İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

PROTECTION AND FAIRNESS ORIENTED COGNITIVE RADIO MAC PROTOCOL FOR AD-HOC NETWORKS (PROFOC)

M.Sc. Thesis by
Beycan KAHRAMAN

Department : Computer Engineering

Programme : Computer Engineering

Thesis Supervisor: Assist. Prof. Feza BUZLUCA

JUNE 2009

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Beycan KAHRAMAN
(504071508)

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Supervisor (Chairman) : Asst. Prof. Feza BUZLUCA (ITU)
Members of the Examining Committee : Prof. Dr. Sema OKTUĞ (ITU)
Assoc. Prof. İbrahim ALTUNBAŞ (ITU)

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

AD-HOC AĞLARDA ADALET VE KORUMA TABANLI KAVRAMSAL RADYO MAC PROTOKOLÜ (PROFOC)

YÜKSEK LİSANS TEZİ
Beycan KAHRAMAN
(504071508)

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Tez Danışmanı : Yrd. Doç. Dr. Feza BUZLUCA (İTÜ)
Diğer Jüri Üyeleri : Prof. Dr. Sema OKTUĞ (İTÜ)
Doç. Dr. İbrahim ALTUNBAŞ (İTÜ)

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FOREWORD

Special thanks to my family and my friends for their ceaseless patience and support to my education for years. I would like to express my deep appreciation and thanks for my supervisor Assist. Prof. Feza BUZLUCA. In addition, I would like to thank to TUBITAK for the economical support during my M. Sc. Thesis study.

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Beycan Kahraman
Computer and Mathematical Engineer

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ABBREVIATIONS

ACK	: Acknowledgment
AD-HOC	: For this, to the thing (Latin)
COMNET	: Cognitive Mesh Network
CR	: Cognitive Radio
CSMA/CA	: Carrier Sense Multiple Access/Collision Avoidance
CW	: Congestion Window
DARPA	: Defense Advanced Research Projects Agency
DSA	: Dynamic Spectrum Access
FCC	: Federal Communications Commission
GPRS	: The General Packet Radio Service
IEEE	: Institute of Electronics and Electical Engineers
MAC	: Media Access Control
MANET	: Mobile Ad Hoc Network
MR	: Mesh Routers
PDA	: Personal Digital Assistant
PHY	: Physical
PROFOC	: Protection and Fairness Oriented Cognitive Radio MAC Protocol for Decentralized Ad-hoc Networks
PU	: Primary User
SDR	: Software Defined Radio
SPTF	: Spectrum Policy Task Force
SU	: Secondary User
TTL	: Time to Live
UML	: Unified Modeling Language
WiFi	: Wireless Fidelity
WiMAX	: Worldwide Interoperability for Microwave Access
WLAN	: Wireless Local Area Network
WMN	: Wireless Mesh Networks

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PROTECTION AND FAIRNESS ORIENTED COGNITIVE RADIO MAC PROTOCOL FOR AD-HOC NETWORKS (PROFOC)

SUMMARY

Cognitive radio networks have the potential to share underutilized frequency bands opportunistically and flexibly among users. We propose a CSMA/CA-based MAC protocol for cognitive radio ad hoc networks to make efficient use of spectrum holes, while protecting primary users (PUs). The protocol enables secondary users (SUs) to utilize the unused licensed spectrum channels with a tolerable harm in QoS of PUs. To limit interference with primary communication and to improve throughput, this protocol uses the following three protection schemes: limiting packet size of SUs below a tolerable limit, assigning larger congestion window size to SUs that compete for channel resources with PUs, and requiring SUs to wait before attempting to access the channel. These three protection schemas guarantee PUs to handle the channel below a predetermined toleration limit.

Each SU maintains a dynamic channel state table to select a proper channel without sensing its current availability. Using these tables, each SU decides its next data channel. The main point is that SUs do not change its data channel after each collision and behave as an existing user until a limit value. This method minimizes both spectrum handovers and communication overhead associated with continual spectrum sensing. To evaluate protocol performance, we have developed a discrete event simulator. Results from different scenarios show that our protocol increases throughput and decreases access delay of secondary users, while protecting PUs. The protocol also supplies fairness for SUs in communication with its CSMA /CA based design.

AD-HOC AĞLARDA ADALET VE KORUMA TABANLI KAVRAMSAL RADYO MAC PROTOKOLÜ (PROFOC)

ÖZET

Kavramsal ağların, yeterince etkili başarım sağlanamayan frekans kanallarını kullanmada önrmli bir potansiyeli mevcuttur. Kavramsal ağlar, spektrumdaki boşlukları doldururken spektrumda önceden yer alan lisanslı kullanıcılara da zarar vermeden iletişimlerini devam ettirme olanağı sunmaktadırlar. Bu tezde, AD-HOC ağlarda kullanılabilecek CSMA/CA tabanlı bir kavramsal radyo MAC protokolü öneriyoruz. Önerilen protokol etkili bir şekilde spektrum boşluklarını doldururken lisanslı kullanıcıları da sağlam bir şekilde koruyabilmektedir. Başarımı arttırırken lisanslı kullanıcıları koruma işlemi, önerdiğimiz üç yöntem ile sağlanmaktadır. Bunlar: ikincillerin paket boyutunu sınırlandırmak, ikincillerin çekişme penceresinin boyutunu arttırmak ve son olarak da, her iletişimin ardından ikincil kullanıcıların lisanslı kullanıcılara bir süre yol vermeleridir. Bu üç yöntem lisanslı kullanıcıların hissedeceği rahatsızlığı gözardı edilebilecek seviyeye düşürmeyi garantilerken, ikincillerin boş durumdaki frekans kanallarını kullanabilmelerini sağlamaktadır.

Bu yöntemlerin yanında, ikincil kullanıcılar dinamik kanal durum tabloları tutmaktadırlar. Böylece spektrumu sezmeye gerek kalmadan uygun kanala geçiş sağlanabilir. İkincil kullanıcılar tablolardan yararlanarak sıradaki veri kanalını belirlemektedirler. Buradaki en önemli nokta, ikincil kullanıcıların her çakışmadan sonra kanalı hemen değiştirmemesi ve belli bir limite kadar bulunduğu kanalda yer alan diğer kullanıcılar gibi davranmasıdır. Sürekli spektrum tarama işlemi göz önüne alındığında, geliştirilen protokol, hem kanal değiştirme sayısını azaltmakta hem de iletişim başlıklarının boyutunu küçültmektedir. Protokolün performansını daha iyi inceleyebilmek için ayrık zamanda çalışan kavramsal radyo simülatörü hazırlanmıştır. Önerilen protokol farklı senaryolar altında incelendiğinde, lisanslı kullanıcıların korunduğu, toplam başarımın arttırılmasının yanı sıra erişim gecikmesinin de azaltıldığı görülmektedir. Bunun yanında önerilen protokol, CSMA/CA tabanlı yapısının sonucu olarak ikinciller arası iletişimde adaleti de sağlamaktadır.

1. INTRODUCTION

During last decade, we have experienced a comprehensive progress in wireless technologies. Researches show that a significant advance comes in ad-hoc networks. It seems to be the future technology to benefit from ad-hoc networks in our daily life. Detecting heart attack and informing the essential employees, faster fire detection, warning the drivers about traffic congestion, etc. could be examples of the usage of future ad-hoc networks.

Nowadays wireless transmission technologies are the leading local area network (LAN) technologies. Recent studies about wireless communication show that most of the available spectrum has been allocated for distinct technologies as radio and tv channels, 802.11 WiFi, 802.16 WiMax, GPRS, etc. On the other hand, there is a poor utilization in these licensed spectrum bands. In addition to insufficient and underutilized spectrum usage, the most convenient parts of the spectrum have allocated before [1]. Figure 1.1 shows the frequency spectrum usage of Turkey [2].

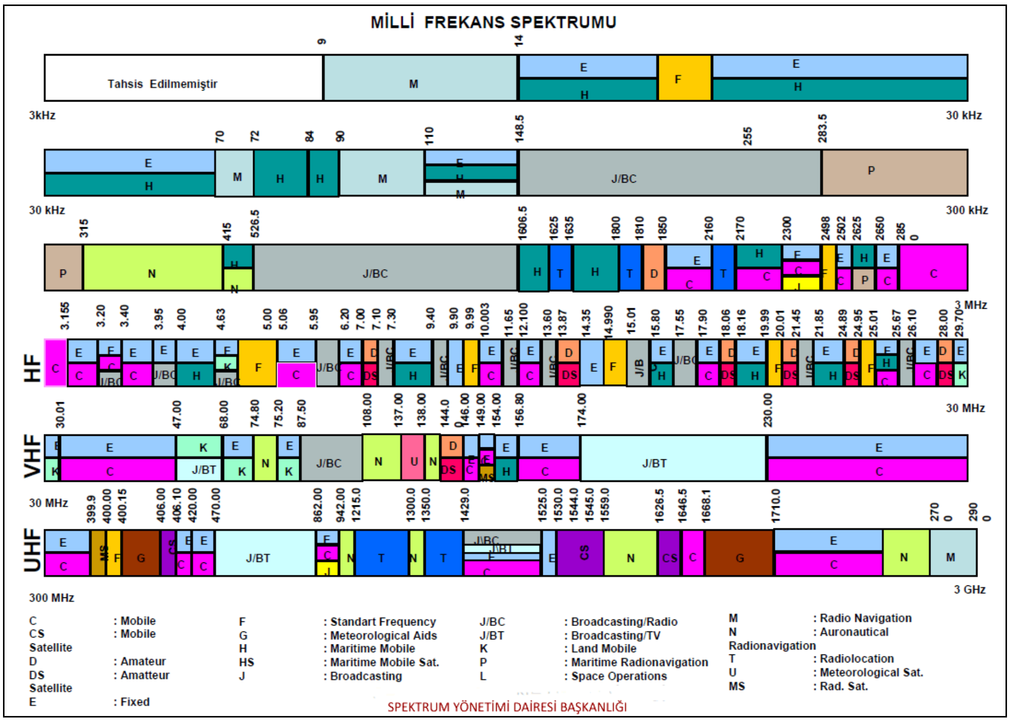

Figure 1.1 : National Frequency Spectrum

It is impossible for nowadays technologies to use very high frequency bands in a long distance and also, it is not possible to use low frequency bands and low frequency intervals in fast communication technologies. These are arising from the nature of the frequency spectrum.

In 2000, localized set of measurements conducted by the DARPA indicated that "Spectrum use was not very high". Furthermore, the FCC Spectrum Policy Task Force (SPTF) concludes that "Spectrum access is a more significant problem than spectrum scarcity. The SPTF recommends that new rules be developed to allow more intensive access to the spectrum, including opportunistic spectrum" in 2002 [1].

In this instance, dynamic spectrum access (DSA) is a promising technology in order to use the spectrum efficiently, because these are seen as opportunities to provide more services and new technologies without having to allocate new spectrum. Moreover, the DSA methods propose an efficient mechanism to solve the three problems given above. The most effective DSA usage is handled by software defined radios (SDR) which is a radio that includes a transmitter in which the operating parameters of frequency range, modulation type or maximum output power (either radiated or conducted), or the circumstances under which the transmitter operates can be altered by making a change in software without making any changes to hardware components that affect the RF emissions. The most well known SDR technology is cognitive radio, a radio or system that senses and is aware of its operational environment and can be trained to dynamically and autonomously adjust its radio operating parameters accordingly [1]. Thus, cognitive radio is the one that takes the attention of most researchers.

With the success of cognitive radios, unlicensed (secondary) users can access the unused parts of the spectrum (white spaces) owned by licensed (primary) users [3]. There are two principles that a cognitive radio must obey: Firstly, it should bound the harm to primary users (PUs) that is consisting of borrowing the licensed spectrum. Secondly, cognitive radios should exist with existing spectrum systems [4]. Figure 1.2 includes a cognitive function to analyze existing spectrum users, and measure properties of its own communication channels, and a set of rules expressed through a policy engine which define what the radio is allowed to do, and what it is not allowed to do [5].

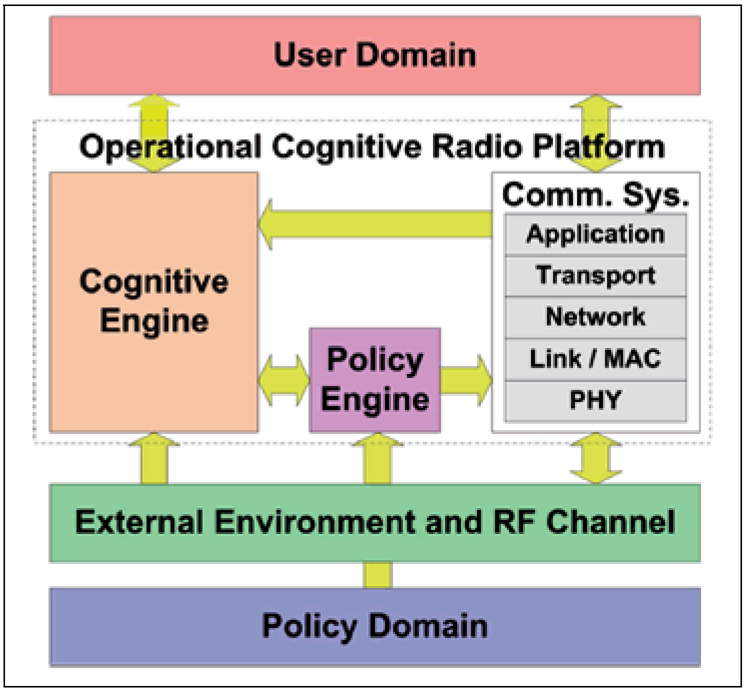

Figure 1.2 : Architecture of a cognitive radio.

2. COGNITIVE RADIO AND PROPOSED PROTOCOLS

2.1 Cognitive Radio

J. Mitola, the inventor of cognitive radio defines it as "The term cognitive radio identifies the point at which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to: (a) detect user communications needs as a function of use context, and (b) to provide radio resources and wireless services most appropriate to those needs." [6].

Cognitive radio (CR) techniques provide the capability to use or share the spectrum in an opportunistic manner. On the other hand, DSA techniques allow the CR to operate in the best available channel. More specifically, the CR technology will enable the users to (1) detect which parts of the frequency bands are available and sense the presence of licensed channels when a user operates in a licensed band in order not to cause harmful interference with other users (spectrum sensing), (2) select the best available channel by capturing the best available spectrum to meet user communication requirements (spectrum management), (3) coordinate access to this channel with other users and providing fair spectrum scheduling method among coexisting cognitive users (spectrum sharing), and (4) vacate the channel when a licensed user is detected that maintains seamless communication requirements during the transition to better spectrum (spectrum mobility). Once a CR supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum. Hence, new functionalities are required in an cognitive network to support this adaptivity[7].

The formal definition of cognitive radio is “a radio that can change its transmitter parameters based on interaction with the environment in which it operates” [8]. In this instance, two main characteristics of the cognitive radio can be defined as [9, 10]:

Cognitive capability: It refers to the radio technology ability that is used to capture or sense the information from its radio environment. It is not easy to realize this capability because monitoring the power in some frequency band of interest is not enough. We need more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Thus, it will be possible to identify the unused parts of the spectrum at a specific time or location. Finding the unused parts, the best spectrum and appropriate operating parameters can be selected.

Reconfigurability: The cognitive capability provides spectrum awareness, on the other hand reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio should be designed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design [7].

The main objective of the CR is to obtain the best available spectrum through cognitive capability and reconfigurability as described before. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum parts without interfering with licensed users. The CR enables the usage of temporally unused spectrum, which is referred to as spectrum hole (white space) [9]. If this band is further used by a licensed user, the CR moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

In order to provide an adaptive operation in the spectrum there are some tasks required which is referred as the cognitive cycle and the three main steps of the cognitive cycle are: (1) after monitoring the available spectrum bands and capturing their information, detecting the spectrum holes (spectrum sensing), and (2) detecting the characteristics of the spectrum (spectrum analysis), and (3) choosing the appropriate spectrum band according to the spectrum characteristics and user requirements (spectrum decision) [7]. The inventor of cognitive radio states these operations and sub steps as shown in Figure 2.1 [11].

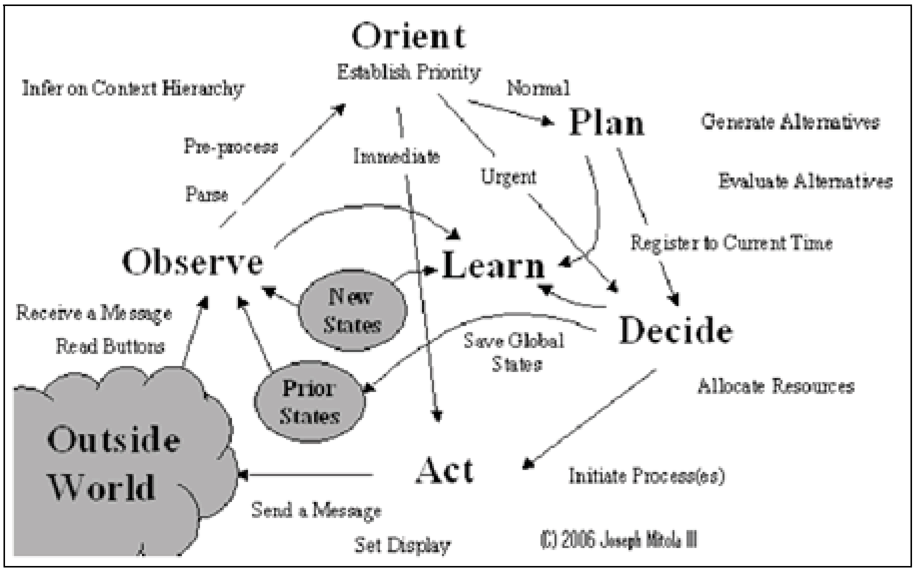

Figure 2.1 : Operations of Cognitive Radio

2.2 Proposed Protocols

There have been many researches about cognitive radio MAC protocol design. IEEE 802.22 is the world-wide first standard which is a first draft of cognitive radios [12] which is running for three previously defined data channels. In [13], the authors proposed an opportunistic spectrum access MAC protocol. They assumed that time is divided into beacon intervals and all of the secondary users (SUs) are synchronized by periodic beacon transmissions. In [14], an opportunistic cognitive MAC protocol for coexistence with WLAN is proposed. Using the prediction of transmission duration, they succeeded in improving the performance of low-throughput networks. A cognitive MAC protocol using statistical channel allocation is proposed in [15]. The protocol consists of three major operations: environment sensing and learning, CRTS/CCTS exchange over the control channel, DATA transmission and ACK over data channels. In [16], the authors are focused on hardware constraints to maximize the throughput by optimizing the sensing decision in a sequence of sensing processes and they formulate the problem as a well-defined optimal stopping problem.

In [17], authors design a CR that can coexist with multiple parallel WLAN channels while abiding by an interference constraint. The interaction between both systems is characterized by measurement and coexistence is enhanced by predicting the WLAN's behavior based on a continuous-time Markov chain model. In [18] the authors propose the cross-layer based opportunistic multi-channel medium access control (MAC) protocols, which integrate the spectrum sensing at physical (PHY) layer with the packet scheduling at MAC layer, for the wireless ad hoc networks. They enable MAC layer for SUs to identify and utilize the leftover frequency spectrum in a way that constrains the level of interference to the PUs. In the proposed protocols, each SU is equipped with two transceivers. One of them is tuned to the dedicated control channel, while the other one is designed specifically as a cognitive radio that can periodically sense and dynamically use the identified un-used channels. The MAC structure is described in Figure 2.1.

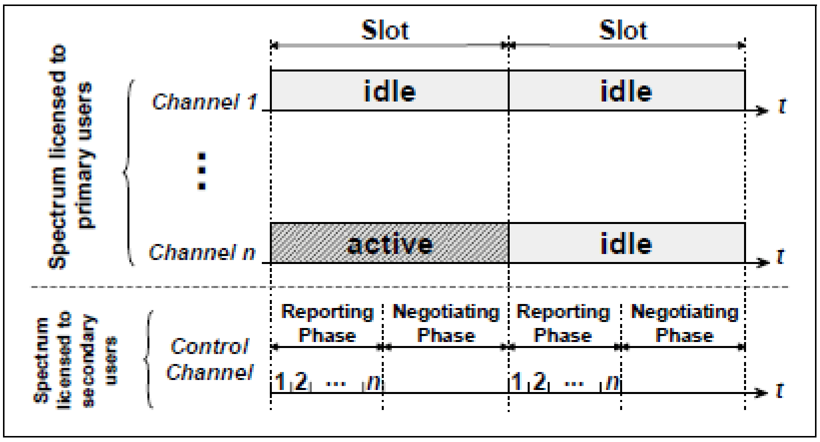

Figure 2.2 : CR MAC protocol runs in synchronization

In [19] the authors propose new techniques to leverage two optimizations for CR networks that are specific to such contexts: opportunistic channel selection and cooperative mobility. They present a new formal model for MANETs consisting of cognitive radio capable nodes that are willing to be moved (at a cost). They develop an effective distributed algorithm for mobility planning, and powerful new filtering and fuzzy based techniques for both channel estimation and channel selection. In [20], Wireless Mesh Networks (WMNs) are envisaged in personal, local, campus, and metropolitan areas to extend Internet access and other networking services. Mesh routers (MR) form the connectivity backbone while performing two main tasks that are packet forwarding and providing network access to the mesh clients. However, the performance of such networks is limited by traffic congestion, as only limited bandwidth is available for supporting the large number of nodes in close proximity. In [21], the authors introduce a distributed spectrum management architecture where nodes share spectrum resource fairly by making independent actions following some spectrum rules. They present five spectrum rules to regulate node behavior and maximize system fairness and spectrum utilization, and analyze the associated complexity and overhead. They also show analytically and experimentally that the proposed rule-based approach achieves similar performance with the explicit coordination approach, while significantly reducing communication cost. In addition to these, there are many other researches about CR MAC concept.

2.3 Unsolved Problems

However, there are some issues about these protocols, which can be criticized. First of all, time synchronization could be inconvenient, and the knowledge of the complete spectrum is hard to acquire. Another issue is about supplying fairness to SUs. Working in opportunistic manner could be harmful in this case. Some of the researches are loading control channel as an unlimited resource. However, it will be used for many channels and by much more CR devices. Lastly, the cost of the system should be low and the creation of CR devices is preferred to be easy. In the thesis, we present a protection and fairness oriented CSMA based cognitive radio MAC protocol (PROFOC) for cognitive ad-hoc networks that assures protection of PUs, fairness and high throughput for secondary communication. The proposed protocol has three protection schemes applied to secondary users, which are larger congestion windows size, limited packet length and the obligation to wait a while before attempting to access a channel. The PROFOC protocol also includes a mechanism to determine the time and destination channel of a spectrum handover operation. This method, that is based on dynamic channel state variables, reduces the overhead of continuous spectrum sensing, the frequency of handovers and as a result it decreases the access delay of SUs.

The remainder of the thesis is organized as follows. In Section II, we describe the proposed protocol with details. After describing the protocol, we will focus on the simulation in section III. In the fourth section, we will show the results of simulations. In section V, we will conclude the work and discuss some parameters and implementation issues.

3. PROPOSED PROTOCOL

The most appropriate and effective parts of the spectrum are used for some well-known technologies as WiFi, WiMAX, etc. In addition to that, there are existing users for these distinct technologies and for their reserved spectrum intervals. In addition, these users are running with formerly defined protocols. So, one of the most important responsibilities of the PROFOC design is to adapt with these existing systems without any change in their certain structure. In this instance, PROFOC presents an optimal protection for the existing users while adapting to their behavior with some altered parameters.

Another issue about CR MAC design is that, the protocol should be equipped for numerous unpredicted interruptions and long-term disconnections. So, PROFOC suggests the ACK messages to be handled in upper layers of CR network, in order to decrease the complexity of the design and focus on primary users only. Therefore, the protocol reduces the repetition of the packets whenever not necessary.

It is hard and costly to create time synchronized MAC protocols for global spectrum usage. These devices can be only used for some special implementations. A more general solution should adapt itself to the whole spectrum environment when necessary as in PROFOC design. However, protection of PUs become very crucial in asynchronic MAC protocols. There are many proposed protocols that could not guarantee the QoS of PUs to be affected under a limit value, because they omit the living spectrum environment which will result untolerable living spectrum problem. To explain, users should not handle the channel resources immediately after changing their data channels, because there is a possibility that some PUs have also reach their tolerance limit. PROFOC protocol resolves untolerable living spectrum problem with its well-defined protection schemes. The solution will be detailed in the next sections.

The proposed PROFOC protocol consists of three major operations as most of the proposed algorithms do: sensing and observing the environment, CRTS/CCTS exchange over dedicated control channel, data transmission over data channels [12-14]. In our study, we mostly focus on decreasing overhead associated with continuous spectrum sensing and improving the quality and performance of data transmission. We assume that the acknowledgement messages are handled in upper layers in CR design. The operation of the PROFOC protocol could be summarized as follows: agreement over control channel, competition for data channel and, decision of next operating channel. These steps are explained below.

3.1 Agreement over control channel

During a communication, next data channel is determined by the sender SU by using channel state variables as explained later in next sections. Only at the beginning of a connection as the channel states are unknown to the sender, it selects a fixed data channel and announces it to the receiver over the control channel. By simplifying this negotiation process, our algorithm will eliminate continual spectrum sensing problem, which is a power consuming process. At the beginning, the senders may choose a channel that has not white spaces for that moment, but this problem is fixed by our protocol as explained in the following sections.

3.2 Competition for data channel

In the proposed design, when a SU wants to initiate a transmission, it follows CSMA/CA protocol with altered congestion window (CW) parameters to capture the channel. If a secondary user obtains the channel, it starts transmitting its data to its secondary pair. Here, SUs compete with PUs; however, the proposed protection schemes will guarantee the PUs' service quality to be affected under a limit value.

Protection schemes for QoS of PUs

Our design includes three protecting schemes for PUs. They are: choosing larger CW size for SUs, limiting maximum packet length of SUs and requiring SUs to wait before accessing the channel. The detailed explanations are given below.

3.2.1 Choosing larger CW size for SUs

In our PROFOC design, we set SUs' initial size of CW as a larger value than PUs'. Choosing the initial value of the SUs' CW size as k times larger than PUs', where k is an integer greater than 1, we get the series $\{2^n\}$ for the PUs [22-23] and, $\{k.2^n\}$ for SUs. Therefore, the transmitting probabilities of two users could be digitized with the lemma given below.

LEMMA: Two users that have different congestion window values, the series $\{k.2^n\}$ and $\{2^n\}$ to be more specific, will result $P_1 \geq \frac{k-1}{k} + (2k-1)P_2$, where P_1 and P_2 shows the probability of capturing the channel of these users (*k*=2,3,… and *n*=1,2,3…). (Refer to appendices for the proof.)

For example, choosing k=4, we have $P_{SU} \rightarrow \frac{1}{32}$ and $P_{PU} \rightarrow \frac{31}{32}$ transmitting probabilities of secondary and primary users respectively for the limit values, since $P_{SU} + P_{PU} \leq 1$ when they compete.

As a result, we have two deductions from this lemma. First, PUs have much more chance to win when they compete. Secondly, SUs interference probabilities are decreased when there are many SUs on the same channel.

3.2.2 Limiting maximum packet length

Choosing larger CW size for SUs is not enough alone to protect PUs. We have limited the maximum packet length of SUs, according to PUs tolerance limit. Whenever a secondary user occupies the channel, we should guarantee that the channel will be empty after a specific duration which is the maximum tolerance limit of the primary user.

As a result, cognitive radio MAC layer should fragment the data packets according to the each channels’ QoS parameters. This will protect PUs from durable SU transmissions. However, it is still not enough for PUs’ QoS. We must guarantee them to take the control of the channel certainly after a secondary transmission. Next section describes the logic behind the last protection scheme.

3.2.3 Waiting obligation for SUs before accessing a channel

After each transmission, SUs should wait PUs for a short duration t_{wait} in order to preserve QoS of PUs. Assume that a SU competes for the data channel, handles the channel resources and starts a transmission with its pair. Shortly after, a PU needs the channel resources in order to send some data to a receiver. The previous schema guarantees that it will not wait longer than its tolerance limit for its channel. However, there may be other SUs that are waiting for the same channel, as well as the first secondary group might need to communicate again too. Figure 3.2 demonstrates a possible example.

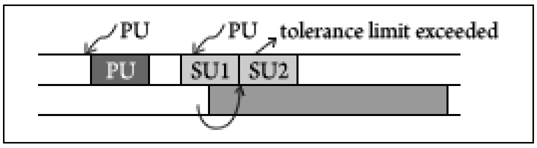

Figure 3.1 : Living spectrum problem

At that point, we should guarantee the PUs to gain the channel under this situation. In order to solve the problem, each secondary user waits for a while before attempting to access a channel, so that a primary user can capture the channel and start its transmission. If SUs cannot catch any transmission tries, it’s their turn to compete for the channel resources.

With the help of three protection schemas we have change one of the main problems of CR from “which channel should be selected for the next operating step” to “how long should we stay on a previously selected channel”.

3.3 Decision of the next operating channel

Instead of sensing all channels continuously, in the PROFOC protocol, SUs maintain a table of linear channel state variables, which are calculated for each channel using

$$U_t = aU_{state} + (1-a)U_{t-1} \tag{3.1}$$

where $U_{state} \in (0,1)$ shows the success of current transmission, U_t is linear channel state variable of a channel at time t and a is the factor of system model that is a real number between 0 and 1. With this prediction model, each SU updates its channel state table by using only local data. The variable decreases if the SU experience a collision in this channel ($U_{state} = 0$) and increases with the successful transmission ($U_{state} = 1$) according to the factor a [24-25]. We added two more parameters to this model, namely U_c and $U_{\lim it}$. A SU decreases state variables of all channels by U_c , which it has not used for a predetermined time interval. Hence, we increase the possibility to be selected of channels that are not used for a long period. If

$U_t > U_{\lim it}$, sender SU selects the channel that has the smallest channel state value and informs its pair over the control channel. Two purposes of this method are eliminating the overhead associated with continuous spectrum sensing and decreasing the access delay of SUs by minimizing the frequency of spectrum handovers, which is a time consuming process. Instead of trying to jump into another channel after each collision, in this protocol SUs may prefer to stay in the same channel and wait the previous communication to be completed. Simulation results show that if system parameters are selected properly this mechanism can decrease the access delay of SUs.

3.4 Analysis of Access Delay of PUs

Besides analyzing the performance of SUs, we also analyze PUs service quality and performance of access delay. We have developed an analytical model for calculating access delay for PUs as given in **(3.2)**:

$$T^{p}_{access\,delay} = P^{s}_{use} * \left(t^{s}_{data} / 2 + CW_0^{p} / 2\right) + \left(1 - P^{s}_{use}\right) * \left(CW_0^{p} / 2\right) \qquad \textbf{(3.2)}$$

where $T^{p}_{access\,delay}$ is the average access delay of primary users, P^{s}_{use} is the average spectrum usage of SUs and $CW_0{}^{p}$ is the initial value of the congestion window size of the PUs. In addition to the **(3.2)**, another increase can be done by probabilistic mean. According to number of collisions in a competition between PUs and SUs $T^{p}_{access\,delay}$ will be increased to $\overline{T}^{p}_{access\,delay}$ as

$$\overline{T}^{p}_{access\,delay} = T^{p}_{access\,delay} + T_i^{CW} / 2 \text{ with possibility } P_i \qquad \textbf{(3.3)}$$

where T_i^{CW} is the duration of i^{th} CW size and P_i is the possibility of experiencing i collisions consecutively.

One of the main problem is that there could be a long waiting time for SUs, due to modified backoff algorithm and extra t_{wait} duration. If we analyze the effect of aggravation caused by t_{wait} in channel resources, we get:

$$S_{decrease} = \frac{t_{wait}}{t_{wait} + t^{s}_{data}} \qquad \textbf{(3.4)}$$

where $S_{decrease}$ is the average ratio of unnecessary waiting time occurred because of t_{wait}. It is easy to show $S_{decrease} \leq 0.02$. It means that, in order to guarantee QoS of PU to be affected under a limit value, we abandon at most %2 of the channel resources. In addition to this, we have analyzed the total throughput of the SUs which is also affected by modified backoff calculation with the parameter k.

PROFOC design grants SUs to stay on their current data channels for a while, even if they experience some collisions until a limit value. Therefore, it changes the complete design of the CR MAC concept. Staying on a channel gives a user some chance to decide the duration to change the channel using some control variables. Thus, the problem of "finding a free channel to communicate better" is replaces with the problem of "staying long on a more appropriate channel". In this case, the formidable part - that is spectrum sensing - could completely subtracted from the MAC design as in PROFOC protocol. By the way, PROFOC remains still succeeding against best possible random protocol in both overall throughput and access delay which will be simulated in next sections [26].

4. SIMULATION

4.1 Simulation parameters

We have added TTL (time-to-live) for each packet, which is counted in MAC layer. Packets that cannot reach their destination before their lifetimes expire are discarded. So we can observe the efficiency of our protocol. As a result, our design shell ensures that packets of PUs are transmitted and secondary packets are lost as the load in the system increases.

We choose CW multiplier k as 4, which was described by the lemma in the previous section. Choosing k smaller makes SUs interfere more with PUs and protection on primary group starts failing. However, increasing k too much decreases the overall throughput of the network. We have added channel change duration t_{cc} to our system that is a time a SU needs to switch from a channel to another. We are using this parameter to compare our protocol with others, where SUs change their data channel after each collision. Even though the value of t_{cc} is chosen very small, which is only 5 ms, the performance of the proposed protocol is remarkable. t_{data}^{p} and t_{data}^{s} expresses mean data arrival duration of the PUs and SUs respectively. Packet sizes are exponentially distributed and arrival rate of data is distributed in Poisson. Other parameters about the simulation are given in Table 4.1:

Table 4.1 : Simulation Parameters

a	0.125
$U_{\lim it}$	0.75
$U_{t=0}$	0.5
U_{c}	0.01
t_{data}^{p}	50 ms
t_{data}^{s}	10 ms (limit 20ms)
t_{wait}	0.2 ms
$t_{TTL}^{p} = t_{TTL}^{s}$	250 ms

In our simulation, spectrum is divided into N channels. We deal PUs as a group in order to focus on secondary user's performance, since the collisions between PUs is not investigated in the thesis.

4.2 Simulation Design

We have created a discrete event simulator in order to test the competence of the new protocol with protection schemes. The simulator is created in C++ language in Visual Studio 2008 environment. The spectrum environment is represented by some classes of spectrum, channels, users, etc. We also need control channel and data channel for distinct operations. Another diverseness is needed in representing primary and secondary users. We need distinct behaviors for two of these users in the same environment [27-28]. The UML diagram of the project is shown in Figure 4.1.

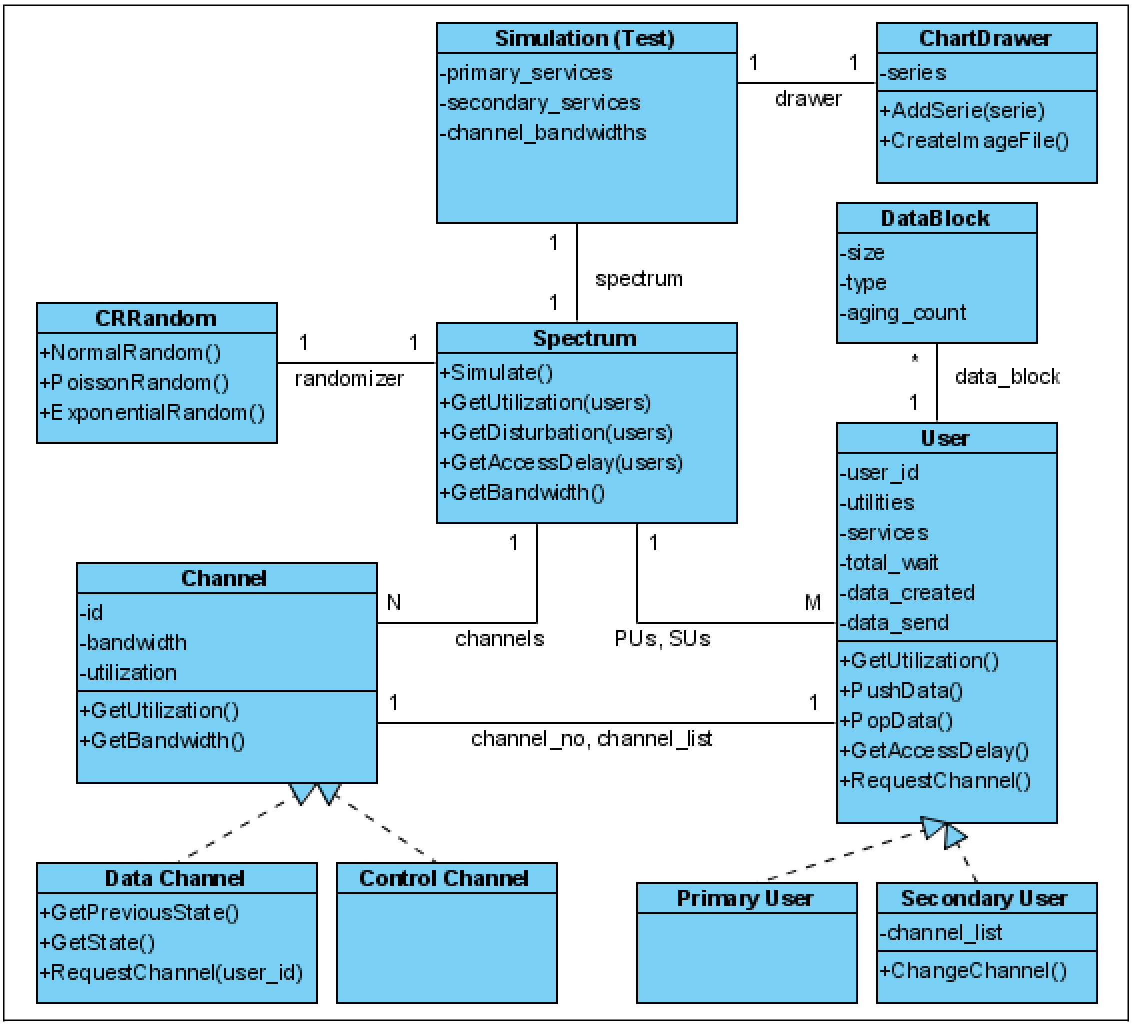

Figure 4.1 : UML class diagram of discrete event simulator

In addition, a CR randomizer is created in order to use a better approximation in Poisson and exponential distributions. The simulation starts with initializing all objects in the environment. After initializing process, spectrum simulates the environment. In each time step, primary and secondary users try to handle the channel resources if they have any data to send. If the channel senses only one of them, the channel informs the users that a user handles the channel resources. Otherwise, channel informs about a collision and users will adjust their parameters according to this result. The sequence diagram of the Simulate() function is given in Figure 4.2.

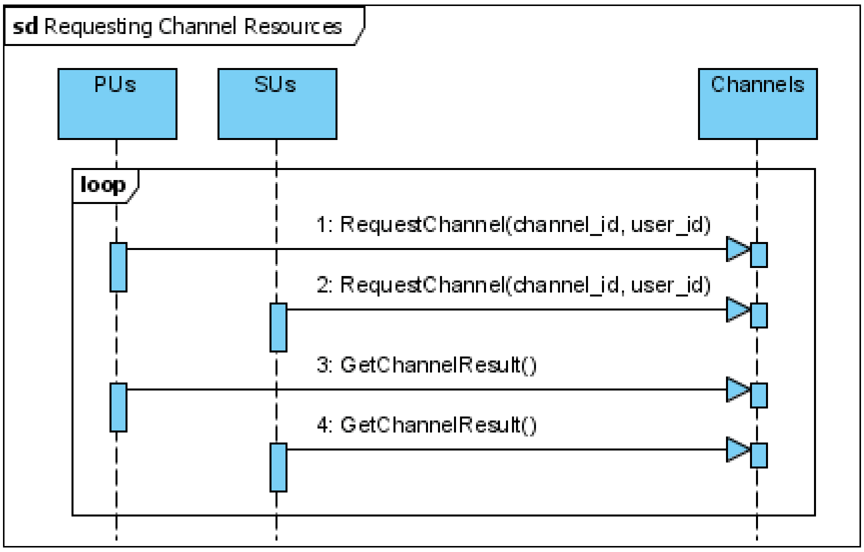

Figure 4.2 : Function Simulate(): Requesting channel resources

After the simulation duration ends, the results are collected from created objects and results are analyzed. According to different types of scenarios, the results are graphed using chart drawer object.

5. TESTS AND RESULTS

5.1 Analysis of the Protocol

Our first test appraises the protection of PUs. We increase the pressure of SUs on primary group to analyze the stability of the protection schemes. In this test we take only one channel into consideration, in which the primary group and each secondary users have %20 service request ratios. After adding a primary group, we have increased the number of secondary pairs up to 15 and created more requests than the channel bandwidth can handle. As it is depicted in Figure 5.1, in highly utilized situation, SUs throughput decrease as they cannot send their data packets because of congestions. However, the throughput of the primary group is preserved because primary packets can reach the receivers without any lose with the help of protection schemes. It should be mentioned that all of the SUs' channel state variables reached the channel change limit $U_{\lim it}$ after increasing the number of SUs; however, they could not change their operating frequency since there is only one possible channel in this first test. As a result of first simulation, we concluded that secondary pairs increase the utilization of the channel while protecting primary users.

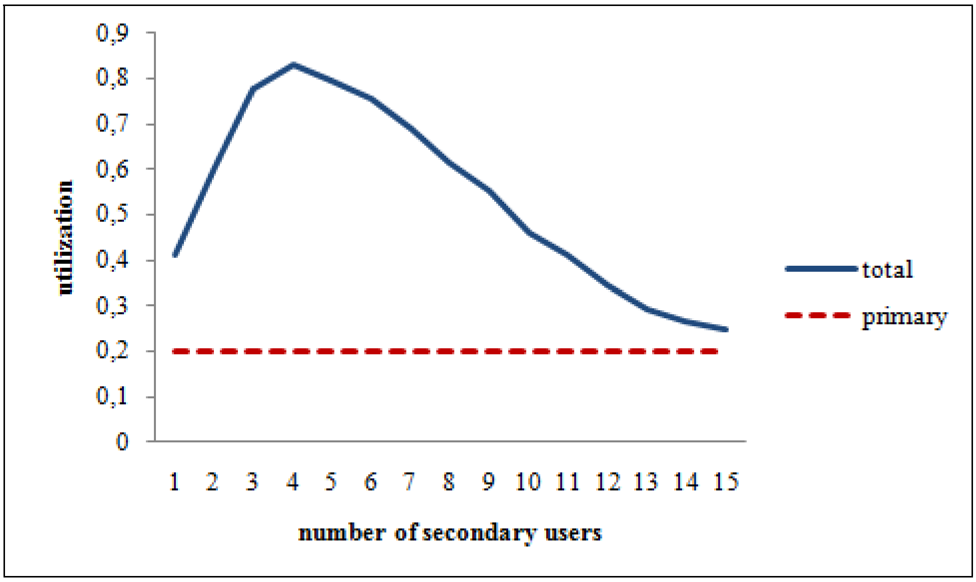

Figure 5.1 : Protection of PUs under flooding of SUs

In the second simulation, we have analyzed the fairness between SUs. In this test, there are 3 channels, 2 primary groups with 0.2 utilization requests and 5 SUs. We have increased the service request of each SU from %10 to %100. The results in Figure 5.2 show that besides preserving the QoS of PUs, the protocol ensures fairness in secondary communication. All SUs have nearly the same utilization.

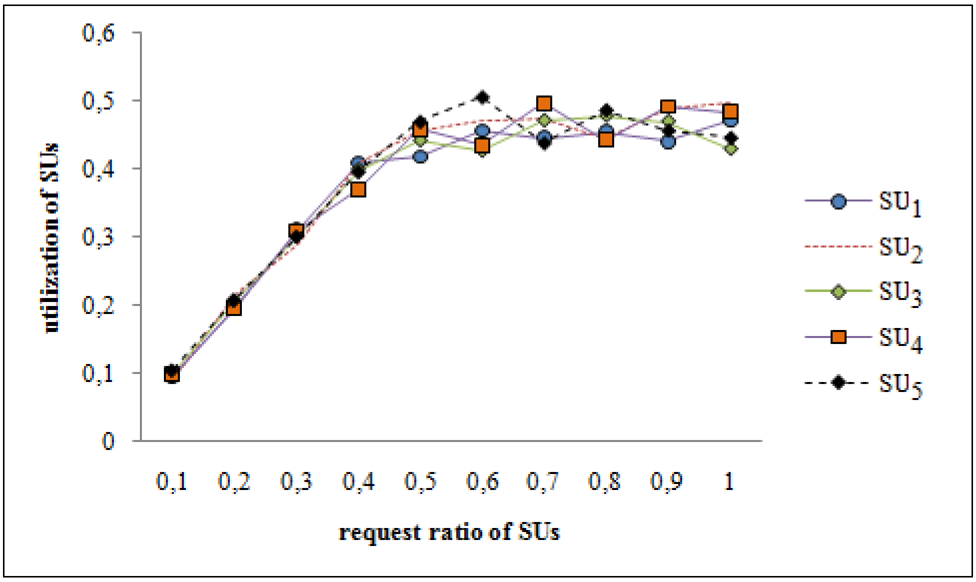

Figure 5.2 : Fairness in secondary communication

In third simulation, we focus on the effect of the usage of the channel state variables. In this test, the spectrum includes 2 channels, a primary group with %30 service request ratio and 10 SUs with variable service request ratios. As described in the protocol, secondary pairs will not change their data channel after each collision. If the state variable (U_t) of the related channel is still lower than a predefined limit ($U_{\lim it}$) it will remain on the same channel and try to get the channel after the concurrent transmission. The idea is decreasing the access delay of SUs by minimizing the frequency of spectrum handovers, which is a time consuming process. In order to compare with the proposed protocol, the rival protocol is chosen as the smart random selection CR (SRS-MAC) protocol where the users assumed to know the entire spectrum environment and randomly select one of the free channels. SRS-MAC protocol is created by using the same protection schemes with the proposed PROFOC protocol. As it is shown in the Figure 5.3, the PROFOC ensures higher throughput and over performs the SRS-MAC, even though the channel change time t_{cc} is chosen to be only 5ms. As a result of this simulation, we have concluded that changing the channel after each collision may not be the best choice always.

Waiting for white spaces in the previously selected channel can increase the performance of the protocol.

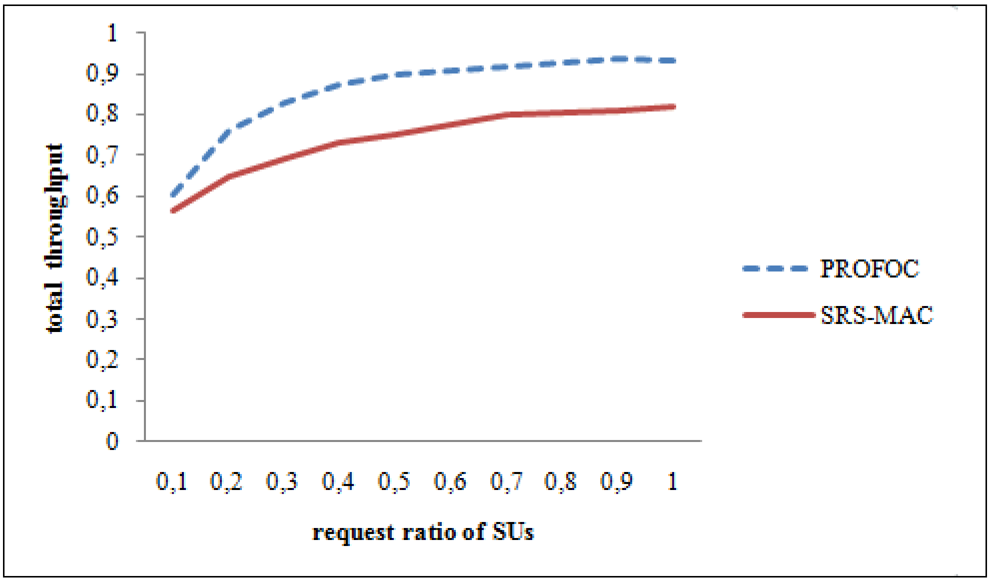

Figure 5.3 : Comparison of access delay of PROFOC vs SRS-MAC

In the same environment, we also analyze the access delay of the two protocols. Access delay is the average of time that a SU must wait to access the channel to deliver a data packet. Results in Figure 5.4 show that the proposed PROFOC protocol has lower access delay than the SRS-MAC protocol. The reason of this result is SRS-MAC changes its data channel after each collision.

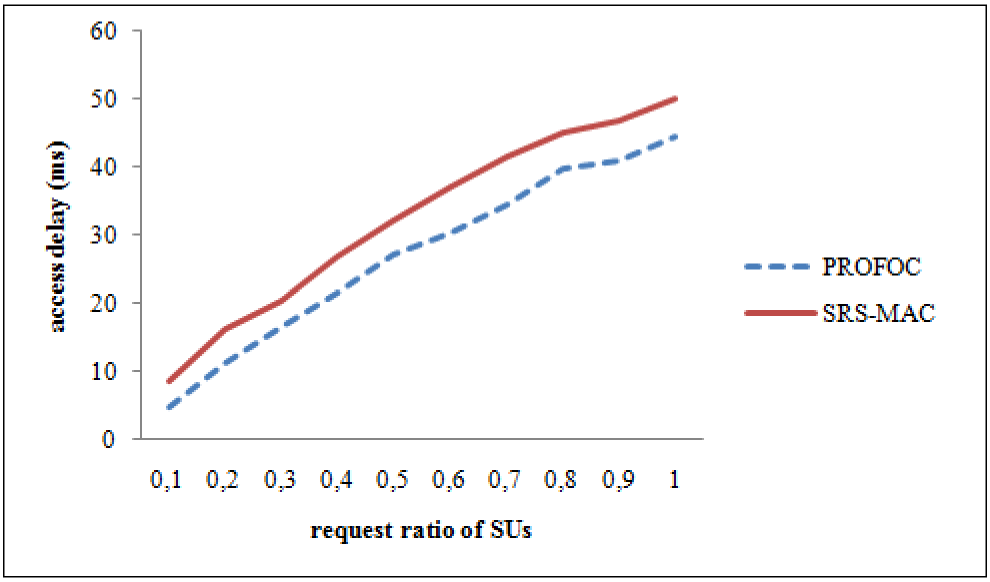

Figure 5.4 : Comparison of access delay of PROFOC vs SRS-MAC

We also investigated the number of handovers of the PROFOC protocol and compared it with the SRS-MAC. We used the same environment as the previous two simulations. As shown in Figure 5.5, number of handovers increases dramatically for the SRS-MAC protocol because the SUs are changing their data channel after each collision.

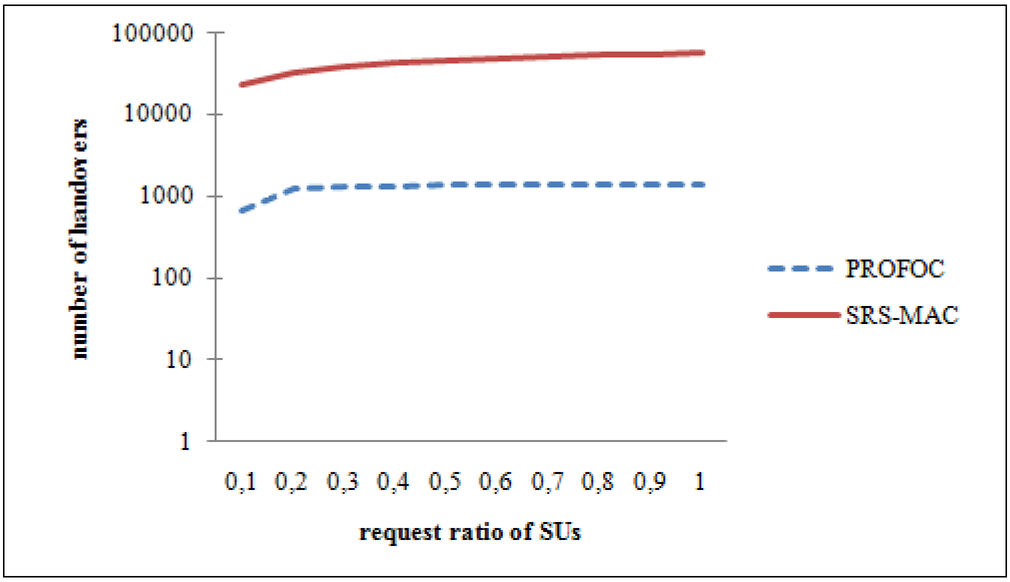

Figure 5.5 : Comparison of number of handovers

5.2 Analysis of the Constant Variables

After these tests, we have focused on the values of the constant variables. There are three main variables that change the system performance directly: $U_{\lim it}$, U_c and α. So, we will study three different cases in order to improve the total system performance according to access delay. In the first case, α is been changed from 0.05 to 0.25 and others are remain default values. The low utilized and high-utilized environment results are shown in Figure 5.6 and Figure 5.7 respectively.

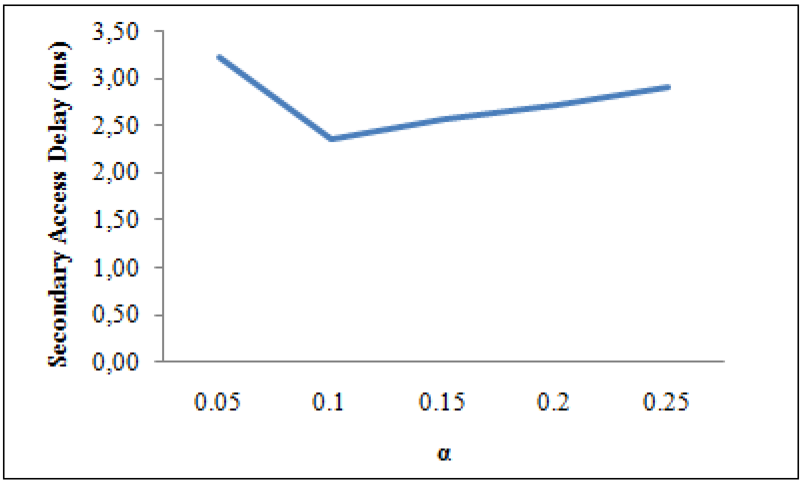

Figure 5.6 : SU access delay according to α under low utilized environment

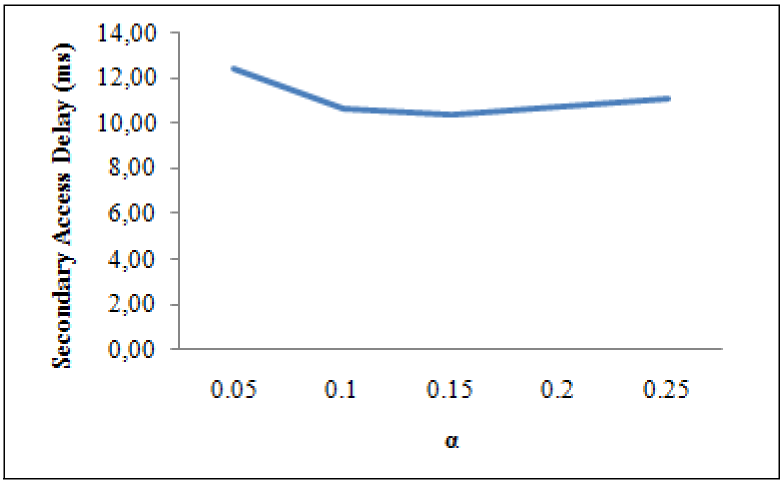

Figure 5.7 : SU access delay according to α under highly utilized environment

As shown in both figures, the best possible α value changes with the environment and should be between 0.1 and 0.2 in order to gain a better result. α should be used lower in low utilized environment, because the users chooses to stay in their current channel. Changing the data channel after each collision will decreases the performance.

Second case of the performance analysis of the parameters is change in U_c. Starting from 0.00 to 0.04 we get the results in the Figure 5.8 and Figure 5.9 that are shown below.

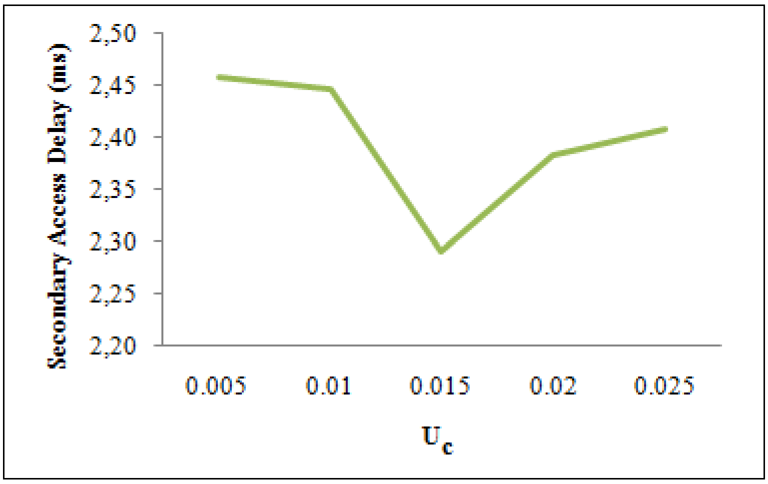

Figure 5.8 : Access delay of SUs according to U_c under low utilized environment

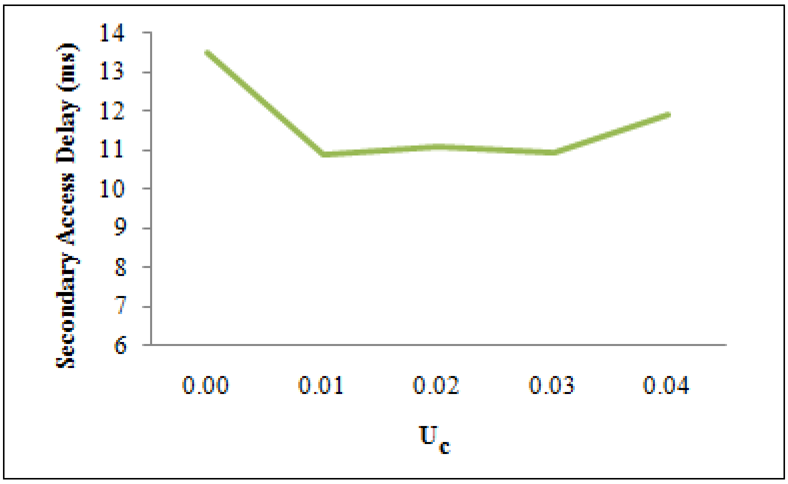

Figure 5.9 : Access delay of SUs according to U_c under highly utilized env.

As shown in both low and highly utilized figures, there is a range of U_c that should be defined. The static decrease made on dynamic state variables with the progress in time should be chosen around 0.01 and 0.03 to increase the performance of PROFOC in these environments.

In the last case, we will analyze the effect of change in $U_{\lim it}$ variable on the protocol. Starting from 0.45 to 0.85 we get the results in the Figure 5.10 and Figure 5.11 that are shown below.

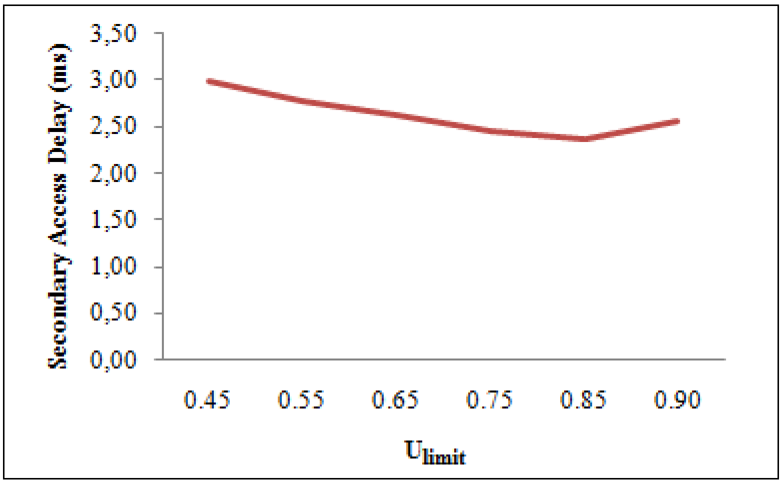

Figure 5.10 : Access delay of SUs according to U_{limit} under low utilized env.

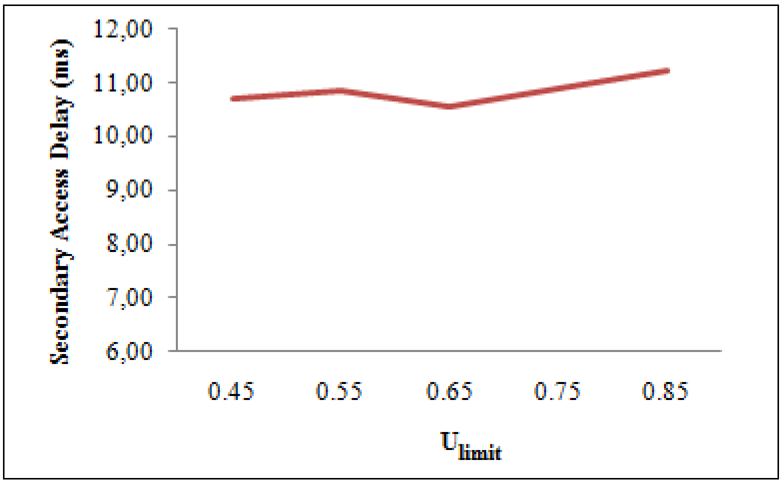

Figure 5.11 : Access delay of SUs according to U_{limit} under highly utilized env.

As shown in the figures, the protocol wants to decrease the number of handovers in low utilized environments. Increasing the primary request ratio of the channel resources will result SUs to search for a better environment.

In addition to increasing the performance by changing parameters, we tried to decrease the number of parameters of the protocol. Therefore, we have create CR-RAND protocol which chooses channels randomly in order to analyze the importance of the channel state variables. The result is shown in Figure 5.12.

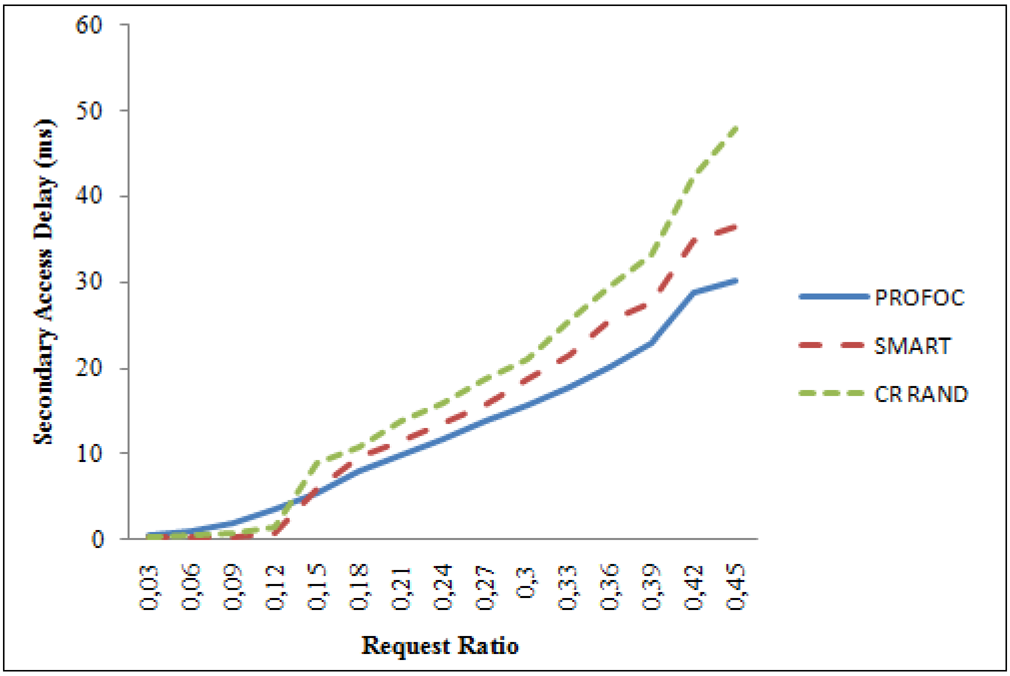

Figure 5.12 : Access delay of SUs, three MAC algorithms

Test results show that, the performance of CR-RAND decreases more than SMART MAC protocol only when the decision of the next operating channel will be selected randomly. Using channel state tables will increase the performance.

5.3 Analysis of Access Delay of PUs

Next simulation will show the importance of the t_{wait} parameter. We have stated in the previous chapters that limiting SU packet size to be under PU tolerance limit is not enough alone. The simulation results encourages our claim which is shown in Figure 5.13.

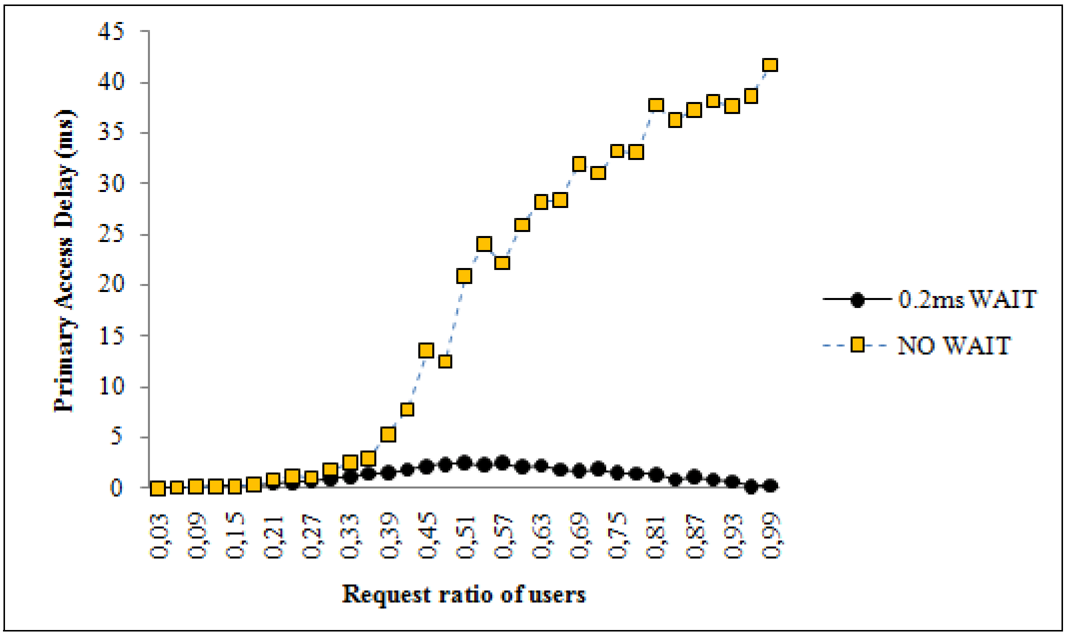

Figure 5.13 : Access delay of PUs according to request ratio of users I

As a last test, we have analyzed the access delay of PUs. We have defined the access delay analytically in the previous chapters. So, we could compare it with simulation results. In first case, we have increased both PU and SU request ratio to be changed from 0 to 1. The access delay of PUs are increasing until a value and then decreases for both analytic and simulation results. The reason for this is, request ratios of PU more than %50 will result, decrease in ratio of handling the channel of SU. Therefore, the spooling of PU and average access delay of PU are decreases as shown in Figure 5.14. The simulation results are near secondary packet size, not half of the packet size as we predict. Both the increase in number of packet collisions and behavior of Poisson distribution are cause this.

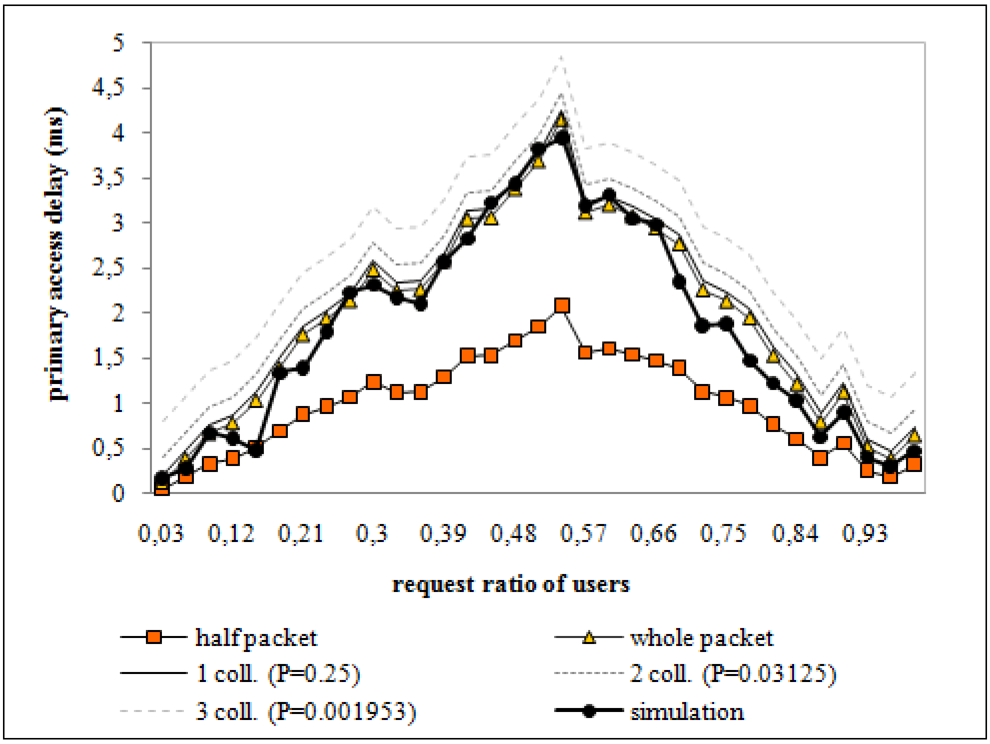

Figure 5.14 : Access delay of PUs according to request ratio of users II

In second case, we use static request ratio for SU. Primary request ratio still increases from 0 to 1. The comparison of analytical and simulation results are shown in Figure 5.15. As seen in both cases, we could limit the access delay of primary users by probabilistic approach. Simulation results are always lower than averagely 3-collision case. Also the probability is about 10^{-3}.

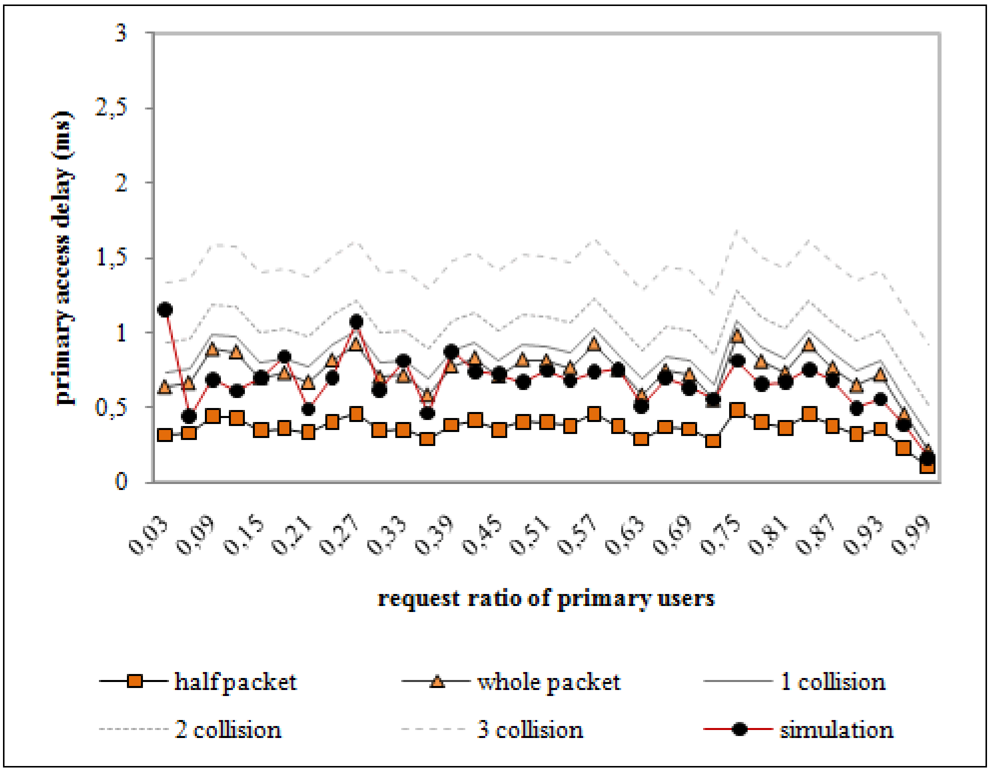

Figure 5.15 : Access delay of PUs according to request ratio of users III

In both scenarios, access delay is decreasing when the utilization increases to the limit because no SU could communicate under this platform. So, no SU results, no more access delay for PU.

6. CONCLUSION AND RECOMMENDATIONS

In this thesis, we have proposed an efficient MAC protocol for cognitive ad-hoc networks. PROFOC is a CSMA/CA based protocol that implements protection schemes for primary users while increasing the total throughput of the system. Dynamic channel state variables are used to select a proper data channel without sensing its current availability. This method minimizes spectrum handovers, which is a time consuming process. A discrete event simulator has been created in order to evaluate the proposed protocol. The results show that the proposed protocol is successful in protecting PUs, providing fairness in secondary communication and ensuring lower access delay compared to the smart random selection protocol.

We choose the bandwidth of the channels and the service request ratios of the secondary users to be identical for each case in the simulations in order to express the performance of the proposed protocol. However, the protocol has been also tested with channels that have distinct bandwidths and SUs that have variable request ratios. Results show that, regardless of the environment parameters, the three protection schemes are protecting the primary users and preserving their QoS.

Another comment is that the protection schemes and CW based design could be used with other channel selection methods than the mechanism with the channel state variables. We are expecting that protection for QoS of PUs and fairness in secondary communication will be supplied for other channel selection methods too.

In order to increase the performance of the protocol, we may use different k , U_c and a values for distinct channels with different attributes such as bandwidth, delay, etc. Thus, the CR device can choose better channels more frequently which will result an improvement on the total system performance. Calculation of proper parameters for different attributes is left as future work.

As a last discussion, the proposed protocol is prepared for spectrum overlay technique, where secondary devices are working with the same power level of PUs while protecting their QoS. However, the protection and fairness schemes could also be used for the spectrum underlay technique, where the power level of secondary communication is under the primary level. In this case, the primary communication will interrupt the secondary communication whenever it is necessary even if the secondary transmission is continuing at that moment.

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APPENDICES

APPENDIX A.1 : Proof of the lemma

APPENDIX A.1

After digitizing the series $\{k.2^n\}$ and $\{2^n\}$, we have the channel capturing probabilities as

$$P_1 = \frac{k-1}{k} + \frac{1}{k}\frac{4k-3}{4k} + \ldots + \frac{1}{k}\frac{2}{4k}\cdots\frac{2^{2n}k - 2^n - 2^{n-1}(2^n-1)}{2^{2n}k} \qquad \textbf{(A.1.1)}$$

$$P_2 = \frac{1}{k}\frac{1}{4k} + \ldots + \frac{1}{k}\frac{2}{4k}\frac{4}{16k}\cdots\frac{2^{n-1}(2^n-1)}{2^{2n}k} \qquad \textbf{(A.1.2)}$$

Then, we could write

$$P_1 = \sum_{m=0}^{n}\left(\frac{2^{m+1}k - 2^m - 1}{2^{m+1}k}\prod_{i=0}^{m-1}\frac{1}{2^i k}\right), \qquad \textbf{(A.1.3)}$$

$$= \sum_{m=0}^{n}\left(\frac{2^{m+1}k - 2^m - 1}{2^{m+1}k}\frac{1}{k^m}\frac{1}{2^{(m-1)m/2}}\right),$$

$$= \sum_{m=0}^{n}\left(\frac{(2k-1)2^m - 1}{2^{(m^2+m+2)/2}k^{m+1}}\right) \text{ and,} \qquad \textbf{(A.1.4)}$$

$$P_2 = \sum_{m=1}^{n}\left(\frac{2^m - 1}{2^{m+1}k}\prod_{i=0}^{m-1}\frac{1}{2^i k}\right), \qquad \textbf{(A.1.5)}$$

$$= \sum_{m=1}^{n}\left(\frac{2^m - 1}{2^{m+1}k}\frac{1}{k^m}\frac{1}{2^{(m-1)m/2}}\right),$$

$$= \sum_{m=1}^{n}\left(\frac{2^m - 1}{2^{(m^2+m+2)/2}k^{m+1}}\right). \qquad \textbf{(A.1.6)}$$

Hence, we could compare the probabilities **(A.1.4)** and **(A.1.6)** as

$$P_1 \geq \frac{k-1}{k} + \sum_{m=1}^{n}\left(\frac{(2k-1)(2^m-1)}{2^{(m^2+m+2)/2}k^{m+1}}\right),$$

$$P_1 \geq \frac{k-1}{k} + (2k-1)\sum_{m=1}^{n}\left(\frac{2^m - 1}{2^{(m^2+m+2)/2}k^{m+1}}\right),$$

$$P_1 \geq \frac{k-1}{k} + (2k-1)P_2. \qquad \textbf{(A.1.7)}$$

CURRICULUM VITA

Candidate’s full name:	Beycan Kahraman
Place and date of birth:	Eskicuma / Bulgaria [30.08.1983]
High School:	İzmir Fen Lisesi
Undergraduate:	ITU Computer Engineering [2007] ITU Mathematical Engineering [2008]