum (spectrum hole) is found, the secondary user adapts its transmission power, frequency band, modulation, etc., so that it minimizes the interference to the PUs. Even after starting the transmission, SU should be able to detect or predict the appearance of PU so that it makes the spectrum available for PU.

CR MAC protocol has responsibilities to coordinate channel access to licensed bands. It enables multiple CR users to share the spectrum resource by determining who will access the channel and when it will be performed. This protocol design is necessary to accomplish the QoS of data transmission. The design of OSA MAC protocol should consider where the SUs adaptively and dynamically seeking and exploiting opportunities in both licensed and unlicensed spectrum. SU has responsibilities to make real time decision when and where to sense and determine which spectrums are available, select the best available channel for better spectrum utilization, coordinate spectrum sharing among different unlicensed and licensed users, and vacate the channel when licensed users is detected.

MAC protocol for OSA was discussed in [19]-[21]. It is classified into random, time slotted, and hybrid protocols. POMDP framework is categorized as hybrid protocol, which exploits partially time slotted and partially random access. In this protocol, control signalling generally over synchronized time slot. However, the following data transmission may have random channel access schemes without time synchronization.

3.3.1 Spectrum Access Models

Unlike infrastructure-based CR MAC protocols, CR MAC protocols for ad hoc networks do not have a central entity to control and operate the network. To enhance the performance of spectrum usage, CR users, which should be aware of the primary user's activities within the same transmission area, need to determine and control the spectrum sensing, sharing, and access robustly. All these tasks necessitate efficient cooperation with the neighbouring nodes located in the same transmission range. Therefore, maintaining time synchronization across the network and obtaining valuable information from surrounding nodes are some of the major factors that need to be considered in the sensing and access protocols design. Different spectrum sensing, sharing, and access approaches are proposed in the literature.

In this section, we focus on the most famous techniques that have been identified as one of the key techniques for designing cognitive MAC for wireless Ad Hoc networks. Therefore, to address the problem of MAC design, the existing MAC and routing protocols can be developed and enhanced to be convenient for wireless ad hoc networks. Multiple channels technique, for example, can be assigned between nodes to multiple radios at the same time, so such problems can be minimized and more data can be sent between nodes increasing the overall throughput of the network. In addition, different MAC protocols based on modification of the existed standards (e.g. IEEE802.11, CDMA, and OFDM) were developed for utilizing multiple channels. The notion of “soft” channel reservation, for example, was proposed to give preference to the channel that was used for the last successful transmission. Schemes that negotiate channels dynamically were also proposed to enable users to communicate in the same region simultaneously. Other techniques such as single or multiple transceivers for each node have been widely discussed.

Additionally, spectrum access techniques have responsibility of enabling CR users to share the spectrum resource by determining which user will access the channel, and when a user can access the channel [22]-[23]. Different CR MAC protocols based on different architectures and radio technologies have been investigated. Generally, MAC protocols for CR-based networks for both infrastructure and mobile ad hoc networks can be classified into three categories: (i) random access protocols, (ii) time slotted protocols, and (iii) hybrid protocols [21]. In addition, the number of radio transceivers can be applied in this classification. In the random access approach, the access to the medium is based on the Carrier Sensing Multiple Access and Collision Avoidance (CSMA/CA) scheme, where the time slotted approach aims to divide the time into multiple slots for both control and data transmission. Finally, Hybrid protocols are assumed to be a combination of random access and time slotted approaches. This type of protocols uses a partially slotted channel scheme and tries to access the channel randomly.

In addition, for the secondary network scenario, many models based on Graph Colouring theory, Game theory, Markov Decision Process (MDP) theory or other approaches have been also proposed. All of these approaches are the most known approaches proposed for designing the cognitive MAC offering different solutions and aspects that aim to increase spectrum efficiency by allowing cognitive users to exploit the existence of the huge unused licensed spectrum with respect to the legacy system. More details concerning the previous work related to spectrum access techniques are discussed below.

3.3.1.1 Direct Access Approach

In CR systems, direct access to the channel has two strategies: The first access strategy is to direct the CR user either to select a channel to access or to give up accessing any channel. The second access strategy is to direct the CR user only to reach its local goal without any consideration of others or the global network, which avoid the global optimization issue. Similar to traditional MAC protocols, direct-access-based MAC protocols for CR networks are classified into two categories including distributed protocols for Ad Hoc networks and centralized protocols for infrastructure networks. The direct access approach is generally inherited from IEEE 802.11 with some improvements to adapt to multichannel environments. Furthermore, the distributed protocols are further divided into two classes: Contention-based MAC protocols and Contention-free MAC protocols.

Contention-based MAC protocol, also known as random access MAC protocols, is a communication protocol that allows many users to use the same radio channel without pre-coordination. Hence, the negotiation (handshake) scenario only happens between the sender and the receiver. The "listen before talk" scenario applied in IEEE 802.11 is the most well-known example for contention-based protocol. However, as this type of protocols is based on handshaking scenario, the sender and the receiver should find a control channel on which they exchange the control messages. In the case of performing duplex data communication, the sender and receiver should also choose an unoccupied channel on which they exchange their information. In CR networks, after finishing their sensing process, nodes exchange their sensing outcomes, and then evaluate the available resource and negotiate the channel for communication. This complete process is also known as Channel Filtering Sender Receiver (CFSR) handshake.

Contention-free MAC protocols, also known as coordination-based MAC protocols, are protocols in which each node coordinates with other nodes that locate in common transmission range to the intended sender or receiver to make its decision. While contention causes message collisions, which occurring when traffic is high and correlated degrading the performance, a contention-free MAC protocol does not allow any collisions. However, as the direct coordination approach requires information exchange among nodes throughout the network, the scalability issue is a bottleneck for such MAC protocols. Furthermore, the proposed solutions for contention-free MAC protocols recommend the time synchronization approach for the CR users, which is usually very critical and difficult on for large scale of users in the system. Time splitting and cluster negotiation are the recommended solutions for this problem. In time splitting solution, over the time scale, a specific time interval is divided for negotiation allowing each node to be assigned a time slot for negotiation so that it can periodically broadcast negotiation packets through its time slot [24]. In cluster negotiation solution, nodes are grouped into different clusters and only nodes within the same cluster coordinate with each other [25].

3.3.1.2 Graph Theory Approach:

Using graph-theoretic approach, a bidirectional graph G = (V, L, E), for example, can be used as a framework, where V is a set of vertices denoting the users, L is the colour list at each vertex denoting the available channels, and E is a set of undirected edges between vertices representing interference between any two vertices [26]. Therefore, each node in the cognitive radio system can be modelled as a vertex in a graph, and vertices joined by coloured edges to indicate the available channels in the system. The channel assignment problem can be then modelled as a graph colouring problem and heuristics are provided for different criteria for fairness [27]. In [28], assignment of channels to nodes scenarios was presented aiming at forming topologies depending on the parameter that is desired to be optimized. After a sensing scenario, the available channels can be modelled as a layered graph. Frequency assignment problems such as common broadcast frequencies, non-interfering frequencies, and direct source-destination communication frequencies, have been taken a deep discussion in [29]. It have shown that each can be modelled as a generalized graph colouring problem. In this context, centralized and distributed heuristics for efficient channel assignment were presented. On the other hand, applying Ad Hoc routing protocols, the channel allocation problem with capacity constraints can be modelled as a mixed integer nonlinear programming problem. Thus, using linear programming relaxations, tight lower bounds can be achieved. Moreover, based on Lagrangian relaxation and gradient search methods, heuristics for a distributed approach were proposed [30]. However, the colouring scheme is constrained by the problem of colour-sensitive graph colouring when a specific coloured edge cannot be assigned to any two vertices simultaneously if that colour already exists between the two vertices.

3.3.1.3 Game Theory Approach:

Moving to the Game-theoretic approaches, various strategies are also developed to analyse competitions between the players, which represent the CR users and the primary users, to achieve optimal solutions. A game theoretic approach, for example, can be formulated as follows: The players in the game are the secondary users and the primary user. The primary user is willing to share some portion of the spectrum with the secondary users. The primary user charges a secondary user for the spectrum at a rate of the total size of spectrum available for sharing. The payoff for each player is the profit of the secondary user. The Nash equilibrium is also considered as the solution of this game [31]. Therefore, based on the Game-theoretic approaches, in many research papers (e.g. [32]−[34]) the spectrum access in cognitive radio networks have also been studied. In [32], an *n*-player noncooperative game theoretic approach for secondary user spectrum access was presented. A utility function based on the access delay and collision probability was proposed, and the existence and convergence to Nash equilibrium was shown. The author of [33] investigated the interference problem and defined an interference temperature constraint to limit the interference caused to the primary users. An algorithm for the optimal supported link subset was proposed and the spectrum sharing problem is modelled as a potential game to show the existence of a deterministic pure strategy Nash equilibrium. To reduce the unfairness problem in spectrum access, the author of [34] presented the homo-equalise game-theoretic model for secondary user spectrum access. In their model, users were modeled to behave like a human society. The learning-automata-based approach was also studied in [35]. In such approach, users were classified as quality sensitive and price sensitive users. The authors also considered a model in which users could cooperate to achieve better spectrum utilization. In [36], the achievable capacity in cognitive radio networks was studied where the authors considered cases of a genie aided cognitive radio channel. In such scenario, the receiver is no causally provided the message from the transmitter in an interference channel, and then compared this with the case of a causal cognitive radio channel to obtain an achievable capacity region. However, this assumption may not be realistic in some cognitive radio systems.

3.3.1.4 Markov Decision Process Approach:

In addition, various spectrum sensing and access techniques are proposed and developed based on Markov decision process theory (e.g., [37]-[41]). A partially observed Markov decision process (POMDP), for example, was used for dynamic spectrum access in wireless ad hoc networks. An analytical POMDP framework for opportunistic spectrum access was also developed to allow CR users to access the spectrum by using a decentralized cognitive MAC strategy [37]. The decision-theoretic approach aims at identifying optimal policies to optimize the performance of the CR network. Investigating the limited sensing capability of each SU in cognitive radio systems under POMDP frameworks is also discussed widely. Some works presented cross layer design approach to implement partial sensing results to optimize spectrum access. However, most of the presented works in such approach considered that only single user senses either single or multiple channels. Although POMDPs have recently received much attention in scheduling approaches, in general they still require exponential computational complexity and memory.

3.3.2 Scheduling of CR MAC Protocols

In general, previous work on scheduling of CR MAC protocols has considered two main scenarios: *primary network scenario* and *secondary network scenario*. For the primary network scenario, the spectrum can be slotted into small bands (e.g. [42]-[44]) or un-slotted (e.g. [45]-[47]). In this sub-section, we focus only on time slotted approaches.

In [42] the authors presented a scenario for accessing the medium in which the secondary transmitter can sense all the available primary channels, whereas the receiver does not participate in any sensing action. After sensing the medium, the transmitter decides which channel to access. However, a cross-layer approach was presented in [37]. Considering the hardware limitation and energy constrains, the authors suppose that the secondary transmitter can only sense a subset of the possible primary channels at the beginning of each time slot. The authors of [43] preferred to optimize the on-line learning capabilities of the secondary transmitter and ensure perfect synchronization between the secondary transmitter and receiver. The authors also proposed a scenario where only a limited number of channels are sensed by the secondary user at every time slot before making a decision on which cannel to access. In addition, cognitive MAC schemes for sharing spectrum with a set of parallel WLAN bands are proposed in [44]. The proposed schemes are classified according to fully observable and partially observable systems. It has shown that both schemes achieve almost the same performance.

3.4 Proposed Model

Decision-making process is a cognitive process leading to the selection of action among variations. To automate the decision-making process, it is recommended to provide a model of dynamics for the domain in which the machine will be making decisions. A future reward is expected to be maximized by the immediate decision.

3.4.1 POMDP Framework

A POMDP can be described as a six tuple (S, A, Ω, T, O, R).

where:

- ***S*** is a finite set of states of the system, which represents all the possible underlying states the process can be in
- ***A*** is a finite set of actions the agent can do, i.e. it is all the available control choices at each point in time.

- ***Ω*** is a finite set of observations the agent can obtain, which consists of all the possible observations that the process can emit.

- ***T*** is the state transition function, which encodes the uncertainty in the process state evolution, and **T(s,a,s')** is the probability of ending in state **s'** when the agent is in state **s** and executes action **a**.

- ***O*** is the observation function, which relates the process outputs (observations) to the true underlying state of the process, and **O(s',a,o)** is the probability of making observation **o** while the agent doing action **a** and ending in state **s'**.

- ***R*** is the reward function, which gives the immediate utility for performing an action in each of the underlying process states, and **R(s,a,s')** is the expected reward for taking the action **a** in state **s** and ending in state **s'**.

The aim, then, is to model the CR system based on a POMDP, which is an aid in the automated decision-making. Applying POMDP theory help to find a policy (π) that informs CR users what action to be executed at each step with respect to the system legacy. The policy can be a function or a mapping and typically depends on the channel states. Furthermore, a reward structure can be used to motivate immediate decision that will maximize the future reward. The solution of this POMDP yields the optimal tradeoffs between transmission energy and transmission delay (latency).

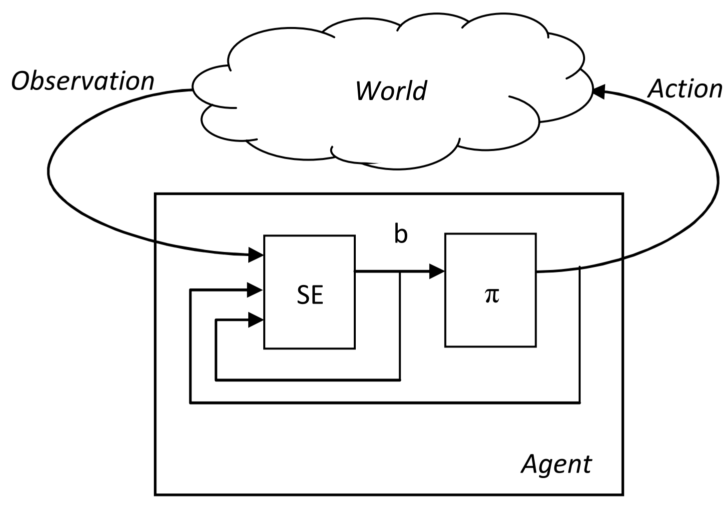

Figure 3-1: A POMDP framework

Figure 3-1 shows the working of a POMDP. In a POMDP world, which is composed of a set of states, initially, an agent believes that it is in a particular state or has a probability distribution over states, called the belief state. The agent takes an action and gets an observation of the new reached state. Given that the new state may not be directly inferred from the observation, the State Estimator (SE) derives the new belief state based on the current observation, the last action, and the previous belief state. Once the new belief state is calculated, the agent takes a new action and the process continues until an end state is reached. The state π represents the POMDP policy, which maps a belief state and hence an observation to an optimal action.

In the next subsections, how to model the network as a POMDP is described. The aim is to use this model to derive a control policy that will yield the greatest amount of utility over some number of decision steps leading to maximizing the future reward:

$$R^T = Max\ [E\{\textstyle\sum_{t=1}^{T} r(t)\}] \qquad (3\text{–}1)$$

Where *r(t)* is the transition reward which is given for each accessed channel and *t* (*t = 1, … , T*) is the number of time slots of the channel.

3.4.2 Primary Network Description

Obviously, the responsibility of MAC protocols in a CR network is to schedule which user and when a CR user can access the available channel. Based on POMDP frameworks, channel sensing and channel access scenarios model the channel opportunity of the network system as a discrete time Markov chain with number of channel states which can be formulated as $M=2^N$ states, where N is the number of channels. A simple channel state diagram for two states is illustrated in Figure 3-2, where the state (S=0) indicates that the channel is occupied by the primary user (busy state) and the state (S=1) indicates that the channel is available to be accessed (free state).

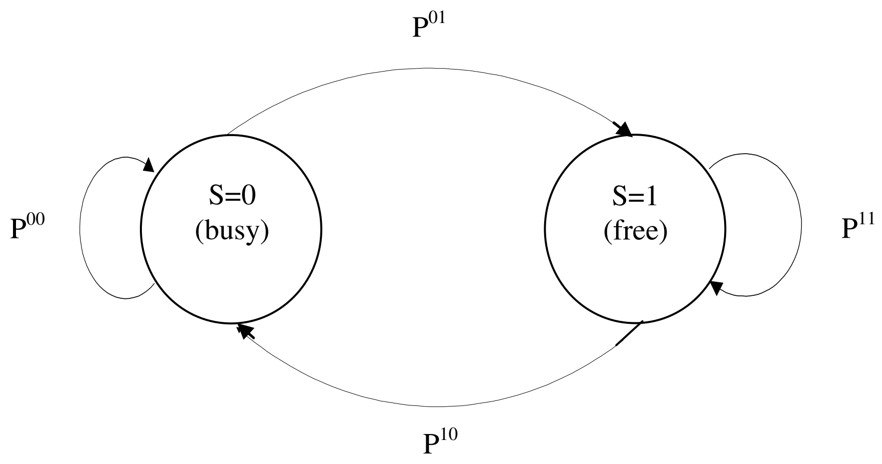

Figure 3-2: The markov process model for N = 1, two possible states {busy state: S = 0, and idle state: S = 1}

Starting from the concept of partially observable term, which means that the CR user selects set of channels to be sensed and set of channels to be accessed, we consider a spectrum consisting of N independent channels, each channel with bandwidth B_n ($n = 1, \ldots, N$). These N channels are licensed to the Primary Users, which have an authority to communicate over it according to a synchronous slot structure. The presence and absence of the primary users in each channel of the network represents the traffic strategy of the primary network and can be modelled as alternative time intervals of busy and free states. At a particular time and due to the absence of the primary users, some of these N channels might be free and available for opportunistic transmission by secondary users, which seek free spectrum spaces to improve their network performance. We also consider each channel to be divided into T time slots. The network state in a slot t ($t = 1, \ldots, T$) is given by $\{S_1(t), \ldots, S_N(t)\}$, where $S_n(t) = 1$ when the channel is free and $S_n(t) = 0$ when the channel is busy. The slotted channels diagram is illustrated in Figure 3-3. The objective, then, is to maximize the throughput of the secondary network under the constraint of interference to primary network by exploiting the sensing history and the spectrum occupancy statistics.

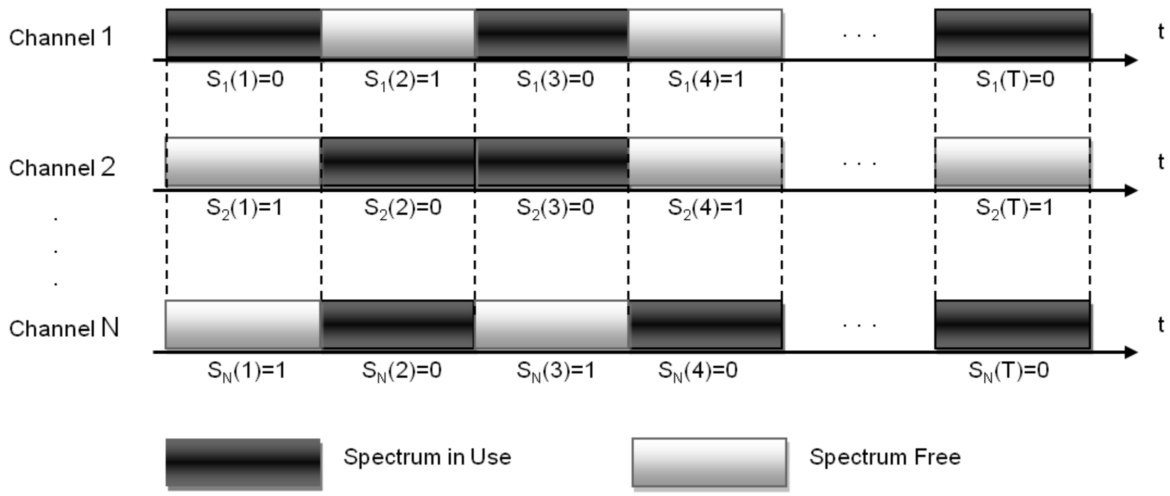

Figure 3-3: The primary network model: N independent channels with T time slots

3.4.3 CR user strategy

According to the primary network design, we consider that the strategy of CR users is to sense the radio spectrum at the beginning of each time slot, detect the occupancy state of different primary channels which can be represented by a one-dimensional variable S_n , $n = 1, \ldots, N$, at time slot *t.* By detecting the occupancy state of different primary channels, the CR user decides to communicate over the *n*th available channel out of the *N* sensed channels. Thus, based on the sensing strategy, the unlicensed users can access to the medium and communicate opportunistically over the unused channels (spectrum holes) in an intelligent way without causing any harmful interference with the licensed users. Upon receiving the transmitted data, the receiver will transmit an Acknowledgement (ACK) and reward function for the successful transmission. This reward can be gained by the SU in each transmission slot. The sensing scenario proposed in this work is without cooperation, where each CR user senses the spectrum availability without exchanging their local observation. The objective is to achieve an optimal spectrum sensing and access strategies which can enhance the performance of throughput in CR wireless networks.

3.4.4 Network Components

We consider the following components forming the core of our proposed model strategy:

States: We define a set of states as follows:

$$S = \begin{bmatrix} S_1(1) & S_1(2) & \dots & S_1(T) \\ S_2(1) & S_2(2) & \dots & S_2(T) \\ \vdots & \vdots & \ddots & \vdots \\ S_N(1) & S_N(2) & \dots & S_N(T) \end{bmatrix} \qquad (3\text{-}2)$$

Where a row vector $[S_n(1), S_n(2), \dots, S_n(T)]$ is a vector state of channel *n*, and the network state in channel *n* and slot t is represented by $S_n(t)$. So with *N* channels and *T* slots for each channel we can get $S = 2^{N\text{x}T}$ different states.

Sub-States: To reduce the computational complexity problem, we define a sub-set of states as a column vector state of slot *t*: $S_t = [S_1(t), S_2(t), \dots, S_N(t)]^T$.

Where the network with *N* channels is represented by $S_t = 2^N$ different sub-states for each time slot. At the start of each time slot the SUs will be invited to sense the medium for the *N* channels of the system. Example: N = 2, so we can get $2^2 = 4$ possible sub-states:

Table 3-1: THE POSSIBLE SUB-STATES FOR N= 2

	Channel 1	**Channel 2**
Sub-State 1	0	0
Sub-State 2	0	1
Sub-State 3	1	0
Sub-State 4	1	1

For any SU, checking the availability of channels at the time slot *t* can be indicated by the column vector by performing the following hypothesis test:

$$\begin{cases} H_0 : S_n(\mathrm{t}) = 1 & \text{if the channel is free,} \\ H_1 : S_n(t) = 0 & \text{otherwise.} \end{cases} \qquad (3\text{–}3)$$

Actions: We now define a set of actions which consist of 2^N different possible actions.

Example: N = 2, so we can get $2^2 = 4$ possible actions: (i) transmit nothing, (ii) transmit through channel one, (iii) transmit through channel two, and (iv) choose one of the available channels to transmit through and send a packet to other SUs informing them that there are other available channels to be used.

We assume that at some point of time, the SU sensed the current state as: $S = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$

Taking action "sensing $S_{n,1}$" will lead to four possible next states:

There are no available slots: $S' = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$

There is only one slot available at channel one $S_1(1)$: $S' = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$

There is only one slot available at channel two $S_2(1)$: $S' = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$

Or there are two available slots $S_1(1)$ and $S_2(1)$: $S' = \begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix}$

The SU, which acts as a decision maker, has to select which channel to be accessed based on the early observations.

Information state: We refer to the belief state $\pi(t)$ as the summary statistic of all past decisions and observations:

$$\pi(t) = [\lambda_1(t), \lambda_2(t), \dots, \lambda_N(t)]$$

Where $\lambda_n(t)$ denotes the conditional probability that channel n is available in slot t.

Reward: We finally define the transition reward. We assume that each used channel will give an amount of reward:

$$r(t) = \sum_{n=1}^{N} S_n(t) B_n(t) \qquad (3\text{–}4)$$

Where $S_n(t) \in \{0, 1\}$ is the state of channel n in slot t, and at the beginning of each time slot using the belief state $\pi(t)$, the secondary user decides to access the channel:

$$n^*(t) = \arg\max_{n=1,\dots,N}[\lambda_n(t)] \quad (3–5)$$

3.4.5 Problem Formulation

We consider that the information state is updated after each action and observation with the application of Bayes' rule as follows:

$$\pi(t+1) = [\lambda_1(t+1), \lambda_2(t+1), \dots, \lambda_N(t+1)]$$

The conditional probability $\lambda_n(t+1)$ is considered to be depends on the channel transition probabilities P^{01} and P^{11}. We assume that the channel transition probabilities P^{01} and $P^{11}$are random variables that update their values after sensing all the primary channels at the start of each time slot. To update the channel transition probabilities P^{01} and P^{11}, the secondary user should keep track of the history of all transition states as described in [43]:

- Number of state transitions from busy to busy:

$$S_n^{00}(t) = \sum_{i=1}^{t-1}(1 - S_n(i))(1 - S_n(i+1)) \quad (3–6)$$

- Number of state transitions from busy to free:

$$S_n^{01}(t) = \sum_{i=1}^{t-1}(1 - S_n(i))S_n(i+1) \quad (3–7)$$

- Number of state transitions from free to busy:

$$S_n^{10}(t) = \sum_{i=1}^{t-1} S_n(i)(1 - S_n(i+1)) \quad (3–8)$$

- Number of state transitions from free to free:

$$S_n^{11}(t) = \sum_{i=1}^{t-1} S_n(i)S_n(i+1) \quad (3–9)$$

Depending on the previous state transitions, P^{01} is updated as follows:

$$P^{01}(t) = \frac{S^{00}(t)+S^{01}(t)}{t} \quad (3–10)$$

and P^{11} is updated as follows:

$$P^{11}(t) = \frac{S^{10}(t)+S^{11}(t)}{t} \qquad (3–11)$$

We consider that the initial belief state is given as the stationary distribution of the channel occupancy state:

$$\pi(0) = \frac{P^{01}}{1+P^{01}-P^{11}} \qquad (3–12)$$

Since the belief state $\pi(t) = [\lambda_1(t), \lambda_2(t), \dots, \lambda_N(t)]$, we will consider three different strategies to calculate the conditional probability of the availability of a channel:

1) In the first strategy, the conditional probability $\lambda_n(t+1)$ is considered to be depends on the channel transition probabilities P^{01} and P^{11} as follows:

$$\lambda_n(t+1) = \lambda_n(t)\, P^{11} + \left(1-\lambda_n(t)\right) P^{01} \qquad (3–13)$$

2) In the second strategy, the conditional probability $\lambda_n(t+1)$ is considered to be depends only on the last belief state $\pi(t)$ as follows:

$$\lambda_n(t+1) = \lambda_n(t) \max\,[\pi(t)] \qquad (3–14)$$

where $\max[\pi(t)]$ is to find the maximum conditional probability of the previous belief state.

3) In the last strategy, the initial belief state $\pi(0)$ is considered to be generated randomly:

$$0 < \pi(0) < 1$$

3.5 Simulation Results

In this section, based on the POMDP framework proposed in the previouse section, simulation results for different scenarios of POMDP-based cognitive MAC protocols that based on greedy sensing approach are presented. In order to evaluate the performance of the cognitive MAC protocols, the proposed mechanism and scenarios have been modeled and implemented in MATLAB. In the simulation, the number of primary channels are assumed to be three independent channels (N=3), each with bandwidth B = 1 (b/s) and number of slots T = 30. Moreover, a prior knowledge about the channel transition probabilities P^{01} and P^{11} (P^{01}={0.1, 0.3, 0.5}, P^{11}={0.9, 0.7, 0.5}) are assumed.

Based on the given parameters, the beliefe state will be updated each time according to the different presented scenarios .In the simulation, the sensing errors are ignored and we only focus on one secondary user. We first investigate the throughput achieved by the SU using three different strategies and then we test the impact of increasing the number of channels in impoving the throughput of the SU network.

3.5.1 Throughput with different scenarios

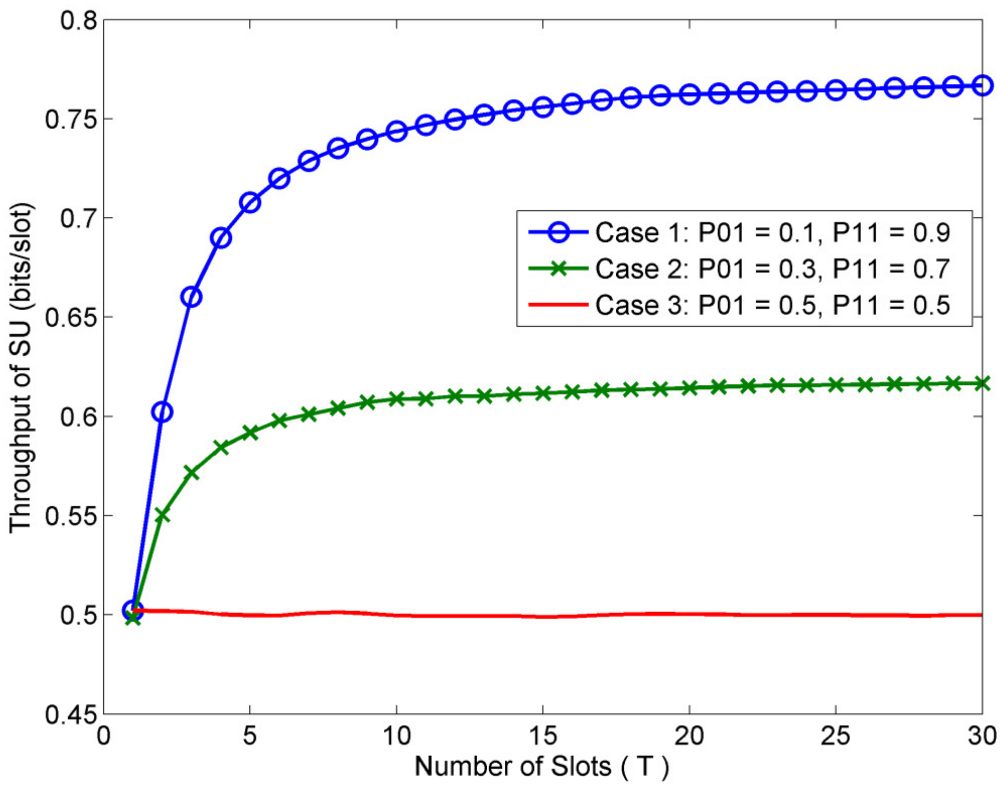

Figure 3-4: Throughput comparison using Equation (3-13) with different parameters (bandwidth B = 1, number of channels N = 3, and different transition probabilities {P01, P11})

Figure 3-4 shows the throughput comparison between the different spectrum occupancy statistics after applying (3-13), with prior knowledge about the channel transition probabilities {P^{01}, P^{11}}. In case 1 and case 2 with assumed large values for the probability of the channel state remain unchanged from the idle state {P^{11} = 0.9 and 0.7 respectively}, we observe an increase in the aggregate throughput of SU over time for both cases. On the other hand, the comparison of case 1 with case 2 shows that whenever the probability of channel unchanged from idle state is bigger, the throughput achieved by the SU is higher. This corresponds to large message length and large inter-arrival time. However, in case 3 where the values of transition probabilities are equals, 0.5 for each, (which means the channel is as likely to change the state or remain at the current state), we notice no change in the throughput of SU over time.

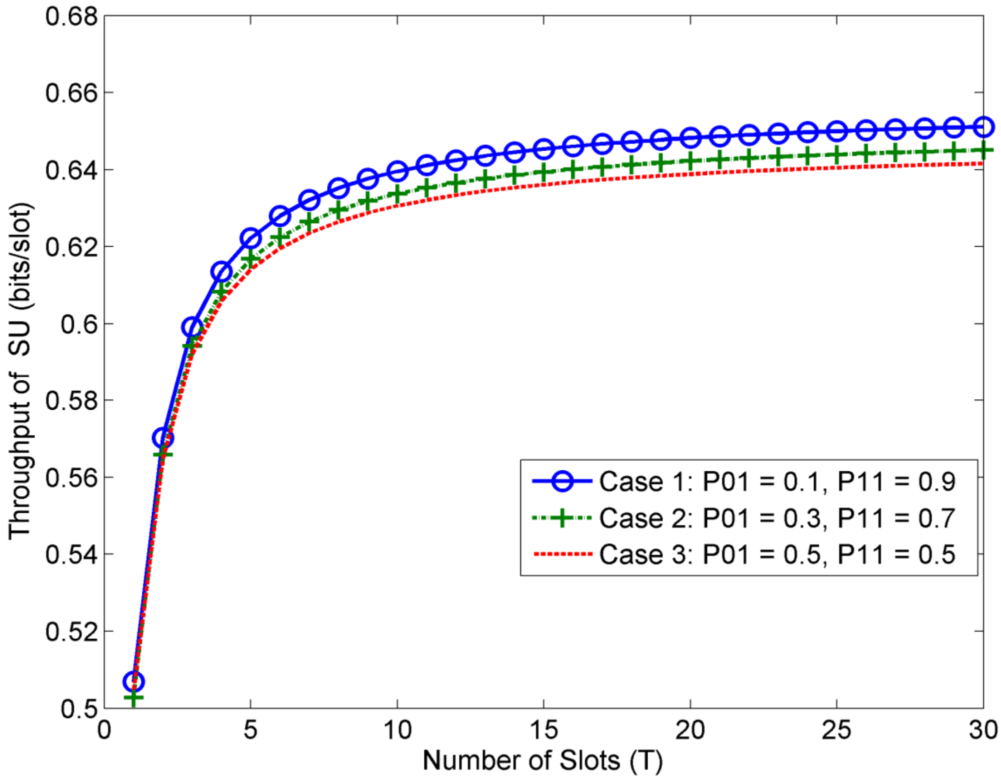

Figure 3-5: Throughput comparison using Equation (3-14) with different parameters (bandwidth B = 1, number of channels N = 3, and ignoring the transition probabilities in updating the belief state)

Applying (3-14) on the same senario by ignoring the channel transition probabilities, Figure 3-5 shows the throughput comparison between the different spectrum occupancy statistics where the updated information state depends only on the last belief state $\pi(t)$. In other words, we keep using the channels transition probabilities $\{P^{01}, P^{11}\}$ to generate the initial belief state in each case and ignoring it in updating the belief state. It is obvious from Figure 3-5 that the three cases achieved high throughput over time. Comparing Figure 3-5 to Figure 3-4, Figure 3-5 shows sharp improvement in the throuhput of SU especially for case 3 and case 2. These results reflect the usage of (3-14) where the SU always expects the channel to stay available.

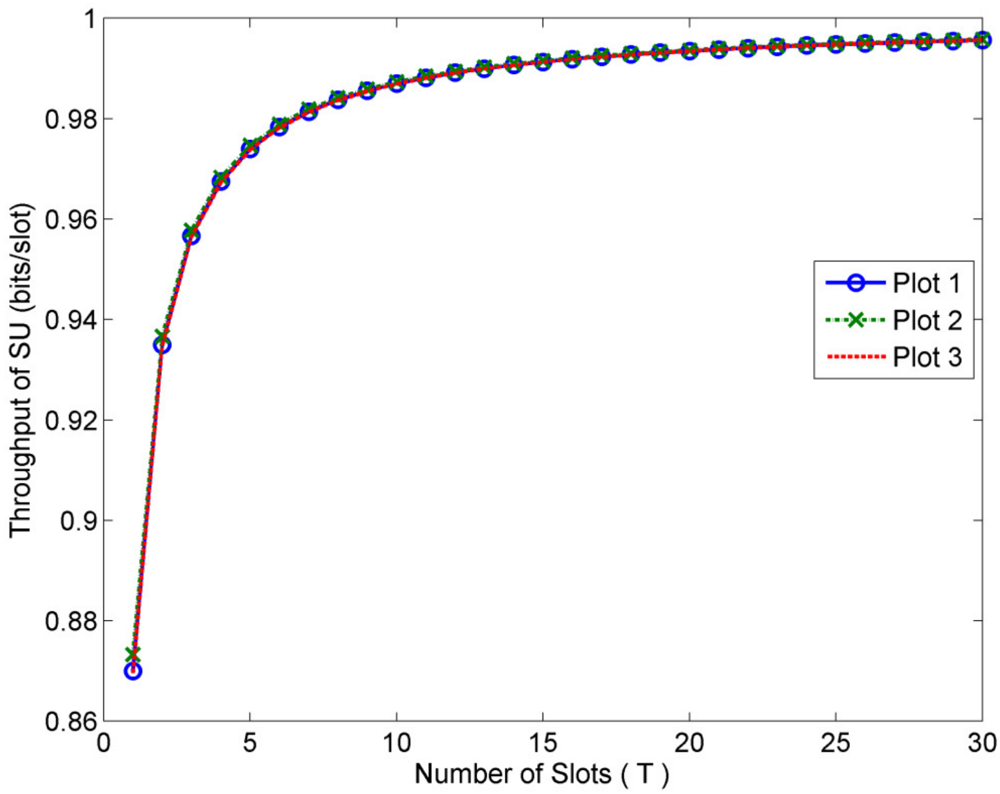

Figure 3-6: Throughput comparison using Equation (3-14) with different parameters (bandwidth B = 1, number of channels N = 3, and generating the initial belief state randomly)

We further proceed by applying the same scenario with some changes. We consider that the initial belief is generated randomly and we do not need to use the channel transition probabilities any more. By using (3-13) to update the belief state, we plot the aggregate throughput by repeating the simulation three times. As shown in Figure 3-6, the three plots are almost congruent achieving the highest aggregate throughput.

3.5.2 Throughput comparison

Figure 3-7 shows the throughput comparison between the results achieved in Figures 3-4, 3-5, 3-6 and the scheme results achieved in [37]. In general, it can be observed that the three scenarios proposed in this chapter as well as the proposed in [37] achieve an increase in the aggregate throughput of SU overtime. However, applying scenario 2 when the updated information state depends only on the last belief state, a sharp increase in the throughput overtime can be achieved compared to the other two scenarios and the scenario proposed in [37]. In other words, using the channel transition probabilities $\{P^{01}, P^{11}\}$ to generate the initial belief state and ignoring it in updating the belief state can increase the throughput of the SU sharply overtime. These results reflect the usage of Equation (3-14) where the SU always expects the channel to stay available. In addition, it is obvious from Figure 3-7 that the third scenario achieves the highest throughput overtime compared to the other two scenarios and the scenario proposed in [37]. Hence, by applying Equation (3-14) to update the belief state and generating the initial belief randomly, it can be observed that the achievable throughput is the highest. Furthermore, the achivable throughput in scenarios 2 and 3 converges asymptotically overtime achieving significant improvement in the throuhput.

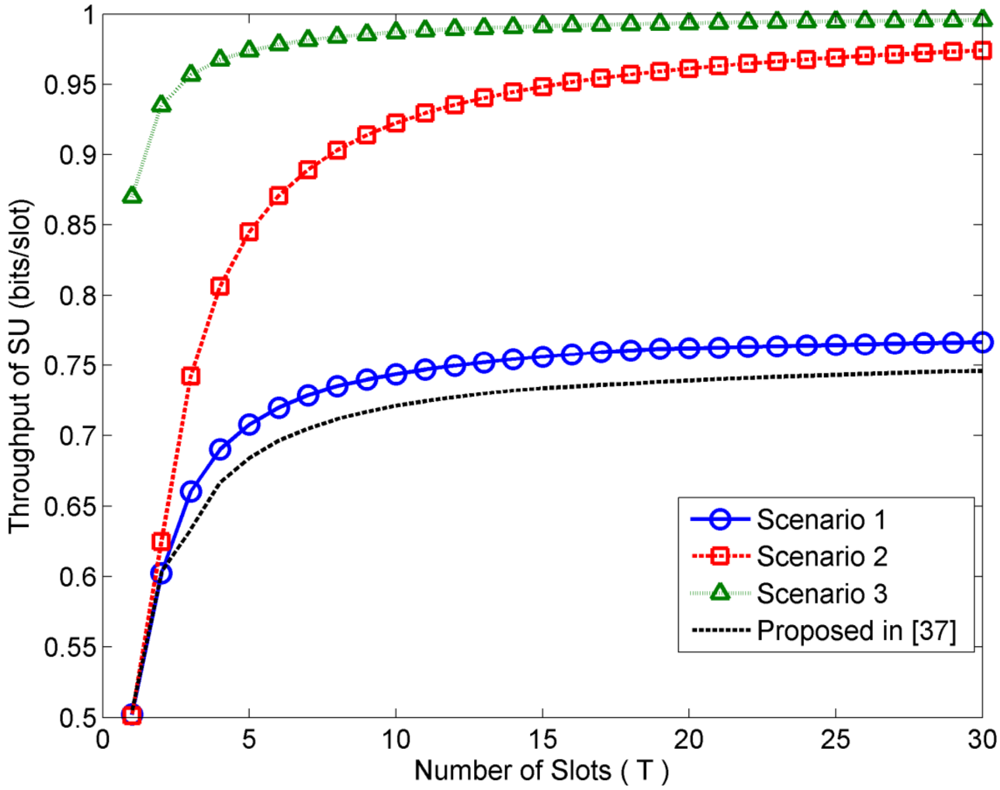

Figure 3-7: Throughput comparison using Equation (3-13), (3-14) and the scheme results proposed in [37]:

3.5.3 Throughput with different number of channels

In the second scenario, we consider one of the above mentioned three cases. We set the channel transition probabilities at a specific values $\{P^{01} = 0.1, P^{11} = 0.9\}$, as case 1 performs the best throughput in Figure 3-4 and Figure 3-5. We apply this scenario to a different number of primary channels {N = 2, 3, 4, and 5}, with bandwidth B = 1 and number of slots T = 30. After applying this scenario, firstly considering the channel transition probabilities by using (3-13), secondly ignoring the channel transition probabilities in updating the information state by using (3-14), and finally by generating the initial belief state randomly, Figures 3-8, 3-9 and 3-10 show the throughput comparison of the greedy approach.

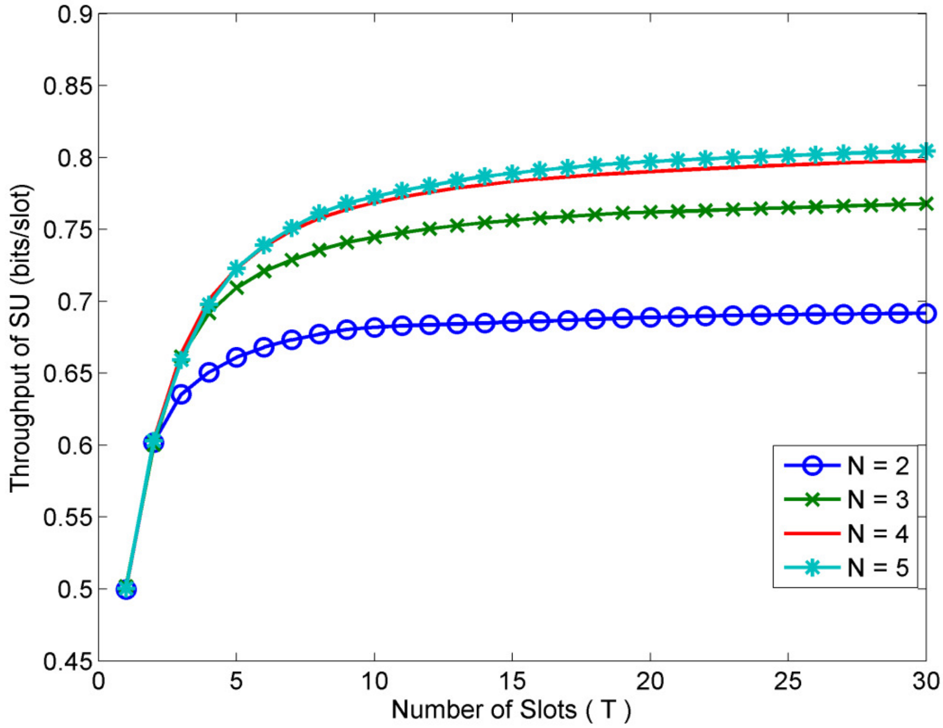

Figure 3-8: Throughput comparison using Equation (3-13) with different parameters (bandwidth B = 1, transition probabilities {P01 = 0.1, P11 = 0.9}, and different number of channels N)

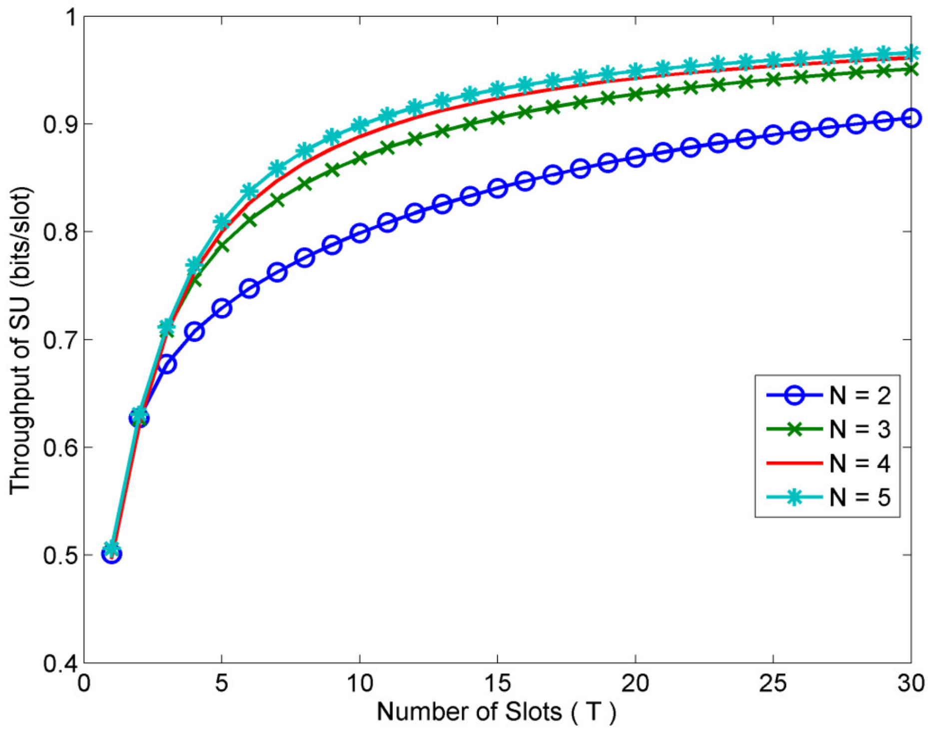

Figure 3-9: Throughput comparison using Equation (3-14) with different parameters (bandwidth B = 1, different number of channels N, and ignoring the transition probabilities in updating the belief state)

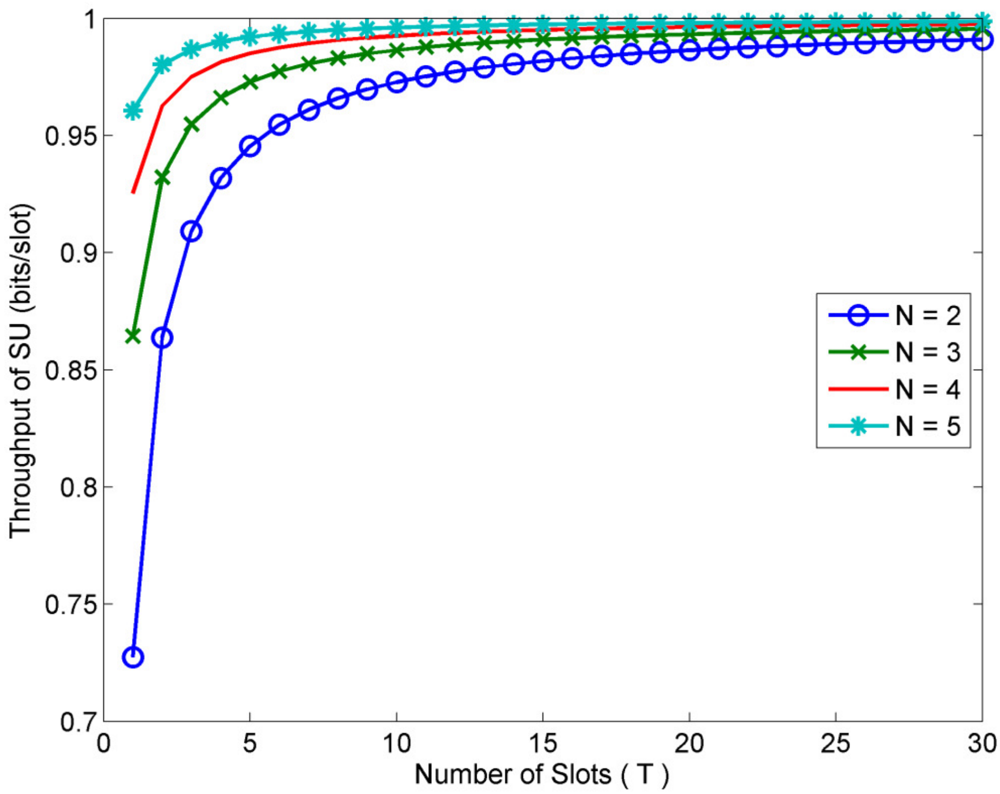

Figure 3-10: Throughput comparison using Equation (3-14) with different parameters (bandwidth B = 1, different number of channels N, and generating the initial belief state randomly)

In general, we observe that the aggregate throughput of SU increases as the number of channels increases in the three strategies. While Figure 3-8 and Figure 3-9 show similar increase in the aggregate throughput for all cases {N = 2, 3, 4, and 5}, Figure 3-10 shows that the achievable throughput converges asymptotically, achieving the highest throughput. These results again reflect the usage of (3-14) where the SU always expects the channel to stay available. In addition, applying this strategy is shown to achieve a throughput very close to the upper bound; as a result, a convergence of throughput is observed.

3.6 Conclusion

In this chapter, a POMDP-based cognitive MAC protocols for multi-channel wireless ad hoc networks have been studied. Using multiple channels and assuming a time slotted strategy for the primary network, we propose that the unlicensed user makes efficient decisions for sensing and accessing the medium based on the channel transition probabilities and the belief state. By updating the belief state that summarizes the knowledge of the network state based on all past decisions and the channel transition probabilities or previous belief states, the secondary user perform more spectrum efficiency. Using three different scenarios, our results demonstrate an improvement in the aggregate throughput using a greedy strategy achieving better results when compared to other mechanisms. Furthermore, by generating the belief state randomly, we present an alternative way to improve the aggregate throughput of the SU. In addition, we demonstrate that the aggregate throughput can be improved whenever the number of channels increases. However, sensing errors are ignored in this work. False alarm and miss-detection probabilities need to be considered in the next chapter. In addition, PHY and MAC layers need more investigation to achieve an optimal cross-layer design which can enhance the performance of throughput in CR-based multi-channel wireless ad hoc networks.

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Chapter 4

Sensing Error-Aware Cognitive MAC protocols for MANETs

4.1 Introduction

In Cognitive Radio (CR) Networks, Quality of Service (QoS) guarantee is a challenging problem that has attracted fabulous efforts [1]–[4]. Although the basic concept of CR is intuitive, designing efficient cognitive network protocols to fully capitalize CR's potential to increase the network performance is still a challenging issue. To satisfy the increasing QoS requirements of the users, the service providers are faced with a situation where they require a larger amount of spectrum. This has raised the interest in unused spectrum access. However, interference between the unlicensed and the licensed users can be occurred when the unused spectrum is further used by the licensed users. In order to exploit transmission opportunities in different licensed bands, the tension between Primary User (PU) protection and CR user spectrum access should be wisely balanced. Therefore, spectrum sensing and spectrum access are the two key CR functions, which have been discussed widely in the literature. Spectrum sensing is the art of performing some sort of measurements on a part of the licensed spectrum, so a decision related to spectrum usage based upon the sensing outcomes can be taken. Thus, spectrum sensing has been considered as an important enabler for spectrum access. In a scenario in which there exist a licensed (primary) user, any unlicensed (secondary) user needs to ensure that the primary user is protected, i.e., that no secondary user is harmfully interfering any primary user operation. On other words, spectrum sensing can be used to detect the presence (or absence) of the primary user before accessing the spectrum.

To regulate the way of accessing the spectrum, FCC [5] have recently paved way for utilizing the spectrum unutilized by TV channels, which also known as TV white spaces. In these regulations, spectrum sensing has been considered to play a major role in accessing the spectrum and utilizing the white spaces opportunistically. Alternatively, some other solutions can be thought complements to the spectrum sensing such as using a database of spectrum usage, which can be queried for spectrum opportunities or advertising spectrum opportunities over a Cognition enabling Pilot Channel (CPC). However, such solution requires, firstly, that all the primary users report any usage of the spectrum to the database owner continuously, and secondly, a connection to that database via the Internet for example. Although reliable spectrum sensing is sometimes a challenging task, it should be noted that spectrum sensing also seems to be an attractive distributed approach for finding unused spectrum opportunities.

Therefore, some of the important design factors and issues that should be addressed in the Medium Access Control (MAC) protocol design for CR networks can be summarised as follows:

1- How to identify transmission opportunities,

2- How secondary users determine, among the licensed channels, which channel(s) and when to access for data transmission, and

3- How to avoid harmful interference to primary users under the omnipresent of spectrum sensing errors.

4.2 Background and Related Work

4.2.1 Spectrum Sensing Methodologies

Spectrum sensing is the main issue that has to be considered to enable the CR users to explore vacant spectrum opportunities and then to avoid interference with the primary users. It is an application of detection theory in which the final decisions may be binary hypothesis, i.e., either the spectrum is occupied (busy), or the spectrum is not occupied (free). However, the decision making process is further complicated when the CR's sensing overheads need to be accounted for each step. It has been shown that sensing a channel takes tens of ms and probing a new one takes from 10 to 133 ms, depending on the association and capture speed between the transmitter and receiver after each channel hopping [6]. Furthermore, to reduce collisions with newly activated PUs, a CR's transmission over an idle channel must be limited to avoid any interference with the PU. Accordingly, the CR user needs to sense the spectrum again. The accumulated overhead after sequentially sensing several channels could be comparable with or even greater than the CR's actual transmission time.

Additionally, we need to account for the impact of sensing errors on the network throughput. It has been shown that generally there are two types of spectrum sensing errors: (i) *false alarm*, when an idle channel is identified as busy, thus a spectrum opportunity will be wasted, (ii) *miss detection*, when a busy channel is identified as idle, thus leading to collision with primary users, since CR users will attempt to use such idle channels. In fact, sensing errors exist in all real systems. They significantly affect the system throughput. When a sensing error occur, a CR may falsely identify an idle channel as being occupied, thus missing a transmission opportunity. Under this hypnotises, the amount of time the CR user spends on sensing a channel becomes a variable to be optimized. Obviously, a shorter sensing time reduces the scanning time of a channel, but also increases the probability of a false alarm, which in turn increases the number of channels the CR needs to sense. This is leading to possibly longer overall channel search time, and thus a reduction in the network throughput. In this context, the tradeoffs between sensing time and sensing accuracy need to be carefully evaluated. Although spectrum sensing has been studied widely [7]-[10], most of the previous studies were based on the assumption that each CR user has the full band sensing ability. In fact, the cost to achieve wide band spectrum sensing by a single CR user is quite high. It should be realistic to assume that SU has the capability to sense a limited bandwidth of spectrum during a certain amount of time. The limited sensing issue brings new challenges in the design of spectrum sensing and access strategy in CR system.

In general, three approaches for spectrum sensing techniques are proposed in the literature, *primary transmitter detection, primary receiver detection,* and *interference* *temperature management* (ITM) [11]. While the primary transmitter detection technique is based on the detection of the weak signal from a primary transmitter through the local observations of CR users, the primary receiver detection aims at finding the primary users that are receiving data within the communication range of a CR user. Although, in CR systems the transmitters' signal that can be detected by the sensing process, the primary receivers that need to be protected from the secondary users' transmission. However, in most CR applications the CR user cannot reliably detect the primary receivers. Hence, the focus is usually on transmitter detection. Meanwhile, the secondary usage of the spectrum could be done when appropriate agreements have been set up between the primary user and the secondary user.

This chapter is mainly focuses on the transmitter detection. Generally, there exist several different approaches for transmitter detection, which is used in different sensing scenarios. The most well-known approach is the signal detection approach, which can be classified into three categories: (i) energy detection [12], (ii) matched filter (MF) detection [13], and (iii) cyclostationary detection [14]. Moreover, different developed algorithms based on the mentioned approaches are proposed in the literature, for example, eigenvalue-based detection [15]-[17]; and covariance-based detection [18]-[19]. Furthermore, spectrum sensing can be performed individually or it can be collaborative in which measurements from several sensors are combined in a fusion centre to obtain a more reliable decision. In this manner, cooperative spectrum sensing offers increased detection performance by spatial diversity of the sensors. Figure 4-1 shows an example of cooperative spectrum sensing. A survey of various spectrum sensing techniques can be found in [20] and the references therein.

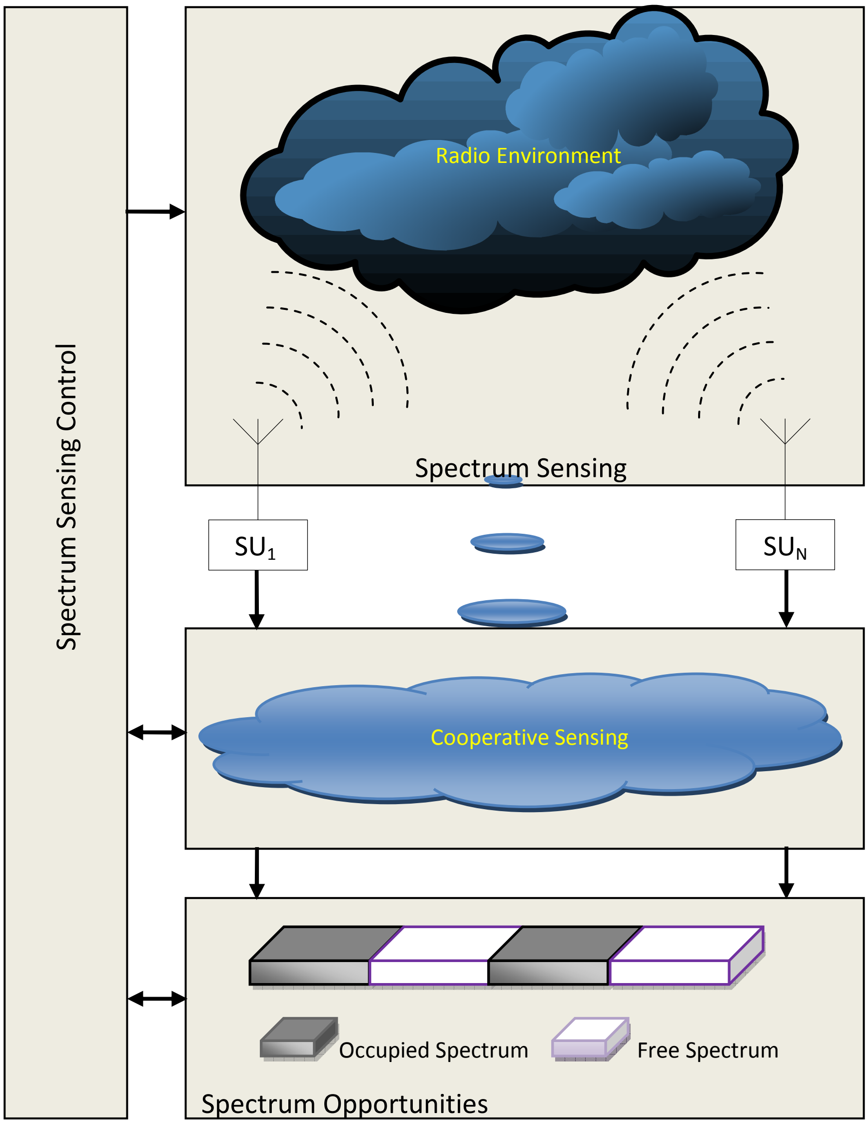

Figure 4-1: The scenario of cooperative spectrum sensing in CR Networks

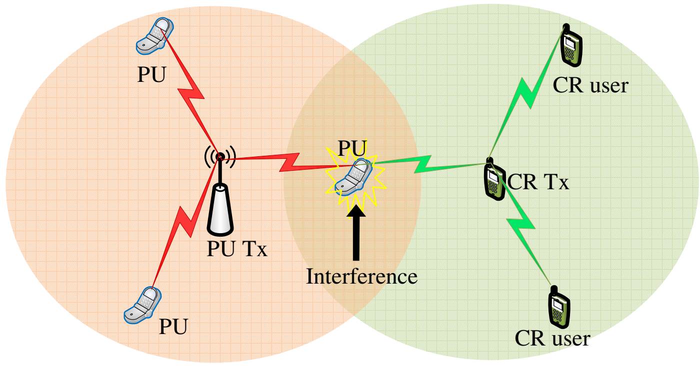

Figure 4-2: Illustration of hidden primary user in CR networks

However, as shown in Figure 4-2, some factors such as shadowing, hidden terminal problem may significantly affect the detection process of primary signal. When spectrum sensing is performed using a single sensor, that sensor may be located in a common transmission range with two different nodes that are located in different clusters and they do not see each other. This is known as the *hidden terminal problem*.

4.2.2 Design challenges for spectrum sensing

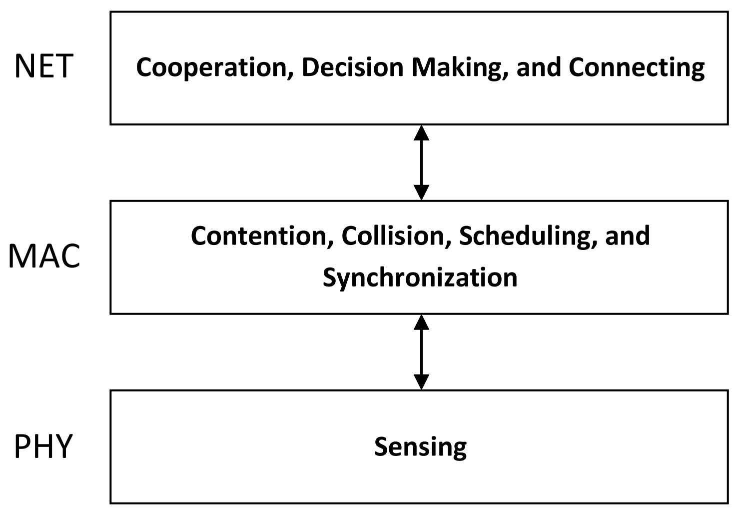

Figure 4-03: The architecture for collaborative spectrum sensing in a CR network

In CR networks, a collaborative spectrum sensing is performed across multiple layers in the network, involving (i) signal processing at the Physical (PHY) layer, (ii) channel sharing at the Medium Access Control (MAC) layer, and (iii) node collaboration at the Network (NET) layer. Figure 4-3 shows the architecture of collaborative spectrum sensing across multiple layers in a CR network.

The most challenge issue for CRs in wireless networks is to reliably detect the primary user's signal to minimize the interference to the primary communications. In general, it is difficult to distinguish between a white noise signal and a weak primary signal attenuated by a bad channel. This is due to the fact that the signals are usually undermined by channel shadowing or multipath fading. Therefore, fading or shadowing may result in the hidden terminal problem which can be illustrated in Figure 4-4. A CR node (CR1) inside the protection region (guard region) of a primary transmitter (PU Tx) cannot detect the primary signal due to shadowing. In such case, CR1 will assume that it is outside the protection region of PU Tx and any transmission made by this node in the primary transmission area may cause harmful interference to the primary user.

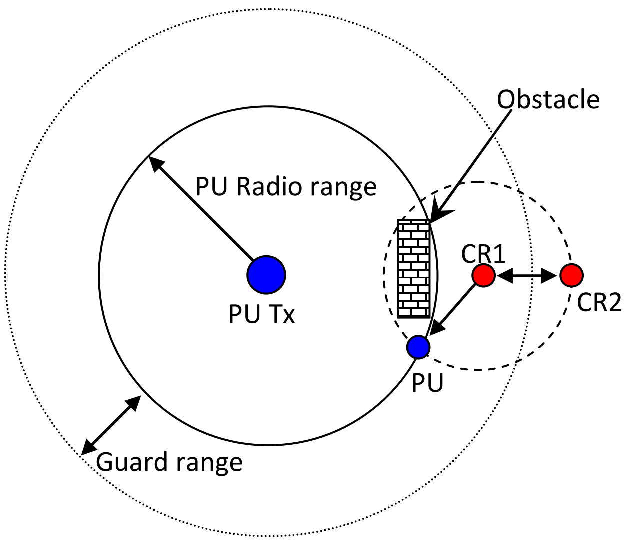

Figure 4-4: Shadowing which caused by the hidden terminal problem

To prevent the hidden terminal problem, based on collaborative sensing, the sensing results of multiple CRs could be fused and exploit spatial diversity among different CRs to enhance the sensing reliability. In such way, the CR users would have better results of detecting the primary signal after exchanging their sensing information and exploiting the built-in spatial diversity to reduce the collision probability. Therefore, based on its single sensor sensing, a secondary user may not engage in a decision of transmission unless it is highly confident in its detection of a spectrum opportunity, i.e., it must be able to detect a transmitter even as it experiences deep fading.

On the other hand, the efficient cooperation schemes should be investigated to reduce power requirements while optimizing the sensing reliability. Important design issues such as the overhead reduction associated with sensing information exchange and the feasibility issue of control channels should take more consideration. In general, operating characteristics such as false alarm and missed detection probabilities of the sensor detector should be selected by considering the achievable opportunistic throughput of secondary users and the probability of colliding with primary users. To this end, the sensing node must use conservative detection thresholds and/or highly sensitive receivers, which cause high *false alarm* probability and high cost devices, respectively. However, detection of the presence of primary user should be in such a way that the *missed detection* probability and the *false alarm* probability should not exceed a certain levels, because both probabilities have unique implications for cognitive networks. Small *false alarm* probability is needed in order to provide possible high throughput in dynamic spectrum access networks, since a false alarm wastes a spectrum opportunity. On the other hand, small *missed detection* probability is necessary in order to limit the interference to the PUs.

4.2.3 MAC and PHY Layers sensing

Spectrum sensing by far is the most important task that have to be done efficiently by the cognitive radio to establishment dynamic spectrum access. Cognitive radio is a more general term that may involve obtaining the spectrum usage characteristics across multiple dimensions such as time, space, frequency, and code, as well as determining what type of signals are occupying the spectrum, i.e., modulation scheme, waveform, bandwidth, carrier frequency, etc. Certainly, this task will require more powerful signal analysis techniques with additional computational complexity.

In cognitive radio networks, spectrum sensing schemes may be reactive or proactive according to the way of detecting the white spaces. Reactive schemes are energy efficient and operate on an on-demand basis in which a SU starts sensing the spectrum only when it has data to transmit. Proactive schemes, on the other hand, aim at minimizing the delay caused by the users in finding an idle channel by maintaining a list of licensed channels that sensed available for opportunistic access through periodic sensing process. While utilizing a white space, the SU no longer has a choice regarding the sensing mode and has to sense the channel proactively at periodic time intervals since it needs to vacate the channel as soon as any primary users reclaim that channel [21]. Generally, spectrum sensing can be realized as a two-layer mechanism. MAC layer sensing determines when SUs have to sense which channels and for how long. On the other hand, PHY layer sensing focuses on efficiently detecting PU signals.

4.2.3.1 MAC Layer Sensing

In multiple channels and multiple SUs scenario, MAC layer sensing techniques aim at scheduling the sensing process for efficient discovery of spectrum opportunities. The Important issues associated with such sensing scenario in dynamic spectrum access networks are how often to sense the availability of licensed channels, in which order to sense the channels, and how long a sensing period should be. The field of MAC layer sensing and scheduling has recently attracted significant efforts [22]-[26].

For example, based on the theory of partially observable Markov decision process (POMDP), an analytical framework for opportunistic spectrum access is proposed in [22]. The proposed decision-theoretic approach integrates the design of spectrum access at the MAC layer with spectrum sensing at the PHY layer and traffic statistics determined by the application layer of the primary network. As a result, an optimization on the performance of SUs and a limitation on the interference to the primary users can be achieved. To maximize the secondary network performance, a joint channel sensing and transmission scenario in multichannel systems is proposed in [23]. The proposed strategy based on choosing, intelligently, the sequence of channel probing/sensing and the optimal action on each channel. The proposed scheme aims at taking a set of decisions about which channels to probe, in what order, when to stop, and upon stopping which channel to use for data transmission. Additionally, issues such minimizing the delay of detecting an available channel and maximizing the discovery of spectrum opportunities by sensing-period adaptation has been addressed in [24]. In this context, a sensing-period optimization mechanism and an optimal channel-sequencing algorithm, as well as an environment adaptive channel-usage pattern estimation method have been developed by considering underlying ON-OFF PU's channel usage patterns.

Proceeding with the MAC layer sensing approach, an Extended Knowledge-Based Reasoning (EKBR) scheme to improve the fine sensing efficiency by jointly considering a number of network states and environmental statistics, including fast sensing results, short-term statistical information, channel quality, data transmission rate, and channel contention characteristics has been proposed in [25]. Consequently, an efficient spectrum sensing by making certain tradeoffs between data transmission rate and sensing overhead has been achieved. In [26], the spectrum sensing and transmission problems is formulated together to form an optimal stopping algorithm that aims at maximizing the average reward per unit time under the constraint of the collision cost. The SU will receive a reward for each successful transmission or a penalty if a collision with the PU is occurred. The algorithm works for two purposes: First, for general sensing-transmission structure, including but not limited to periodic or per-packet sensing. Second, for general unslotted PU idle time distribution. However, in such case, it requires SU to have the perfect knowledge of PU idle time distribution.

4.2.3.2 PHY Layer Sensing

The PHY layer sensing approach aims at detecting the presence of primary signals rapidly and robustly. The most well-known PHY layer detection methods, as mentioned before, are energy detection, matched filter (coherent) detection, and feature (cyclostationary) detection. They have been extensively investigated in [27]-[31]. It is accomplished by using or not using the parameters of the primary users' signals such as transmission power, waveform, and modulation schemes. We discuss the three methods below.

❶ ***Energy detection***: Energy detection can be considered as one of the lowest complexity schemes, which has been widely used in radiometry. It requires limited a priori information of primary signals to perform non-coherent detection through energy detection. An energy detector measures the energy of the primary signal in a radio resource in form of test statistic to be compared with a predetermined threshold. If the measured energy exceeds the threshold, the presence of primary user is declared, otherwise the radio resource is declared as not occupied, i.e., the spectrum is available for opportunistic usage. The well-known limitation for energy detection is the Signal-to-Noise Ratio (SNR) wall caused by uncertainties in background noise power [29]. It is considered as the smallest power under which the signal cannot be detected. Thus, energy detection relies on accurate knowledge of the noise power. However, this is impossible in practice since noise might vary over time due to factors such as interference. Moreover, energy detection is a non-specific detection method in which no particular knowledge of the signal properties is needed, i.e., energy detection can be used for declaring whether a resource is occupied or not, but it cannot identify the type of signal that is occupying the channel (e.g., primary signal or secondary signal). Other challenges with energy detection that it needs a priori information of the noise level to adjust the detection threshold and inability to detect spread spectrum signals.

❷ ***Matched Filter Detection***: In the case of a received single path signal in additive white Gaussian noise, the MF detector can be considered as the optimal way for spectrum sensing since it maximizes the SNR. However, a MF detector requires a priori information of primary signal at both PHY and MAC layers. Such information might be modulation type, pulse shape and packet format. An MF detector works by correlating the received primary signal with the predetermined information. Meanwhile, it has to be synchronized with primary signal in timing and carrier frequency. Thus, the amplitude and the phase of the signal are extracted and the magnitude is compared to a certain threshold value. If it is above the threshold value, a detection decision is made. The main advantage of matched filter is that due to coherency it requires less time to achieve high processing gain, i.e., MF detection has very good detection capabilities. However, it is very vulnerable to uncertainty and any changes in the primary signal. Moreover, a different detector is required in order to detect each primary signal, which makes coherent detection undesirable if multiple primary systems are to be sensed. It also requires a priori knowledge about the primary signal, which may not be available for all applications.

❸ ***Cyclostationary Detection***: A cyclostationary signature is a feature, intentionally embedded in the physical properties of a digital communications signal has statistical properties vary periodically over time. It may be easily generated, manipulated, detected, and analysed using low complexity transceiver architectures. This feature is present in most transmitted signals, requires little signalling overhead, and may be detected using short signal observation times. A wide sense cyclostationary process has an autocorrelation function, which is cyclic with a certain periodicity for all time indices. Cyclostationary detection is typically a statistical test based on the estimated autocorrelation function of one or several known cyclic frequencies and power spectral density. Cyclostationary detection exploits more knowledge about the primary signal than energy detection does. It is an effective tool for overcoming a number of the principal challenges associated with cognitive network and dynamic spectrum access applications. It has the potential to provide reliable signal classification even at low SNR [32]. Cyclostationary detection outperforms energy detection by exploiting an inherent periodicity in the primary users' signal. However, cyclostationary detection's improved performance is at the cost of increased complexity.

In addition, different other algorithms based on the mentioned approaches have been proposed. In [33], for example, a blind sensing algorithm based on oversampling the received signal is proposed. The proposed algorithm uses a novel combination approach to handle the band-limited signals without need to any a priori knowledge of the primary signal or the noise power. Based on the oblique projection operator, the estimation is involved in two signal statistics, one provides an estimate of the primary signal present in the received data, and the other signal statistic provides an estimate of the noise variance. On the other hand, based on the eigenvalues of the covariance matrix of the received signal, other blind sensing methods are proposed in [17]. Firstly, a Maximum-Minimum Eigenvalue (MME) detection algorithm is based on the ratio of the maximum eigenvalue to minimum eigenvalue, and secondly, the Energy with Minimum Eigenvalue (EME) detection algorithm is based on the ratio of average power of the received signal to the minimum eigenvalue. Both MME and EME algorithms use the received signal samples, and only limited information on the transmitted signal are needed. By comparing the MME and EME algorithms to the energy detection scheme, it has shown that the two algorithms outperform energy detection in two ways: First, MME and EME do not use the noise power for making the decision of the primary signal presence. The reason behind that is that the estimation of noise power is naturally embedded in the algorithms. Consequently, MME and EME are robust to noise uncertainty and variation. Second, MME and EME algorithms provide better performance than energy detection when the detected signals are highly correlated [17]. However, such advantages are at the cost of increased complexity.

4.2.4 Related Work

Several spectrum sensing schemes have been proposed to address the optimal channel selection problem either considering or ignoring the sensing errors. In [34], an implicit assumption that the channel sensing is always accurate is considered. However, the impact of sensing time on the optimization is ignored under this assumption. Furthermore, to distinguish the benefit of transmitting over an optimal channel, the optimization is formulated under a utility-function objective. In contrast, in [35], the optimization is formulated as a rate of return problem. The idea behind that is to describe the multiplicative relationship between the number of bits sent in a single transmission and the total time spent on preparing for and executing this transmission. As a result, the average throughput achieved per transmission is improved. Additionally, other works have been proposed to address the issue by exploiting the channel-quality information ignoring various operational details. For example, in [36] the authors suggest maximizing the spectrum efficiency by adjusting CRs' sensing periods according to the channel conditions. However, various practical considerations such as sequential sensing/probing, overhead, and sensing errors have been ignored. In their work, the authors also assumed that the CR users can sense all the channels simultaneously. An OSA for a slotted system have been studied in [37] and [38]. The authors assumed that a CR can only sense, probe, and access one channel in one slot. However, if a channel is sensed available and not used by the CR user due to it is occupied or its quality is poor, the CR user is not allowed to sense or probe other channels. Even though there might still be considerable chance for the CR user to discover an alternative channel, the sequential exploration of channel diversity is ignored in these works. Similar work has been introduced in [39] where an optimal sensing and transmission times under an interference constraint for a single channel system is studied. The proposed technique aims at maximizing the spectrum efficiency. However, the effect of a multi-channel setup, whereby the CR may scan multiple channels before starting a transmission is ignored in the work. A candidate-set-based scheme, where each CR user may preselect a subset of channels of relatively good quality in a statistical sense, is suggested in [40] and [41]. Before transmitting its data, a CR user needs to sense and choose a channel from this subset. However, various CRs selecting the same subsets may overlap significantly with each other leading to poor network performance in a multiple users' environment.

On the other hand, a myopic approach based on the obtained occupancy state estimation for independent and dependent channels has been addressed in [42]-[44]. While [42] has pointed out obvious throughput improvement of myopic sensing as time increases under independent channels, [43] demonstrated that it is not the case under dependent channels. In [44] the authors introduced two heuristic approaches with three integrated components to exploit channel correlation: (i) a spectrum sensor at the physical (PHY) layer as “PHY layer approach”, (ii) a spectrum sensing strategy at the MAC layer as “MAC layer approach”, and (iii) a spectrum access strategy as “MAC layer approach”. It has been shown that exploiting channel correlation at the PHY layer is more effective than at the MAC layer. In addition, the performance of the PHY layer spectrum sensor can improve over time by incorporating the MAC layer sensing and access decisions. Furthermore, the authors in [43] have demonstrated how sensing errors at the PHY layer affect MAC design and how incorporating MAC layer information into PHY layer leads to a cognitive spectrum sensor whose performance improves over time by learning from accumulating observations.

In addition, alternative approaches that improve sensing reliability are proposed in [45]-[49]. In [45] the authors proposed a cognitive radio-enabled transceiver and multiple channel sensors to exploit the vacant spaces in the spectrum. The authors also introduced the four-way handshakes scheme and demonstrated that both the traditional and multi-channel hidden terminal problems can be solved. Furthermore, the authors in [46]-[48] have focused on the development of cooperative sensing schemes among multiple CR users. In [46] the authors proposed methods to optimize the detection performance by operating over the linear combination of local test statistics. The proposed methods would approximate the maximum probability of detection approach for any given probability of false alarm. Moreover, by allowing neighbouring secondary users to exchange sensing information through a dedicated control channel, a cooperative spectrum sensing has been proposed in [47]-[48] to improve detection accuracy. In [49] the authors proposed a spectral feature detector for spectrum sensing. Using the asymptotic properties of Toeplitz and circular matrices, the authors have demonstrated that this spectral feature detector is asymptotically optimal at very low SNR. Although very good understandings on the availability of licensed channels have been gained recently, there is still a critical need to develop analytical models that take channel sensing errors into account for guiding the design of CR MAC protocols.

Differentiate of the previous work, in this chapter; the sensing strategy considering the sensing errors is investigated. In particular, we aim to test the impact of *false-alarm* and *missed-detection* probabilities on the MAC layer performance. Based on this sensing strategy, how the unlicensed users can access to the medium unused by the primary users in an intelligent way without causing any harmful interference with the licensed users is investigated. The objective is to achieve an optimal cross-layer design, spectrum sensing at physical layer and spectrum access at MAC layer, which maximize the aggregate throughput in CR wireless ad hoc networks under the constraint that the false-alarm probability does not exceed a specified level. More precisely, we adapt the threshold level depending on the value of the missed-detection probability to ensure that the false alarm probability does not affect the throughput of the secondary users.

4.3 System Model

4.3.1 Network Description

Developing the cognitive MAC protocols proposed in chapter 3, we assume primary users access the licensed channels following a synchronous time slot structure. The channel states are independent to each other and each evolves over time following a discrete-time Markov process. On the other hand, secondary users use their software defined radio (SDR)-based transceivers to sense and estimate the licensed channels status and to access the channels when they are found to be available. We explicitly consider the sensing errors in developing the CR MAC protocols.

4.3.2 Time Slotted Spectrum Sensing

4.3.2.1 Problem Formulation

Obviously, spectrum sensing is a critical function of CR networks; it allows secondary users to detect spectral holes and opportunistically use under-utilized frequency bands without causing harmful interference to legacy systems. Because of low computational complexity, the energy detector approach has been considered as one of the most common ways for spectrum sensing. The spectrum sensing problem can be formulated as follows:

$$y(n) = \begin{cases} w(n) & \mathcal{H}_0(white\ space) \\ s(n) + w(n) & \mathcal{H}_1(occupied) \end{cases} \tag{4–1}$$

In general, the performance of the detection algorithm can be summarized with two probabilities: probability of false alarm P_F and probability of detection P_D. P_F is the probability that the test incorrectly decides that the considered frequency is occupied when it actually is not, and it can be written as

$$P_F = P_r(T(y) > \lambda \mid \mathcal{H}_0) \tag{4–2}$$

Where $T(y)$ is decision metric of the sensing process and λ is the detection threshold.

P_D is the probability of detecting a signal on the considered frequency when it truly is present. Thus, a large detection probability is desired. It can be formulated as

$$P_D = P_r(T(y) > \lambda \mid \mathcal{H}_1) \tag{4–3}$$

and the missed detection as

$$P_{MD} = 1 - P_D \tag{4–4}$$

Assuming that under the hypotheses H_0 when the primary user is absent, the received signal has the following simple form

$$y(n) = w(n) \quad (4\text{–}5)$$

And under the hypotheses H_1 when the primary user is active, the received signal has the following form

$$y(n) = s(n) + w(n) \quad (4\text{–}6)$$

Where $s(n)$ is the primary user's transmitted signal, and $w(n)$ is the Additive White Gaussian Noise (AWGN) sample. For M independent measurements is taken at the beginning of each slot, the decision metric for the energy detector is given by

$$T(y) = \frac{1}{M}\sum_{n=0}^{M} |y(n)|^2 \quad (4\text{–}7)$$

Let $\sigma_{n,0}^2 = \sigma_w^2$ and $\sigma_{n,1}^2 = \sigma_s^2$ denote the noise and the primary signal power, respectively, in channel *n*. The white noise can be modelled as a zero-mean Gaussian random variable with variance $\sigma_{n,0}^2$ as: $w(n) = \mathcal{N}(0, \sigma_{n,0}^2)$. We also consider that the signal can be modelled as a zero-mean Gaussian random variable with variance $\sigma_{n,1}^2$ as: $s(n) = \mathcal{N}(0, \sigma_{n,1}^2)$. The decision metric $T(y)$ is normally distributed under both the mentioned hypotheses as follows

$$T(y) \sim \begin{cases} \mathcal{N}(0, \sigma_{n,0}^2) & \mathcal{H}_0(S_n = 0) \\ \mathcal{N}(0, \sigma_{n,1}^2 + \sigma_{n,0}^2\,) & \mathcal{H}_1(S_n = 1) \end{cases} \quad (4\text{–}8)$$

4.3.2.2 Joint Sensing and Scheduling

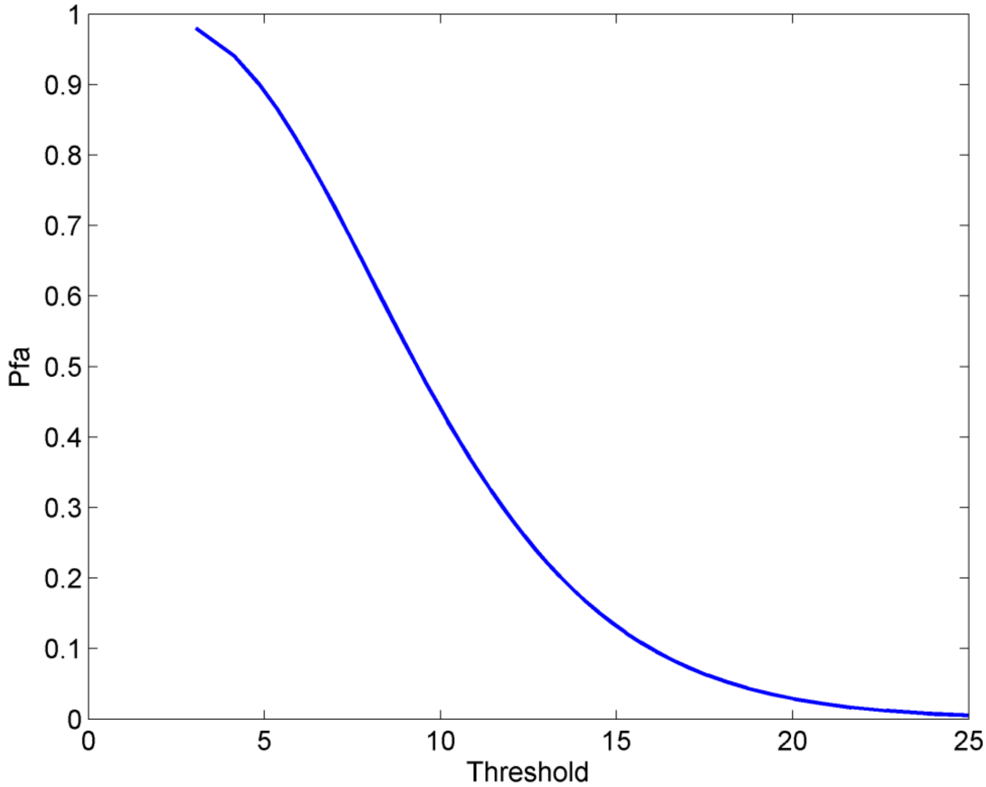

Figure 4-5: False alarm probability vs. threshold

We recognize that it is hard to distinguish between a white spectrum and a weak primary signal attenuated by noise and deep fading. However, we develop our proposed model to investigate the effect of sensing errors on the MAC layer performance. In this section, we present the joint sensing and scheduling scheme. We consider $\delta_{n,t}$ as a threshold which can be determined from the summary statistic of the t^{th} time slot in the n^{th} channel. For each time slot, the decision on the presence or absence of primary signals can be made by CR users according to the threshold δ_t which can be written as a column vector state of the slot t: $\delta_t = [\delta_{1,t}, \delta_{2,t}, \ldots, \delta_{N,t}]^T$. To ensure enhanced throughput, false-alarm probability should not exceed a specified level. To achieve the goal, we aim at adapting the threshold level, which can be increased with the increase of SNR. The relation between the threshold and false alarm probability is illustrated in Figure 4-5. Globally, the statistics across the network can be represented in matrix form as follows:

$$\delta = \begin{bmatrix} \delta_{1,1} & \delta_{1,2} & \dots & \delta_{1,T} \\ \delta_{2,1} & \delta_{2,2} & \dots & \delta_{2,T} \\ \vdots & \vdots & \ddots & \vdots \\ \delta_{N,1} & \delta_{N,2} & \dots & \delta_{N,T} \end{bmatrix} \quad (4\text{-}9)$$

For the energy detector, the probability of false alarm is given by [37]

$$P_F = 1 - \gamma\left(\frac{M}{2}, \frac{\delta}{\sigma_{n,0}^2}\right) \quad (4\text{–}10)$$

And the probability of missed detection is given by

$$P_{MD} = \gamma\left(\frac{M}{2}, \frac{\delta}{\sigma_{n,1}^2 + \sigma_{n,0}^2}\right) \quad (4\text{–}11)$$

Where

$$\gamma(m, a) = \frac{1}{\Gamma(m)} \int_0^a t^{m-1} e^{-t} dt \quad (4\text{–}12)$$

is the incomplete gamma function.

To ensure certain values for P_F and P_{MD}, the required number of measurements M is given by

$$M = 2\left[Q^{-1}(P_F) - Q^{-1}(1 - P_{MD})\sqrt{1 + 2SNR}\right]^2 SNR^{-2} \quad (4\text{–}13)$$

Where SNR denotes the ratio of the primary signal power to the noise power, i.e.

$$SNR = \frac{\sigma_{n,1}^2}{\sigma_{n,0}^2} \quad (4\text{–}14)$$

4.4 Simulation Results

In this section, we present simulation results for a developed scenario of POMDP-based cognitive MAC protocols using the sensing scheme described in section 4.3 under the constraint of the sensing errors. In order to test the impact of sensing errors, the proposed schemes and sensing scenarios have been modeled and implemented in MATLAB. In the simulation, the number of channels are assumed to be three independent channels (N=3), each with bandwidth B = 1 (b/s). In the simulation we also assume that number of time slots T = 15 and the number of samples M = 10. Moreover, we assume a prior knowledge about the channel transition probabilities P^{01} and P^{11} {P^{01}=0.2, P^{11}=0.8}.

In this scenario, we consider the sensing errors and we investigate the impact of *false-alarm* and *missed-detection* probabilities on the MAC layer performance. We consider a scenario that maximizes the aggregate throughput under the constraint that the *false-alarm* probability does not exceed certain levels. In our simulation, we adapt the threshold according to the value of P_{MD} and SNR.

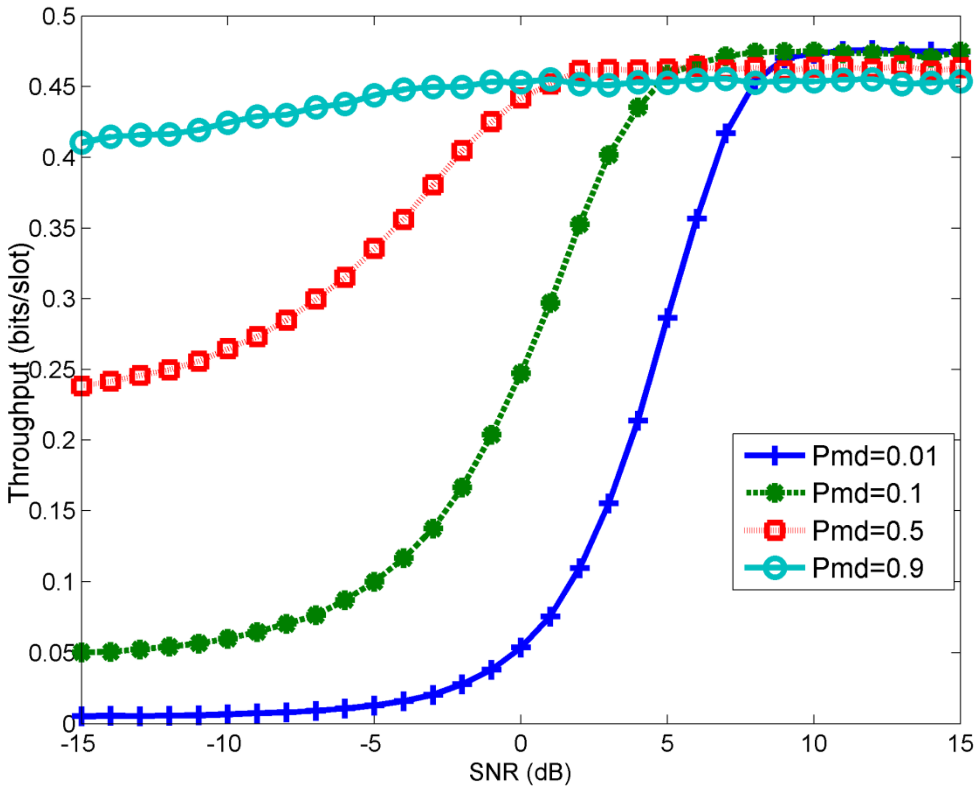

Figure 4-6: Throughput comparison vs. SNR with different parameters (bandwidth B = 1, number of channels N = 3, and different values of missed detection)

Figure 4-6 shows the throughput of the secondary user versus the SNR curve using the sensing method described earlier. It is clear that the throughput of the secondary user increases with the increase of SNR. We note that when the P_{MD} is small, the detection threshold increases with the increase of SNR, which leads to an adapted P_{FA}. Therefore, at low SNR, the throughput of the secondary user is limited by the large P_{FA} and will be enhanced as the P_{MD} is increased. This is because at large P_{MD}, the P_{FA} will be very small which is leading to improved throughput at a price of more collisions with the PUs. On the other hand, at high SNR, the P_{FA} is reduced at the expense of less transmission time in each slot, which also leads to high throughput. In other words, the simulation results show that a small P_{MD} provides a better throughput at high SNR, whereas a large P_{MD} gives high throughput at low SNR. The fact behind that can be illustrated in Figure 4-7, which demonstrates that high spectrum efficiency can be obtained at high SNR whenever the P_{MD} is small. In contrast, at low SNR, the spectrum efficiency is maintained at certain level (around 0.54) due to either large P_{FA}, or large P_{MD} leading to more collisions with the PUs.

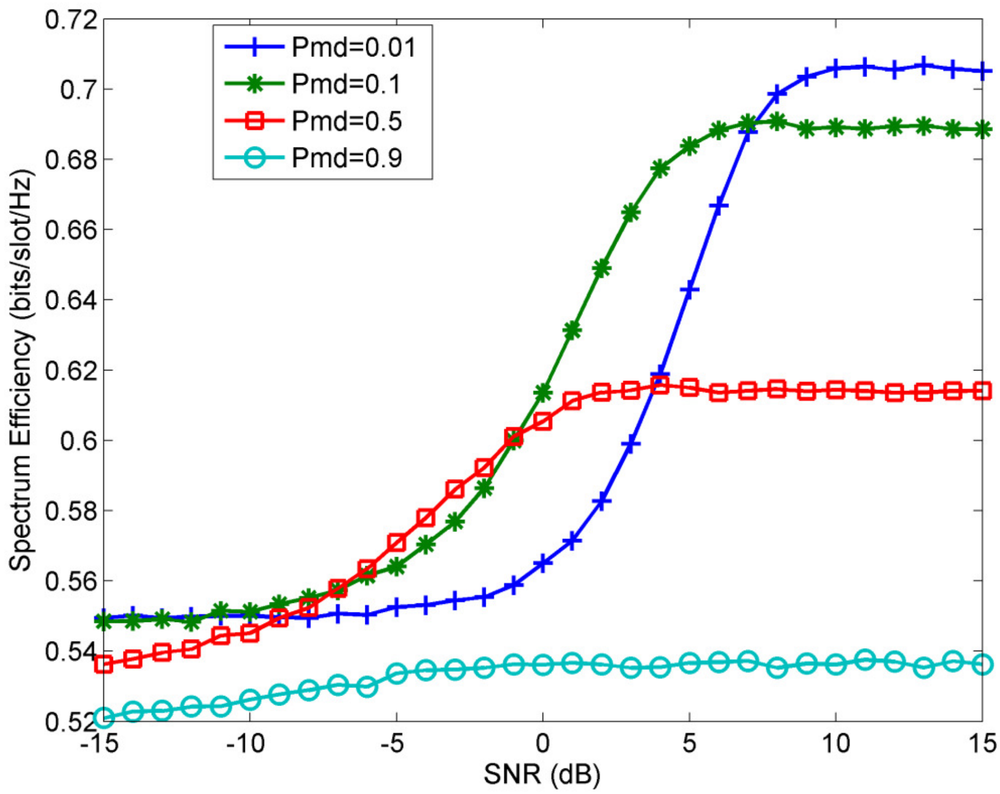

Figure 4-7: Spectrum efficiency vs. SNR with different parameters (bandwidth B = 1, number of channels N = 3, and different values of missed detection probability)

Essentially, we can consider two regions for studying the impact of sensing errors on the MAC performance in CR wireless networks. The first region is at low SNR where the concern is how to maintain the P_{FA} small enough to achieve better throughput. The second region is at high SNR where the transmission rate is limited due to the bandwidth limitation, i.e. less transmission time in each slot. Therefore, reducing P_{FA} by adapting the detection threshold level at the second region can improve the aggregated throughput. In addition, allowing large P_{MD} at the first region is preferred to ensure enhanced throughput.

4.5 Conclusion

In this chapter, a sensing error-aware cognitive MAC protocols for MANETs is introduced. Using multiple channels and assuming slotted structure for the primary network, we investigated the impact of *false-alarm* and *missed-detection* probabilities on the MAC performance. Based on a joint sensing and scheduling scheme, the simulation results have shown that the throughput of the secondary user can be improved with the increase of SNR by decreasing the P_{FA} which can be adapted by the threshold level. Moreover, allowing large P_{MD} at low SNR leads to decreasing in P_{FA}, as a result high throughput can be achieved.

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Chapter 5

Priority Based and Cooperative Sensing for Cognitive Wireless Mesh Networks

5.1 Introduction

Wireless Mesh Networks (WMNs) is a feasible solution to support last-mile broadband services. In mesh mode, nodes can assist each other in transmitting packets through the network. Nodes also can discover and communicate with each other directly without involving central access points. In addition to send and receive messages, a node can play the role of infrastructure network to act as an Access Point (AP) or a Mesh Router (MR) serving a number of users or Mesh Clients (MCs) and offer a short way to packets to find their destinations [1]. It also has the ability to connect the network to external destination to be used as a backbone network. The MCs could be mobile users or stationary workstations that exchange data through the whole network. They direct their traffic to their respective MRs, which then forwards it over the backbone, in a multi-hop manner, to reach the gateway, which is usually linked to external network. Like the other router-based networks, a mesh network offers multiple redundant communications paths. In a mesh network, each node has at least two paths for sending data. If a node or one of its links fails for any reason, messages can be routed to its destination through alternate paths. Beside reliability and redundancy, a mesh network has many other characteristics, include (scalability, self-forming, self-healing, self-organization, mobility, accessibility, compatibility and interoperability with existing wireless networks, power-saving, and multiple radios).

Although WMNs are introduced as a solution to enhance the performance of wireless communications with flexible network architectures, easy deployment and configuration, and fault tolerance, the high density of nodes may affect the network capacity. Analytical results have shown that the throughput capacity is reduced significantly when the network density increases [2]. Many researchers addressed the problem of capacity of WMNs and most of them proved that the capacity can be increased as the size of the network is increased, that means the number of clients are increased or many nodes are added to the system. In WMNs, as the traffic is directed to the gateways (GW), which are connected to external network, gateways would pose bottleneck problem. In this case, we need to reduce the bottleneck wireless links along the path to the gateway. Hence, additional wired points can be added to the network can ensure enhanced capacity.

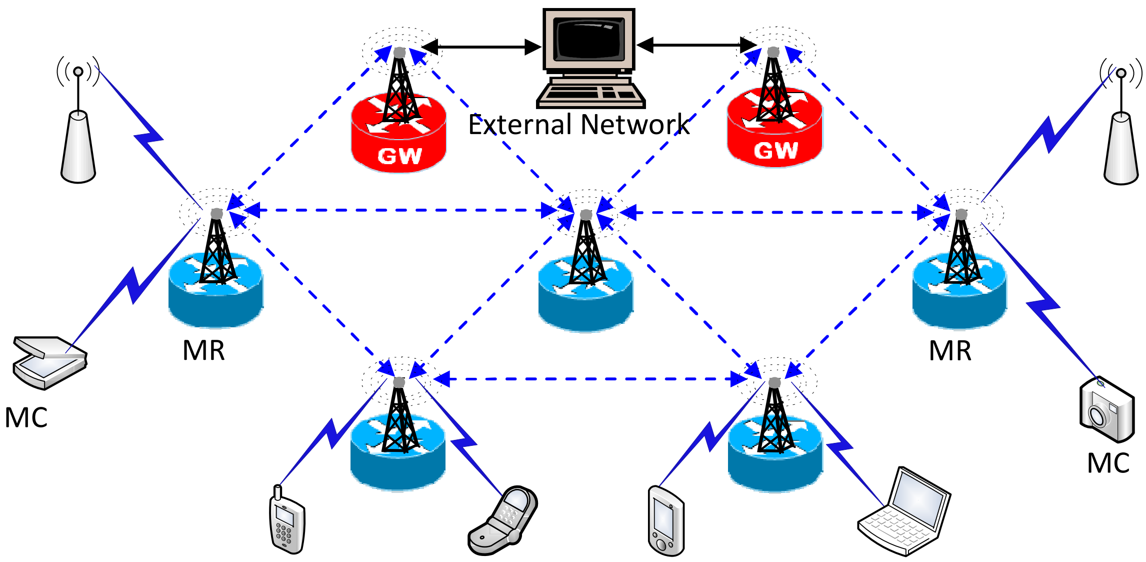

Figure 5-1: Wireless Mesh Network Topology: Multiple nodes cooperate to relay a message to its destination

In fact, the capacity of WMNs depends on the traffic behaviour at the Medium Access Control (MAC) layer. As each node has to transmit relayed traffic as well as its own, the congestion and the fairness are the important issues that need to be widely addressed. Figure 5-1 illustrates a typical example of WMNs. In addition, the frequency band which currently used by mesh-based architectures is shared by AP-based Wireless Local Area Network (WLAN) devices, Bluetooth, and others, which leads us to the problem of spectrum scarcity. All these factors affect directly or indirectly the performance of WMNs. Other factors can be considered influence the performance of WMNs such as interference between simultaneous transmissions, fading and environmental noise. Thus, there is a strong motivation to identify unused portions of the spectrum, which can be used to carry the mesh network traffic. This also accelerated the emergence of opportunistic spectrum access (OSA) concepts leading to a Cognitive Radio (CR) technology [3]. Using this technology in WMNs effectively reduces the node density per transmission channel, and thus improves the network throughput.

5.1.1 Cognitive Wireless Mesh Networks

A cognitive wireless mesh network is a static multi-hop wireless network in which each node is equipped with a multiple smart cognitive radios, has the ability to sense the external environment, and according to the sensing history makes intelligent decisions to use the spectrum frequency opportunistically by changing its transmission parameters according to the current state of the environment. Basically, cognitive radios have the ability to perform spectrum sensing continuously to recognize the status of the radio spectrum environment. Once white spaces (unused spectrum) are identified, the CR mesh users can change its transmission parameters, such as carrier frequency, bandwidth, power efficiency, and modulation schemes, according to the interactions with the environment in which it operates. However, interference between simultaneous transmissions, fading and other environmental noise can affect such networks hardly and limit its performance. As a result, spectrum sensing, spectrum access, and spectrum sharing have recently become a wide area of research in wireless mesh networks. Consequently, Network architecture, number of radio transceivers, and multiple channel techniques, have been considered in developing of most MAC protocols.

However, for efficient communications, CR mesh networks require new techniques such as improved spectrum sensing, enhanced spectrum assignment, and cross layer design. Hence, spectrum sensing can be considered as the main issue that has to be considered to avoid interference with the licensed users. The most effective way to detect the availability of spectrum holes is to detect the licensed users that are sending or receiving data within the transmission range. To enhance the detection probability, different signal detection methods such as energy detection, matched filter detection, or others can be used. All of these methods offer different solutions that aim at increasing the mesh network performance by allowing MRs and MCs to exploit the existence of the huge unused spectrum. More details concerning the previous work related to spectrum sensing and primary signal detection can be found in the next section.

5.1.2 Cooperative Spectrum Sensing

An effective way to mitigate the interference between the CR user and the primary user is the cooperative spectrum sensing. Cooperative spectrum sensing is proposed as a solution for increasing the sensing reliability by exploiting the spatial diversity of multiple cognitive users [4]. The objective of cooperative spectrum sensing is to decide whether the primary user is active or not by using the available data measurements from multiple users. As the CR user must have more sensitive capability than the primary user to avoid any expected interference, cooperative spectrum sensing can reduce the demanding sensitivity requirements on an individual CR user and enhance the sensing performance for the entire network. The basic idea of cooperative sensing process is to overcome noise uncertainty, shadowing, and multipath fading by allowing neighbouring CR users to share sensing information through a dedicated common control channel [5].

Generally, cooperative spectrum sensing process is conducted in three consecutive stages: (i) sensing, (ii) reporting and (iii) decision making. The first two stages, i.e., the sensing and reporting stages, are conducted by the *CogMCs*. While in the reporting stage, all the local sensing observations are reported to a fusion centre, in the decision making stage, *CogMR* will make a final decision on the primary users' activity.

Furthermore, in cooperative spectrum sensing, the reporting schemes can be categorises into three types:

- Hard combination, in which CR users exchange only one bit of its sensing information indicating whether or not the observed primary users' energy is above a certain threshold. In this context, it can be noted that hard decisions along with energy detection (discussed in chapter four) is the simplest cooperative sensing scheme and provide a lower bound on the cooperative performance.

- Soft combination, in which CR users exchange their observation data, continuously, with the fusion centre. However, such scenario will introduce huge overhead affecting the network performance. Hence, this type of cooperative sensing is rarely used in practice. The main application of soft combination scheme is to analytically give an upper bound on the performance of cooperation.
- Softened hard combination, in which two to three bits of individual sensing information are exchanged. In such schemes, it can be observed that less sensing information will be lost at each CR user compared to the hard combination scheme, resulting in performance improvement. It has been shown that exchanging two to three bits of sensing data can achieve good tradeoffs between detection performance and complexity [6].

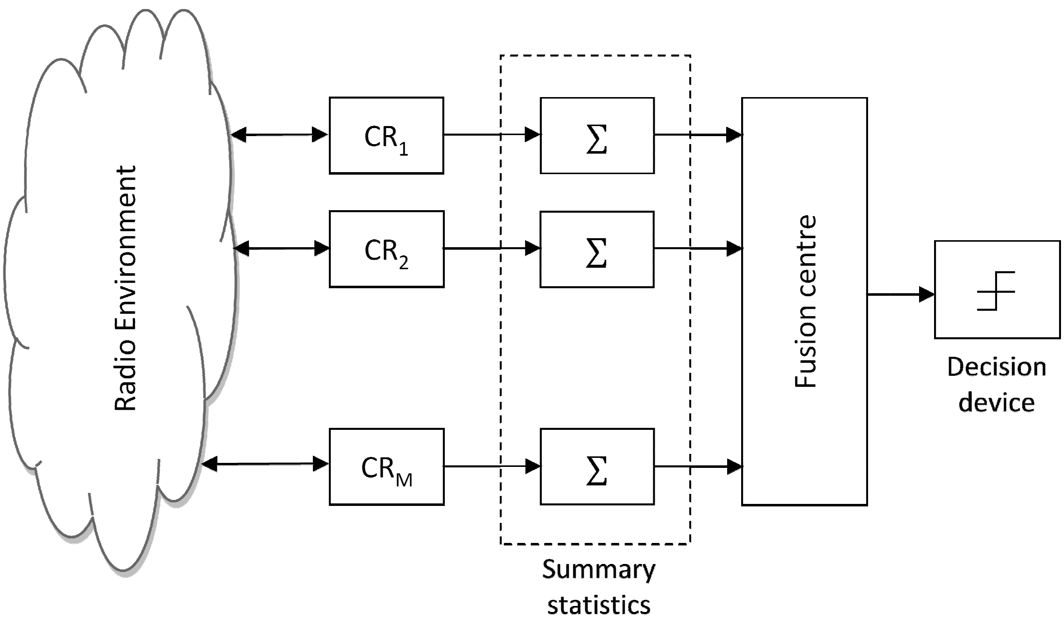

Figure 5-2: Schematic representation of weighting cooperation for spectrum sensing in CR networks

In practice, cooperative spectrum sensing can be implemented in two different scenarios: As shown in Figure 5-3, either centralized or distributed scenario [7]. In a centralized mode, a fusion centre is used to fuse the sensing results from multiple CR users before arriving at the final decision. In the distributed mode, each CR collects the sensing results from its neighbours and performs its own local decision fusion in a distributed manner. Therefore, in a cooperative sensing scheme, each CR user performs periodic sensing processes and sends its accumulated sensing result to a Fusion Centre (FC), as shown in Figure 5-3. A final decision about the presence or absence of the primary user is made by the FC using the local sensing measurements. According to different fusion schemes that have been proposed to combine the local sensing information of the CR users can be categorized as hard and soft fusion schemes [8]-[9].

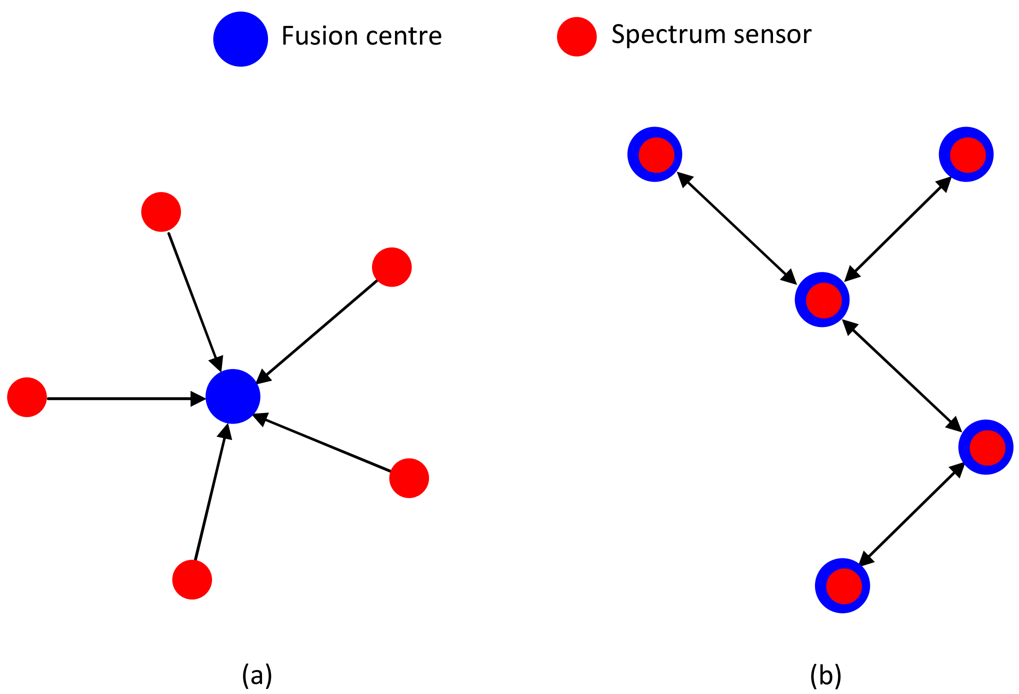

Figure 5-3: Data fusion for cooperative sensing. (a) In centralized mode, the sensing results of individual CRs are sent to a fusion centre in which a global decision is made. (b) In distributed mode, each CR acts as a fusion centre, collecting the sensing measurements from its neighbouring nodes and making its decision independently.

In the literature, several fusion techniques have been proposed [10]-[11]. The OR and AND rules, for example, is the most well-known techniques which attracted many researchers. In such rules, easily implementation by using simple logics can be applied. Moreover, the OR and AND rules can be considered as special cases of the general k-outof-N rule when k is 1 or N, respectively.

In general, in a cooperative sensing scenario, the final decision can be made through two methods: data fusion and decision fusion:

- *Data Fusion:* where the measurements are processed jointly and then the final decision is made based on the calculated statistics.

- *Decision Fusion:* where each user's measurement is processed separately and decisions are made individually. Once the decision is made for each measurement, the final decision is made by fusing the individual decisions. There are different rules available for making final decision on the presence or absence of the primary user:

  1) *Logic-OR Rule:* This rule is a simple decision rule, which can be described as follows: if one of the decisions decides the presence of the primary user, then the final decision declares that there is a primary user [12].

  2) *Logic-AND Rule:* This method of rules works as follows: if all decisions decide the presence of the primary user, then the final decision declares that there is a primary user [13].

  3) *Majority Rule:* This rule can be considered as one of the simplest suboptimal fusion rules that can be used. It is based on the majority of the individual decisions made by each user. If half of the decisions or more decide that there is a primary user, then the final decision declares that there is a primary user. This rule is also known as voting rule where the vote is compared to a given threshold [14].

Although there have been few works on the optimization of the k-outof-N rule in order to find the optimal k, there have been many efforts to design efficient cooperation schemes for the multiple spatially distributed users to improve the sensing reliability. The objective is to maximize the detection probability while maintaining the missed-detection probability as small as possible. In [10], by considering the detection threshold to be constant, the detection error probability is minimized in order to find the optimal k when. However, the probability of primary user presence or absence is not considered in the error function. Furthermore, the detection error probability, which is considered as the weighted sum of the false alarm probability and detection probability, does not have a meaningful interpretation. In [11], in order to find the optimal k as well as the optimal sensing time and false alarm rate, the author proposed to maximize the overall data rate of the cognitive radio network which subject to an interference with the primary user.

The advantages of cooperation sensing in CR networks make spectrum sensing for dynamic spectrum access robust without need to additional requirements and reduce the demanding sensitivity requirements on an individual CR user especially in noisy environments. Moreover, it decreases the SNR wall and reduces the average sensing time for a single CR user. However, all these advantages come at the cost of additional overhead signals due to huge sensing information are needed to be exchanged among CR users.

Although some of the cooperative sensing schemes such as hard combination and softened hard combination schemes have been proposed to reduce the bandwidth of the control channel, the overall band allocated to different CR users in a CR network as a common control channel for information exchange is significantly large. However, this dedicated spectrum may not be available. Therefore, an alternative mechanism for coordination is required. In order to access the common control channel, a predefined set of sensing parameters, frame structures and access mechanisms must be recognised and supported by all CR users [15].

Additionally, as the cooperation overhead generally increases with the increase of the number of cooperating users in the same cluster due to the increased volume of data that needs to be reported to the cluster head, the number of involved cooperating users should be investigated carefully to avoid any undesired overheads. Furthermore, another issue for cooperative spectrum sensing is the trust between different SUs' sensing outcomes especially when only some of the secondary nodes within the same cluster are located and share its information with other secondary users in the same network. Certainly, such issue is leading us to the problem of Always Yes Liar (always reports presence of the PU in cooperation regardless what it actually senses in order to deny the other SUs' opportunistic usage of that channel). On the other hand, other trust issues such as Always No Liar (always reports absence of the primary user regardless of its actual sensing result) may render the cooperative sensing result useless [4]. Therefore, in the research field, many research articles have discussed such issues and many solutions have been proposed to overcome such problems. More related work is discussed in the next section.

5.2 Related Work

Different papers, based on different algorithms and approaches, have discussed the issue of Cognitive Wireless Mesh Networks (*CogNesh*) performance. In order to solve the Common Control Channel (CCC) problem, the authors of [16] proposed a cluster-based approach to discover and control the neighbour nodes; in the case of the global control channel is absent. Moreover, the network topology optimization is addressed and a topology management algorithm. They have shown the potential convergence to a suboptimal configuration scheme in dynamic channel assignment.

A distributed approach for channel selection in cognitive wireless mesh networking and solutions for a neighbour cluster operation are proposed in [17]. In their system model, the authors proposed a scenario based on the power estimation to decide the medium access. Under the outage probability constraints, the transmission capacity achieved by the CR users in a *CogMesh* network is studied in [18]. A physical interference model is proposed to determine the probabilities of successful transmissions in both the primary and secondary networks. Using different infrastructure-based schemes, the achievable transmission capacity is obtained based on Shannon's Theory. In [19], Quality-of-Service (QoS) performance metrics including end-to-end delay, packet loss probability and throughput in *CogMesh* networks are investigated. While the ON/OFF channel usage model is used to characterise the primary users' activity, the mesh routers are modelled as a finite-buffer bulk-service queuing system. Moreover, the proposed model is developed to study the impact of the number channels and the channel utilisation on the network performance. An analytical results and simulation experiments have shown that the QoS performance metrics are logical of good degree of accuracy. However, some issues influence the network performance such as sensing errors did not meet enough investigation in these works.

In general, in term of considering the sensing errors, most of the existing spectrum sensing schemes that proposed for CR wireless networks focus on the detection of the primary signal based on the local environment observations of the CR users. To enhance the detection probability, different signal detection methods are introduced. One of these methods is the energy detection [20] which is used widely in the field of research. However, it has shown that the energy detection is still has poor performance under low signal-to-noise ratio (SNR) conditions. This is because the noise variance is not accurately known at the low SNR, and the noise uncertainty may influence the energy detection measurement [21]. Another challenging issue, which affects energy detection techniques, is the inability of CR users to differentiate between the interference from other secondary users sharing the same channel and the licensed users' signals. Furthermore, the threshold used in energy selection depends on the noise variance, and any small error occurs in noise power estimation can result in significant network performance degradation.

The main objective of spectrum switching is to select an alternative channel such that the CR user can switched into to retain its on-going transmission. To facilitate the coexistence process between channels, a CR user will sense the frequency spectrum and periodically choose a sequence of channels before starting its data transmission. Once the CR user is interrupted by the next primary user transmission phase, the CR user should have the ability to switch into a vacant channel, which pre- determined in a pre-sensing phase [22]. Hence, using this technique can reduce the waiting time for spectrum handoff since the target channel is a priory selected based on a pre-determined channel list. However, the pre-determined channel list mechanism can possibly infeasible to be adopted in target channel selection for spectrum handoff prone to several faults due to fading and environment change. To support the idea of pre-sensing phase as well as to establish a viable pre-determined channel list mechanism, a channel reservation scheme was proposed in [24]. The channel reservation scheme aims at exploiting the balance between blocking probability and forced termination in order to reserve idle channels for future spectrum handoff. However, those reserved idle channels cannot be ensured available at the time for spectrum handoff. As a result, the performance of pre-sensing strategies cannot be guaranteed especially under the fast fading channel environments. Furthermore, assuming that all the channels can be correctly sensed, assumed in most of the existing works, is considered impracticable in realistic environments.

In addition, issues such as spectrum sensing, spectrum access and the interference between CR users and primary users have been investigated widely in recent years. In terms of considering sensing errors, the authors of [24] exploited the probabilities of missed detection and false alarms by using Hidden Markov Models (HMMs) and incorporated them in spectrum sharing. The Virtebri Algorithm has been used in their proposed scheme to reduce the computational complexity. HMMs were also used in [25] where the authors studied the spectrum occupancy state of licensed radio bands. In their work, they proposed a scenario predicting the duration of spectrum holes of primary users, and thus allowing CR users to utilize the spectrum unless the primary user started new transmission phase. A white space (spectrum hole) reservation algorithm to reduce spectrum handoff and thus minimizing the delay caused by spectrum handoff was proposed in [26]. Hence, spectrum matching and system performance is improved by trimming down spectrum switching.

Minimizing interference to PUs, attaining fairness among the CR users, and improving the capacity of the network were the main goals of proposing different scheduling schemes in [27]. The authors proposed a rate and interference alleviation based scheduling scheme exploiting channel variation across the network, and interference based scheduling scheme exploiting packet delay along with QoS provisioning for multiple CR users. With cooperative sensing and considering correct detection of the absence of the primary signal as additional information to be done in spectrum sensing cycle, the achievable data rates in CR networks can be increased [28]. The achievable rate for a genie-aided CR channel scenario is introduced in [29], where two cognitive transmitters communicate with two different cognitive receivers. In such scenario, at least one of the cognitive users has prior information about the activity of the primary users. Considering distributed and time-varying side information, the capacity of the cognitive channel was taken more attention in [30]. However, in practice, the exact path of the states is hidden to SU and the only data available to the SU are perceived data. Hence, spectrum sensing is prone to several faults.

In this chapter, we focus our study on a CR-based MAC protocols for WMNs. We investigate a *CogMesh* that composed of a set of CR MRs (*CogMRs*), CR MCs (*CogMCs*), and Primary Users (PUs). *CogMRs* should continuously make efficient decisions on which channels to sense and access in order to exploit the available spectrum opportunities. Moreover, we investigate the issue of spectrum switching and how a frequency bands scenario can be applied to facilitate sharing multiple channels between nodes such that the interference between these nodes can be minimized and more data can be sent between nodes at the same time increasing the overall throughput.

5.3 System Model

To describe the proposed model, we first introduce the concept of *CogMesh*, which is defined as a self-organized network contains a set of PUs and Secondary Users (SUs). The

PUs are licensed users that have the priority to access the medium and use the frequency bands whenever they have ready data to send. The SUs are a set of *CogMRs* and *CogMCs* that can opportunistically access the frequency bands unutilized by the PUs.

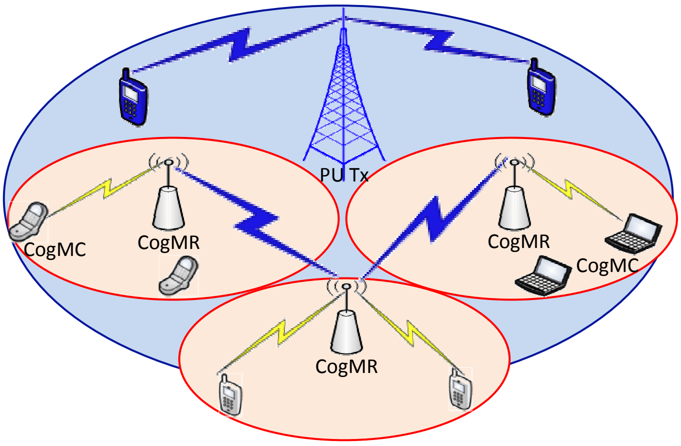

Figure 5-4: A CogMesh Network

To model our system, in this chapter, we also use the concept of cognitive cell, which consists of a CogMR and a group of CogMCs as illustrated in Figure 5-4. We also consider a spectrum frequency consisting of N independent channels licensed to the PUs which have an authority to access the spectrum frequency according to a synchronous slot structure. We also consider that each channel is divided into T time slots. The network state in a channel n ($n = 1, \ldots, N$) and a slot t ($t = 1, \ldots, T$) is given by $S[n,t]$, where $S[n,t]$ takes the digit 1 when the channel is free and the digit 0 when the channel is busy. Thus, the free and busy states reflex the absence and presence of the PUs in each channel respectively. This description of the spectrum frequency can be designed in two dimensional array as shown in Figure 5-5.

	Slot-1	***Slot-2***	⋯	***Slot-T***
Channel-1	*S[1,1]*	*S[1,2]*	⋯	*S[1,T]*
Channel-2	*S[2,1]*	*S[2,2]*	⋯	*S[2,T]*
⋮	⋮	⋮	⋱	⋮
Channel-N	*S[N,1]*	*S[N,2]*	⋯	*S[N,T]*

Figure 5-5: Two dimensional array

Moreover, the traffic conditions of the system are considered to be modeled according to Poisson process with average arrival rate λ_p for the licensed users and λ_s for the *CogMesh* users. All the packets are assumed to be one slot in length. At the beginning of each time slot, after sensing the spectrum frequency, each CR user is keeping a sequence of all unused channels which can be dynamically selected with suitable probability that balance the traffic loads of *CogMesh* users. In such model, the transmission of *CogMesh* users is stable if and only if the packet arrival rate λ is less than the packet transmission rate (i.e. packet service rate μ), $\lambda < \mu$.

In addition, we introduce the concept of *CogMesh*, which is defined as a self-organized network containing a set of secondary users and a set of primary users are allowed to coexist.

- *Primary Users* (PUs) are licensed users that have the absolute priority to access the spectrum frequency according to a synchronous time slot structure as described above. Thus, primary packets have absolute priority over the *CogMesh* packets and an interruption to the *CogMesh* users transmission must be made on the arriving of the PU packets.
- *Cognitive MRs* (CogMRs) are secondary users allowed to coexist with the PUs and access the medium to use the vacant frequency bands of the primary network opportunistically. Before performing such access, based on its sensing outcomes as well as the sensing outcomes of their clients, *CogMRs* should prepare a list of the available channels, which can be accessed by the *CogMesh* users.
- *Cognitive MCs* (CogMCs) are secondary users that participate in the sensing process such that they exchange the real time knowledge of its environment periodically with the *CogMRs*. According to a decision, which must be made by their *CogMRs* parents,

they adjust its parameters dynamically and may be allowed to access the frequency bands on condition that the spectrum sensed as free of PUs' utilization.

5.3.1 Problem Formulation

In a *CogMesh* network, spectrum sensing is considered as the main issue that enables the *CogMesh* users to explore spectral holes and opportunistically use the unutilized frequency bands with respect to legacy system. Moreover, sensing errors at the PHY layer could affect the MAC design. It has shown that the performance of the PHY layer spectrum sensor can improve the MAC performance overtime by incorporating the MAC layer sensing and access decisions [31]. In a *CogMesh* network, the spectrum sensing issue can be formulated as follows:

$$y(n) = \begin{cases} w(n) & \mathcal{H}_0(white\ space) \\ s(n) + w(n) & \mathcal{H}_1(occupied) \end{cases} \qquad (5\text{–}1)$$

where $s(n)$ is the primary user’s signal, and $w(n)$ is the Additive White Gaussian Noise (AWGN).

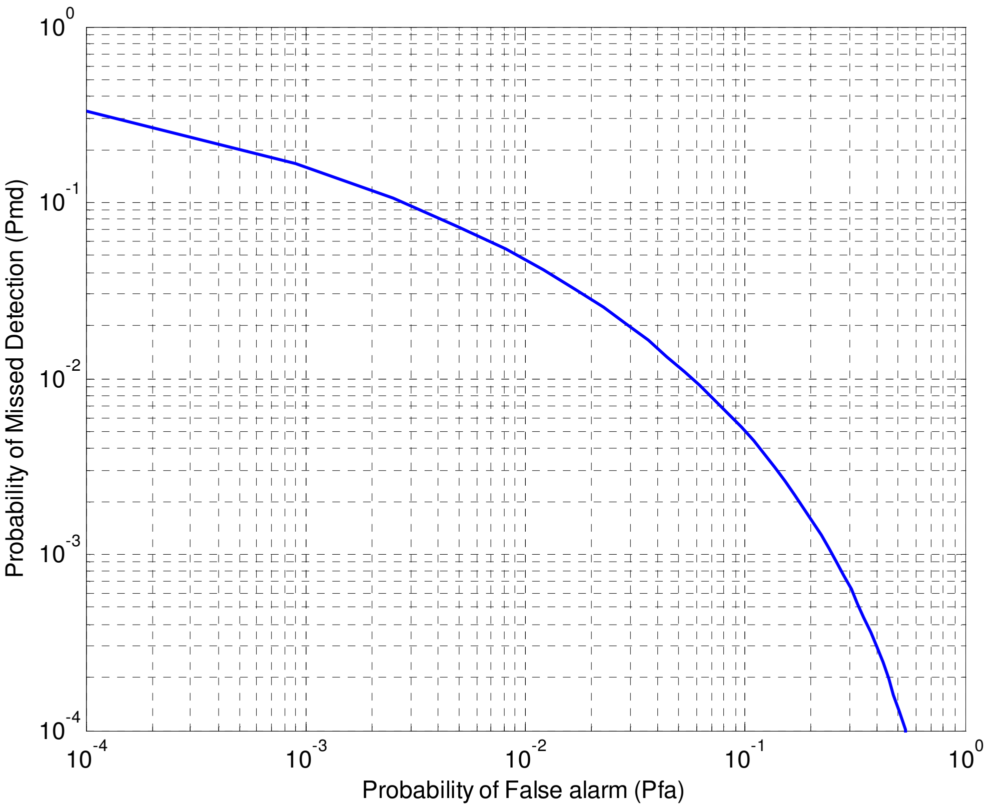

Figure 5-6: Complementary ROC of energy detection under AWGN

In addition, in a *CogMesh*, the issue of the primary signal detection can be summarized with two probabilities: (i) Probability of detection P_d where a primary signal is considered when it truly is present. (ii) Probability of false alarm P_f where the test statistic incorrectly decides the presence of the primary signal when it is not. Figure 5-6 shows the complementary ROC of energy detection. The average probability of P_d, P_f and missing of energy detection P_{md} over Rayleigh fading channels can be given, respectively, by:

$$P_d = E[Prob\{\mathcal{H}_1|\mathcal{H}_1\}] \quad (5\text{–}2)$$

$$P_f = E[Prob\{\mathcal{H}_1|\mathcal{H}_0\}] \quad (5\text{–}3)$$

$$P_{md} = E[Prob\{\mathcal{H}_0|\mathcal{H}_1\}] = 1 - P_d \quad (5\text{–}4)$$

5.3.2 Interference avoidance

Obviously, the main issue in a *CogMesh* network is to perform an efficient spectrum sensing to avoid interference caused by a simultaneous packets transmission of *CogMesh* users and PUs located in the same transmission range. Therefore, *CogMesh* users should use the feature of exchanging the real time knowledge of its environment to adapt its parameters dynamically. Hence, to achieve such scenario accurately, this chapter proposes a time band counter based on the past utilization of the channels by PUs, which can be maintained at each *CogMR*. By using the time band counter, we ensure a prior knowledge about the spectrum occupancy, which results in some desired advantages. First, reducing the number of switching times, and second, minimizing the average waiting time of *CogMesh* users. This approach guides us to allocate a channel to a *CogMesh* user based on the past utilization of the channel. Furthermore, to minimize the percentage of any sensing errors, we consider that the *CogMesh* user first senses the activities of PUs within its transmission range. If a channel is sensed as free, i.e. no PUs activity is sensed, the transmitter sends a short request-to-send (RTS) message to the receiver. The receiver, upon receiving the RTS successfully, knows if the channel is available or not according to the *CogMR's* maintained counter which contains a sequence of the available channels. If the channel found free at the receiver side, a clear-to-send (CTS) message is sent to the transmitter. A successful exchange of RTS-CTS is followed by data transmission period, which takes place on the agreed common available time slot. Finally, the receiver, upon successfully receiving the data, replies with an acknowledgement (ACK) message to confirm a successful reception. This mechanism can be illustrated in Figure 5-7.

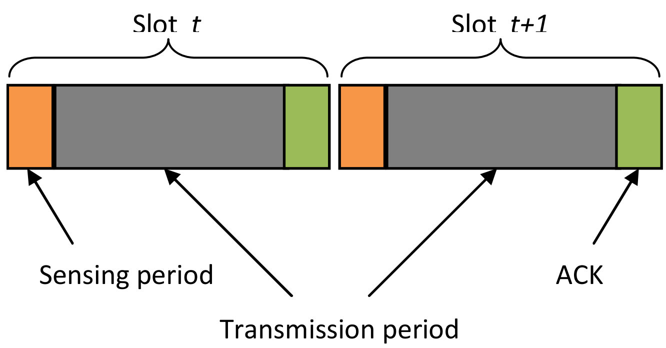

Figure 5-7: Illustration of time slot structure in CR networks

5.3.3 Message Fragmentation

We also study the issue of transmitting long messages by the *CogMesh* users. Since we propose a time slot model, the data messages should match the slot size. Therefore, in the case of transmitting long message, fragmentation is necessary for some reasons: First, to avoid the problem of fairness, since transmitting longer message takes longer transmission time, which prevents other *CogMesh* users from fairly accessing the channel. Second, to avoid the problem of interference, since transmitting longer message most likely be subject to loss of the channel availability and spectrum opportunity, which causes interference with PUs. Third, to maximize the probability that each packet can be delivered correctly to the destination. In fact, transmitting a long message may decrease large control overheads and longer delay. However, sending a long message is prone to the fault of only part of this message may have been received. To address such critical situations in a dynamic environment, we propose a segmentation scenario in which the transmitted message does not exceed certain length.

The multi-channel and time slotted model proposed in this chapter propose the fragmentation of a long message into many independent small packets as a solution of such mentioned problems. Hence, a long message can be divided into many small packets to match the length of the transmission time dedicated to each time slot. The features of using this mechanism can be illustrated as follows: First, if one packet is lost, *CogMesh* users do not need to retransmit the entire message. Instead, users need to retransmit the lost packet. Second, *CogMesh* users can possibly stay on a channel that has just been identified as free channel. This possibility, certainly, guides us into two other advantages: (i) Only one RTS and one CTS can be used before the sender starts its data transmission. (ii) This allows *CogMesh* users to deliver more data packets through multiple slots without the need to move to another channel. A higher data transmission rate can also be achieved, which improve the network performance. However, the sender needs to wait for an ACK from the receiver for each single packet transmitted. If it fails to receive an ACK from the receiver, the sender starts retransmitting the current packet immediately according to its time band counter, which maintains a sequence of the available channels.

5.3.4 The Sensing and Access Strategies

Let us now present two different scenarios of *CogMesh.* In the first scenario, we assume a *CogMesh* in which a *CogMR* manages a number of *CogMCs* forming a mesh cell or cluster. Each *CogMR* in the network performs the sensing process individually. In the second scenario, we assume that both *CogMR* and *CogMCs* located in the same cluster exchange the sensing information forming a cooperative system.

5.3.4.1 Individual Behavior

Obviously, in a *CogMesh* network, each *CogMR* is allowed to coexist with the PUs and use the vacant channels of the primary network as described earlier. In an individual behaviour, considering a *CogMR* controls a number of *CogMCs* forming a mesh cluster, the *CogMR* is assumed to perform the sensing process individually without relying on its *CogMCs*. In such scenario, the energy detection of the received signal can be denoted by *Y*. It is considered to be collected by the *CogMR* in a time slot *t*. Hence, the *CogMR* decides the absence or presence of PUs according to the result of comparing the collected energy to a predetermined threshold (δ) as follows:

$$K(Y_t) = \begin{cases} 1 & \text{if } Y_t > \delta \\ 0 & \text{otherwise} \end{cases} \qquad (5–5)$$

where $t = 1, \ldots, T$ is the number of time slots and Y_t denotes the energy collected by the mesh user in time slot *t*.

5.3.4.2 Cooperative Behavior

In the second scenario, to increase the performance of the *CogMesh* network, both *CogMR* and *CogMCs* within the same cluster are assumed to be cooperative users such that they exchange the real time knowledge of its environment periodically to adapt its parameters dynamically. Moreover, we consider that both *CogMR* and *CogMCs* are allowed to coexist with the primary network and use the vacant PUs' channels to send and receive their data packets. Based on the sensing outcomes of different *CogMCs*, the *CogMR* within the same cluster decides if a time slot *t* at the channel *n, S[n,t],* is free or not. To perform such a process perfectly, we consider that each *CogMR* maintains a counter *C* to store its binary decision between 0 (busy) and 1 (free) according to the sensing outcomes of its *CogMC* as follows:

$$C = \sum_{i=1}^{M} K^{i}(Y_t) \qquad (5\text{–}6)$$

where $K^{i}(Y_t)$ is the sensing outcome of the $CogMC_i$ and M is the number of *CogMCs*.

In other words, considering each *CogMR* in the *CogMesh* manages *M CogMCs* located within the same network cluster, the *M CogMCs* are invited to participate in spectrum sensing at the beginning of each time slot according to the system model described in section 5.3. Using (5-5), each *CogMC* decides the absence or presence of the PU and keeps its summery statistic $K^{i}(Y_t)$, where $i = 1, ..., M$ is the i^{th} *CogMC* that participates in the sensing process, independently. In turn, the *CogMR*, who exchanges its real time knowledge of the environment with its *CogMCs* periodically, receives the sensing outcomes from its *CogMCs* and decides if the current channel is free or not according to the information maintained at the counter *C* as follows:

$$K(Y_t) = \begin{cases} 1 & \text{if } \; C > M/2 \\ 0 & \text{otherwise} \end{cases} \qquad (5\text{–}7)$$

5.3.4.3 Throughput Aggregation

We assume a white noise modeled as a zero-mean Gaussian random variable and variance $\sigma_{n,0}^2$ as $w(n) \sim \mathcal{N}(0, \sigma_{n,0}^2)$, and a primary signal modeled as a zero-mean Gaussian random variable and variance $\sigma_{n,1}^2$ as $s(n) \sim \mathcal{N}(0, \sigma_{n,1}^2)$. For energy detector, the probability of detection is given by:

$$P_d = 1 - \Gamma\left(\frac{L}{2}, \frac{\delta}{\sigma_{n,1}^2 + \sigma_{n,0}^2}\right) \qquad (5\text{–}8)$$

and the probability of false alarm is given by:

$$P_f = 1 - \Gamma\left(\frac{L}{2}, \frac{\delta}{\sigma_{n,0}^2}\right) \qquad (5\text{–}9)$$

where *L* denotes number of independent measurements are taken at the beginning of each time slot sensing and $\Gamma(m,a)$ is the incomplete gamma function and given by:

$$\Gamma(m,a) = \frac{1}{\Gamma(m)} \int_0^a t^{m-1} e^{-t} dt \qquad (5\text{–}10)$$

After finishing the sensing process at each time slot, based on the information state *λ(n,t),* the mesh users should decide which channel to be accessed according to the optimal policy:

$$n^*(t) = \arg\max_{n=1,\dots,N} [\lambda(n,t)] \qquad (5\text{–}11)$$

The information state can be updated for the next time slot as follows:

$$\lambda(n,t+1) = \lambda(n,t)\, P_f / \Big(1 + \big(1 - P_f\big)\lambda(n,t)\Big) \qquad (5\text{–}12)$$

To obtain the expected transition reward, each mesh user is given a unit reward for each free channel accessed by that user. The overall reward for a time slot *t* is given by:

$$r(t) = \sum_{n=1}^{N} S[n,t] \qquad (5\text{–}13)$$

Finally, to maximize the throughput of mesh users, we need to maximize the expected sum of rewards as follows:

$$R^T = \max\left(E\{\textstyle\sum_{t=1}^{T} r(t)\}\right) \qquad (5\text{–}14)$$

5.3.5 Waiting Time Analysis

Let W^p *and* W^s denote the waiting time of a typical packet for a PU and a CR user, respectively. In an exponential service of parameter μ, according to Little's law [32], the average waiting time for the PU's packet is calculated as M/M/1 queuing system as follows:

$$E[W^p] = \frac{\rho^p \, E[T]}{(1-\rho^p)} \qquad (5\text{–}15)$$

where $\rho^p = \lambda_p E[T]$ is the primary channel utilization and *E[T]* is the average transmission time for each packet.

According to Pollaczek-Khintchine [32] formula, the average transmission time of a packet *E[T]* is identical independent distributed (i.i.d) and follows a general law *E[T]* = 1/μ for all the packets. In such case, the service for each packet is deterministic. In this work, it is assumed to be one time slot in the system. Hence, the service is constant modeled as M/D/1 queuing system as a special case of the M/G/1 queuing model. Accordingly, the average waiting time for the PU's packet is given by:

$$E[W^p] = \frac{\lambda_p \, E[T^2]}{2(1-\rho^p)} \qquad (5\text{–}16)$$

where $E[T^2]$ is the second moment of the average transmission time.

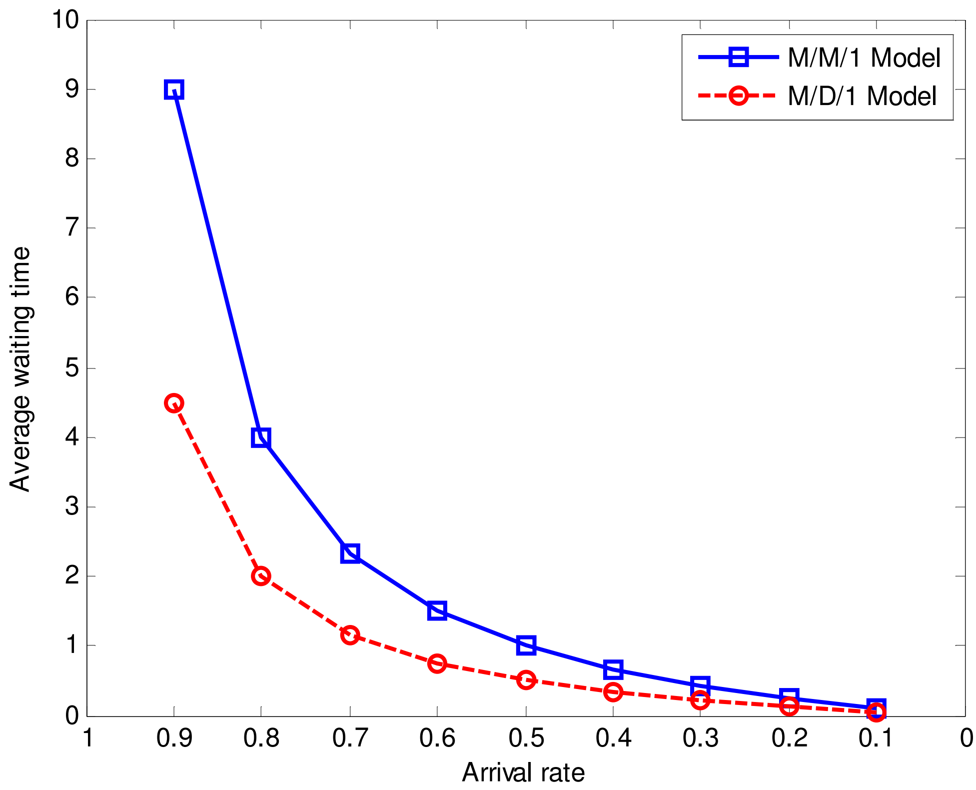

Figure 5-8: Average waiting time vs. arrival rate

Keeping the average transmission time constant, Figure 5-8 depicts the behavior of the average waiting time of the PU's packet as a function of arrival rate λ_p. It is clear that the waiting time in the queue of type M/D/1 is minimized by 50% compared to M/M/1 type.

However, in a *CogMesh* network, the waiting time of a *CogMesh* user packet depends on the number of packets in the queue for both *CogMesh* users and primary users, denoted as $L^S$and L^p respectively. Certainly, the primary packets have absolute priority over the *CogMesh* packets, which means that a *CogMesh* user must interrupt its transmission and vacate the channel on arriving the PU's packets. Therefore, we are interested to apply the Preemptive-resume priority rule to calculate the average waiting time for the *CogMesh* users' packets. We start from the fact that the PU packets have the absolute priority over the *CogMesh* user packets and we calculate the average number of primary packets in the system, which is given by:

$$E[L^p] = \frac{\rho^p}{(1-\rho^p)} \qquad (5\text{–}17)$$

Since the transmission time of both *CogMesh* and primary users are exponentially distributed with the same mean, hence the overall number of packets in the system is given by:

$$E[L^p] + E[L^s] = \frac{\rho^p+\rho^s}{(1-\rho^p-\rho^s)} \qquad (5\text{–}18)$$

By inserting (5-17), we get the average number of *CogMesh* user packets in the system:

$$E[L^s] = \frac{\rho^p+\rho^s}{(1-\rho^p-\rho^s)} - \frac{\rho^p}{(1-\rho^p)} \qquad (5\text{–}19)$$

and by applying Little's law, we obtain the average waiting time for a *CogMesh* user packet as follows:

$$E[W^s] = \frac{E[T]}{(1-\rho^p)(1-\rho^p-\rho^s)} \qquad (5\text{–}20)$$

Noting that the determined formula is for M/M/1 queuing model. Applying Little's law and considering the absence of CR user packets in the presence of primary packets, we obtain the average waiting time for the PU packet for M/G/1queuing model as follows:

$$E[S^p] = E[T] + \frac{\lambda_p E[T^2]}{2(1-\rho^p)} \qquad (5\text{–}21)$$

The overall delay of *CogMesh* user packets in the system can be calculated as the sum of average waiting time in the queue and average transmission time to obtain:

$$E[S^s] = \frac{\lambda_p E[T^2] + \lambda_s E[T^2]}{2(1-\rho^p)(1-\rho^p-\rho^s)} + \frac{E[T]}{(1-\rho^p)} \qquad (5\text{–}22)$$

5.4 Simulation Results

In this section, the presented cooperative sensing scheme for cognitive wireless mesh networks and sensing strategies are implemented in MATLAB. To validate the proposed model, we consider a spectrum frequency divided into 5 independent channels, each with 20 time slots. Applying the sensing scheme described in section 5.3, we consider a *CogMesh* network composed by a cluster consisting of a *CogMR* leads 10 *CogMCs*. Moreover, based on the queuing theory models discussed in section 5.3, the impact of arrival rate on the performance of *CogMesh* is investigated. In this scenario, the priority is given to the primary packets to be served first and any secondary transmission will be interrupted upon receiving any new primary packets.

5.4.1 Impact of Sensing Errors on MAC Performance

In this sub-section, a cooperative sensing scheme with interference mitigation for WMNs is presented. In particular, we investigate the impact of *false-alarm* (P_f) and *missed-detection* (P_{md})probabilities on the MAC layer performance. We propose a sensing strategy in which the MRs (unlicensed users) can use the available licensed spectrum without causing harmful interference with the licensed users. Moreover, sensing errors are considered in the simulation. We consider a scenario that maximizes the aggregate throughput under the constraint that the proposed sensing scenario described earlier is a function of the sensing errors allowed by the primary network.

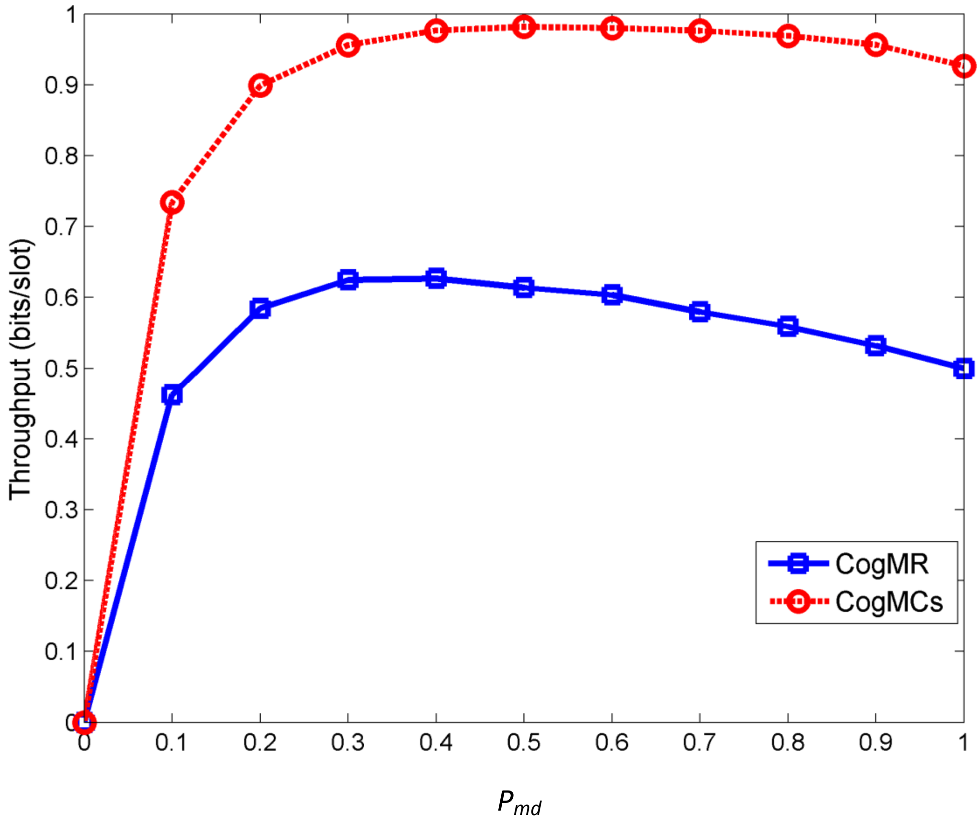

Figure 5-9: Throughput comparison under different Pmd

Figure 5-9 shows the throughput comparison between two different scenarios. First, applying the individual behavior scenario where the *CogMR* is the sole responsible for sensing its environment. Second, applying the cooperative behavior scenario where the *CogMCs* are invited to participate in the sensing process. We observe an increase in the system throughput of the network with the increase of P_{md} for both cases. This is because increasing the P_{md}, will decrease the P_f, which leading to improved throughput for the mesh network at a price of more collisions with the primary network. However, comparing the results achieved by the two scenarios, Figure 5-9 shows that the second scenario more effective in achieving high throughput. Since, in the simulation, we assumed that the *CogMR* to decrease the sensing outcomes received from the *CogMCs* by a certain percentage increased by 5% according to its arrival, where the first delivered is expected to be the nearest one, this will increase the probability of sensing the channel as free. Moreover, due to frequent collisions, any increase in the P_{md} will affect the overall spectrum efficiency. As a result, as shown in the plot, a slight decrease can be noted in the aggregate throughput starting at certain points.

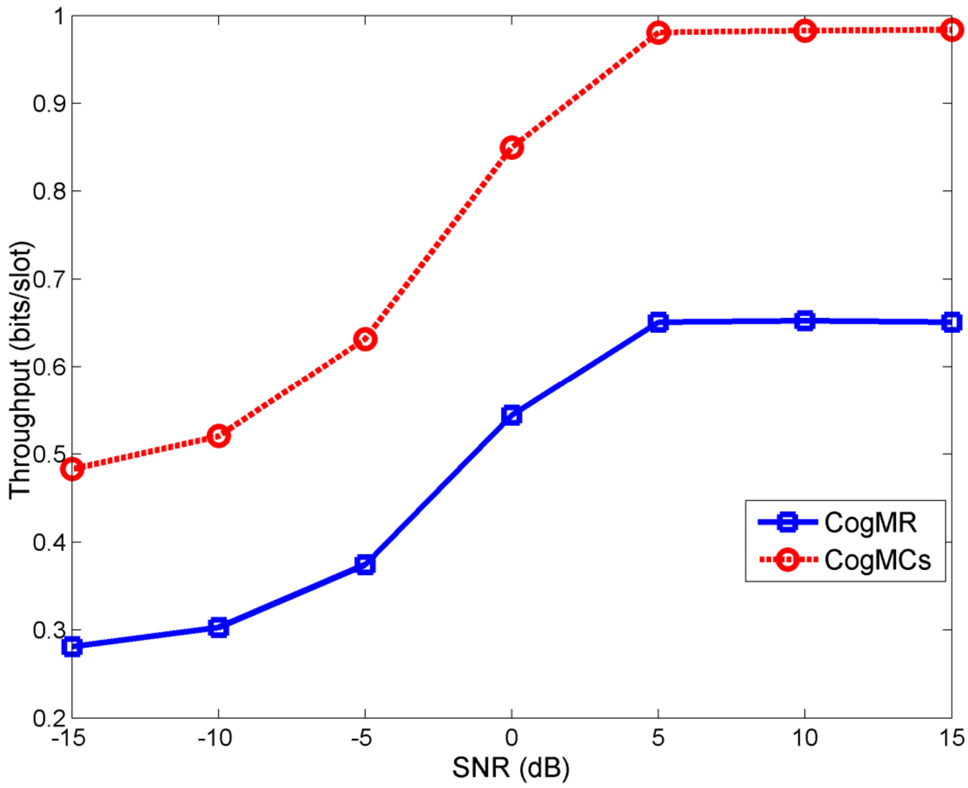

Figure 5-10: Throughput vs. SNR with fixed Pmd (Pmd = 0.5)

On the other hand, Figure 5-10 plots the throughput of the mesh network applying the two scenarios versus the SNR. In this part of simulation, we assume that P_{md} is fixed at 0.5. It is clear that the throughput of the mesh network increases with the increase of SNR. In the simulation, we also adapt the threshold according to the value of SNR. Hence, we can consider a scenario that maximizes the system throughput under the constraint that the P_f does not exceed certain levels. Therefore, reducing P_f by adapting the detection threshold level with the increase of SNR result to an improvement in the system throughput. In addition, comparing the results achieved by the two scenarios, we observe that the second scenario achieves better throughput for the same reason mentioned above. Moreover, Figure 5-10 shows that the throughput achieved by applying the cooperative scenario has further improvement, almost 10%, at high SNR.

5.4.2 Waiting Time Analysis and System Throughput

In this sub-section, we proceed applying the cooperative sensing scheme with interference mitigation for WMNs. A spectrum frequency with 5 independent channels, each divided into 20 time slots are also considered. Moreover, we assume that the arrival rate is fixed at 0.5. Firstly, this scenario is applied on a cognitive radio network with one *CogMesh* user. Secondly, a *CogMesh* network composed by a cluster consisting of a *CogMR* leads 10 *CogMCs* is considered.

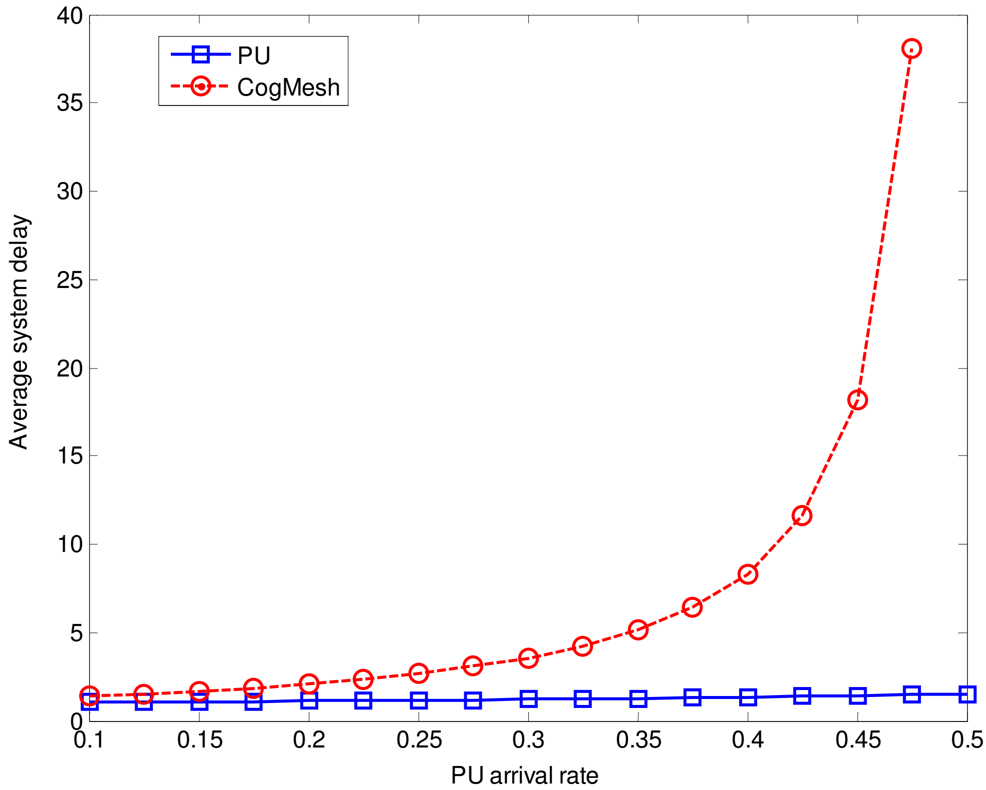

Figure 5-11: Average system delay under different primary arrival rate

Figure 5-11 shows the average delay of both PU packet and *CogMesh* user packet under different PU arrival rate. It is clear that the delay of *CogMesh* packets can be reduced until certain PU arrival rate, where a higher primary traffic results in a longer process time on channel sensing and negotiation, which leads to significant increase in the average waiting time of *CogMesh* user packets. This is due to the fact that the primary packets have the absolute priority over the *CogMesh* user packets. Moreover, the slight increase in PU's packet delay is mainly contributed by the collisions that occur due to the *CogMesh* user's traffic. However, if each channel in the system is considered as a sub-server, and allocates the *CogMesh* users' packets according the usage matrix and the state function S*(n,t)*, the mean arrival rate is reduced for a particular channel and the average delay of *CogMesh* user packets is reduced. In other words, increasing the number of channels allows more data transmission, which means increasing the *CogMesh* user rate and minimizing the overall packet delay. Therefore, the scenario of multiple *CogMesh* users compete to sense and transmit its data packets on multiple channels is proposed. In this scenario, a prior knowledge about the channels transition probabilities {α = 0.2 and β = 0.8} is considered.

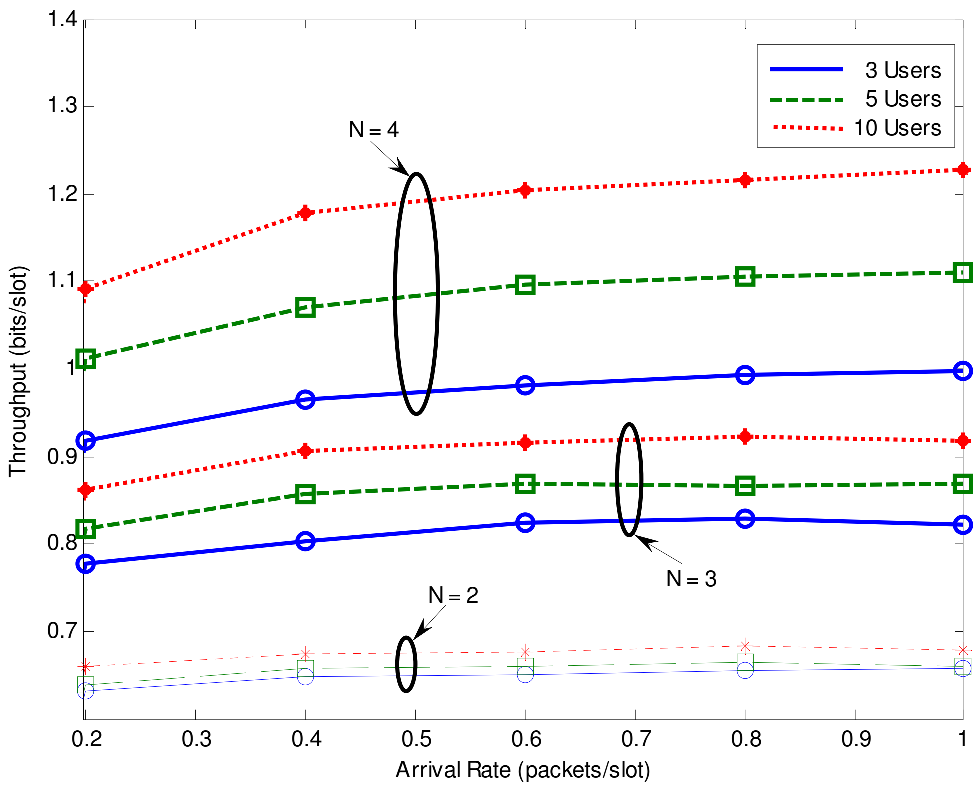

Figure 5-12: Throughput vs. different arrival rate

Moreover, we apply different number of channel [N = 2, 3, 4], and different number of users [3, 5 and 10] to test the effect of the number of channels on the network performance. In this scenario, we assume the message arrivals are forming a Poisson process with message arrival rate λ. The transmission time of one packet is assumed to be one slot in this simulation. As shown in Figure 5-12, the throughput of the *CogMesh* users, measured in bits/slot, increases with the increase of message arrival rate. In addition, it can be observed that increasing the number of channels can result in throughput improvement. In addition, it can be observed that 10 users scenario can achieve better results in the case of using 4 channels compared to 3 users scenario, about 20% higher, where in the case of using 3 channels is only 10%, and less than 5% in the case of using 2 channels.

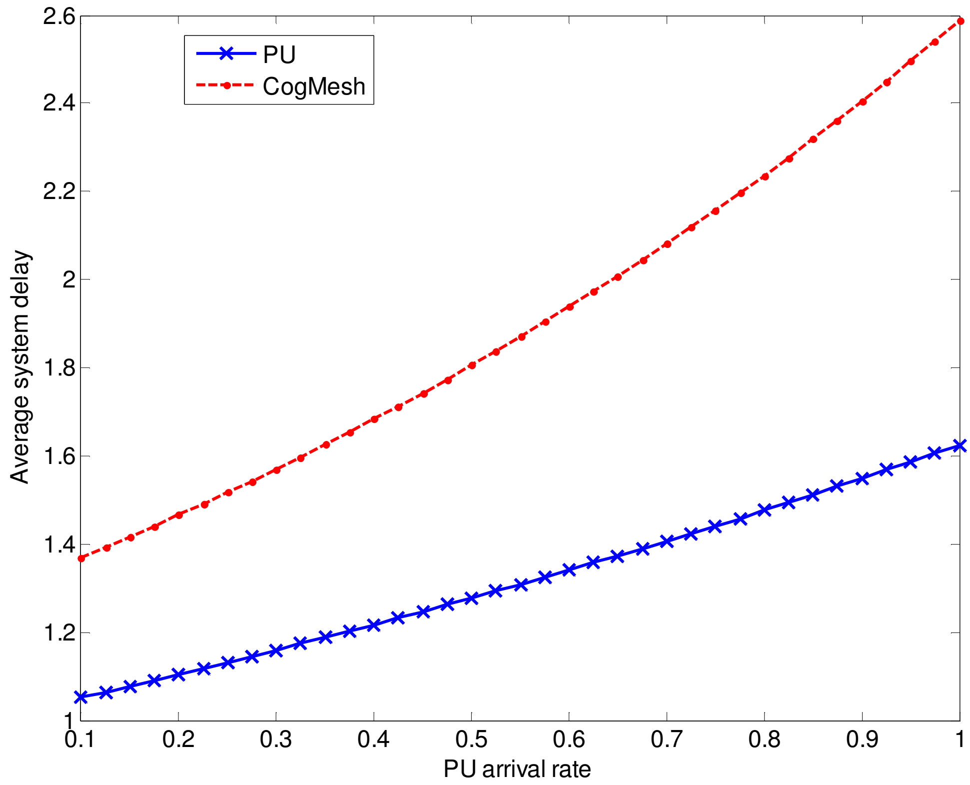

Figure 5-13: Average system delay vs. arrival rate for M/D/1 queuing model

Now, we consider a *CogMesh* network composed by a cluster consisting of a *CogMR* leads 10 *CogMCs*. Figure 5-13 shows the average delay of both PU traffic and *CogMesh* users traffic under different PU arrival rate. In general, it can be observed that the average delay of both *CogMesh* packets and PU packets increases with the increase of the primary arrival rate. It can also be observed that the gap between the two curves is increased with the increase of the PU arrival rate. This is because the primary user packets have the absolute priority over the *CogMesh* users packets, so any increase in the PU traffic limits the *CogMesh* users transmission. In other words, any increase in the arrival rate leads to more time spent in spectrum sensing and scheduling to alleviate any expected interference. Moreover, the increase in primary packets delay is mainly contributed by the collisions that occur due to the *CogMesh* users traffic. However, considering each channel in the system as a sub-server allocates the *CogMesh* users packets according to the state function S*[n,t]*, the mean arrival rate is reduced and the average delay of *CogMesh* users packets is reduced. In other words, increasing the number of channels allows more data transmission, which means increasing the *CogMesh* users rate and minimizing the overall packet delay.

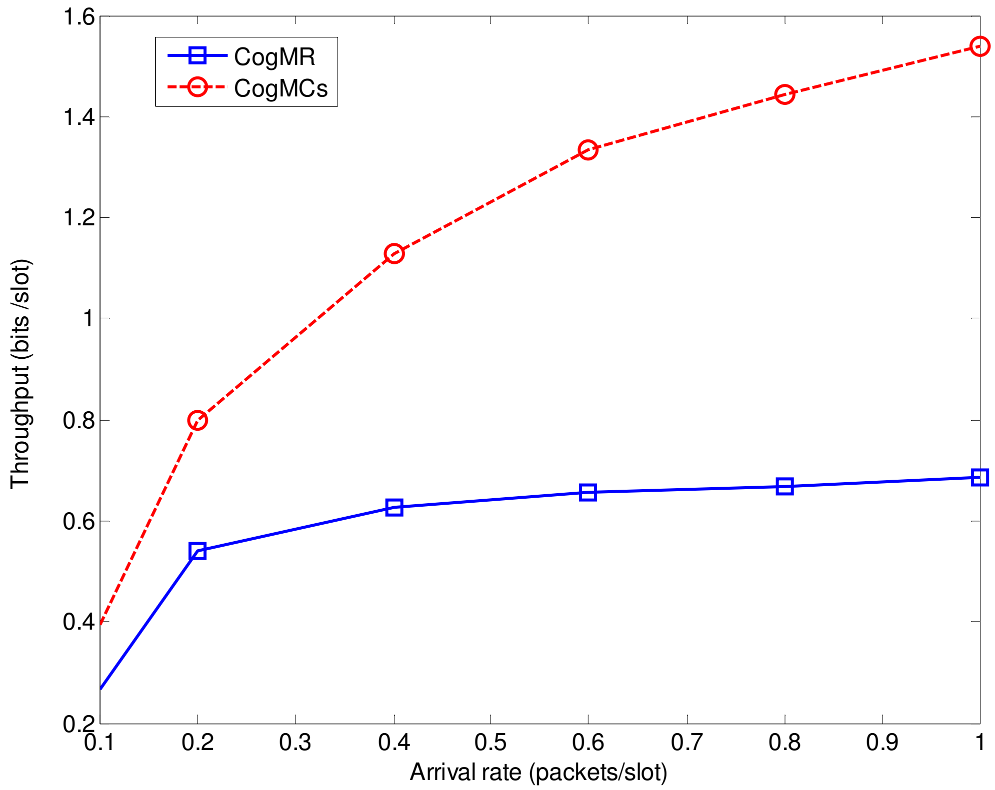

Figure 5-14: Throughput vs. arrival rate

On the other hand, the cooperative scenario of multiple *CogMCs* participate in the sensing process is proposed. In this scenario, A prior knowledge about the channels transition probabilities {α = 0.2 and β = 0.8} is considered. Moreover, we apply different number of users, first considering the *CogMR* perform the sensing process individually, and then considering 10 *CogMCs* participate in the sensing scenario to test the effect of the number of users on the network performance. In this scenario, we assume the message arrivals are forming a Poisson process with message arrival rate λ. The transmission time of one packet is assumed to be one slot in this simulation. As shown in Figure 5-14, the achievable throughput increases with the increase of message arrival rate. However, the *CogMCs* achieve higher throughput compared to *CogMR* and the gap between both plots increases as the arrival rate increases. Hence, it can be observed that increasing the number of users can increase the overall throughput of the network.

5.5 Conclusion

In this chapter, a cognitive MAC approach for wireless mesh networks is presented. Using multiple channels and assuming time slotted structure for the primary network, the impact of sensing errors on the MAC layer performance is investigated. The results have shown that any increase in the *missed-dettection* probability leads to a decrease in the *false-alarm* probability. As a result, an improved throughput for the mesh network can be achieved. However, this allows more collisions with the primary network, which affect the spectrum efficiency. Moreover, the results demonstrate that the aggregate throughput of *CogMesh* can be improved with the increase of SNR by decreasing the *false-alarm* probability which can be adapted by the threshold level.

On the other hand, , using multiple channels and assuming time slotted structure for the primary network, we studied the issue of interference caused by a CR users to primary network. In this work, the long message segmentation is also discussed, and a cooperative sensing and access scheme for *CogMesh* networks is proposed. Moreover, the queuing system delay is studied, and a novel technique based on the priority queuing system for dynamic channel allocation in *CogMesh* networks is presented. The results have shown that any increase in the arrival rate leads to increase in the system delay. However, the average packet delay can be reduced by 50% using the M/D/1 queuing model and increasing the number of channels can imrove the network performance. Considering each channel in the system as a sub-server, the average delay of *CogMesh* user packets is reduced, and high throughput can be achieved as the number of arrival rate is increased.

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Chapter 6

Conclusion

The aim of this thesis was to resolve some of the issues in cognitive radio networks, especially related to spectrum sensing, sharing and access. This thesis introduces a multi-channel time slotted cognitive Medium Access Control (MAC) protocols for Mobile Ad-Hoc Networks (MANETs). Based on the theory of the Partially Observed Markov Decision Process (POMDP), the introduced protocols senses the radio spectrum, detects the occupancy state of different primary channels, and then opportunistically communicates over unused channels (spectrum holes). Moreover, based on the POMDP framework, multi-channel and time slotted approach, and using three different scenarios, the proposed protocols makes efficient decisions on which channels to sense and access, and maximizes the throughput of the secondary user by maximizing the expected sum of rewards R achieving better results when compared to other mechanisms.

In addition, this thesis investigates the impact of sensing errors on the MAC layer performance. On other words, this thesis investigates how the unlicensed users can access to the licensed spectrum and use opportunistically the unutilized channels in an intelligent way without causing any harmful interference with the licensed users. By developing the introduced protocols, a similar scenario is applied to study the impact of *false-alarm* and *missed-detection* probabilities. In this context, a sensing error-aware cognitive MAC protocols for MANETs is introduced. Based on a joint sensing and scheduling scheme, the proposed protocols achieves an optimal cross-layer design, spectrum sensing at physical layer and spectrum access at MAC layer, which enhances the throughput of the secondary user. The simulation results have shown that the throughput of the secondary user can be improved with the increase of Signal-to-Noise Ratio (SNR) by maintain the *false-alarm* probability as small as possible which can be adapted by the threshold level. Moreover, allowing large *missed-detection* probability at low SNR leads to decreasing in *false-alarm* probability, as a result high throughput is achieved.

On the other hand, the thesis presents a priority based cooperative sensing scheme with interference mitigation for cognitive Wireless Mesh Networks (WMNs). In particular, the impact of sensing errors on the MAC layer performance is investigated and a sensing strategy in which the MRs (unlicensed users) can use the available licensed spectrum without causing harmful interference with the licensed users is proposed. The simulation results have shown that the proposed scheme can improve the throughput of cognitive WMNs. Additionally, based on multi-channel and time slotted scenario, a novel technique for long message fragmentation and dynamic channel allocation in cognitive WMNs is presented. The proposed scheme determines the optimal channel for spectrum switching and allocates the packets in a scenario such that the average delay of *CogMesh* users packets is reduced and high throughput can be achieved to improve the CR network performance. The proposed model is then used to evaluate the effects of the number of channels and channel utilization on the network performance.

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List of Publications

Book Chapters:

1. Abdullah Masrub, “MAC Protocols for Cognitive Radio Ad Hoc Networks: Sensing Error-Aware and Spectrum Access Strategies,” Book Chapter in the Book, Self-Organization and Green Applications in Cognitive Radio Networks, Jan. 2013.

Published papers:

1. H. Al-Hmood, R.S. Abbas, A. Masrub, H.S. Al-Raweshidy, “An Estimation of Primary User's SNR for Spectrum Sensing in Cognitive Radios,” International Conference on Innovative Computing Technology (INTECH 2013), London, UK, Aug. 29-31, 2013.

2. M.S. Iqbal, A. Masrub, V.P. Selvan, H.S. Al-Raweshidy, “A Performance Enhancement of IEEE 802.15.4 Standard to Overcome Hidden Nodes Effect on Low Data Rate Ad Hoc WSNs,” International Conference on Innovative Computing Technology (INTECH 2013), London, UK, Aug. 29-31, 2013.

3. A. Masrub, R.S. Abbas, H. Al-Hmood, M.S. Iqbal, H.S. Al-Raweshidy, “Cooperative Sensing for Multiple Channel Access in Cognitive Wireless Mesh Networks,” IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (IEEE BMSB'13), London, UK, June 4-7, 2013.

4. A. Masrub, H.S. Al-Raweshidy, “Priority-Based Cooperative Access for Cognitive Wireless Mesh Networks,” International Conference on Future Generation Communication Technology (FGCT'12), London, UK, Dec. 12-14, 2012.

5. A. Masrub, H.S. Al-Raweshidy, “Time Slotted Based Cognitive MAC Protocols for Multi-Channel Wireless ad hoc Networks,” IEEE International Wireless

Communications and Mobile Computing Conference (IEEE IWCMC'12), Limassol, Cyprus, Aug. 27-31, 2012.

6. A. Masrub, H.S. Al-Raweshidy, M. Abbod, “Cognitive Radio Based MAC Protocols for Wireless Ad Hoc Networks,” International Conference on Developments in eSystems Engineering (DeSE'11), Dubai, UAE, Dec. 6-8, 2011.

Papers under review:

1. A. Masrub, H.S. Al-Raweshidy, “Advances in Cognitive MAC Protocols: Time-Slotted Cross-Layer Approach,” Submitted to IET Communications Journal, under revision since April 2013.

2. A. Masrub, H.S. Al-Raweshidy, “Cognitive Wireless Mesh Networks: Impact of Sensing Errors on MAC Performance,” Submitted to IEEE VT Magazine.

3. A. Masrub, M.S. Iqbal, H.S. Al-Raweshidy, “Delay Analysis for Multiple Channel Access in Cognitive Radio Networks,” IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE PIMRC'13), London, UK, Sep. 8-11, 2013.

4. M.S. Iqbal, A. Masrub, V.P. Selvan, H.S. Al-Raweshidy, “Performance Evaluation of IEEE 802.15.4 Standard for Low Data Rate Ad Hoc Wireless Sensor Networks,” IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE PIMRC'13), London, UK, Sep. 8-11, 2013.

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6. A. Masrub, H. Al-Hmood, R.S. Abbas, H.S. Al-Raweshidy, “Sensing Error Aware Cognitive MAC for Wireless Networks,” IEEE Global Telecommunications Conference (IEEE GLOBECOM'13), Atlanta, USA, Dec. 09-13, 2013.

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