QoS Support for Voice Packet Transmission over Cognitive Radio Networks

by

Khaled Ali

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Abstract

Cognitive Radio Networks (CRNs) provide a solution for the spectrum scarcity problem facing the wireless communications community. However, due to the infancy of CRNs, further research is needed before we can truly benefit from CRNs. The basic concept of CRNs relies on utilizing the unused spectrum of a primary network, without interfering with the activity of primary users (PUs). In order to successfully achieve that, users in a CRN has to perform spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing. The latter, which is the focus of our research, deals with how secondary users (SUs) share the unused spectrum.

Furthermore, to be able to utilize CRNs in practical applications, a certain level of quality-of-service (QoS) should be guaranteed to SUs in such networks. QoS requirements vary according to the application. Interested in voice communications, we propose a packet scheduling scheme that orders the SUs' transmissions according to the packet dropping rate and the number of packets queued waiting for transmission. Two medium access control (MAC) layer protocols, based on the mentioned scheduling scheme, are proposed for a centralized CRN. In addition, the scheduling scheme is adapted for a distributed CRN, by introducing a feature that allows SUs to organize access to the available spectrum without the need for a central unit.

Finally, extensive simulation based experiments are carried out to evaluate the proposed protocols and compare their performance with that of other MAC protocols designed for CRNs. These results reflect the effectiveness of our proposed protocols to guarantee the required QoS for voice packet transmission, while maintaining fairness among SUs in a CRN.

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Dedication

To my loving parents: ***Mustafa*** *and* ***Magda***

To my supportive brothers: ***Mohammed*** *and* ***Sameh***

To my beautiful niece: ***Reem***

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List of Abbreviations

BER	Bit error rate
BC	Backup channel
BP	Beacon period
CAC	Call admission control
CCC	Common control channel
CFC	Contention free channel
CI	Confidence interval
CIT	Contention information table
CLD	Cross layer design
CP	Contention period
CPAR	Constant packet arrival rate
CR	Cognitive radio
CRN	Cognitive radio network
CSMA	Carrier sense multiple access
CSMA/CA	Carrier sense multiple access with collision avoidance
CTS	Clear-to-send

CU	Central unit
CW	Contention window
DSAN	Dynamic spectrum access networks
DTP	Data transfer period
FCFS	First come first serve
IE	Information event
MAC	Medium access control
MHCRN	Multi-hop cognitive radio networks
NDS	Non delay sensitive
NRT	Non real time
PHY	Physical layer
PIT	Primary user information table
PU	Primary user
QAM	Quadratic amplitude modulation
QoS	Quality-of-service
QP	Quiet period
QPSK	Quadratic phase shift keying
RC	Rendevouz channel
RIT	Reservation information table
rt-CTS	Real time clear-to-send
RTS	Request-to-send
SINR	Signal to interference plus noise ratio
SU	Secondary user
TDMA	Time division multiple access

ts	Timeslot
WLAN	Wireless local area networks
xG	Next generation

List of Symbols

Γ	Number of consecutive frames a user spends in a state
κ	Confidence interval constant
λ	Rate parameter of exponential distribution of the ON state
μ	Rate parameter of exponential distribution of the OFF state
σ^2	Variance of the number of admitted SUs
Θ	95% confidence interval for the average number of admitted SUs
θ	Mean of the number of admitted SUs
A	Number of request transmission attempts in the network
B	Backoff duration
C	Capacity of the primary system
CW_{max}	Maximum contention window size
CW_{min}	Minimum contention window size

CW_{rt}	Contention window for real time traffic
f_n	n^{th} time frame
I	Random variable uniformly distributed in [0,1]
ID	Mini-slot identification number
K	Number of channels available in the system
L	Voice call duration in frames
m	Acceptable delay bound in frames
N	Number of secondary users in the system
p	Optimal transmission probability
P_D	Upper bound (acceptable) packet dropping rate
P_d	Actual packet dropping rate
Q	Number of packets queued waiting for transmission
T_c	Duration of a timeslot representing a channel
t_n	n^{th} timeslot
T_{OFF}	Average time a user spends in the OFF state
t_{OFF}	time a user spends in the OFF state
T_{ON}	Average time a user spends in the ON state
t_{ON}	time a user spends in the ON state

V	Number of packets generated
X	Integer random variable uniformly distributed in [0,9]

Chapter 1

Introduction

1.1 Cognitive Radio Networks

Recently, there has been a rapid increase in the demand on wireless communications and its applications. In fact, wireless communication has become the desired means of communications for many applications, mainly because of the freedom associated with the mobility available for a wireless terminal. However, there are some characteristics of a wireless channel, which do not impact a wired channel, that present a challenge for wireless communications. For instance, fading, shadowing, and spectrum scarcity are some of the characteristics that degrade a wireless network [7, 8, 9].

Moreover, in each country, there is an organization that is responsible for allocating various bands of the spectrum, which is the collection of available radio frequencies, to different users, and currently we are running out of the spectrum. On the other hand, it has been found that the allocated spectrum bands, in some cases, are heavily underutilized. In fact, according to [10], the assigned spectrum in some cases is only being accessed 15 % of the time. As a result of this scarcity and underutilization of the available spectrum, the concept of Cognitive Radios (CR) has emerged.

CR was first introduced in 1999, in [1], based on the architecture of software radios [11], and has been the focus of a lot of research since then. Cognitive Radio Networks (CRNs) are networks where unlicensed secondary users (SUs) scan the available spectrum to look for spectrum holes. Spectrum holes are channels that are not being used by licensed primary users (PUs). Once a spectrum hole is located, SUs utilize the available channel in a manner that will not affect the performance of the primary user of the channel. There have been many definitions of CR in the literature [12, 13, 14]; however, all the definitions revolve around the ability of the network to identify unused spectrum, and use it without interfering with the operation of PUs. In addition, a CRN has to be able to identify channel usage patterns of the primary users, in order to efficiently use the available spectrum in a reliable manner [15]. CRNs are sometimes referred to as Dynamic Spectrum Access Networks (DSANs) and Next Generation (xG) communication networks [10].

A CRN goes through a cycle, called a cognitive cycle, which starts by listening to the PUs' activities and ends by allocating resources for SUs. As shown in Figure 1.1, a cognitive cycle can be divided into five stages [1]:

- Observe stage, where the CRN learns about the surrounding radio environment, such as the activity of the primary user;
- Orientation stage, where requirements of the users in the CRN are prioritized;

- Plan stage, where the available alternatives, such as which channels are available and which channels have the best performance, are evaluated;
- Decide stage, where the resources are allocated to the different users in the CRN, according to their requirements;
- Act stage, where the message from the source to the destination is transmitted.

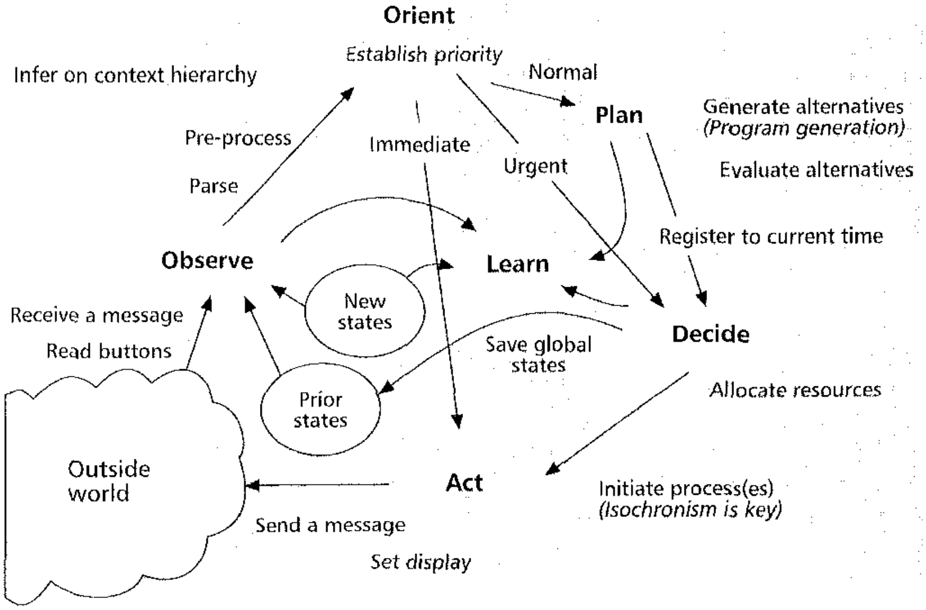


Figure 1.1: The cognitive cycle [1].

The cycle does not have to always pass by the five stages in a consecutive manner [1]. For instance, after finding the requirements of the users in the CRN, if these requirements are immediately met, the cycle can go to the act stage directly. Furthermore, the key functions performed by a CRN, as described in [10, 15], are spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing. Spectrum sensing is responsible for detecting spectrum holes and presence of primary users [16]; on the other hand, spectrum management deals with assigning the available resources to the users in the CRN in the best possible manner [17]. Spectrum mobility, however, manages how users switch between available channels, and finally spectrum sharing, which is the focus of this thesis, is how users in a CRN share the spectrum in a fair manner, and how a level of quality-of-service (QoS) can be guaranteed for secondary users.

Note that, through this thesis, the terms “CRN” and “Secondary System” are interchangeable. Besides, a user in the CRN is referred to as CR user, secondary user, or user. However, every time a primary system or a primary user is the intended subject, the term “primary” is always used.

1.2 MAC Layer in Cognitive Radio Networks

In a CRN, the medium access control (MAC) layer has three main functions [18]:

- Locating the unused spectrum, which is known as spectrum sensing;
- Coordinating the transmission of different users, which is known as spectrum sharing;
- Determining the optimal times of spectrum sensing and data transmission.

Spectrum sensing is defined as the monitoring of unused spectrum by detecting the spectrum holes in the available spectrum bands [10, 16]. This process has to be done without causing any interference to the primary user. Moreover, spectrum sensing is usually done in two manners [18]: primary transmitter detection, and primary receiver detection.

Spectrum sharing, also known as spectrum access, can be defined as the process by which different users access the available spectrum. There are various MAC protocols that strive to optimally share the spectrum among the users of a CRN. The main challenges for spectrum sharing in cognitive radio networks are interruption of control signals by primary users in the network and adaptation to the predefined patterns of primary users' activities [18, 19]. The goal of our research is to design a MAC algorithm that not only allows the users to share the available spectrum holes without interfering with the PUs' activities, but also guarantees a minimum level of QoS, while maintaining fairness among the SUs.

Spectrum sharing can be categorized in many ways. One way to classify the existing MAC protocols for CRNs is according to the architecture of the network on which the protocol is utilized, i.e. whether it is centralized or distributed. In a centralized CRN, there exists a base station (a central unit) that coordinates the spectrum access procedures; while in a distributed cognitive radio network, such as an ad-hoc network, the spectrum access procedure is handled by all users [10]. Another way to classify the current MAC protocols for CRNs is to assort the protocols according to the employed access mechanism; for instance, whether the protocol is a random access, a time slotted, or a hybrid protocol [18].

In addition, MAC protocols can be categorized according to whether the protocol is for a single or multiple radio systems [3], or whether it supports QoS or not. The classification according to the access mechanism utilized by the protocol is used in this introduction, because it enables us to see the differences in structure among available CR MAC protocols, and allows us to understand the challenges that require further research. That being said, the differences among the three access categories are discussed in the following two paragraphs.

First, random access CR MAC protocols do not require time synchronization among the users. It is usually based on carrier sense multiple access with collision avoidance (CSMA/CA), where users that want to transmit a packet monitor the channel and, if the channel is free, transmit after a random backoff period to avoid collision with each other. However, time slotted CR MAC protocols require time synchronization among the various users in the network, and synchronization among users is required for both control signals and data transmission.

Finally, in hybrid CR MAC protocols, part of the communication is done by time slotted access and part by random access. Usually, control signals are transmitted over time slots, while data is transmitted using random access. However, some hybrid MAC protocols have the time slotted feature for all the users in the network, but the access to a given slot is random. Note that this categorization applies for both centralized and distributed networks [18].

To demonstrate the difference among the three access mechanisms, a protocol from each category will be discussed in Chapter 2 . For random access CR MAC, a protocol based on CSMA [2], which is suitable for a centralized CRN, will be presented. Furthermore, for time slotted CR MAC, C-MAC [3], which is a MAC protocol for an ad-hoc CRN, will be discussed. Finally, for the hybrid CR MAC category, SYN-MAC [4], which is for an ad-hoc CRN, will be discussed.

1.3 MAC for Quality of Service in Cognitive Radio Networks

In order to guarantee a certain level of QoS for delay sensitive applications such as voice, a CRN, as any other telecommunication system, has to be able to avoid saturating the available channels and to allocate resources for each user according to its requirements [20]. The saturation of a channel is avoided by employing what is called connection admission control, while appropriate resource allocation is known as service differentiation.

Furthermore, QoS has different parameters depending on the application, such as delay, jitter, packet loss, signal to interference plus noise ratio (SINR), and bit error rate (BER) [10]. There are delay sensitive applications such as voice, and loss sensitive applications such as data communications. The majority of the available CR MAC protocols that support QoS deal with the SINR and BER parameters of QoS. For instance, a QoS resource allocation scheme proposed in [21] focuses on SINR, BER and minimum rate requirements. However, in [5] the protocol provides a QoS for delay sensitive traffic, albeit the delay sensitive message has to have a predetermined length.

That being said, in [6], the authors introduce a protocol that guarantees a level of QoS for voice users based on rotating an index among SUs; however, the protocol does not maintain fairness among the SUs. The indexing protocol [6] will be discussed in more details in Section 2.5.

Note that, to be able to provide QoS for delay sensitive traffic, proactive handoff is preferable[22]. If an SU detects the return of a PU, the secondary user has to vacate the spectrum and terminate any activity on the said spectrum. Furthermore, the SU has to locate another available channel to continue its activities, within a reasonable time frame. This is called reactive spectrum handoff.

For delay sensitive communications, instead of waiting for the primary users to appear, the secondary users should locate another channel while transmitting and, according to the available statistics which are gathered during the observe stage of the cognitive cycle, predict the return of the PU and, thus, vacate the channel before the PU demands access to the channel, after establishing a new connection on another channel. This is known as proactive spectrum handoff. However, the proactive spectrum handoff is more complex than the reactive one, since it requires the statistical knowledge of the PUs' utilization of the available spectrum.

1.4 Problem Definition and Research Objective

Cognitive radio networks are expected to solve the problem of spectrum scarcity to a certain degree; however, in order for a CRN to be employed in practical applications, a measure of QoS has to be provided. So far in the literature, QoS is not the main focus of researchers who study CRNs. The majority of researchers who consider QoS provisioning, do so only for parameters such as throughput [23], SINR [3], and BER [24]. Even protocols that provide a level of QoS for delay sensitive applications have some drawbacks such as predetermined message size [4] or fairness among SUs [6]. Thus, protocols that guarantee QoS for delay sensitive applications, such as voice, are much needed.

After discussing the functionality of the MAC layer in a CRN and the necessity of

QoS for voice communications, we define our research problem. Our main goal is to utilize the unused spectrum of a primary network to transmit voice packets. Hence, our objective is to design a MAC protocol which guarantees that any SU admitted to a CRN will have enough resources for the duration of the call. In addition, this MAC protocol has to promote fairness among all SUs in the CRN, while ensuring that the performance of the users in the primary network is unaffected.

That being said, our research objective is to design a MAC protocol that schedules SUs' packet transmission, while achieving the following:

- Guaranteeing a packet dropping rate below a certain bound for all SUs in the CRN,
- Maintaining fairness among all SUs of the same class in the CRN, and
- Avoiding interference with the activities of the users in the primary network.

1.5 Thesis Organization

The remainder of the thesis is organized as follows. In Chapter 2, we discuss related MAC protocols designed for cognitive radio networks, while our system model is presented in Chapter 3. Furthermore, two MAC protocols that guarantee QoS support for SUs in a centralized CRN are proposed in Section 4.1. On the other hand, a QoS supporting MAC protocol for a distributed CRN is presented in Section 4.2. Performance evaluation of the proposed MAC protocols is presented in Chapter 5. Finally, in Chapter 6, we conclude our thesis by highlighting our research contribution, and present possible future research directions.

Chapter 2

Related Work

In this chapter, we present five MAC protocols designed for both centralized and distributed CRNs. Because of the relative infancy of CRNs, there are not many protocols that address QoS. For instance, out of the five protocols presented in this chapter, three protocols do not provide any QoS support, namely CSMA based CR MAC [2], C-MAC [3], and SYN-MAC [4].

On the other hand, CR MAC with QoS provisioning [5] and QoS for voice CRNs [6] provide a certain measure of QoS for SUs with delay sensitive applications; however, only the latter does not require that the size of the transmitted message to be known prior to transmission. In fact, QoS for voice CRNs successfully attempts to handle the demands of voice service among secondary users in a CRN, albeit with shortcoming in fairness among SUs.

In addition, four of these protocols do not require a centralized control unit, namely

C-MAC, SYN-MAC, CR MAC with QoS provisioning, and QoS for voice CRNs. Table 2.1 provides a quick comparison among the five MAC protocols. Detailed discussion of each protocol is presented in the following sections.

Protocol	**Type of Network**	**QoS Support**	**Access Technique**
CSMA based CR MAC	Centralized	No	Random
C-MAC	Ad-hoc	No	Time Slotted
SYN-MAC	Ad-hoc	No	Hybrid
QoS provisioning MAC	Ad-hoc	Yes	Time Slotted
QoS for voice CRNs	Ad-hoc	Yes	Time Slotted

Table 2.1: Overview of the five MAC protocols.

2.1 CSMA based CR MAC protocol

In this protocol, both primary and secondary systems are carrier based systems with a four-way handshaking procedure, and each of the systems is composed of a base station responsible for its users. Moreover, in the primary system, the transmission occurs according to the conventional carrier sense multiple access (CSMA), where a PU that wants to transmit a packet listens to the channel for a certain period of time to determine if the channel is idle or not. If the channel is idle, the PU sends a request-to-transmit (RTS) to its base station. Once a clear-to-send (CTS) is received, the PU transmits its data. However, if a CTS is not received, the PU continues to listen to the channel until the channel is idle for the backoff duration and, then, retransmits its RTS to the base station.

The primary system has an acceptable level of interference, with which it can function properly. The acceptable interference level is known to the secondary system, and hence an SU does not have to wait till the channel is idle to transmit. Instead, it adjusts its transmission rate and power to avoid causing unacceptable interference to PUs. Thus, with adjusting the transmission rate and power, both the primary and the secondary systems can coexist, and any interference resulting from that will be acceptable to both systems.

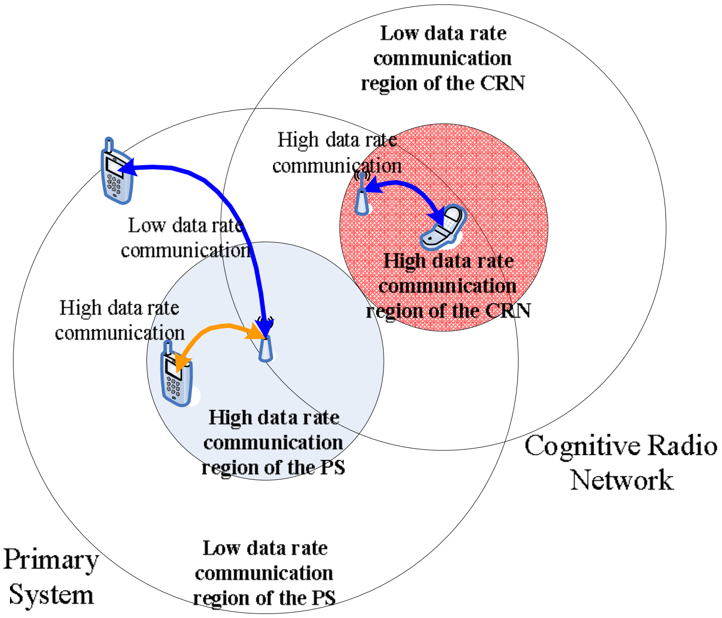


Figure 2.1: A setup which enables the coexistence of both primary and secondary systems [2].

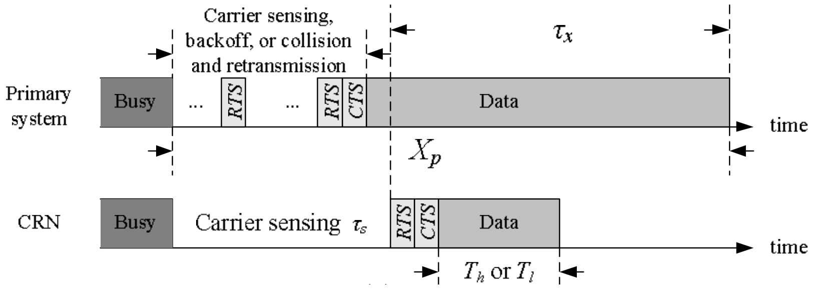
Figure 2.1 shows the configuration, with which simultaneous transmissions in both systems can be established [2]. Both primary system and secondary system use the following transmission rates:

- Low data rate, along with transmission schemes that are impervious to noise such as quadrature phase shift keying (QPSK), is used for communications between the base station and users with low received signal power far from the base station;

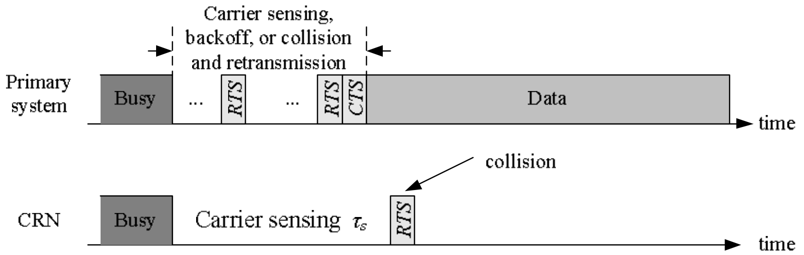
- High data rate, along with transmission schemes that are susceptible to noise such as 64-QAM (quadrature amplitude modulation), is used for communications between the base station and users with high received signal power near the base station.

Since both PUs and SUs have to listen to the channel for a certain duration before contending for it, the sensing period (backoff duration) assigned to SUs has to be longer than the sensing period assigned to PUs. This is done to ensure that PUs have priority over SUs to access the channel. Moreover, if a(n) PU(SU) requires access to the channel, it senses the channel for the appropriate time, and sends an RTS to its base station. Figure 2.2 shows the four-way handshake procedure used to content for the channel, as explained in the following.

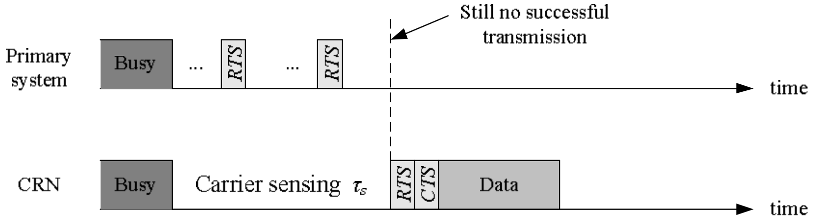
- Case 1: If the channel is busy and is being used by a PU, as shown in Figure 2.2(a), the base station of the secondary system calculates the acceptable transmission rate, in order to avoid interference to the PU beyond the acceptable level, and sends the values to the SU in the CTS. If no such transmission is possible, the base station does not send the CTS to the SU.
- Case 2: If the channel is busy and is being used by an SU, as shown in Figure 2.2(b), and an RTS collision for a SU occurred, the SU has to sense the channel for another backoff duration before retransmitting its RTS.
- Case 3: If the channel is idle, as shown in Figures 2.2(c) and 2.2(d), when no PUs are transmitting, the base station of the secondary system issues a CTS to the secondary user and contends the channel for the secondary user [2]. Note that, if a PU senses the channel during the transmission of the SU, the PU finds the channel busy. This is a drawback for this protocol .



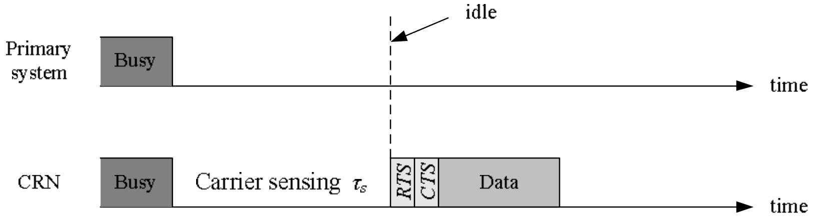
(a) PU and SU transmitting simultaneously



(b) SU RTS fails



(c) PU RTS fails



(d) PU idle

Figure 2.2: CSMA with a four-way handshaking procedure [2].

2.2 C-MAC

This protocol is designed for distributed CRNs, and it employs multiple channels, not only to increase the capacity of the wireless network, but also to be able to vacate the channel if a primary user demands it. Even though the C-MAC is a multi-channel MAC, it is assumed that each node is equipped with a single half-duplex transceiver. Figure 2.3 shows how each channel in the spectrum is slotted into superframes and how each superframe is divided into a beacon period (BP) followed by a data transfer period (DTP).

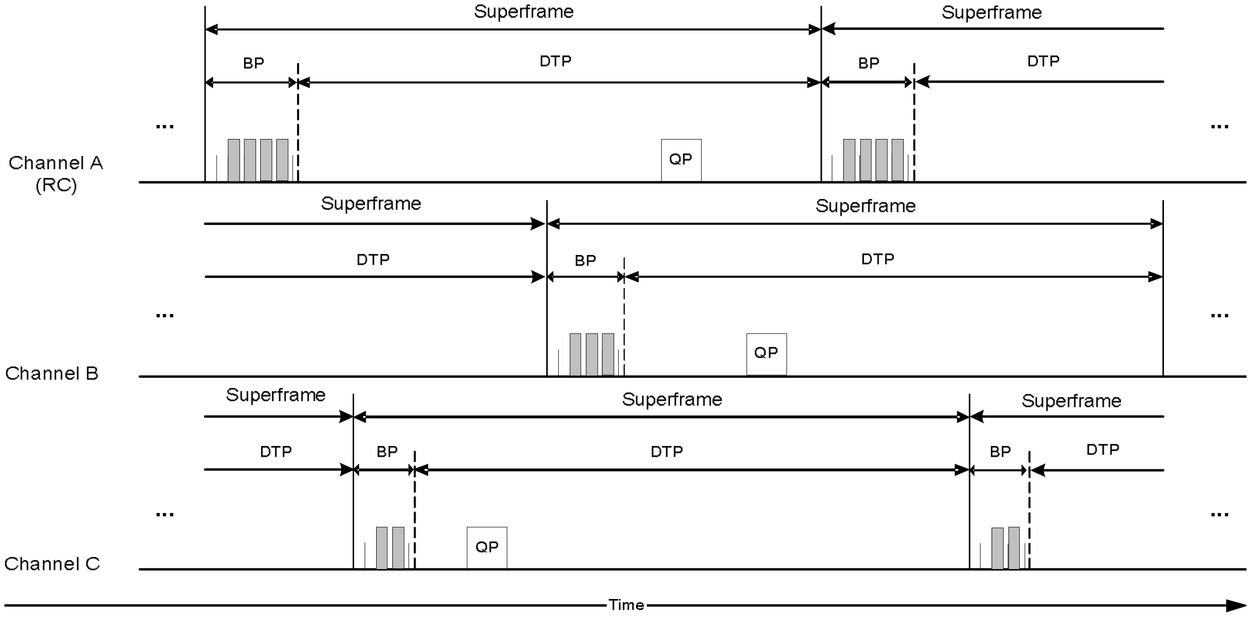


Figure 2.3: Slotted time used in CMAC [3].

In addition, the BP is slotted and during these slots users are required to transmit their beacons. These beacons include information that helps SUs manage the network. As shown in Figure 2.3 [3], the uniqueness of this protocol is in that the BPs across all channels do not overlap and, hence, a user that is scanning all the channels after start-up can gather information about all channels by listening to the channels consecutively. The DTP has quiet periods (QP), during which users listen for primary users and perform out-of-band sensing. For instance, a user in channel A performs out of band measurements of channel B in the QP of channel B.

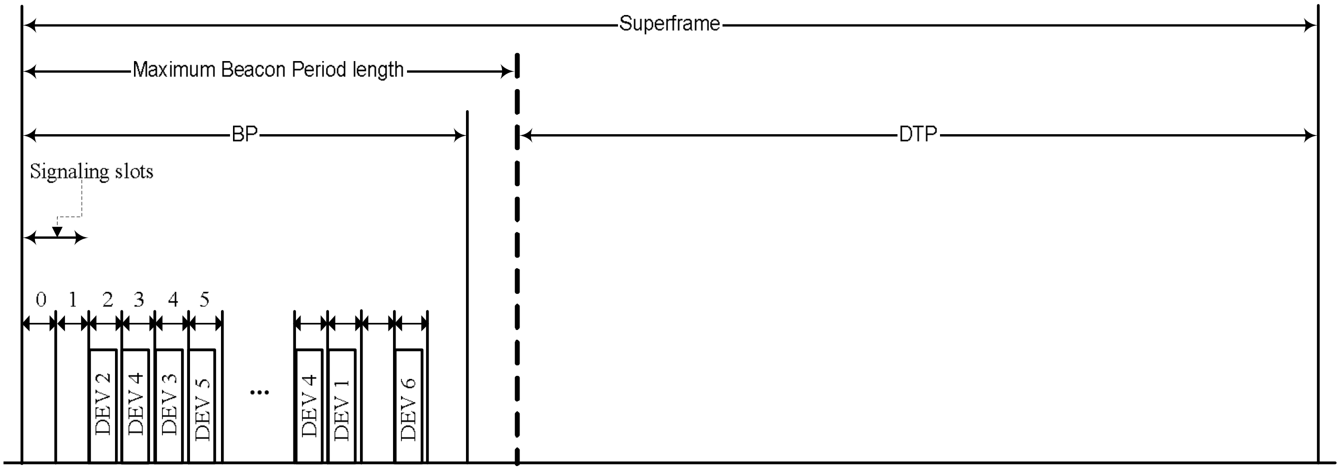


Figure 2.4: The superframe structure in C-MAC [3].

The channel that is known to be available most of the time is chosed by the secondary system to communicate network information among SUs. This channel is called the rendezvous channel (RC). In addition, a backup channel (BC) is chosen, in case a primary user demands to use the RC. Noted that the RC is what the C-MAC is built on, because it is used to share information among the SUs to manage the network. Some of the information shared on the RC is discovery of neighbors and load balancing for available channels in the spectrum.

Once a user decides to join the network, it scans the entire spectrum to determine which channels are available and performs various measurements. If a primary user is not detected, the user listens to the beacons on each available channel, for the duration of a superframe, to gather information about the RC. If the RC is already set by an existing user, information about it is available in the beacon frame header; however, if it is not set, the user will continue scanning other channels to look for information of the RC, and select a channel as the RC for the secondary system.

As soon as the RC is located, the user may join the BP by transmitting its beacon during the first two slots in the BP, as shown in Figure 2.4. After that, the user is assigned a permanent beacon lot in the BP. Once the user is assigned a permanent slot, it has to transmit its beacon during the BP in each superframe on the channel that the user is utilizing. In this beacon, information received from other users, such as neighbours' beacon slots and communication schedules, is included.

If a user, say User A, is on the RC and wishes to transmit on a different channel, it announces its desire in its beacon and hops to the new channel. Existing users in the RC rebroadcast this information and any user that wants to communicate with User A can switch and join the new channel's superframe. However, all nodes are required to switch back to the RC every so often for resynchronization.

On the other hand, if User A is not currently on the RC and wants to hop to a different channel, it has to go back to the RC and announce its new channel before switching to it. Besides, each node calculates the load on each channel, from the BP, and rebroadcasts this information in the RC during its periodic visits. Thus, all the users in the system can determine the load of the various channels in the spectrum.

Finally, if a PU is detected by an SU, this information is communicated through the SU's beacon in the next superframe. Note that control signals are transmitted in all super frames so that a channel dedicated only for control signals is not required. Besides, beacon frames employ high noise resistant transmission schemes to ensure that the beacon is received by all users in the channel; in this way, SUs are aware of the existence of PUs. This is supposedly done in a timely fashion. SUs vacating a channel switch to the RC and, thus, re-establish the communication as soon as possible.

2.3 SYN-MAC

SYN-MAC [4] is designed for multi-hop cognitive radio networks (MHCRN), where data packets are transmitted across the network by hopping, so to speak, from one user to another. In regular multi-hop networks, a packet from a source is passed on to its neighboring nodes, which carry on and pass the packet to their neighbors. This process is repeated until the packet reaches the destination and, thus, all data is transmitted from the source to destination through a number of intermediate nodes. However, in MHRCN, channels across the network may vary in both quality and availability. Thus, two neigbouring users can communicate if and only if there is a common available channel with quality that satisfies the transmission requirements.

Instead of reserving a channel for communicating control signals among SUs, the authors assume that each user is equipped with two radios. One of these radios is for data communications, i.e., used to send and receive data from other users. The other is for listening to control signals being transmitted on the various channels, instead of reserving a channel only for control signals.

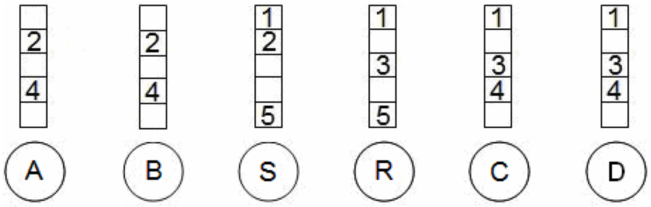


Figure 2.5: Users and their available channels [4].

The number of channels available at each node is time variant, and is mainly affected by the primary user activities. However, it is assumed that the maximum number of channels at each node does not exceed K. The first user in the network divides the time into K slots. Each of these slots has the same length T_c, and each slot represents a channel in the spectrum. Once the time is divided, the first user transmits a beacon at the beginning of each slot in the channel corresponding to that slot.

Any new user that joins the network picks a channel in the spectrum and listens to it, looking for the beacon transmitted by the first user, so as to determine whether the time has already been slotted or not. Since the duration of each slot is T_c, any user that wants to join the network has to listen to a channel for at least $K \times T_c$, in order to guarantee that it will hear the beacon transmitted by the first user.

Once the beacon is heard, the user synchronizes itself with the time slots set by the first user, and exchanges information about its available channel sets with its neighbors. This stage is called the network initialization stage. Now, all users in the network are aware of the time slots and the channels. In addition, they are aware of the channel(s) that are available to their neighboring users. This is important because, as mentioned earlier, in order to communicate with its neighbors, an SU has to find a common channel with them.

There are four information events (IEs), which require exchange of control signals among users:

- IE-1 indicates the arrival of a new user, and is broadcasted to neighboring users;
- IE-2 indicates a change in the availability of a channel(s) due to the presence of a PU, and is broadcasted to neighboring users;
- IE-3 informs the neighboring users about changes in the channel of communication so as to adjust the routing of packets (since multi-hop is used, it is assumed that the route is recalculated at each hop);
- IE-4 is exchanged between an SU and its neighbor, with which the SU wants to communicate.

Finally, to further elaborate on the functionality of the protocol, we discuss the following two scenarios:

- Communication between two SUs: If user S wants to communicate with user R, user S knows that channels 1 and 5 are common with user R, as shown in Figure 2.5 [4]. Hence, user S waits till the slot corresponding to one of these channels arrives and then exchanges control signals with user R. Once the channel is contended for, as shown in Figure 2.6, user S transmits its data to user R.
- Return of a PU: If a PU is detected by an SU on a certain channel, an IE-2 is immediately generated and exchanged with the SU's neighbors. However, in some cases the IE-2 cannot be communicated instantaneously. For instance, if users B

and C detect a PU on channel 4, as shown in Figure 2.6, they both issue an IE-2. User B can only communicate with its neighbours on channel 2, as shown in Figure 2.5 and, thus, it has to wait for the time slot corresponding to channel 2 in order to transmit its IE-2 [4]. Similarly, user C can transmit its IE-2 to its neighbours only through channel 3 because channel 1 is busy; therefore, user C's neighbours will only be aware of the presence of the PU when the time slot for channel 3 comes. This delay in communicating the presence of the PU might cause interference to the activities of the PU and is considered a drawback for SYN-MAC.

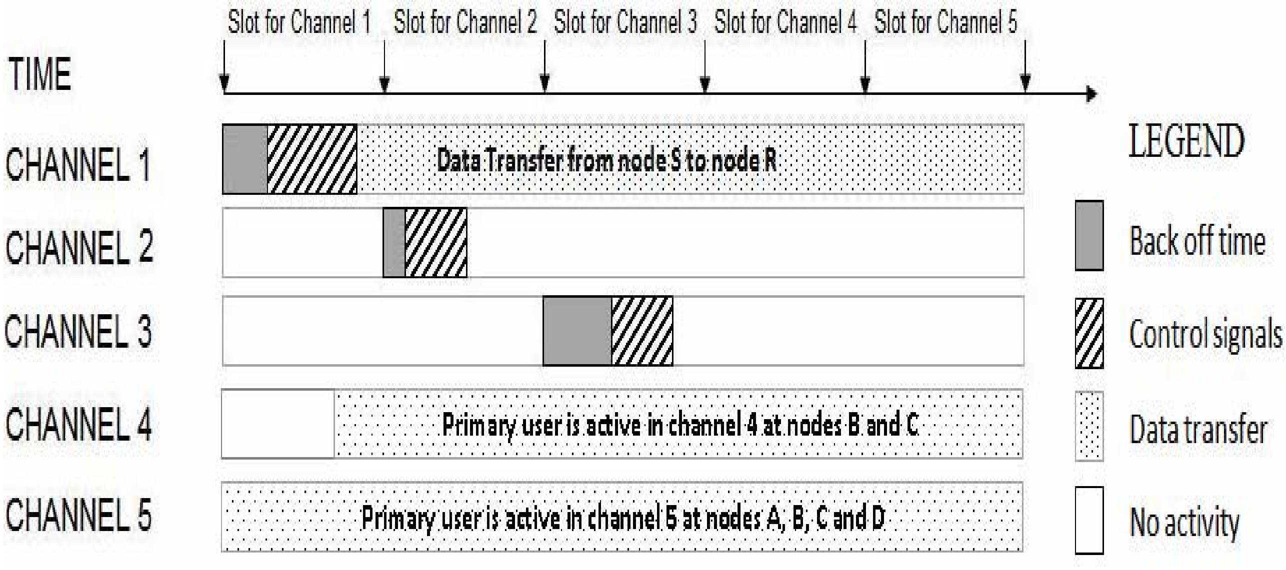


Figure 2.6: Five time slots and activities on the corresponding channels [4].

2.4 CR MAC with QoS provisioning

This MAC protocol is designed for distributed CRNs and is based on the carrier sense multiple access with collision avoidance (CSMA/CA) [5]. The protocol provides a level of QoS for SUs that support delay sensitive applications, and it is tailored to address some of the stages of the cognition cycle [1], namely observe, plan, decide, and act stages.

Data transmission is done in rounds, where each round includes a contention free period (CFP) and a contention period (CP), as shown in Figure 2.7. The durations of the CFP and the CP are not fixed, but vary from round to round according to the type of traffic utilizing the channel and the number of users in the system. For instance, if the traffic is delay sensitive, the CFP will be larger than the CP period, to allow the transmission of delay sensitive traffic. In the following, how the protocol functions in each stage is discussed in details.

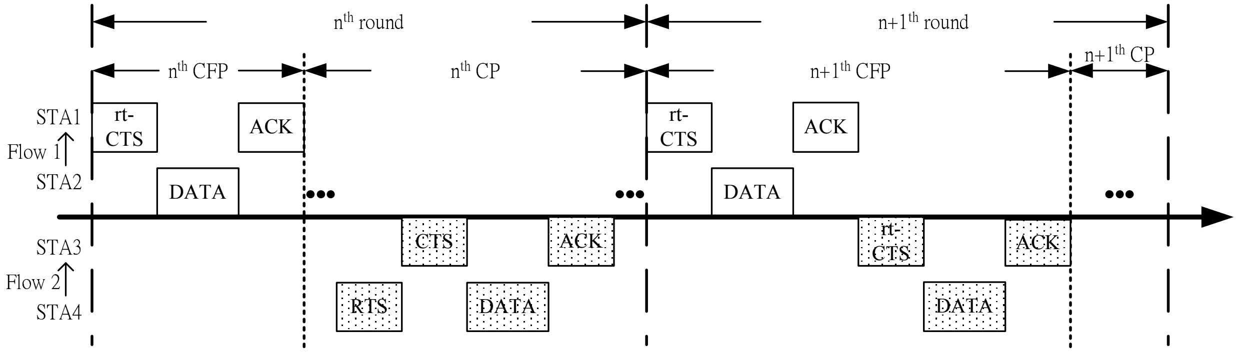


Figure 2.7: Time slots for data transmission [5].

In the observe stage, which is the first stage in the cognitive cycle, the neighbour list is created. This list consist of three tables: the primary user information table (PIT), the reservation information table (RIT), and the contention information table (CIT). In the PIT, information about the PUs' location, duration of activity, and length of transmission, is stored. In the RIT, information about the delay sensitive traffic is recorded. This information includes length of delay sensitive transmissions, location of the source, and transmission sequence. Finally, information about non delay sensitive (NDS) traffic, such as the location of the source of non real time (NRT) traffic, the frame transmission time of NDS data, and the number of users that transmit NDS data, is included in the CIT.

The following stage in the cognitive cycle is the plan stage. In this stage the protocol is focused on avoiding interference with the primary users' activities, providing priority access to real time traffic, and promoting fairness among SUs with NRT traffic. Avoiding interference with PUs' activities is achieved by using a gating mechanism, while giving real time traffic the priority to access the available channel(s) is performed by utilizing a linear backoff algorithm. Finally, fairness among SUs with NRT traffic is established by using a stall avoidance scheme. The gating mechanism, the linear backoff algorithm, and the stall avoidance scheme are described briefly in the following paragraphs [5].

The gating mechanism checks for PUs' activities when an SU wants to transmit. If a PU is detected, the SU is denied access to the channel. However, if all PUs are idle, the SU is allowed to transmit using p-persistent CSMA, where p is the optimal transmission probability.

The main purpose of the linear backoff algorithm is to ensure that delay sensitive traffic has access to a channel in a timely fashion. Instead of increasing the size of the contention window (CW) exponentially, as usually done in CSMA, the protocol uses the following equation:

$$CW_{rt} = minimum(CW_{max}, CW_{min} \times (A - 1)) \tag{2.1}$$

where CW_{rt} is the contention window for real time traffic, A is the number of request transmission attempts in the network, CW_{max} is the maximum contention window size, and CW_{min} is the minimum contention window size.

Thus, delay sensitive traffic has a priority over NDS traffic. Finally, the stall avoidance scheme reduces the transmission delay among NRT traffic by reducing the overall transmission delay variance and, subsequently, reducing the CW for NRT traffic. Note that only transmission delay for NRT traffic is considered when calculating the variance.

In the decision stage of the cognitive cycle, the protocol reserves the available channel for delay sensitive traffic. This is done by the destination (receiver) of the real time traffic. Once the destination receives an RTS, it responds with an rt-CTS (real time clear-to-send) to the source, after which the first frame of the delay sensitive traffic can be transmitted. In addition, the reservation is made for the rest of the message (remaining frames) to be transmitted. This reservation forbids any other user from using the channel(s) for the duration of the delay sensitive message. As seen in Figure 2.7, station 4 sends an RTS to station 3 in the CP period of round n and, once the communication is established, the first frame is transmitted in the same round. However, from round $n+1$, the rest of the frames of the delay sensitive message, from Station 4 to station 3, are transmitted in the CFP period.

Finally in the act stage, the users in the CRN are synchronized with respect to the frame transmission time. This is done by using the control signals of the delay sensitive traffic to indicate the start of the CFP and the CP in each round.

2.5 QoS for Voice CRNs

A MAC protocol that provides QoS support for voice communications in CRN is proposed in [6]. This protocol is one of the earliest protocols that tackle the issue of QoS support for voice services in CRNs. It is designed for distributed networks, utilizing the vacant channel of a primary wireless local area network (WLAN).

The primary network is assumed to have a single channel, which is shared by all primary users. Time is slotted, and a PU accesses each timeslot with a certain probability. Thus, at the beginning of each timeslot, all SUs sense the channel and, if it is not used by any of the PUs, one of the SUs transmits a packet.

Furthermore, all PUs in the system are not voice users, while the SUs are. Although SUs are voice users, they do not follow the ON/OFF model, but have a constant packet arrival rate. Each of the SUs packets has a delay bound, after which the packet is dropped if not transmitted.

Two MAC schemes are proposed in [6]. One is a contention based, and the other is contention free. Both of the schemes utilize the timeslot shown in Figure 2.8. As shown, the timeslot is divided into four durations: sensing, contention, transmission, and acknowledgement. In the sensing duration, all SUs listen to the channel to determine whether or not it is being utilized by a PU. If the channel is idle, one of the SUs utilizes the channel, and finally an acknowledgement is transmitted to the source to ensure successful transmission of the packet.

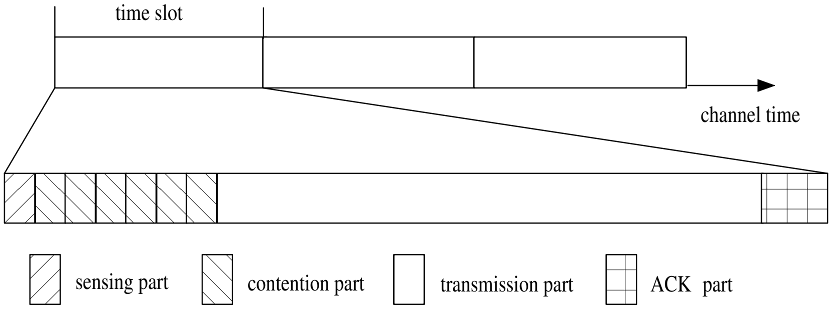


Figure 2.8: A timeslot for voice CRN [6].

The proposed schemes, contention based and contention free, differ in the manner of utilizing the contention part of the timeslot which is made up of mini-slots. In the contention based approach, each of the SUs randomly chooses a backoff duration. This backoff duration is a multiple of mini-slots. At the beginning of each timeslot, all SUs that have a packet to transmit sense the activities of the PUs in the sensing duration. If the channel is free, according to its respective backoff duration, each SU waits for its mini-slot and transmits its packet. Thus, the user with the smallest backoff duration will transmit first.

On the other hand, in the contention free approach, the indexes representing the mini-slots are rotated among the SUs in a round robin manner. At the time it joins the network, each SU is allocated a mini-slot in a deterministic order. After each time slot, the mini-slot indexes are rotated among the users; thus, the user with the highest mini-slot index in the current timeslot will have the lowest mini-slot index in the next timeslot. Regarding the channel access, similar to the contention based scheme, all SUs listen for the activities of the PUs and, if the channel is idle, the SU with the lowest mini-slot index and a packet to transmit will have access to the channel.

Although this protocol manages to guarantee a level of QoS to voice users, fairness among the SUs in the network cannot be guaranteed. The main reason behind the lack of fairness is the systematic round robin fashion used to share the mini-slot indexes among the users. For instance, consider that user A has a packet to transmit in the current time slot, t_n, while user B and user C do not have any packets waiting for transmission. Assume user A has the lowest index among the three users, followed by user B, then user C. Thus, if the channel is idle during timeslot t_n, user A will be able to transmit the queued packet. However, if the channel is busy during timeslot t_n and idle during timeslot t_{n+1}, then user A will have to wait for timeslot t_{n+1}.

Now, consider mini-slot t_{n+1}. user B and user C have packets waiting for transmission at the beginning of timeslot t_{n+1}. Recall that the mini-slot index is rotated after each timeslot; thus, user A does not have the lowest mini-slot index during timeslot t_{n+1}. In fact, user C has the lowest mini-slot index followed by user A and then user B. As a result, even though user A's packet arrived before user C's packet, user C has priority to access the idle channel. This may result in variance of packet dropping rate among SUs.

Note that this protocol is used in the performance evaluation of our proposed MAC protocol for distributed CRNs. In our comparison, in Chapter 5, we refer to this protocol as Distributed MAC II.

2.6 Summary

In this chapter, we presented five MAC protocols designed for CRNs that are related to our research. First, a CSMA based MAC protocol for centralized CRNs is discussed in Section 2.1. This protocol allows simultaneous transmissions in the primary and the secondary networks by adjusting the transmission rate and power in each network. However, QoS support for SUs is not addressed.

For distributed CRNs, C-MAC, SYN-MAC, CR MAC with QoS provisioning, and QoS for voice CRNs are the four MAC protocols discussed in Sections 2.2, 2.3, 2.4, and 2.5 respectively. C-MAC and SYN-MAC do not provide any form of QoS, while CR MAC with QoS provisioning is designed to provide a level of QoS for delay sensitive application with predetermined length. Finally, QoS for voice CRN successfully provides SUs with a level of QoS suitable for voice communications. However, fairness among the SUs is not maintained.

To overcome the shortcomings of the protocols discussed in this chapter, we propose three MAC protocols that guarantee a level of QoS for voice communications over CRNs and maintain fairness among SUs. The system model for the proposed MAC protocols is presented in Chapter 3. In Section 4.1, two MAC protocols are proposed for centralized CRNs, while a MAC protocol for distributed CRNs is presented in Section 4.2.

Chapter 3

System Model

In this chapter we present our system model. The structure of the network utilized by the primary and secondary users is discussed in Section 3.1. The voice traffic model is introduced in Section 3.2, and the QoS requirements are presented in Section 3.3. Finally the research objectives, along with the hypothesis for the proposed MAC protocols are presented in Section 3.4.

3.1 Network Structure

In our system model, we consider a single-cell primary system that utilizes time division multiple access (TDMA) in its operation. Time is divided into frames and each frame is divided into timeslots. Each of these timeslots is assigned to a primary user. Note that the number of timeslots in a frame depends on the capacity of the primary system, C. Figure 3.1 shows a time frame for a primary system with capacity of 5 PUs.

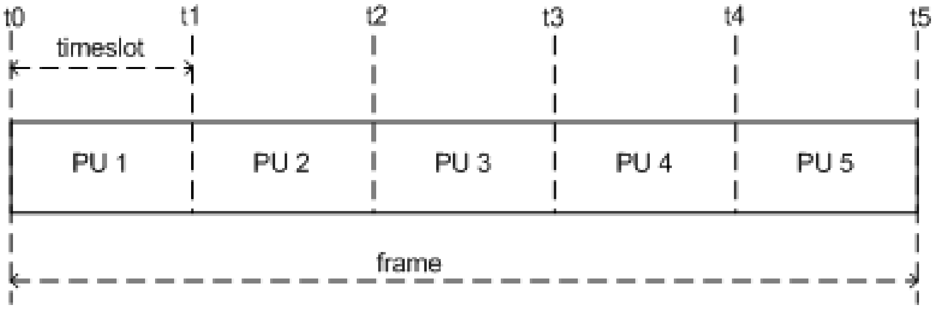


Figure 3.1: One frame duration for a primary system with $C = 5$.

The secondary system utilizes the leftover spectrum of the primary system. If during a certain frame, one of the PUs does not have a packet to transmit, its idle timeslot is used by one of the SUs to transmit a packet. In addition, for simplicity we assume that if a PU is idle for a given frame its assigned timeslot will be free for the duration of the said frame.

A user, either primary or secondary, transmits only one packet per frame, and each user has its own queue with a buffer size equal to the packet delay bound, discussed in Section 3.3. If a PU has a packet to transmit, the PU waits for its assigned timeslot and transmits its packet. However, if an SU has a packet to transmit, the packet is queued until the SU is granted access to the channel.

Finally, we assume that the functionality of the physical layer is ideal, i.e. if a channel is sensed idle, it is indeed idle. In addition, we assume that the channel is error free and, thus, if a user is granted sole access to a timeslot, its packets are transmitted successfully. In addition, we assume routing of the packets is ideal as well and, hence, we are not concerned with establishing a link between the source and the destination before transmission.

3.2 Voice Traffic Model

A voice source typically alternates between active and silent periods. During the active period (ON state) the source generates packets at a constant rate, while in the silent period (OFF state) the source is idle. It has been found that the time spent by a voice source in one of the periods can be represented by an exponential distribution [25], given in equation (3.1).

$$f(x;\lambda) = \begin{cases} \lambda e^{-\lambda x} & \text{if } x \geq 0 \\ 0 & \text{if } x < 0 \end{cases} \tag{3.1}$$

where λ is a rate parameter of the exponential distribution. Note that the exponential distribution approximation is more accurate for the time spent by the user in the ON state; however, for simplicity of analysis, the OFF state is represented by the exponential distribution as well [25].

In our model, both primary users and secondary users, are voice users. Hence, all users follow an ON/OFF model shown in Figure 3.2. The time spent by a user in ON state, t_{ON}, is exponentially distributed with parameter λ, while the time spent by the user in the OFF state, t_{OFF}, is exponentially distributed with parameter μ. Another representation of the random variables t_{ON} and t_{OFF} is shown in equation (3.2).

$$\begin{aligned} t_{ON} &\backsim \exp(\lambda) \\ t_{OFF} &\backsim \exp(\mu) \end{aligned} \tag{3.2}$$

where λ is the rate parameter of ON state, μ is the rate parameter of OFF state, and exp(..) denotes the exponential distribution shown in equation (3.1).

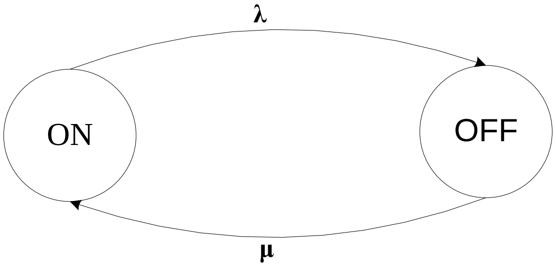


Figure 3.2: The ON/OFF exponential model.

Furthermore, the average time a user spends in a talk spurt, T_{ON}, is $\frac{1}{\lambda}$, while the average time a user spends in a silent state, T_{OFF}, is $\frac{1}{\mu}$. We define the active probability, P_{ON}, as the ratio of the time spent in the ON state to the total time of the conversation. Similarly, the inactive probability, P_{OFF}, is defined as the ratio of the time spent by the user in the OFF state to the total time of the conversation. Thus, from Figure 3.2 we can derive a relation between P_{ON} and the parameters of the ON/OFF model, given by equations (3.3) and (3.4).

$$P_{OFF} = \frac{\lambda}{\mu} P_{ON} \tag{3.3}$$

$$P_{ON} = \frac{T_{ON}}{T_{ON} + T_{OFF}} \tag{3.4}$$

Generally, it is assumed that a voice source is active only forty percent of time, i.e. $P_{ON} = 0.4$. Thus, a voice user spends more time in the OFF state than in the ON state. Once a user is in an ON state, packets are generated at a constant rate of $V \frac{packets}{frame}$. For simplicity, we assume that V=1, which means that if a user is on, in the next frame only one packet will be generated.

3.3 QoS Requirements for Voice Communications

In voice packet communications, a packet has to be transmitted from the source to the destination within a certain time limit, otherwise the packet is dropped. This time limit is known as the delay bound, m frames. The delay bound can be defined in various manners; for instance, a bound on the end to end transmission delay could be considered. However, in our model, we consider the single hop delay bound; in other words, the delay bound in our system is defined as the maximum duration that a packet can be queued for, from its generation upto its transmission.

Another requirement for voice packet transmission is the acceptable packet dropping rate, P_D. This bound indicates the percentage of packets that a voice source can drop without affecting the quality of the call. Normally, P_D for voice communications is usually set to one percent of the total number of packets generated.

3.4 The proposed MAC Protocols

Because of the ON/OFF nature of voice users, the spectrum of the primary system may not be fully utilized. Thus, a certain number of SUs can transmit their packets in the empty portion of each frame. Our objective is to design a packet scheduling scheme that provides a level of QoS to SUs, along with maintaining fairness among users in the CRN.

If SUs packets are transmitted on a first come first serve (FCFS) basis, one of the SUs may endure more packet loss than the average packet loss of the system, because of the randomness of the availability of a free time slot. Thus, some SUs may suffer more packet loss than they ought to. On the other hand, if SUs are ordered according to a certain parameter, such as packet dropping rate, this will guarantee that all SUs in the system will share the loss among themselves, and the variation in packet dropping rate among different SUs in the FCFS protocol will not exist. Note that the MAC protocol based on the FCFS concept will be referred to as Centralized MAC III, in Chapter 5

Only using one parameter to prioritize SUs will not guarantee absolute fairness among users. For instance, if two SUs have the same packet dropping rate and one of them has more packets queued, and if SUs are ordered only according to the packet dropping rate, there is no guarantee that the user with more packets queued will transmit first. This may result in an unfair distribution of loss among all the SUs in the system as well.

The main hypothesis on which we base our MAC protocols is that, if the loss is equally shared among the SUs in the system, QoS to more SUs can be guaranteed. In addition, a level of fairness among SUs in the CRN will be achieved. Thus, in an attempt to solve the problem of fairness and QoS support among SUs, we propose MAC protocols that ordered SUs according to their current packet dropping rate and, then, according to the number of packets queued waiting for transmission.

After discussing the various requirements to support QoS and to maintain fairness among all SUs, we propose three MAC protocols which ensure that all SUs in a CRN will fairly share the available resources and achieve a level of QoS suitable for voice communications. For centralized CRNs, two MAC protocols, that satisfy our research objectives, are presented in Section 4.1, while in Section 4.2, we propose a MAC protocol for a distributed CRN, that promotes fairness among SUs and guarantees a level of QoS suitable for voice communications.

Chapter 4

Proposed MAC Protocols

Three MAC protocols are presented in this chapter. For the three protocols, we assume that there exists a call admission control (CAC) mechanism which maintains enough resources to guarantee QoS for SUs. In Section 4.1, the structure of a centralized CRN, along with two MAC protocols that provide QoS suitable for voice packet transmission over centralized CRNs are presented. Moreover, in Section 4.2, we discuss the architecture of a distributed CRN and propose a MAC protocol suitable for voice communications over distributed CRNs.

4.1 MAC Protocols for Centralized CRNs

For centralized CRNs, the secondary system has a central unit (CU) that manages the activities of all SUs in the system. In addition, this central unit is aware of the activities of the PUs. Thus, at the beginning of each frame, the CU is aware whether or not a certain PU will use its allocated timeslot in the next frame and, hence, individual sensing by each SU is not required to determine the condition of the channel.

In Subsection 4.1.1 we present a MAC protocol that maintains fairness among all SUs in the CRN, and guarantees the level of QoS required for voice communications. Furthermore, a variation of the protocol, suitable for wireless networks that consists of various classes of users, is presented in Subsection 4.1.2.

4.1.1 Centralized MAC I

Centralized MAC I is designed for centralized CRNs that utilize the empty spectrum of a primary system. Each of the primary and the secondary systems has its own CU responsible for its users. Ignoring the functionality of the primary system, we present the structure of Centralized MAC I in the following:
"***Each SU has its own queue. At the beginning of each frame, SUs will be ordered according to their actual packet dropping rate and, then, according to the number of packets queued waiting for transmission. According to this order, SUs will have access to the idle timeslots in each frame***".

Following is the high level design of Centralized MAC I, for the n^{th} time frame f_n:

- Beginning of frame f_n
    1. Determine if a new packet will be generated for each SU;
    2. Order SUs according to their current packet dropping rate;

3. Order SUs with same packet dropping rate according to the number of packets queued for transmission;
4. Identify idle timeslots by determining whether or not the respective PUs have a packet to transmit;
5. Allocate idle timeslots to the top secondary users with packets to transmit;
    - top SUs transmit their packets successfully;
6. Determine if SUs packets has been queued beyond the delay bound;
    - if yes, drop packets;
7. Update SUs status;

- End of frame f_n.

To further elaborate on our protocol, we discuss the following scenario. For simplicity, assume that the capacity of the primary system is equal to 5 PUs. Since time is slotted into frames and each frame is made up of timeslots assigned to the PUs, one frame constitutes 5 timeslots, as shown in Figure 3.1. On the other hand, assume we have 2 SUs, namely SU A and SU B, trying to transmit voice packets when the frame is not fully utilized.

Thus, for the next frame, f_n, we have one of the following three cases:
Case I : SU A has a higher packet dropping rate than SU B. In this situation, SU A will transmit before SU B, even if SU B has more packets queued than SU A. Thus:

- SU A will transmit a packet in f_n if there is at least one idle timeslot in f_n;
- SU B will transmit a packet in f_n if and only if there are at least two idle timeslots in f_n.

Case II : Both SU A and SU B have the same packet dropping rate, but SU B has more packets queued for transmission than SU A. Thus, SU B will have priority to access the next available timeslot, and we have the following:

- SU B will transmit a packet in f_n if there is at least one available timeslot in the next frame;
- SU A will transmit a packet in f_n if and only if there are at least two idle timeslots in f_n.

Case III : Both SU A and SU B have the same packet dropping rate, and both users have the same number of packets queued for transmission. In this case, one of the users will be selected randomly, to transmit in the next idle timeslot in f_n if there is one free timeslot in the frame. However, after the selected user transmits its packet, the other user gets priority in the following frame.

A flowchart that demonstrates the functionality of the Centralized MAC I protocol is presented in Figure 4.1.

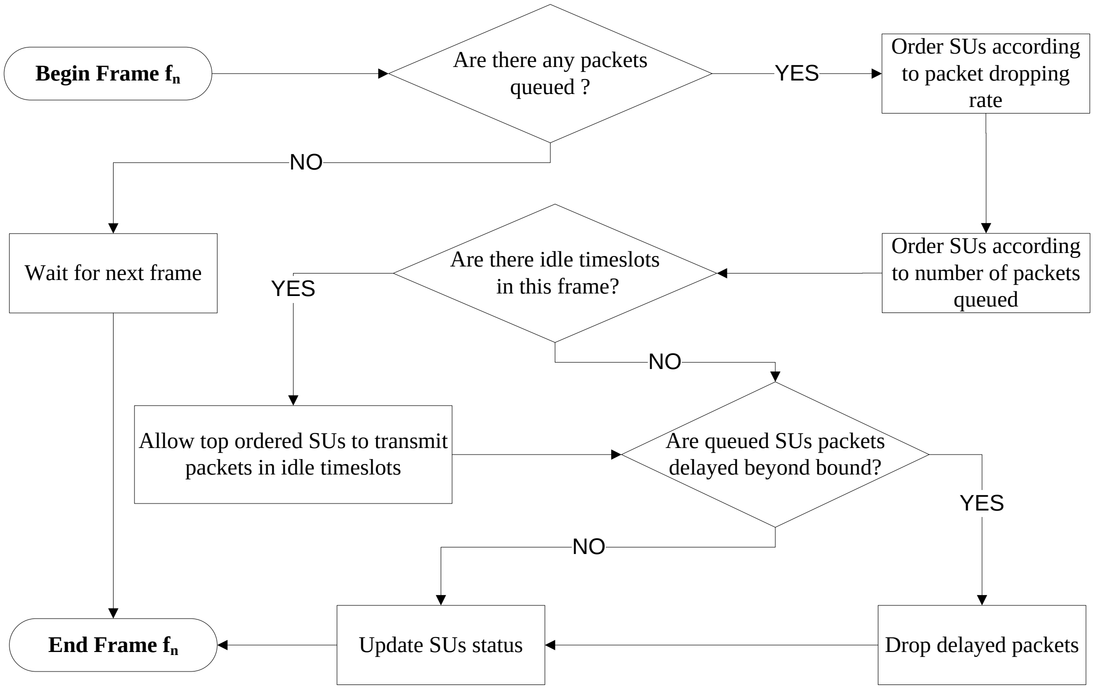


Figure 4.1: Flowchart of the Centralized MAC I protocol.

4.1.2 Centralized MAC II

This protocol requires a single CU for both primary and secondary systems. In other words, PUs and SUs are considered as users of the same network but with different priority classes. Even though PUs have priority over SUs, a PU's packet is not transmitted as soon as it is generated. As long as the PU's packet is within the delay bound, the respective PU is ordered with the SUs. However, if a PU and an SU endure the same packet dropping rate and have the same number of packets queued for transmission, the PU will be granted access to the channel before the SU.

Following is the structure of Centralized MAC II:

“***Each user has its own queue. At the beginning of each frame, all users will be ordered according to their actual packet dropping rate and, then, according to the number of packets queued waiting for transmission and, finally, according to each user’s class. According to this order, users will have access to the idle timeslots in each frame***”.

Following is the high level design for Centralized MAC II, for the next frame f_n:

- Beginning of frame f_n
  1. Determine if a new packet will be generated for each user in the system, PUs and SUs;
  2. Order users according to their current packet dropping rate;
  3. Order users with equal packet dropping rate according to the number of packets queued for transmission;
  4. Order users with equal packet dropping rate and number of packets queued according to class, first PUs then SUs;
  5. Allocate the timeslots to the top users with packets to transmit,
     - top users transmit their packets successfully
  6. Determine if any packet has been queued beyond the delay bound;
     - if yes, drop packets
  7. Update users’ status;
- End of frame f_n

A flowchart that illustrates the functionality of Centralized MAC II is presented in Figure 4.2.

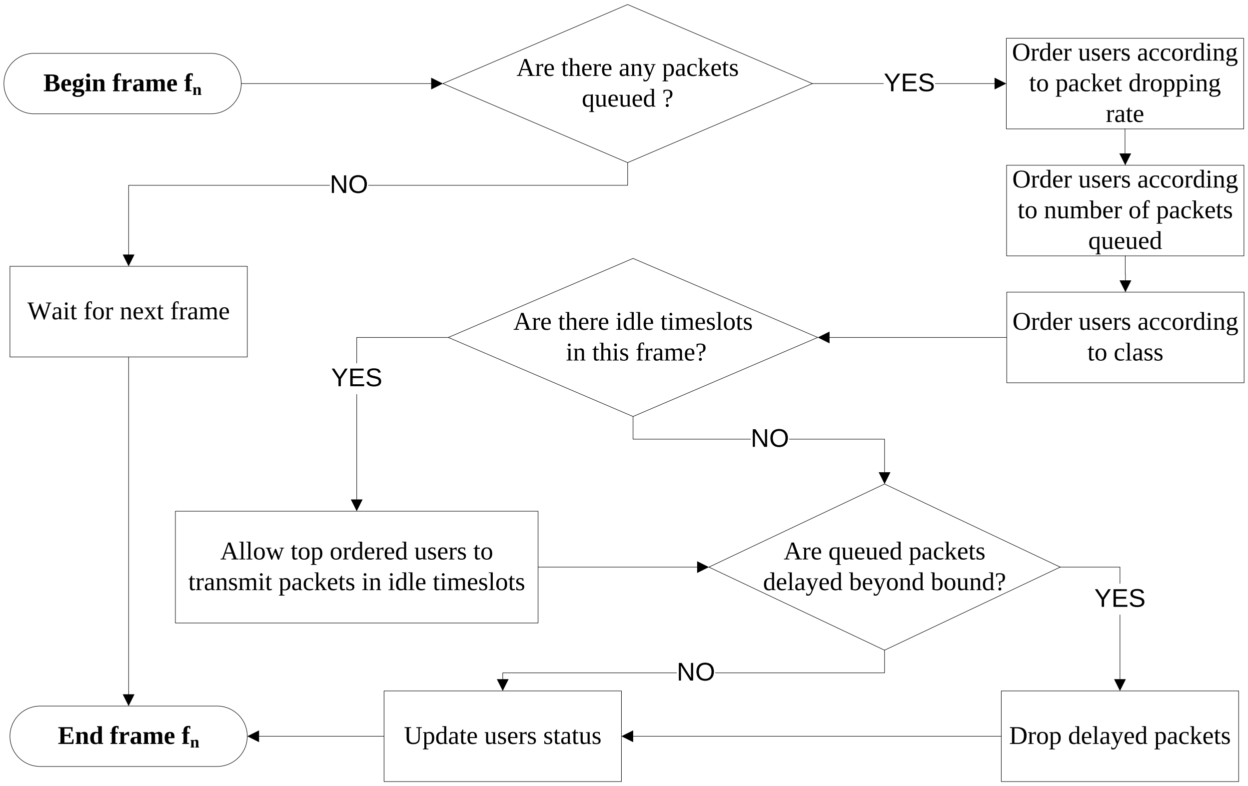


Figure 4.2: Flowchart of the Centralized CRN II protocol.

4.2 MAC Protocol for Distributed CRNs

The major difference between centralized CRNs and distributed CRNs is the absence of a central unit in distributed CRNs. The central unit manages the SUs' requests and allocates channel resources to avoid collisions among SUs. Thus, we need to introduce a property, to the protocol proposed in Section 4.1.1, that allows SUs to access idle timeslots without either colliding with each other or with the PUs.

To organize channel access among SUs, we propose utilizing the concept of backoff durations. To facilitate that, we introduce a sensing period at the beginning of each timeslot, as shown in Figure 4.3. PUs have pre-assigned timeslots during which they transmit their packets. A PU with a packet to transmit is not required to sense the channel. It waits for its timeslot, and transmit its packet right away, i.e. all PUs' backoff duration is zero. On the other hand, SUs are only allowed to transmit in an idle timeslot. Thus, an SU that wants to transmit a packet has to listen to each timeslot for a certain duration; if the timeslot remains idle after that duration, the SU transmits its packet.

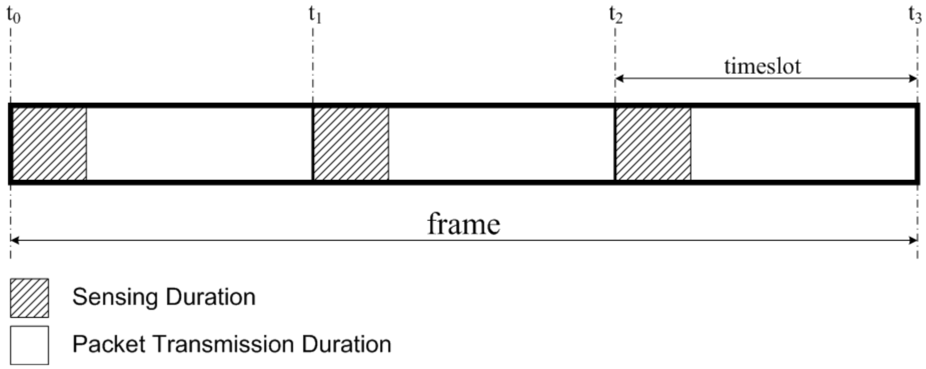


Figure 4.3: One frame duration for a distributed CRN, for a primary system with $C = 3$.

Since SUs are ordered according to the packet dropping rate followed by the number of packets queued, we propose that each user calculates its backoff duration, taking into consideration the ordering criteria. Before introducing the equation that each SU will use to calculate its backoff duration, we define B as the backoff duration, P_d as the actual packet dropping rate, and Q as the number of packets queued waiting for transmission.

The two main criteria on which access to idle timeslots is granted to SUs are P_d

and Q. Thus, while calculating the backoff durations, each of the SUs has to take into consideration its values of P_d and Q. In addition, an SU with a high P_d should have access to an idle timelsot before an SU with a low P_d, even if the latter have a higher value of Q. Thus, the weight of P_d should be higher than the weight of Q in the calculation of the backoff duration. Following is the equation used by each SU to determine its backoff duration:

$$\frac{1}{B} = (10^{j+4} \times P_d) + (10^j \times Q) + (10^j \times I) \tag{4.1}$$

where I is a random variable uniformly distributed in [0,1], and j is one plus the order of m.

Thus, the SU with the smallest B will have priority to transmit a packet in the next available timeslot. In addition, because of the random variable used, collision among SUs, with equal values of P_d and P_q, is avoided. Table 4.1 shows examples of B value for secondary users with various values of P_d, Q, and I.

SU	P_d	Q	I	B
A	0	1	0.542	$\frac{1}{154.2} = 0.006485$
B	0	2	0.127	$\frac{1}{212.7} = 0.004701$
C	0.005	2	0.632	$\frac{1}{5263.2} = 0.00019$
D	0.007	1	0.097	$\frac{1}{7109.7} = 0.000141$
E	0.005	2	0.278	$\frac{1}{5227.8} = 0.000191$

Table 4.1: Examples of B value for various SUs, with $m = 2$ frames.

However, as shown in Table 4.1, because of the small differences among the B values, implementation constrains may arise. One solution to this problem is achieved by allowing SUs to transmit their respective Bs in the first idle timeslot in each frame. In this manner, all SUs in the CRN will be aware of each others requirements and organize access to the remaining idle timelsots in the frame using this information. However, a concern about the required signal processing to achieve such procedure may prove the solution impractical.

To overcome the problem of small time differences among the B values, we propose to discretize the sensing duration into mini-slots as shown in Figure 4.4. In addition, each SU can map its B value to a mini-slot identification number, ID, to reduce collision. As an example, the mapping can be done according to the following equation. Note that, equation (4.2) distinguishes between SUs with $P_d = 0$ (i.e., no packet dropping) and SUs with $P_d > 0$ (i.e., with packet dropping). This improves the ordering mechanism and ensures that SUs with a larger P_d value transmit before SUs with a smaller P_d value.

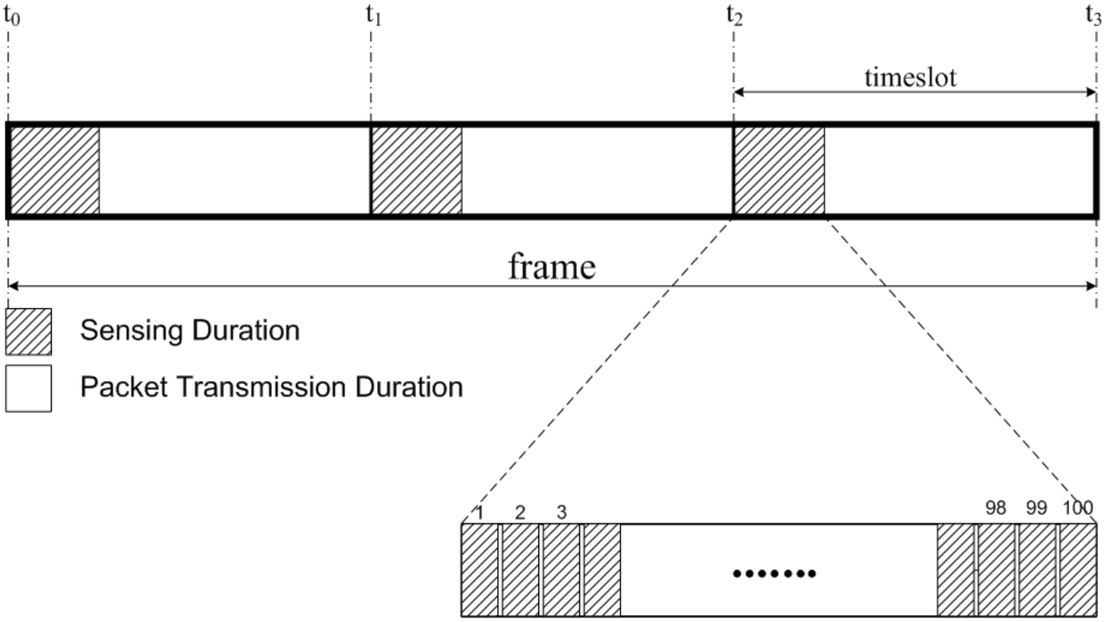


Figure 4.4: Sensing Duration mini-slots.

$$ID = \begin{cases} round(B \times 10^4) & \text{if } P_d = 0 \\ round(B \times 10^5)\text{+X} & \text{if } P_d > 0 \end{cases} \qquad (4.2)$$

where X is an integer random variable taking on a value randomly over the interval [0,9].

SU	B	X	ID
A	64.851×10^{-4}	–	65
B	47.014×10^{-4}	–	47
C	19.000×10^{-5}	2	21
D	14.065×10^{-5}	5	19
E	19.129×10^{-5}	7	26

Table 4.2: IDs for different SUs, with $m = 2$ frames.

Table 4.2 shows the resulting IDs, corresponding to the SUs presented in Table 4.1. Note that a disadvantage of discretizing the sensing duration is the possibility of collision. The value of B, calculated by equation (4.1), is in continuous time and, thus, unique. However, after mapping B to ID, two or more SUs can end up using the same mini-slot. To deal with this issue, once a collision is detected, all SUs recalculate B and ID. After introducing the access mechanism used to organize SUs in distributed CRNs, we introduce our proposed protocol for distributed CRNs in next section.

4.2.1 Distributed MAC I

Following is the high level design for the Distributed MAC I protocol, for an SU active in frame f_n:

- Beginning of frame f_n

1. Determine if a new packet will be generated;
2. Calculate the backoff duration B using equation (4.1);
3. Map the backoff duration B to an ID using equation (4.2);
4. Listen to channel from beginning of timeslot to corresponding mini-slot ID;
    - If channel is idle, transmit packet.
        - ∗ If collision occurs recalculate B and ID and wait for next timeslot
    - If channel is busy, wait for next timeslot
5. Determine if any packet has been queued beyond the delay bound;
    - if yes, drop packets
6. Update status

- End of frame f_n

To further demonstrate the functionality of the protocol, we shall study the same scenarios discussed for the centralized MAC protocol. For simplicity of discussion, we assume that only two of the SUs, mentioned in Table 4.2, are trying to utilize the leftover spectrum at a time. Thus, for the next frame f_n, and using data from Table 4.2, we have one of the following three cases.

Case I: SU C and SU D are the SUs active in the network, and SU D has a higher P_d than SU C. Thus, SU D will have to listen to the channel for a shorter duration than SU C, even though SU C has more packets queued for transmission than SU D. Thus:

- SU D will transmit a packet in f_n, if there is at least one idle timeslot in f_n;

- SU C will transmit a packet in f_n, if and only if there are at least two idle timeslots in f_n.

<u>Case II:</u> SU A and SU B are the SUs active in the network, and SU A and SU B have the same P_d; however, SU B has 2 packets waiting for transmission, while SU A has only 1. Therefore, from equation (4.1), SU B will have a shorter backoff duration than SU A and thus:

- SU B will transmit a packet in f_n, if there is at least one idle timeslot in f_n;
- SU A will transmit a packet in f_n, if and only if there are at least two idle timeslots in f_n.

<u>Case III:</u> SU C and SU E are the SUs active in the network, and both SUs have the same P_d and P_q; the random integer X helps to differentiate between the values of the SUs' respective ID. SU C has a lower ID because its corresponding X is 2 while SU E's X is 7. Therefore, SU C will transmit its packet first. However, after SU C transmits one packet, SU E's P_q will be greater than SU C's P_q and, thus, SU E will have priority to access the next idle timeslot.

A flow chart that demonstrates the functionality of the Distributed MAC I protocol is presented in Figure 4.5. Note that using equations (4.1) and (4.2) does not always guarantee that the SU with the lowest B transmits first. Occasionally, because of the random integer used to reduce collision, an SU with a higher B may transmit first; however, this happens rarely and, thus, this ordering mechanism should be effective.

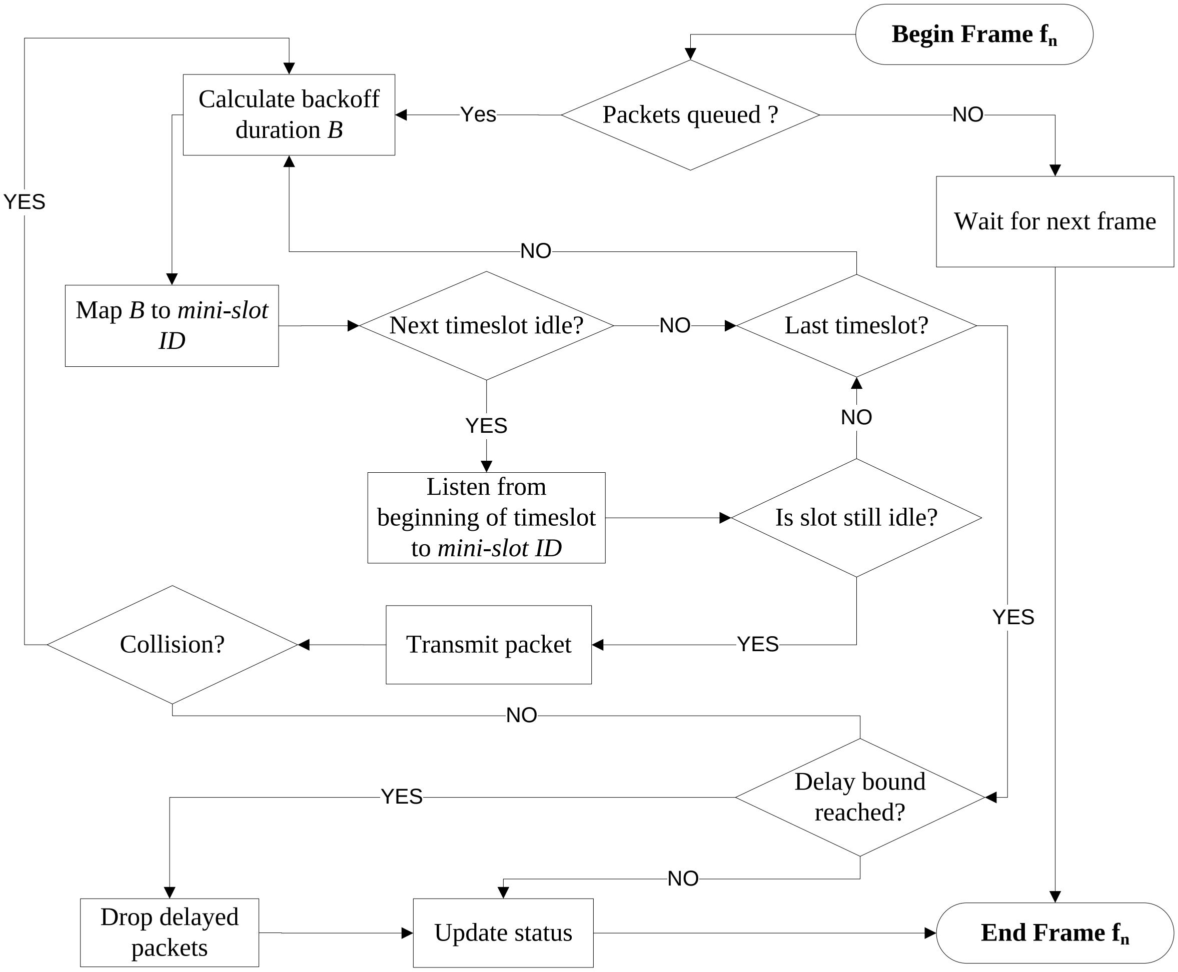


Figure 4.5: Flowchart of the Adhoc CRN I protocol.

4.3 Summary

In this chapter, we introduce three proposed MAC protocols to schedule SUs' packet transmission in CRNs. These protocols are designed to provide SUs with a level of QoS and maintain fairness among all the users in a CRN. The protocols are based on the concept of ordering SUs according to their current packet dropping rate and, then, according to the number of packets queued waiting for transmission.

In Section 4.1, two MAC protocols for centralized CRNs are introduced. The first of the MAC protocols, Centralized MAC I, adheres to the principles of CRs, where PUs always transmit first and SUs only transmit in a timeslot that is not being used by a PU.

However, Centralized MAC II, ignores the principles of CRs. This protocol should prove beneficial in a network that have two classes of services, both of which require the same level of QoS. In this protocol, PUs and SUs are treated as two classes of users with the same rights to access the link, but with two different priorities.

Finally, in Section 4.2, we propose a MAC protocol for distributed CRNs. Basically, a feature that allows SUs to organize themselves without the need for a CU, is added to the protocol for centralized CRNs to adapt it for distributed networks. In the next chapter, we evaluate the performance of our proposed protocols and compare their efficiency with other protocols that provide a measure of QoS for CRNs.

Chapter 5

Performance Evaluation

In this chapter, we compare our proposed protocols with other existing MAC protocols that support QoS for CRNs. Simulation based evaluation is used to study the performance of the proposed protocols. In Section 5.1, we discuss how the simulation is performed. In Section 5.2, we present the simulation results for the proposed MAC protocols for centralized CRNs and compare their performance with a MAC protocol that transmits SUs packets on a first come first serve basis. Finally, in Section 5.3, we present the simulation results for our MAC protocol designed for distributed CRNs and compare its performance with the protocol proposed in [6].

In our simulation, we consider a primary system with C equal 30 PUs. Thus, each frame is divided into 30 timeslots, and each timeslot is pre-assigned to one of the primary users. Note that each protocol is simulated for hundred thousand frames (i.e. voice call duration, L, is equal to 10^5 frames) and the results, presented in this chapter, are within a 95% confidence interval (CI). Finally, P_D is set to 1% for both PUs and SUs, which is reasonable for voice users [6].

5.1 Simulation Setup

MATLAB is chosen as the simulation environment for our evaluation. To simulate the alternating nature of a voice user, for each user we generate a set of samples for an exponentially distributed random variable to mimic the behaviour of a voice traffic flow. Details on how that is done is presented in Subsection 5.1.1. Furthermore, in Subsection 5.1.2, we discuss how the MAC protocols are implemented in MATLAB. Finally, we discuss how we calculated the confidence interval for our results in Subsection 5.1.3.

5.1.1 Generation of Exponential Random Variables

To generate a set of on and off durations that represent the behaviour of a voice source, we started by creating a set of users. For each user, we choose a value randomly from 0 to 1. If the value is less than or equal P_{ON}, the user starts in the ON state; otherwise, the user starts in the OFF state.

Once the starting state of the user is determined, we generate an exponential random variable, γ, using the parameter corresponding to the state. If the user starts in the ON state, $\gamma = t_{ON}$, while if the user starts in the OFF state, $\gamma = t_{OFF}$. Note that t_{ON} and t_{OFF} are defined in equation (3.2). In addition, voice traffic flows of all users in the network have the same parameters, i.e. the time spent by all users in the ON(OFF) state is exponentially distributed with parameter $\lambda(\mu)$.

Note that γ is a real number and it is used to represent the number of consecutive frames the user spends in a state, i.e. a user spends γ frames in a certain state. However, for our simulation we want the representative of the number of consecutive frames a user spends in a state to be an integer. Thus, we define the number of consecutive frames a user spends in a state as $\Gamma = \lceil \gamma \rceil$ frames. Finally, we alternate the parameter used to generate γ, between λ and μ, until the sum of the generated Γs in frames is at least equal to the voice call duration, L.

5.1.2 Implementation the MAC protocols

For each of our proposed protocols, we generated a MATLAB file that follows the procedure of the protocols discussed in Subsections 4.1.1, 4.1.2, and 4.2.1. Regarding the protocols used for comparison, we created a MATLAB file for each of the protocol discussed in Sections 3.4 (for centralized CRNs) and 2.5 (for distributed CRNs).

For fairness sake, we create a set of 150 users and generate samples of exponential random variables that mimic the behaviour of a voice user for each user. We store these samples in a $150 \times L$ matrix. This matrix is used when evaluating the performance of all protocols. In this manner, the performance of each protocol can be fairly compared.

Finally, to determine the number of SUs, N, admitted with guaranteed QoS by each protocol, we perform our simulation in rounds. We start the first round with N set to 1 and calculate the P_d for the user after running the simulation for a duration of L frames. If

P_d is less than P_D, in the following round, we increment the value of N by 1 and repeat the procedure of calculating P_d. This process is repeated until any of the SUs in the system has a P_d greater than P_D. Once the threshold of P_D is passed, i.e. one of the SUs' $P_d > P_D$, we set the N value to be that of the previous round.

5.1.3 Calculating the Confidence Interval

To calculate the confidence interval, we run the simulation several times. Each time, a unique sample of exponential random variables is generated for each user as discussed in Subsections 5.1.1 and 5.1.2. Using these sets of samples, we perform our simulation. The simulation results constitute of the number of SUs admitted by each protocol, N versus the number of PUs in the primary network.

The mean, θ, and the variance, σ^2, of the generated results are used to estimate the 95% confidence interval for the mean value of N (the number of SUs admitted by each protocol), Θ, using equation (5.1).

$$\Theta = \theta \pm \kappa\sigma \tag{5.1}$$

where κ is equal to 1.96 for a 95% confidence interval.

5.2 Centralized MAC Protocols

In this section, the performance of Centralized MAC I (presented in Subsection 4.1.1), Centralized MAC II (presented in Subsection 4.1.2), and Centralized MAC III (presented in Section 3.4) is studied.

There are three main parameters that affect the performance of a MAC protocol designed for voice users, namely P_{ON}, T_{ON}/T_{OFF}, and m. P_{ON} determines the percentage of time that a user is active, which affects the number of idle timeslots. T_{ON}/T_{OFF} is the ratio that determines, on average, how long a user spends in the ON state versus the OFF state. T_{ON} and T_{OFF} are inversely proportional to λ and μ respectively. Finally, m is the bound which determines whether or not a queued packet has to be dropped.

We begin our evaluation process by choosing a value for P_{ON}, T_{ON}/T_{OFF}, and m, to see the performance of the three protocols. After that, we vary the values of the three parameters to see the effect of each parameter on the performance of the protocols. Effects of varying P_{ON}, T_{ON}/T_{OFF}, and m are presented in Subsections 5.2.1, 5.2.2, and 5.2.3 respectively. Finally, in Section 5.2.4, we study the effect of P_D on the number of SUs admitted by each protocol.

Figure 5.1 shows the number of SUs that can be admitted to the system versus the number of PUs in the system, when $T_{ON}/T_{OFF} = 20/30$, $m = 1$ frame, and $P_{ON} = 0.4$. We notice that Centralized MAC II admits the highest number of SUs among the three protocols. However, Centralized MAC II requires both PUs and SUs to be controlled by the same CU. Furthermore, Centralized MAC I achieves considerably better results than Centralized MAC III, without the complexity associated with Centralized MAC II. Note that the results for the ideal casie is obtained with 100 % multiplexing, which corresponds to the case of no delay requirements in transmitting voice packets (i.e., the delay bound $m \to \infty$).

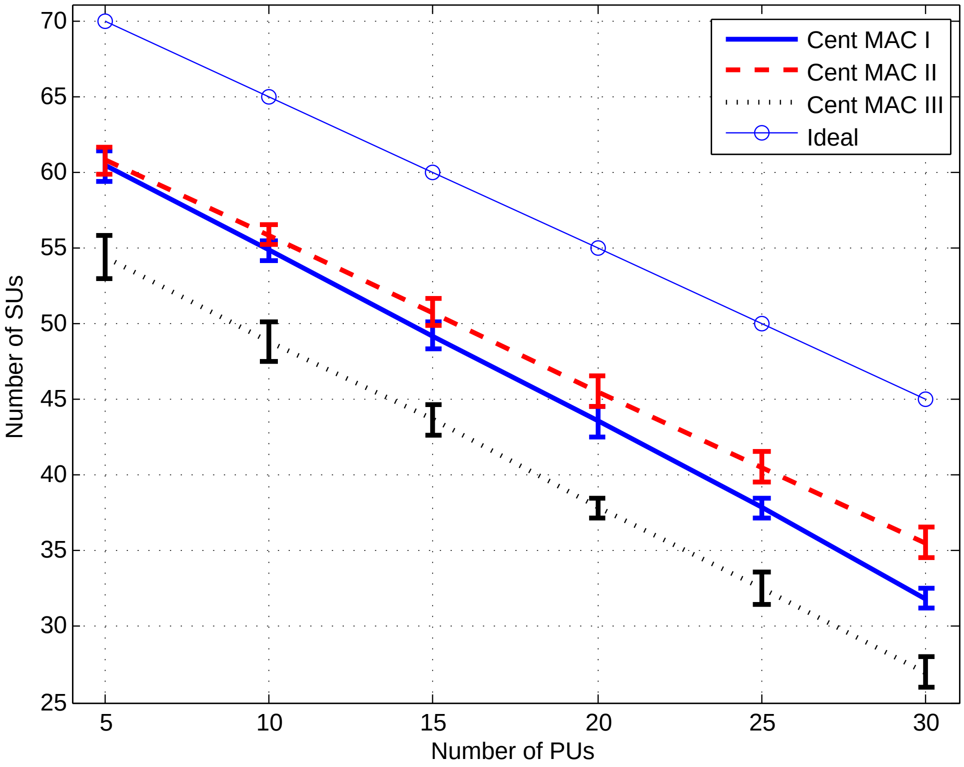


Figure 5.1: Centralized MAC: The maximum number of SUs versus the number of PUs for P_{ON}=0.4, T_{ON}/T_{OFF}=20/30, and m=1 frame.

5.2.1 Effect of P_{ON}

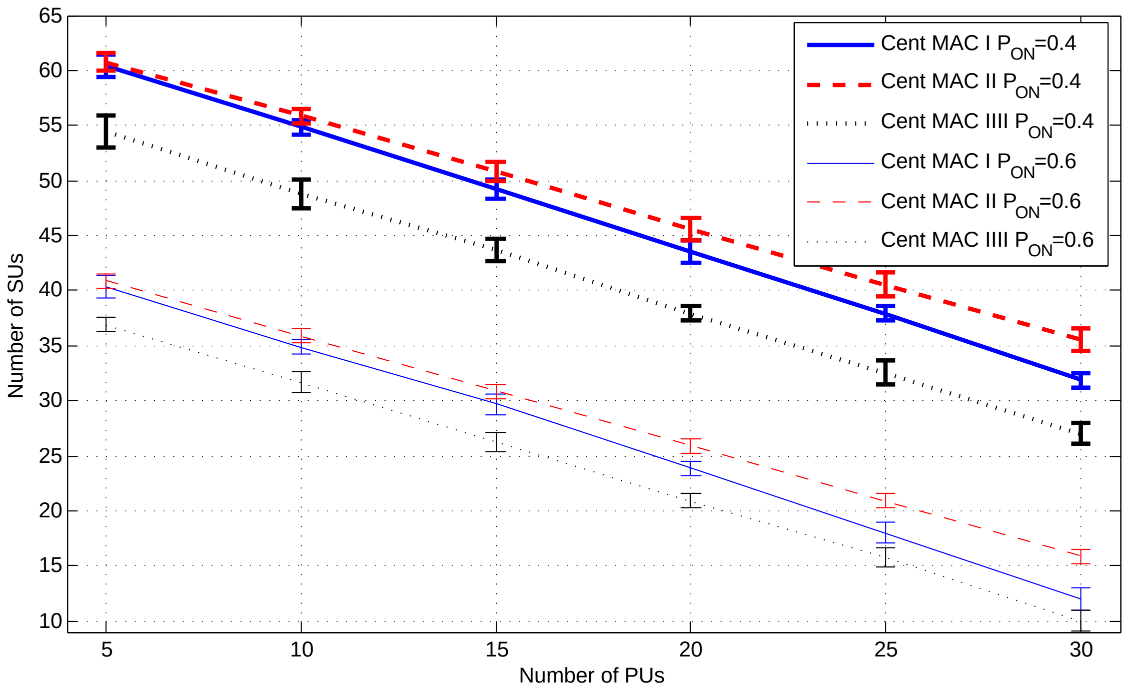


Figure 5.2: Effect of P_{ON} with centralized MAC (T_{ON}/T_{OFF}=20/30 for P_{ON}=0.4 and T_{ON}/T_{OFF}=30/20 for P_{ON}=0.6, and m=1 frame).

Figure 5.2 shows the effect of increasing the active probability P_{ON}. We notice that the higher the value of P_{ON}, the lower the number of SUs that can be admitted to the system. This result is expected because, as P_{ON} increases, PUs occupy more time of the channel, which results in a fewer idle timeslots available for SUs. In addition, SUs spend more time generating packet with a high P_{ON} and, therefore, the service requirements of a fewer SUs can be met as P_{ON} increases.

5.2.2 Effect of T_{ON}/T_{OFF} Ratio

To evaluate the effect of the T_{ON}/T_{OFF} ratio on the performance of the protocols, we vary the values of λ and μ, while maintaining the value of P_{ON} at 40%. In addition, we fix the value of m to 1 frame. Figure 5.3 shows the change in the numbers of SUs admitted by Centralized MAC I and Centralized MAC II as the T_{ON}/T_{OFF} ratio is varied from 2/3 to 200/300. We notice that, as the average time spent by the users in a certain state is reduced, the number of SUs admitted to the system is increased. This is because users switch faster between the ON state and OFF state,which results in better multiplexing among the voice traffic flows.

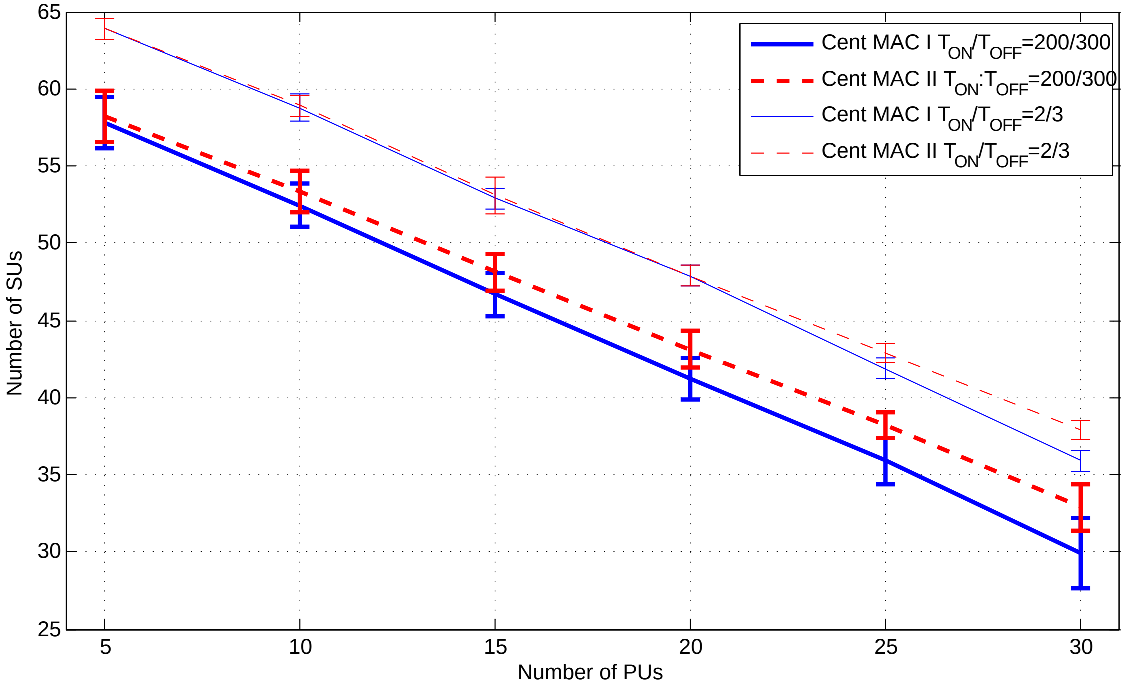


Figure 5.3: Effect of T_{ON}/T_{OFF} ratio with centralized MAC (T_{ON}/T_{OFF}=2/3 and T_{ON}/T_{OFF}=200/300, m=1 frame, and P_{ON}=0.4).

5.2.3 Effect of m

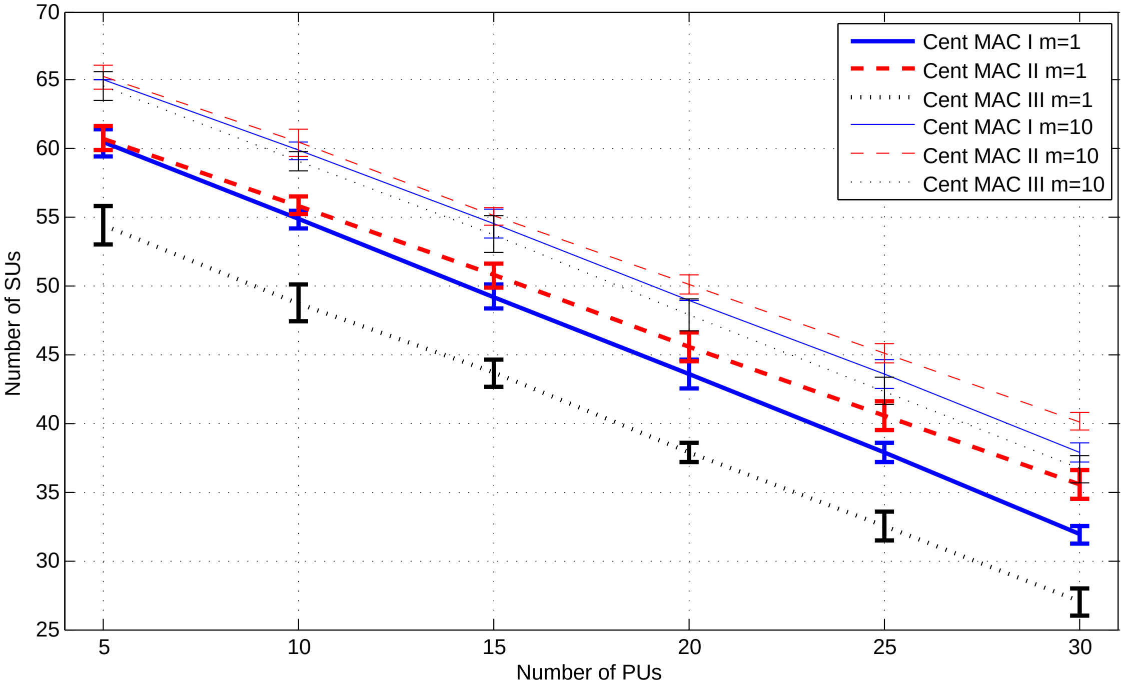


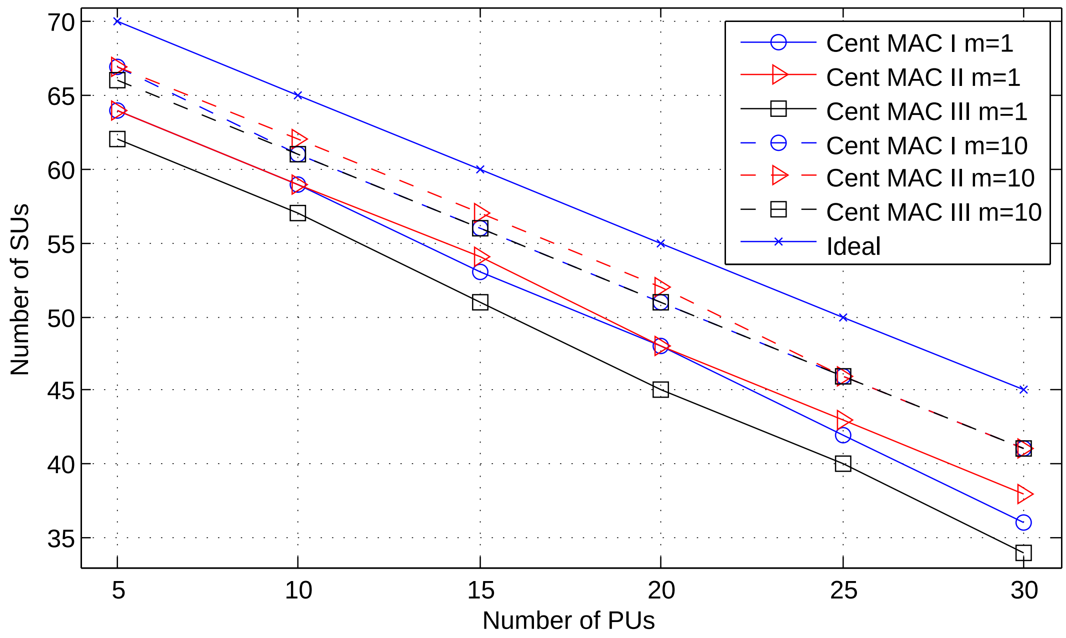
Figure 5.4: Effect of m with centralized MAC ($m = 1$ frame and $m = 10$ frames, T_{ON}/T_{OFF}=20/30, and P_{ON}=0.4).

We increase m to see how it affects the performance of the three protocols. Figure 5.4 shows the performance of the protocols, for T_{ON}/T_{OFF}=20/30 and $P_{ON} = 0.4$, when m is increased from 1 frame to 10 frames. As the delay bound is increased, the number of SUs that can be admitted with a guaranteed level of QoS increases. This result is expected, since a longer delay bound means packets can be queued for a longer time before transmission, so that better multiplexing can be achieved.

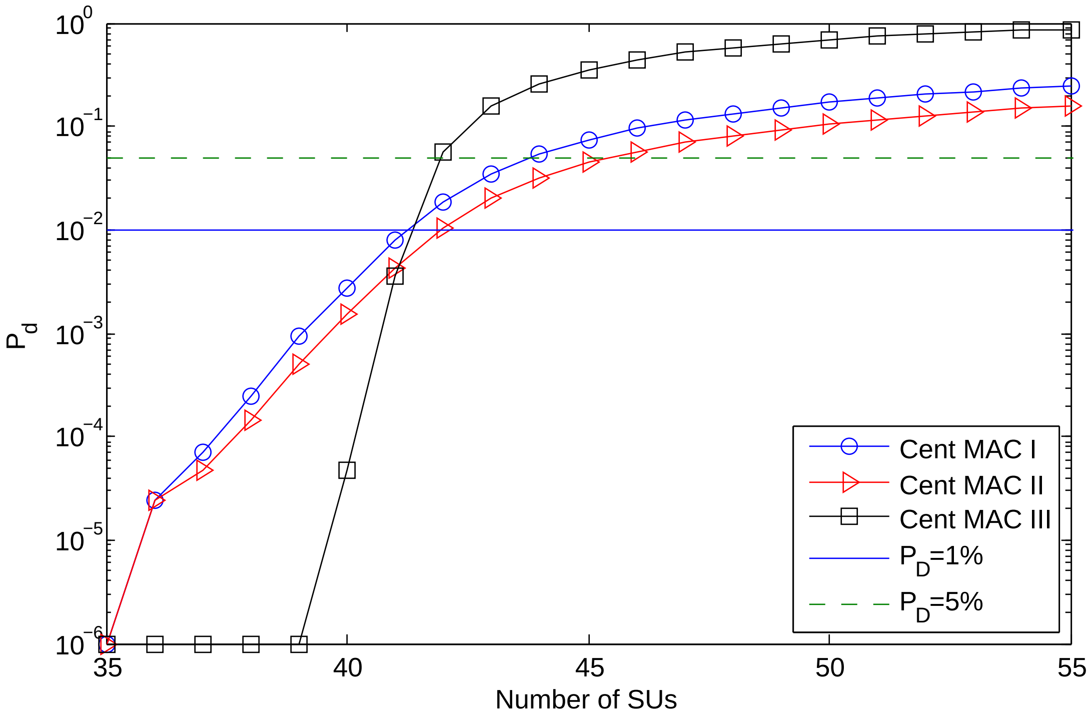
5.2.4 Effect of P_D

Intuitively, increasing the value of P_D will result in an increase in the number of SUs that can be admitted to the system. However, the effect of increasing P_D is not the same on all three protocols. Figure 5.5(a) shows the effect of increasing m, from 1 frame to 10 frames, on the performance of the protocols when the $T_{ON}/T_{OFF} = 2/3$. We notice that this increase resulted in almost identical performance by the three protocols.

However, even though the number of SUs admitted by the three protocols is almost identical for $m = 10$ frames, when we study the increase rate of P_d for the three protocols, we notice that P_d increases at a higher rate when Centralized MAC III is utilized. This is an advantage of our proposed protocols over Centralized MAC III, and can be beneficial for an application that can tolerate a higher value of P_D. For instance, as shown in Figure 5.5(b), if P_D is increased from 1% to 5%, Centralized MAC I and Centralized MAC II will admit 2 more SUs and 4 more SUs respectively, while the number of SUs that will be admitted by Centralized MAC III does not change.



(a) m=1 frame vs m=10 frames



(b) P_D=1% vs P_D=5% , (PU=30 users and m = 10 frames)

Figure 5.5: Effect of P_D with centralized MAC (T_{ON}/T_{OFF}=2/3 and P_{ON}=0.4).

5.3 Distributed MAC Protocols

Similar to the approach taken to study the performance of our proposed MAC protocols for centralized CRNs, we compare the performance our protocol Distributed CRN I, discussed in Subsection 4.2.1, with the performance of Distributed CRN II, proposed in [6] and discussed in Section 2.5. The parameters P_{ON}, T_{ON}/T_{OFF}, and m are compared, in Subsections 5.3.1, 5.3.2, and 5.3.3 respectively. Finally, how the issue of fairness among SUs is addressed by each protocol is discussed in Subsection 5.3.4.

Similar to the case of the centralized CRN protocols, we choose the following values for the simulation parameters: $P_{ON} = 0.4$, $T_{ON}/T_{OFF} = 20/30$, and $m = 1$ frame. Figure 5.6 shows the number of SUs admitted to the system by the two protocols. We notice that our protocol admits more SUs with guaranteed QoS. Note that Distributed MAC II does not require any calculations to be done by the SUs, while in Distributed MAC I each SU has to calculate its B and map it to an ID using equations (4.1) and (4.2) respectively.

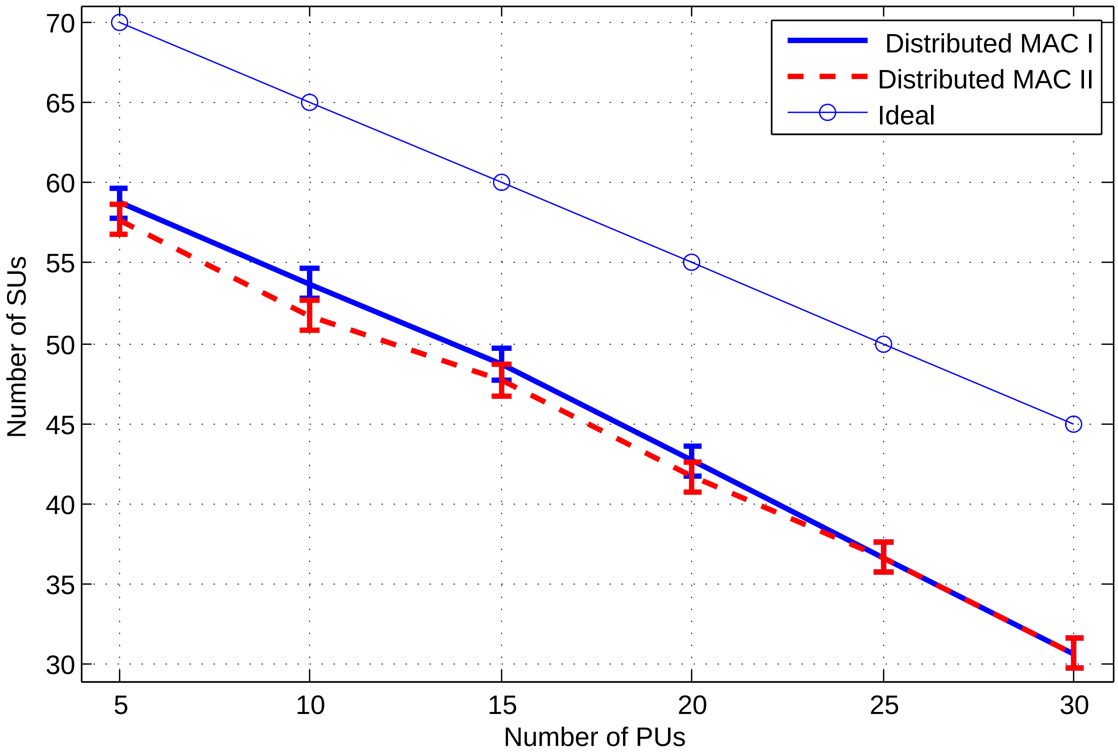


Figure 5.6: Distributed MAC: The maximum number of SUs versus the number of PUs for P_{ON}=0.4, T_{ON}/T_{OFF}=20/30, and m=1 frame.

5.3.1 Effect of P_{ON}

We run the simulation for P_{ON}=0.4 and 0.6 respectively. To change the value of P_{ON} from 0.4 to 0.6, we change the values of T_{ON} and T_{OFF} from 20 and 30 to 30 and 20 respectively. As shown in Figure 5.7, the higher the value of P_{ON}, the lower the number of SUs admitted to the system. This result is consistent with the result obtained from the simulation of the centralized MAC protocols.

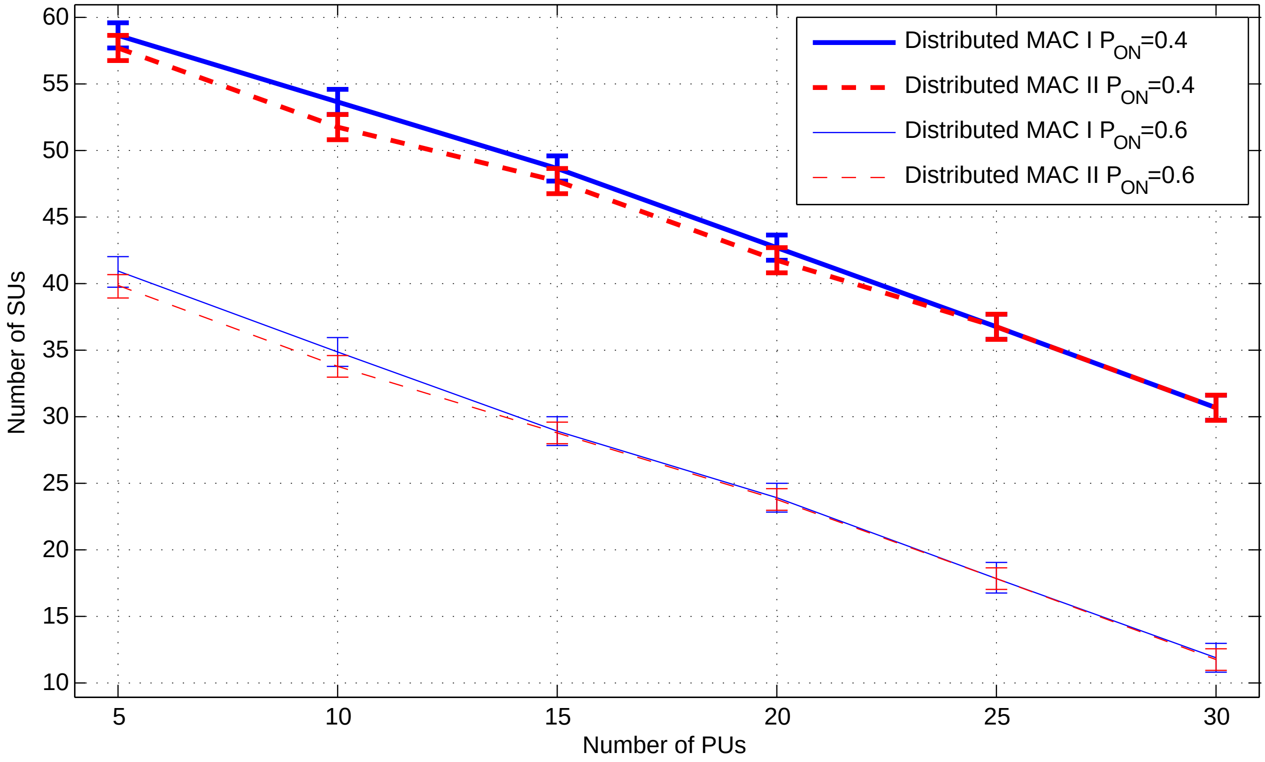


Figure 5.7: Effect of P_{ON} with distributed MAC (T_{ON}/T_{OFF}=20/30 for P_{ON}=0.4 and T_{ON}/T_{OFF}=30/20 for P_{ON}=0.6, and m=1 frame).

5.3.2 Effect of T_{ON}/T_{OFF} ratio

To study the effect of the T_{ON}/T_{OFF} ratio on the performance of the protocols, we vary the values of T_{ON} and T_{OFF} while fixing P_{ON} and m. Figure 5.8 shows the change in performance resulting from varying the T_{ON}/T_{OFF} ratio from 2/3 to 200/300. Similar to the centralized case, the faster the users switch between the two states, the higher the number of SUs that can be admitted to the system with the guaranteed level of QoS.

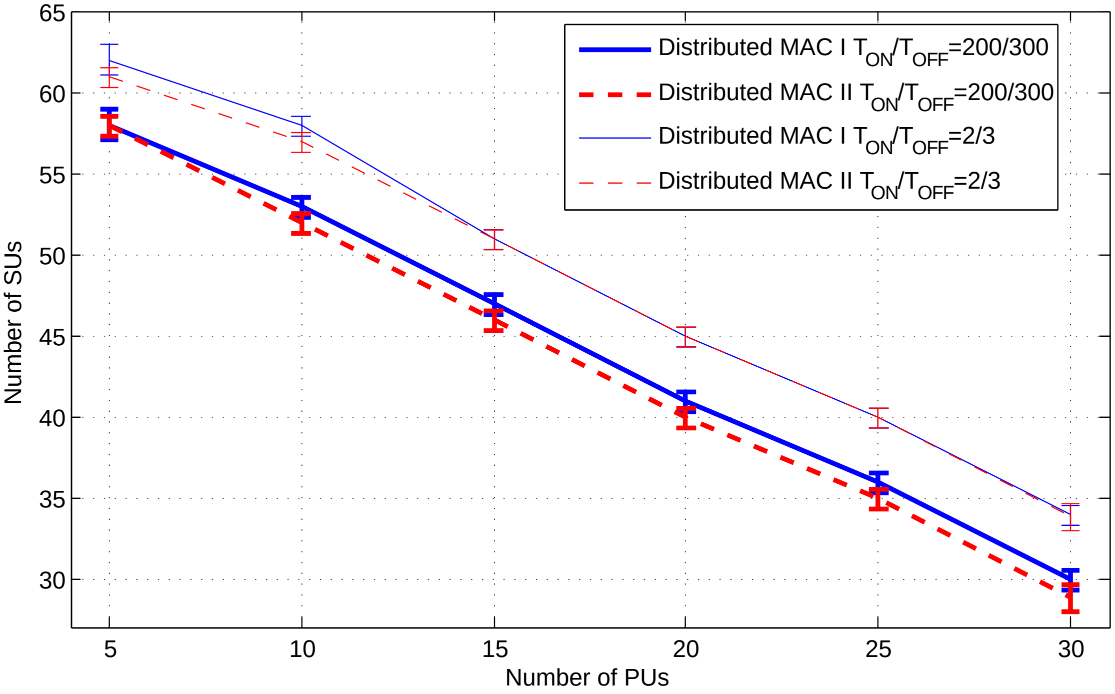


Figure 5.8: Effect of T_{ON}/T_{OFF} ratio with distributed MAC (T_{ON}/T_{OFF}=2/3 and T_{ON}/T_{OFF}=200/300, m=1 frame, and P_{ON}=0.4).

5.3.3 Effect of m

In this section, we increase m from 1 frame to 10 frames. As shown in Figure 5.9, when m is increased from 1 frame to 10 frames, the number of the SUs admitted to the system by both protocols increases, which is the same observation as in the case with the centralized MAC protocols.

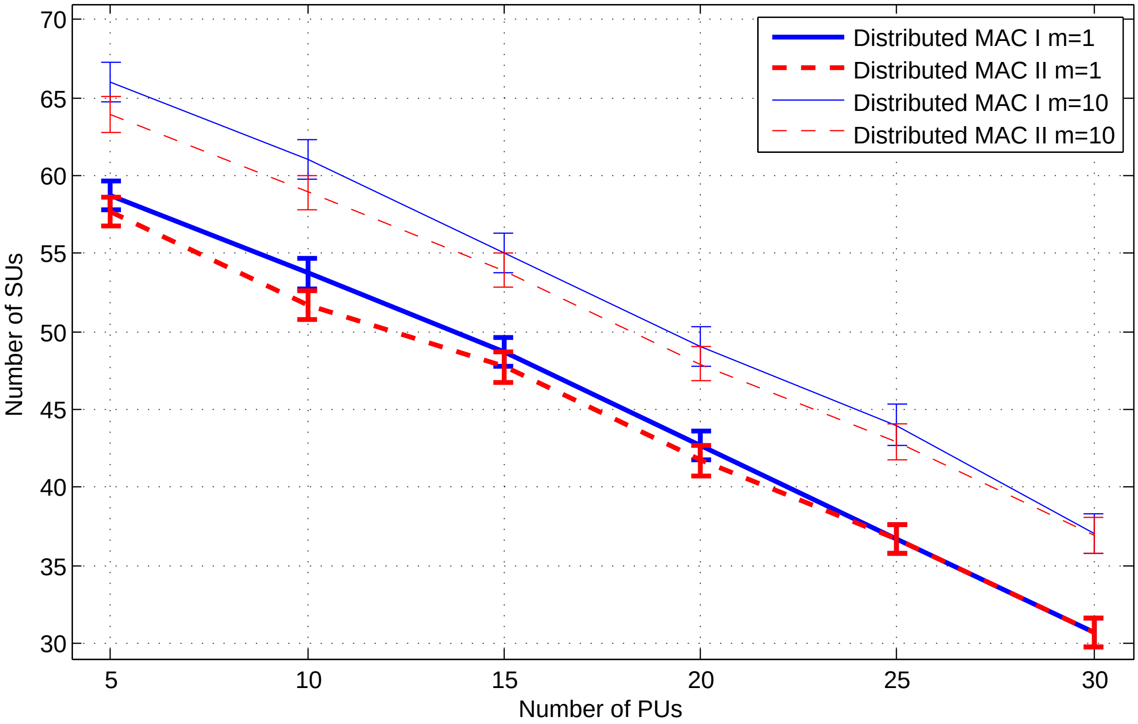
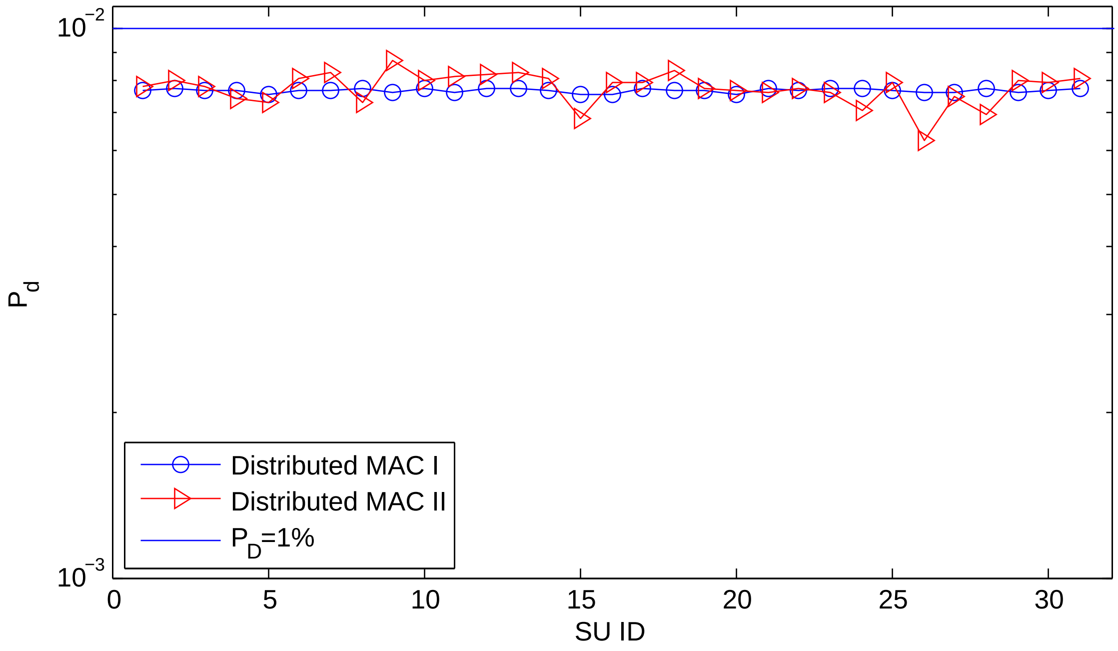


Figure 5.9: Effect of m with distributed MAC (m = 1 frame and m = 10 frames, T_{ON}/T_{OFF}=20/30, and P_{ON}=0.4).

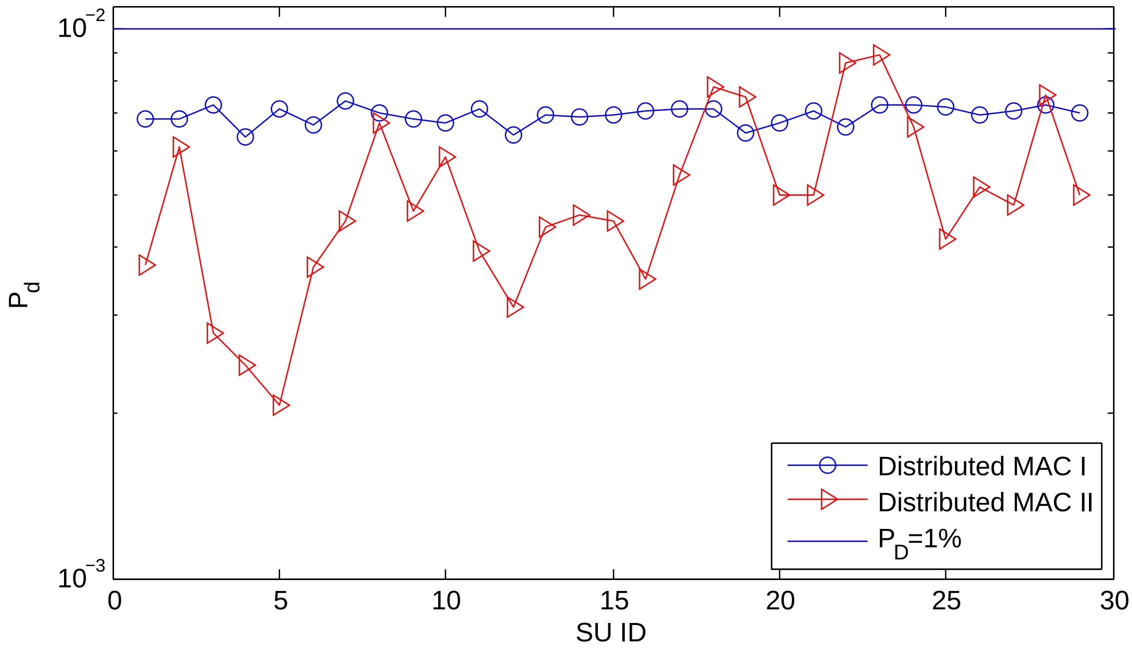
5.3.4 Fairness among SUs

Distributed MAC II is one of the first protocols to successfully guarantee QoS for SUs in a distributed CRN. However, because of the deterministic manner used to organize SUs access to idle slots, Distributed MAC II does not achieve fairness among SUs, specially when the voice call duration, L, is short. Our protocol, on the other hand, grants SUs access to idle timeslots based on their current packet dropping rate and the number of packets queued for transmission and, thus, the value of L is not a factor. Fairness among SUs can be classified into two types, namely short term fairness and long term fairness. Short term fairness indicates the fairness among SUs over short time intervals, while long term fairness reflects the fairness among SUs over the entire duration of the voice call. In the following, we discuss both the short term and long term fairness among SUs achieved by both distributed MAC protocols.

Long term fairness: To study the long term fairness among SUs provided by Distributed MAC I and Distributed MAC II, we run the simulation for the entire duration of the voice call and record the value of P_d endured by each user. We study the fairness among SUs for L equal to 10^5 frames and, then, reduce the value of L to 10^4 frames to study the effect of L on the performance of the protocols. Figure 5.10(a) shows the variance in P_d among SUs, when L is equal to 10^5 frames. We notice that even though Distributed MAC I achieves better fairness among SUs, the improvement in fairness is not significant. However, as shown in Figure 5.10(b), when L is reduced to 10^4 frames, the improvement in long time fairness among SUs is more visible when Distributed MAC I is utilized. This result indicates that Distributed MAC I provides better long term fairness among SUs than Distributed MAC II.



(a) Values of SUs' P_d for $L = 10^5$ frames



(b) Values of SUs' P_d for $L = 10^4$ frames

Figure 5.10: Long term fairness of distributed MAC (T_{ON}/T_{OFF}=20/30, $m = 1$ frame, and P_{ON}=0.4).

Short term fairness: To study the short term fairness among SUs provided by both distributed MAC protocols, we run the simulation for a duration of 10^4 frames and calculate the P_d of the admitted SUs over intervals of 500 frames. Figures 5.11 and 5.12 show the short term fairness for both protocols, for four randomly chosen SUs from the admitted SUs. We notice from Figure 5.11 that the variance of the SUs' packet dropping rate is small when Distributed MAC I is used. In other words, over each interval (500 time frames), all SUs in the CRN endure similar values of P_d. This reflects fairness among SUs.

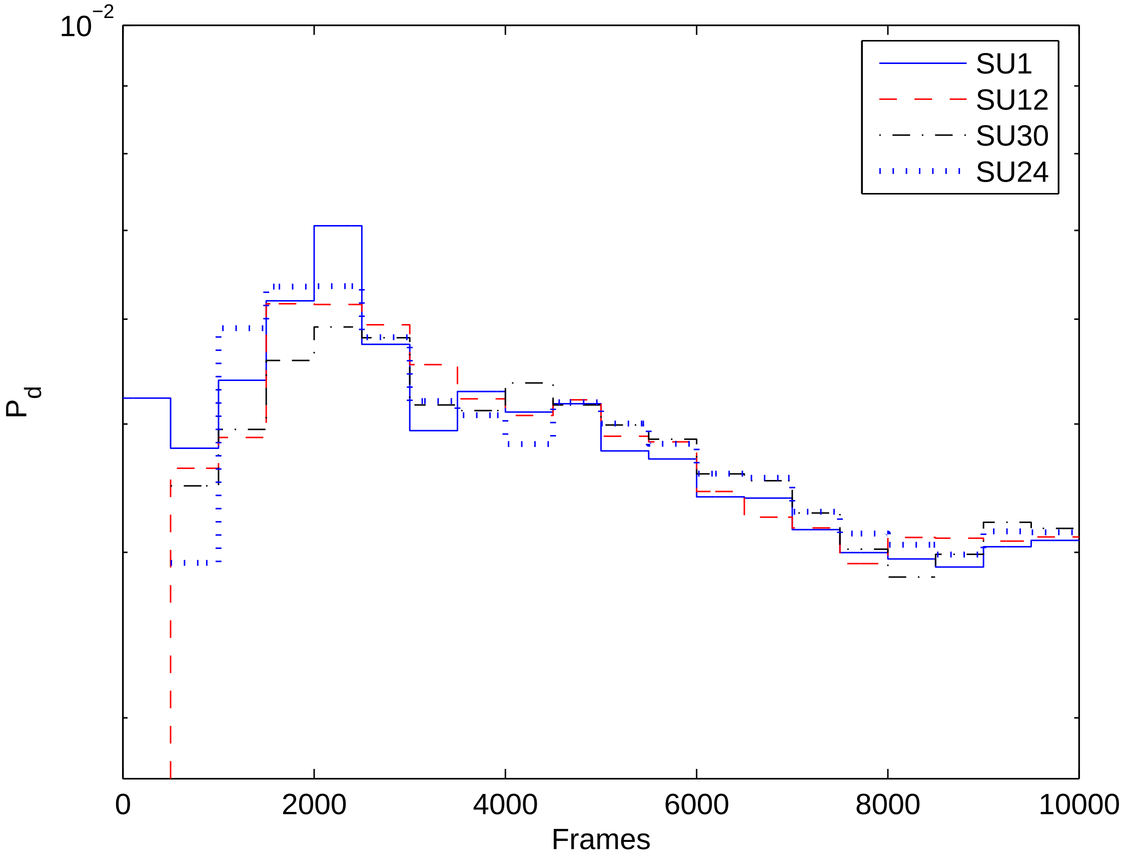


Figure 5.11: Short term fairness of Distributed MAC I (T_{ON}/T_{OFF}=2/3, m = 1 frame, $L = 10^4$ frames, and P_{ON}=0.4).

However, when Distributed MAC II is used, the variance of the packet dropping rate among the SUs varies drastically, as shown in Figure 5.12. This result indicates that Distributed MAC I provides better short term fairness among SUs than Distributed MAC II.

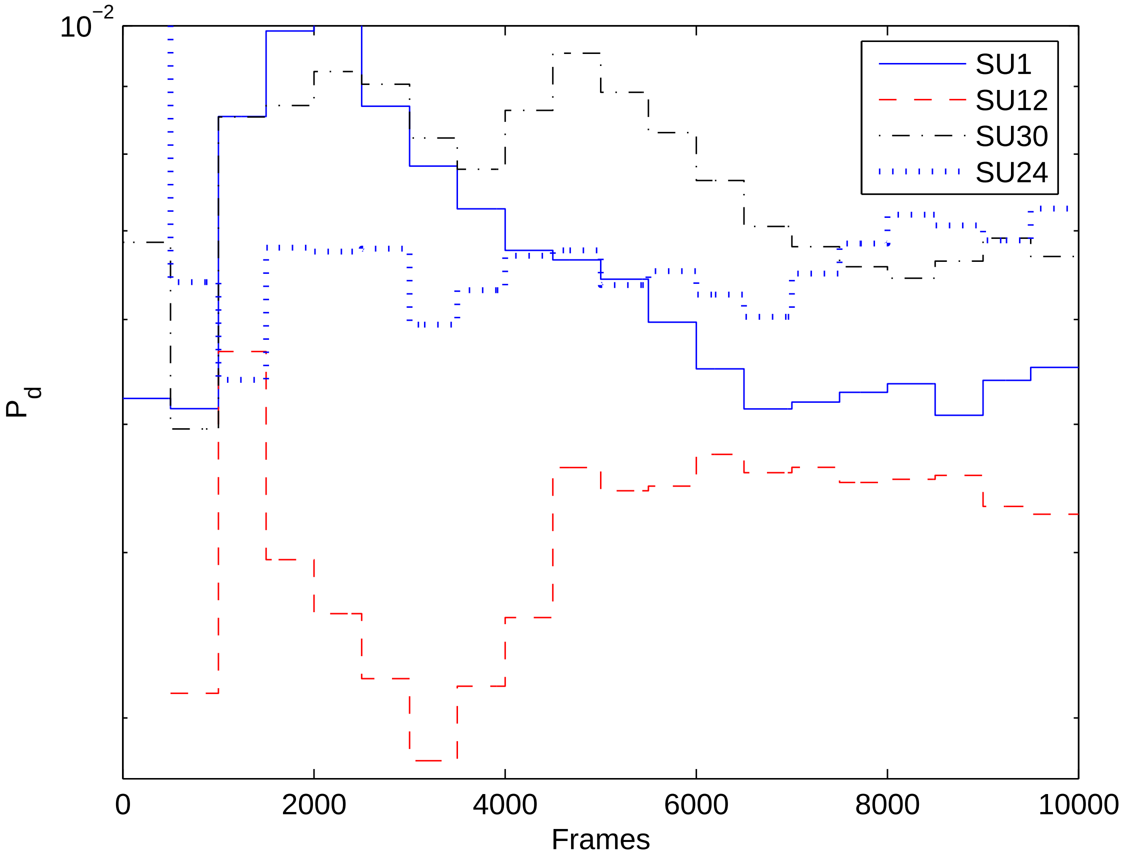


Figure 5.12: Short term fairness of distributed MAC II (T_{ON}/T_{OFF}=2/3, $m = 1$ frame, $L = 10^4$ frames, and P_{ON}=0.4).

5.4 Summary

In this chapter, we present simulation based evaluation for our proposed protocols and compare their performance with other existing MAC protocols designed for CRNs. There are three main simulation parameters that affect the performance of the protocols, namely P_{ON}, T_{ON}/T_{OFF} ratio, and m. We study the effect of these parameters on the value of N (the number of SUs admitted with QoS support). We observe that the effect of the system parameters is consistent for both centralized and distributed networks. Table 5.1 provides a comparison of the results.

Change in Parameter	Effect on CRN
Increase in P_{ON}	Decrease in N
Increase in T_{ON}/T_{OFF}	Decrease in N
Increase in m	Increase in N

Table 5.1: Effect of system parameters on N.

For centralized CRNs, we compare our two protocols, Centralized MAC I and Centralized MAC II, with Centralized MAC III. We show how our proposed protocols admit more SUs with a level of QoS suitable for voice communications when m is set to 1 frame. When m is increased to 10 frames, the performance of the three protocols is almost identical; however, when our protocols are utilized, the increase rate of P_d is lower than when Centralized MAC III is used, which is an advantage for our protocols.

On the other hand, for distributed CRNs, we compared our protocol, Distributed MAC I, with Distributed MAC II [6]. Even though Distributed MAC I provides the necessary QoS for more SUs than Distributed MAC II, the performance of both protocols is relatively close. However, we show how our protocol maintains better short term and long term fairness among SUs than Distributed MAC II.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

Our research objective is to design a MAC protocol that maintains fairness among SUs in a CRN, while guaranteeing a certain level of QoS suitable for voice communications. In addition, the protocol should meet these requirements without interfering with the functionality of the primary system. In Chapter 4 we proposed three MAC protocols for CRNs that fulfill our objective.

Proposing to schedule SUs' packet transmissions based on ordering SUs according to the endured packet dropping rate and, then, according to the number of packets queued for transmission, we are successful to provide a measure of QoS suitable for voice communications and maintain fairness among all SUs in the CRN. This scheduling concept was implemented by three protocols presented in Subsections 4.1.1,4.1.2, and 4.2.1.

The first two protocols, Centralized MAC I and Centralized MAC II, are designed for centralized CRNs, where there is a central unit that manages the network. Centralized MAC I follows the restriction imposed by CRs, which demands that the activities of the primary network should not be affected by the secondary network. Hence, in this protocol, all PUs transmit their packets first, and SUs are only allowed access to the channel if at least one of the PUs is idle.

On the other hand, Centralized MAC II treats PUs and SUs as users of the same network with different priorities. Thus, a PU does not always transmit first. PUs are ordered along with SUs, using the ordering criteria mentioned earlier; however, if a PU and an SU have the same packet dropping rate and the same number of packets queued for transmission, the PU is granted access to the channel before the SU. This protocol can be used to manage schedule packet transmission for users that belong to the same network but are of different classes.

Both of our proposed protocols are evaluated, and their performance is compared to the performance of a MAC protocol that grants SUs access to the channel based on the arrival time of their respective packets. We show how our protocols admits more SUs with the necessary QoS to a centralized CRN, in Section 5.2.

Furthermore, our third protocol, Distributed MAC I, is suitable for scheduling voice packet transmission over distributed CRNs. Following the same scheduling concept used to order SUs in centralized CRNs, we add a feature to allow SUs access to the channel without the need for a central unit. To differentiate among SUs, we proceed by calculating a backoff duration for each user based on the ordering criteria. However, the differences between the backoff durations calculated by equation (4.1) is very small to implement. To overcome this problem, we propose discretizing the sensing duration into mini-slots and map the backoff duration calculated by each SU into a mini-slot, using equation (4.2).

Similar to our approach for evaluating the protocols designed for centralized CRNs, we compare the performance of Distributed MAC I with a MAC protocol that provides a level of QoS suitable for voice communications over distributed CRNs [6], in Section 5.3. The simulation results indicate that Distributed MAC I successfully admits more SUs than Distributed MAC II. In addition, Distributed MAC I maintains better short term and long term fairness among SUs in the CRN.

6.2 Future Work

So far, we manage to design a protocol that allows SUs to access the spectrum successfully. However, in order to benefit from this work, further research in the following areas is required:

1. Spectrum Sensing in Centralized CRNs: Spectrum sensing, which is a physical layer (PHY) functionality, is defined as the monitoring of unused spectrum by detecting the spectrum holes in the available spectrum bands [10]. This process has to be done without causing any interference to the primary user. Moreover, in general an efficient manner to detect spectrum holes is to monitor users that are transmitting and receiving data within the communication range of the network.

   However, in CRNs, the users should utilize any available channel in a wide spectrum range and, thus, monitoring active users is best performed on a user level, after which the information is shared on a network level. Hence, a spectrum sensing scheme that considers the multi-channel environment should be studied.

2. Cross Layer Design between the PHY and the MAC Layers: Despite the enormous success of the layered architecture, researchers propose many cross-layer design (CLD) schemes to efficiently manage resources, especially for wireless networks [26]. Unlike wired networks, wireless networks have scarce resources. In addition, the characteristics of the wireless channel changes constantly, because nodes in a wireless network are mobile and because the surrounding environment has a significant effect on the performance of the wireless channel.

   CLD, as a term, encompasses any protocol, algorithm, or architecture that promotes sharing of information between non adjacent layers. In addition, CLD solutions can be classified into evolutionary and revolutionary. Evolutionary proposals can be regarded as an extension to the layered model, while revolutionary proposals ignore the idea of grouping communication functions into layers. Thus, an evolutionary CLD protocol should be designed for centralized CRNs, to manage both the PHY and the MAC layers.

3. Adapting Developed CLD scheme to an Ad-Hoc CRN: Ad-hoc networks, which are wireless network with no predetermined infrastructure, have some unique characteristics and challenges [9]. Unlike in centralized networks, each node has to manage the power and the bandwidth efficiently; in addition, nodes have to deal with all aspects of managing the network performance.

   Responsibilities such as spectrum sensing, spectrum sharing, routing data, and channel allocation, which are usually done by a specific entity in an infrastructure wireless network, have to be done by each node in an ad-hoc network. Because of the nature of ad-hoc networks, after designing a CLD scheme for centralized CRN, adapting the designed CLD scheme for an ad-hoc CRN should be investigated.

Bibliography

[1] J. Mitola and G. Maguire, "Cognitive radio: making software radio more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, August 1999. xi, 2, 3, 22

[2] S. Lien, C. Tseng, and K. Chen, "Carrier sensing based multiple access protocols for cognitive radio networks," *In Proceedings of IEEE ICC*, pp. 3208–3214, May 2008. xi, 6, 10, 12, 13, 14

[3] C. Cordeiro and K. Challapali, "C-MAC: a cognitive MAC protocol for multi-channel wireless networks," *In Proceedings of IEEE DySPAN*, pp. 147–157, April 2007. xi, 5, 6, 8, 10, 15, 16

[4] Y. Kondaredd and P. Agrawal, "Synchronized MAC protocol for mult-ihop cognitive radio networks," *In Proceedings of IEEE ICC*, pp. 3198–3202, May 2008. xi, 6, 8, 10, 18, 19, 20, 21

[5] L. Wang, A. Chen, and D. Wei, "A cognitive MAC protocol for QoS provisioning in overlaying ad hoc networks," *In Proceedings of IEEE CCNC*, pp. 1139–1143, January 2007. xi, 7, 10, 22, 23

[6] P. Wang, D. Niyato, and H. Jiang, “Voice-service capacity analysis for cognitive radio networks,” *IEEE Transactions on Vehicular Technology*, vol. 59, no. 4, pp. 1779–1790, May 2010. xi, 7, 8, 10, 25, 26, 51, 52, 62, 71, 75

[7] M. Medard, “The effect upon channel capacity in wireless communications of perfect and imperfect knowledge of the channel,” *IEEE Transactions of Information Theory*, vol. 46, no. 3, pp. 933–946, May 2000. 1

[8] S. Shakkottai, T. S. Rappaport, and P. C. Karlsson, “Cross layer design for wireless networks,” *IEEE Communications Magazine*, vol. 41, no. 10, pp. 74–80, 2003. 1

[9] *Wireless ad-hoc and Sensor Networks: a Cross-layer design perspective.* Springer US, 2007. 1, 76

[10] I. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, “Next generation dynamic spectrum access cognitive radio wireless networks: a survey,” *Computer Networks Journal*, vol. 50, pp. 2127–2159, September 2006. 2, 3, 4, 5, 75

[11] J. Mitola, “The software radio architecture,” *IEEE Communications Magazine*, vol. 33, no. 5, pp. 26–38, 1995. 2

[12] F. Jondral, “Cognitive radio: a communications engineering view,” *IEEE Wireless Communications*, vol. 14, no. 4, pp. 28–33. 2

[13] C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, and W. Caldwell, “IEEE 802.22: the first cognitive radio wireless regional area network standard,” *IEEE Communications Magazine*, vol. 47, pp. 130–138, January 2009. 2

[14] F. Jondral, “Software defined radio basics and evolution to cognitive radio,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2005, pp. 275–283, August 2005. 2

[15] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journal on Selected Areas in Communication*, vol. 23, no. 2, pp. 201–220, February 2005. 2, 3

[16] A. W. Min and K. G. Shin, “Impact of mobility on spectrum sensing in cognitive radio networks,” *In Proceedings of International Conference on Mobile Computing and Networking*, pp. 13–18, September 2009. 4

[17] I. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, “A survey of spectrum management of cognitive radio networks,” *IEEE Communications Magazine*, pp. 40–48, April 2008. 4

[18] C. Cormio and K. Chowdhury, “A survey on MAC protocols for cognitive radio networks,” *Ad Hoc Networks*, vol. 7, September. 4, 5, 6

[19] R. Etkin, A. Parekh, and D. Tse, “Spectrum sharing for unlicensed bands,” *In Proceedings of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 251–258, November 2005. 5

[20] J. Gallardo, P. Medina, and W. Zhuang, “QoS mechanisms for the MAC protocol of IEEE 902.11 WLANS,” *Wireless Networks, Springer*, pp. 335–349, 2007. 7

[21] L. Akter and B. Natarajan, “QoS constrained resource allocation to secondary users in cognitive radio networks,” *Computer Communications*, 2009. 7

[22] I. Akyildiz, W. Lee, and K. Chowdhury, "CRAHNs: Cognitive radio ad hoc networks challenges," *Ad Hoc Netwroks Journal*, vol. 7. 7

[23] H. Pham, J. Xiang, Y. Zhang, and T. Skeie, "QoS-aware channel selection in cognitive radio networks: a game-theoretic approach," pp. 1–7, May 2008. 8

[24] A. Attar, M. Nakhai, and H. Aghvami, "Cognitive radio game: a framework for efficiency, fairness and QoS guarantee," pp. 4170–4174, 2008. 8

[25] J. N. Daigle and J. D. Langford, "Models for analysis of packet voice communication system," *IEEE Journal on Selected Areas in communications*, vol. 4, no. 6, pp. 847–855, September 1986. 31

[26] F. Foukalas, V. Gazis, and N. Alonistioti, "Cross layer design proposals for wireless mobile networks: a survey and taxonomy," *IEEE Communications Surveys and Tutorials*, vol. 10, no. 1, pp. 70–85, 2008. 76