İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

A TOKEN BASED CONTROL CHANNEL PROTOCOL FOR COGNITIVE RADIO NETWORKS

M.Sc. Thesis by
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Department : Computer Engineering

Programme : Computer Engineering

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KAVRAMSAL RADYO AĞLARI İÇİN JETON TABANLI KONTROL KANALI PROTOKOLÜ

YÜKSEK LİSANS TEZİ

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FOREWORD

I would like to express my deep appreciation to my family for all their support and guidance that lead me through my educational life. Their deep appreciation has encouraged me to take the steps towards my objectives.

I also want to thank my advisor Assist. Prof. Feza Buzluca for his guidance during my undergraduate and master education.

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Computer Engineer

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ABBREVIATIONS

DSA	: Dynamic Spectrum Access
MAC	: Medium Access Control
CR	: Cognitive Radio
PU	: Primary User, Licensed User
SU	: Secondary User, Unlicensed User
LC	: Licensed Channel
CC	: Control Channel
FCC	: Federal Communications Commission
NTIA	: National Telecommunications and Information Administration
CSMA/CD	: Carrier Sensing Multiple Access with Collision Detection
CSMA/CA	: Carrier Sensing Multiple Access with Collision Avoidance
IEEE	: Institute of Electrical and Electronics Engineers
RTS	: Request to Send
CTS	: Clear to Send
THT	: Token Holding Time
TRT	: Token Rotation Time
TTRT	: Target Token Rotation Time
TTL	: Time to Live
Mbps	: Mega bits per second

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A TOKEN BASED CONTROL CHANNEL PROTOCOL FOR COGNITIVE RADIO NETWORKS

SUMMARY

Cognitive radios are devices with multi-channel operation capabilities. They can work on a part of the spectrum instead of just one channel (frequency band). The necessity for a multi-channel system occurred since the wireless spectrum is clogging because of the static frequency assignments made so far. There are researches that study on adapting current radio systems to work with multiple channels. However, cognitive radios support multi-channel operations both with hardware and software innovations. They have the capability to change their transmission channels without disturbing the user during communication.

The wireless frequency spectrum is clogged but it is underutilized at the same time. Especially TV frequencies are scarcely used by license owners. The idle times of the frequencies are referred to as white spaces. The purpose of developing a cognitive radio is to utilize those white spaces and serve more users with current frequencies.

There are many challenges of cognitive radios, which are very different than the problems of previous network systems. First of all, the station equipped with a cognitive radio (secondary user) should sense the spectrum to eliminate the channels with licensed user activity and to search white spaces. Then, after white spaces are found spectrum management is needed to select the best channel that meets user requirements. After that, secondary user should compete with other secondary users around it for the channel that it selected. This operation is spectrum sharing and a substitute of MAC protocols of previous networks. Spectrum sharing is a challenging protocol of cognitive radio systems since the secondary users are not always tuned to a fixed channel. There is a need to dedicate a common channel that all users will meet. This channel is common control channel and is a vital component of spectrum sharing protocols. Common control channel serves all users and all control information is carried over it. Saturation of the control channel is unavoidable since a small portion of spectrum is reserved for it.

In this thesis, a token based protocol for control channel is proposed to solve saturation problem of control channel without increasing the bit rate. The protocol was evaluated with a discrete event simulator and results were compared with a carrier sensing protocol. The simulation results show that proposed protocol has better channel utilization and lower response delay.

KAVRAMSAL RADYO AĞLARI İÇİN JETON TABANLI KONTROL KANALI PROTOKOLÜ

ÖZET

Kavramsal radyolar, çoklu kanallarla çalışabilme yeteneğine sahip telsiz cihazlardır. Tek bir kanalda (frekans bandı) çalışmak yerine, frekans spektrumunun bir bölümünü kullanabilirler. Çoklu kanal kullanan sistemlere duyulan ihtiyaç frekans spektrumunun sürekli statik atama yapılmasından dolayı dolmasıyla ortaya çıktı. Belli spektrumlar lisanslı kullanıcılara ait olduğu için diğer kullanıcılar bu frekanslardan faydalanamazlar. Bunun yanı sıra pek çok lisansı alınmış frekans bulunmasına rağmen hepsinde etkin kullanım yapılmamaktadır. Özellikle televizyon yayınlarına ayrılan frekans bantların doluluk oranları düşük düzeydedir.

Daha önce de şu an kullanılan tek frekanslı sistemleri çoklu frekansa uyarlama çalışmaları olmuştur. Bu çalışmalarda kullanılan frekanslar yine belli aralıklarda kalabilmektedir. Kavramsal radyo ise tamamen çoklu kanallarda çalışmak için geliştirilmiş; hem donanımsal hem de yazılımsal destek sağlayan bir sistemdir. Lisanslı kanalları dinleyerek frekanslardaki boş alanları bulur ve iletişim için bu boşluklardan faydalanır. Bu sayede aynı sayıda frekans bandıyla daha fazla kullanıcıya hizmet edilir.

Kavramsal radyoları geliştirmede yeni teknik problemler ortaya çıkmıştır. Öncelikli olarak kavramsal radyo kullanan kullanıcı (ikincil kullanıcı) tüm frekans bantlarını tarayarak birincil (lisanslı) kullanıcıların boş bıraktığı alanları bulmalıdır; bu işleme spektrum sezme denilmektedir. Eğer spektrum genişse bu tarama işlemi uzun sürebilir. Bu boşlukları bulduktan sonra spektrum yönetimi başlar. Bulunan boşluklardan kullanıcının ihtiyaçlarına en uygun olanı seçilmelidir. Bu işlemlerden sonra spektrum paylaşım işlemi yapılması gerekir. Spektrum paylaşımı, şu anki sistemlerdeki MAC protokollerinin görevini yerine getirmektedir. Paylaşım kavramsal radyo sistemlerinde tasarlanması zor bir iletişim yöntemidir. İkincil kullanıcılar belli bir anda farklı farklı frekans bantlarında bulunabileceğinden, her kullanıcının bildiği atanmış bir kanalın belirlenmesi gerekir. Bu atanmış kanala kontrol kanalı adı verilir. Kontrol kanalı tüm kullanıcılara hizmet verdiği ve tüm kontrol verisini taşıdığı için tıkanmaması ve hızlı olması gerekmektedir.

Bu çalışmada kontrol kanalı için jeton tabanlı bir protokol geliştirilmiştir. Bu protokol sayesinde kanalın hızı artırılmadan performansının artırılması hedeflenmiştir. Protokolü denemek için bir ayrık olay simulatörü tasarlanmıştır ve sonuçlar çakışmalı bir protokolün sonuçları ile karşılaştırılmıştır. Simulasyon sonuçları jetonlu sistemin kanal kullanım oranını artırdığını ve kontrol kanalından alınan cevap süresini kısalttığını göstermiştir.

1. INTRODUCTION

Wireless networks are growing and spreading day by day since they are easy to deploy and low in cost. Many organizations ranging from military to commercial ones are trying to deploy their own wireless networks. However, that ease of use revealed a disadvantage of wireless systems. As the number of the demands increase, the frequency spectrum that can be used becomes fully occupied caused by the static spectrum assignments to the license owners. Licensed owners not only prevent the others to use their part of the spectrum but also waste the valuable resources by underutilizing them. Especially, television bands are used very scarcely and they are accepted as underutilized.

Dynamic spectrum access (DSA) has drawn much attention as a solution to utilize the spectrum. The idea basically depends on the development of a radio which has the ability to sense and make decisions about the spectrum, satisfy user needs and adopt heterogeneous wireless architectures. Developing such a radio with traditional radio hardware is difficult so software defined radios that can simulate all hardware functionalities came forward. The first design of such a device was suggested by J. Mitola III in 1999 and named as *cognitive radio* [1]. In his dissertation in 2000, the definition of cognitive radio was "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." [2].

Cognitive radio has application areas like government, public safety, commercial and military. Military and public safety applications are in researching stages of this technology [3,4].

From the day cognitive radio was introduced, there have been many researches ranging from increasing spectrum sensing abilities to network layer solutions. One of the important topics is spectrum sharing issues of cognitive radio. Cognitive radios should have the capability of sharing the underutilized spectrum with licensed users and with each other. The fundamental difficulties that arise are synchronization of sender and receiver stations and handovers done when a licensed user, which will be referred as primary user (PU) for the rest of the thesis, arrives. The cognitive radio stations, which will be referred as secondary users (SUs) or unlicensed users for the rest of the thesis, can work on any frequencies due to their adapting capabilities. Therefore, there must be a common way of distributing control information between SUs or otherwise communication parties may never meet on the same frequency to perform their handshakes. Many researches cover that issue and they propose different solutions like distributed or centralized approaches, cooperative or non-cooperative approaches [5]. All these solutions mostly need a dedicated common control channel that all SUs would listen. There are researches that propose a solution without a common control channel but they need either central control, awareness about the neighbors on all channels or synchronization between SUs [6,7,8].

Dedicated common control channel is a predetermined frequency band that is known by all SUs. SUs share control information on that channel and perform their data transmissions on other licensed channels (assuming the underutilized spectrum consist of many licensed channels). Thus, a protocol that all users would obey should be developed for common control channel. Control channel has a vital importance for cognitive radio networks to overcome issues like synchronization and spectrum management. Some researches that use common control channel need synchronization between SUs or between control channel and the licensed data channels [9,10]. Another approach is to perform carrier-sensing methods on control channel [11]. However, carrier-sensing method has its challenges when number of control packages increase in the network. As the collision rate increases, the control channel becomes saturated and delay time of the control channel gets longer. That is a vital disadvantage for a cognitive system since SUs only has a limited time to capture a licensed data channel (LC) before a PU gets in the way.

In this thesis, a token based control channel protocol is proposed to overcome the problems mentioned above. Proposed protocol uses two transceivers; one is for communications on control channel and the other is for communications on LCs. Thus, two communications can be performed simultaneously. Since token rotation time in the network is predictable and stable, the response from the control channel is gathered more quickly and jittering is minimized. In addition, the global information about the network is kept inside the token so decision-making process of the SUs is easier.

The thesis is organized as follows.

In section 2, information about cognitive radio systems, their purpose and challenges, application areas and architectures is given. In section 3, some brief information about MAC protocols is given. Especially, carrier sensing based and token based protocols are explained and compared. Description of the proposed protocol is given in section 4. In section 5; simulation environment, network environment and information about the results are given. Finally in section 6, conclusion and future work are discussed.

2. COGNITIVE RADIO

Cognitive radio is a wireless device with capabilities of changing its working channel, communicating with different modulations and encodings, satisfying user needs and adapting heterogeneous architectures. It is considered as an intelligent radio that is aware of its surrounding environment. Since creating a device with those abilities is challenging with traditional radio devices, cognitive systems are considered as an evolution of software defined radios.

2.1 Software Defined Radio

Software defined radio (SDR) is a system where all the abilities that are implemented by hardware before, will be implemented by software. It is hard to give an exact definition of SDR since it is a flexible system. However, an ideal system should be a closed box, which gathers the RF signals as an input and releases digital processed outputs as shown in Figure 2.1.

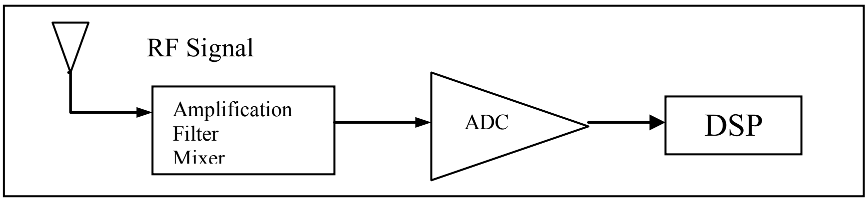

Figure 2.1 : A representational figure of SDR

SDR is preferred in conditions that need flexibility in execution and simplicity in hardware. The architecture and challenges of SDR is not explained in this thesis in detail since the proposed protocol focuses on cognitive radio and MAC layer issues. SDR just covers the basics of the physical necessities of the cognitive radio. A more detailed research can be found in [12].

2.2 Application Areas

Cognitive radio systems are suitable to most applications that need wireless communication. Especially, networks those are difficult to maintain with central units or vulnerable to frequency errors or base station failures. First researches about cognitive radio have drawn attention from public safety and military applications. Spectrum management agencies started to take actions in realization of cognitive systems. Federal Communications Commission (FCC) and National Telecommunications and Information Administrator (NTIA) took steps to open certain parts of the spectrum to secondary users [13].

Military applications are an ongoing area of cognitive radio networks. The ability to change operating frequencies easily, conducts a safer and faster way of communication. This flexibility not only provides a robust transmission but also a wide range of listening capabilities which will be useful to detect intruders.

2.2.1 Real-Time Demanding Applications

Cognitive radios are good systems for many wireless applications but real-time applications can be challenging. The basic rule of a creating a secondary communication system like cognitive radio, is to give priority to PUs. Thus, communication can be interrupted because of an appearance of a PU on LC. Every interruption causes SUs to lose time and delay their next package. Therefore, there is a necessity for a good spectrum management and a control channel protocol.

Public safety applications are a good example since they are mostly voice and video communications. They are urgent and mostly used when central based networks are down. Especially, broadband services will shorten the response time of rescue operations in emergencies [14].

Multimedia applications like 3G need wide spectrum portions, which again consist of real-time communications as voice and video. In reference 15, J. Mitola III proposes a spectrum management method to “expand the bandwidth available for conventional uses (e.g., police, fire and rescue) and extend the spatial coverage of 3G”.

2.3 Cognitive Radio Functionality

Cognitive radios operate very differently from current radios and they have different functions in or cross-architectural layers. There are some fundamental objectives of designing a cognitive radio; spectrum sensing, spectrum management, spectrum mobility and spectrum sharing [5].

Cognitive radios have basic roles like sensing the environment around them and making the right decisions about the spectrum. They should find the unused time periods on LC, which are called *white spaces*, and use them if they fit user requirements. In Figure 2.2, the sensing operation of a cognitive radio is shown.

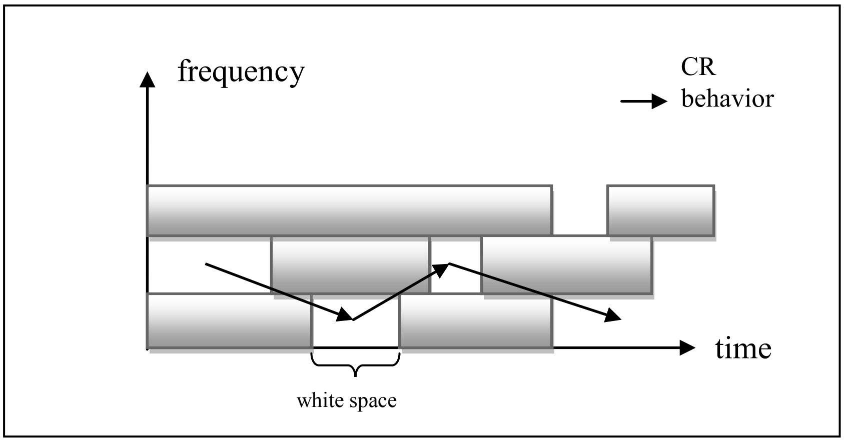

Figure 2.2 : Behavior of a cognitive radio on licensed channel with licensed users

Sensing is a time consuming process for multi frequency systems like cognitive radio. Detecting a licensed user activity on a channel with minimum error and repeating the same for every channel is an important research topic. References from 16 to 18 are some examples of these researches.

After sensing the LC and finding white spaces, another function of the cognitive radio takes action; spectrum management. Spectrum management is the process of selecting the optimum channel that meets user demands. User QoS requirements can be heterogeneous and time bound. Not only one layer of the radio architecture serves for spectrum management; it is cross layer functionality. Figure 2.3 shows the functionalities of the layers.

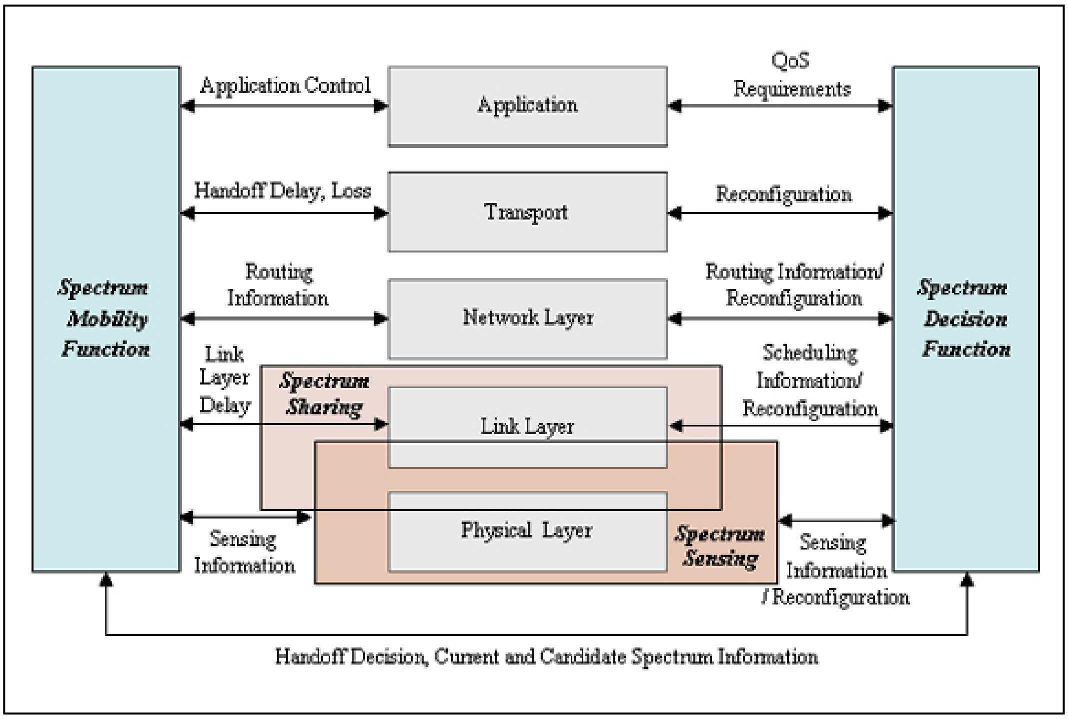

Figure 2.3 : Functions of the layers in cognitive radio systems

The functionalities mentioned above are performed to find the white spaces and make decisions about which one to choose. However, as soon as a licensed user activity is sensed on the channel, unlicensed ones should evacuate the licensed channel. Thus, cognitive radio should have the ability to make handoff from one channel to another during communication. Handoff should be soft and quick to prevent disturbing user's communication. Reference 19 is an example of such a study for spectrum mobility.

The last function of CR is spectrum sharing which will be handled in the next section with more detail since the thesis works on that subject.

2.4 Spectrum Sharing

Spectrum sharing is the function that controls and organizes the activities of SUs in a cognitive radio network. It is the equivalent of MAC protocol in traditional wireless networks. The basic challenge of developing a spectrum sharing protocol is the handshake between sender and receiver. There are many different channels that a SU might be listening at a moment and sender should find a way to inform the receiver about its request. Even when they achieve to meet on a channel and start communication, as soon as a PU activates, they have to leave and agree on a different channel.

Spectrum sharing has two approaches: cooperative or non-cooperative. In cooperative approach, users share their information with each other and decide which channels to use or not. On the other hand, non-cooperative approach depends on the information that the SU gathers from its observations; a more selfish approach. Both approaches mostly need a dedicated common control channel to share global and control information about the network. There are solutions without a control channel too but they need synchronization, which can be challenging for distributed systems [6,20].

MAC layer with control channel can be implemented with different kind of protocols. Many researches range from time division based control channels to carrier sensing based ones are available in the literature. However, the problem of the control channel is that it can become saturated at peak times of the network traffic.

2.4.1 Challenges of a Control Channel Protocol

In cognitive radio networks, SUs are considered as migrant users since they capture the channels only if there is no PU activity. It is hard to find a dedicated channel for such systems for two reasons. First, all SU should be informed of this channel before they start any communication. Second, the selected channel should be available enough to satisfy user requests but PU activity makes it difficult. Many researches assume a dedicated control channel is available and informed to the SU by default [9,10,11]. Some other try to resolve this problem by dynamically determining control channel [21,22,23].

A problem of the solutions with dedicated control channel is saturation when requests increase. Especially, when carrier-sensing protocols as CSMA/CA is used control channel becomes saturated quickly. Frame based and synchronized systems do not have that risk but those are difficult to implement for migrant architectures like cognitive radio. Other disadvantages of carrier sensing schemes will be handled in section 3.

These challenges make it difficult to develop a spectrum sharing protocol for cognitive radios. Spectrum sharing is easier with a control channel but control channel has its own obstacles that need to be solved.

3. MAC PROTOCOLS

There are many technologies introduced for accessing common medium in wireless networks. As the technology evolves, throughput of the networks increases and delays decrease. Even wireless systems become more reliable and robust day by day. Every access protocol introduced has its advantages and disadvantages and they are suitable for different kind of applications. Those medium access protocols serve in the data link layer of the nodes in networks.

The medium access control layer, which is a part of the data link layer, is above the physical layer in OSI model and responsible for data transmission between two adjacent nodes in a network. Multi-hop transmission is not the concern area of this layer. A safe link between the sender and receiver should be created to transmit the data correctly and quickly on the common medium (Figure 3.1). When the number of the users increases, the common medium becomes more and more loaded and collision rate increases. A good medium access scheme should minimize data collisions and package delays.

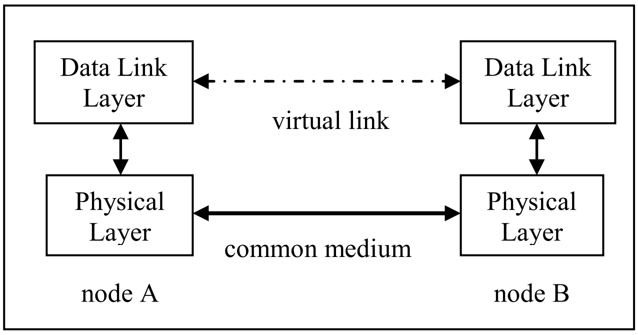

Figure 3.1 : Representation of data link layer and physical layer

In this section, two of these schemes will be described and compared: carrier sensing multiple access with collision avoidance (CSMA/CA) and token based.

3.1 CSMA/CA Protocol

CSMA/CA is a contention based medium access technique that has a precaution to prevent collisions. It is more convenient for wireless networks than CSMA/CD (collision detection) since it is impossible to detect a collision in wireless medium. CSMA/CA uses carrier sensing to detect any other node’s activity on the medium. *Carrier sensing* means listening the physical medium (carrier) for any activities. If there is no activity detected on the medium for a predetermined duration, node transfers its data. However, if the medium is busy transfer is delayed for random length duration (binary exponential back off). The node with shortest duration of delay wins the contention. Therefore, collisions are prevented and throughput is increased.

CSMA/CA was introduced with the popular IEEE 802.11 standard and is widely used by wireless networks [24].

3.1.1 Application areas of CSMA/CA

CSMA/CA has a wide range of application areas since it provides a good performance when requests from the nodes are at normal rates and number of the nodes is not very high. Actually, it is used everywhere the IEEE standard 802.11 and its variations are used. Commercial usage is the most common area from home users to companies. However, CSMA/CA protocol is not suitable for real-time applications since it is prone to long access delays caused by collisions during contention phase. The latency is not predictable and jittering is high.

3.1.2 Disadvantages of CSMA/CA

Wireless networks have two important problems like hidden terminal problem and exposed terminal problem. CSMA/CA solves these issues mostly by using two way handshakes. RTS and CTS packages are sent between sender and receiver to inform each other and the nodes around them. However, this is not a certain solution for exposed terminal problem (Figure 3.2).

Another disadvantage is the high collision rate when the requests from the nodes are frequent. Every random delay after the collisions increases the access delays of the packages.

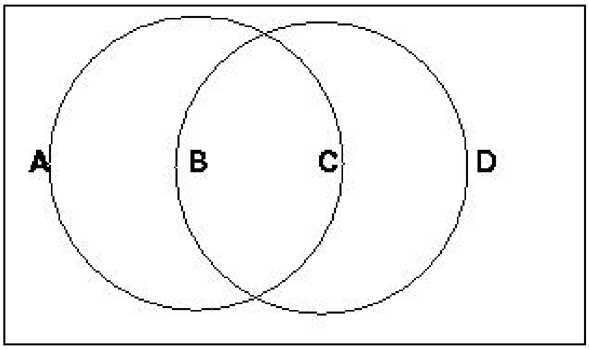

Figure 3.2 : While node B is transmitting to node A, node C is exposed even though it wants to transmit to node D.

3.2 Token Ring Protocol

Token based protocol is a contention free medium access protocol that is free of collisions and is an easier implementation of fairness. They are more useful at highly loaded networks with frequent requests. They are robust and delays are predictable and short, so the throughput of the network increases.

Token based networks organize the medium access by transmitting a token between logically adjacent nodes. The node that captures the token has the right to send its data packages for a limited period. The arrangement of the nodes can be adjustable to give priorities to certain nodes; otherwise, all the nodes have the same chance of occupying the medium since the circulation of the token creates a virtual ring like Figure 3.3.

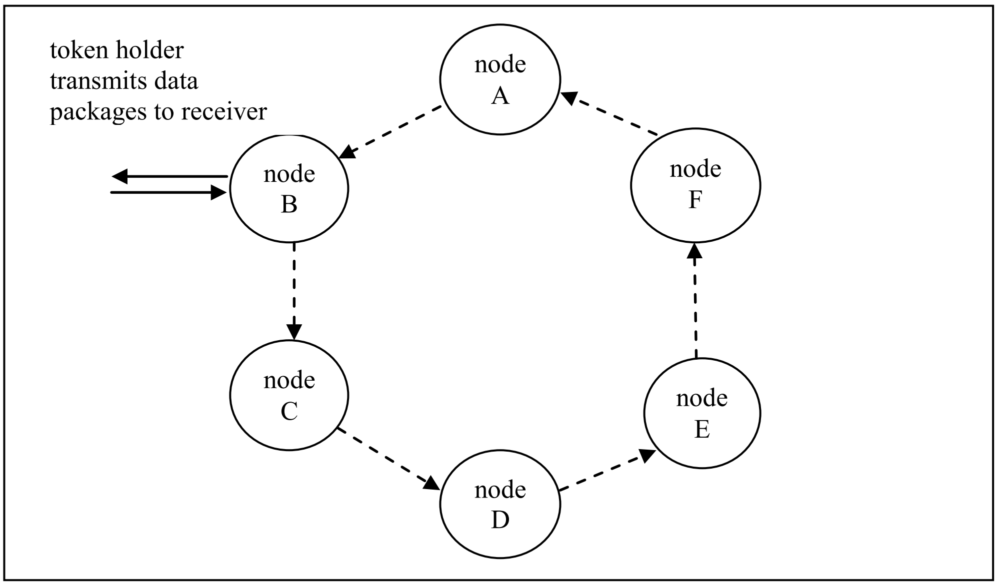

Figure 3.3 : A virtual token ring

There are two types of data transmission in timed token ring networks: synchronous and asynchronous. In timed token ring networks, every node has a token holding time (THT) determined and uses this time from the moment it captures the token. In addition, there is a target token rotation time (TTRT) which is predetermined and nodes try not to exceed this limit by observing the token rotation time (TRT) every time the token circulates. The synchronous data transmission is done during THT, so the length of this parameter is critical. If it is too long, TRT will grow and it will become difficult to serve quickly. The asynchronous data transmission is only done when current TRT is smaller than TTRT and the node has packages to send in its queue. Therefore, selection of TTRT is important too since short TTRT causes low throughput and long TTRT causes unpredictable delays.

3.2.1 Application areas of token ring protocols

Timed token based protocols are known to be predictable because of the predetermined TTRT. There is always a chance of transmitting data for every node at every circulation of the token so it is fair. There is no time wasted because of collisions and back-offs so jittering is little and maximum delays are limited.

These entire properties make token based systems good candidates for real-time applications. In addition, other critical applications that need a stable and robust protocol can benefit from these features.

3.2.2 Disadvantages of token ring protocols

Token based protocols are not suitable for large scale networks since TRT becomes too long. Multiple rings can be used in those network types but new inter-network protocols are necessary for such applications.

3.3 Comparison of CSMA/CA and Token Ring Protocols

In previous sections, we gave the advantages and disadvantages of both protocols. Collecting all the information will expose the reasons of selecting a token based protocol for this thesis.

- The CSMA/CA protocol is a contention based system unlike token based protocol so collisions occur frequently.

- The CSMA/CA protocol is not predictable and consecutive collisions may cause very long access delays even though the medium is available to transmit.
- The CSMA/CA protocol does not quarantine fairness since it is a random access based system. However, token ring gives every user a chance.
- All three reasons above causes the throughput of the network to decrease, especially in high loaded networks.

The purpose of the thesis is to develop an efficient control channel protocol for high loaded cognitive radio networks. The nature of this kind of systems is being migrant so long access delay is a serious drawback for a control channel protocol.

4. A TOKEN BASED CONTROL CHANNEL PROTOCOL FOR COGNITIVE RADIO NETWORKS

The major purpose of this research was to develop a control channel protocol for cognitive radio networks. In section 2, a brief explanation of a cognitive radio is given. Since there would be many channel handoffs, which means the number of requests to control channel would increase, the protocol chosen for the control channel should prevent saturation. In section 3, two popular MAC layer protocols for wireless networks were introduced. Cognitive radios need more complex solutions for spectrum sharing than just a medium access protocol but those two are good candidates for control channel approaches. The comparison made in section 3.3 shows that token based protocol is more suitable for our purpose.

Our study implements a control channel protocol that carries all necessary global information of a cognitive radio network inside a token. All LC information and other control data are carried to SUs by the token so everybody has a clear view of the network and the spectrum. The protocol needs two transceivers to work on both control channel and other LCs (data channels) at the same time. One transceiver listens to the control channel constantly; captures and releases the token, while the other one makes data transmission on LCs (Figure 4.1). Control channel and licensed data channels are two parts of the frequency spectrum that a SU, thus a cognitive radio, has the ability to listen and transmit. The control channel is a smaller part of the spectrum since more space for licensed data channels would increase the throughput. That is why control channels have saturation problems with contention-based protocols.

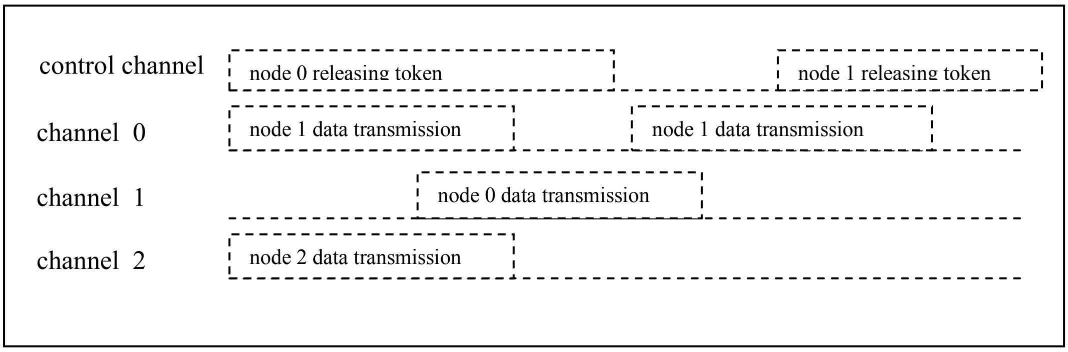

Figure 4.1 : A visualization of the spectrum at a moment

The proposed protocol only focuses on the operations on the control channel in which the token circulates. The operations on licensed data channels (LCs), thus data transmissions and connections, are generic and can be developed according to network necessities. The protocol only gives the advantage of carrying all information about LCs in the token; thus, spectrum management becomes easier.

In order to compare our results with another control channel protocol, we also designed a CSMA/CA protocol and adapted it according to cognitive radio necessities. The details of the protocol will be given in section 5.2.

Before explaining the proposed token based protocol mechanism, the structure of the token will be given.

4.1 Token Structure

The token consist of many fields that represent either global network variables or information about the spectrum. The structure of the token is in Figure 4.2. The length of the token depends on the number of the SUs in the network and number of the channels in the spectrum. The function of every field is explained below.

- *Preamble:* Physical header used to synchronize with the destination. 128 bits used.
- *Destination ID:* The id of the next station that will receive the token. 6 bits are reserved for the field.
- *NoC:* The number of the channels in the spectrum. 6 bits are reserved for the field.
- *NoAC:* The number of the channels that are not occupied by any SU (number of available channels). 6 bit reserved for the field.

- *NoN:* The number of the active SUs in the network. 6 bits are reserved for the field.
- *utilization:* The utilization of each LC is kept in the field. Utilization is observed by an external component and inserted into the token. 4 bits are reserved for the channel since there are ten grades of utilization. While grade 0 represents an empty LC, grade 10 means the LC is totally utilized by a PU.
- *channel occupation:* The occupation information of every LC is kept in this field. One bit is reserved for each LC and the default value of every subfield is NOT_OCCUPIED. When a SU wants to start a communication, it selects an LC and changes its subfield to OCCUPIED. Length of the field is the number of LCs.
- *destination node occupation:* The occupation information of each SU in the network is kept in this field. Each subfield reserved for a SU is 6 bits and has a default value NOT_OCCUPIED. When a SU wants to communicate with another, it writes the number of the selected channel into the destination's subfield. Thus; when destination reads the token and realize that its subfield's value is a channel number, it tunes its second transceiver on the selected channel. The length of the field is the number of the SU times six (6 bits used to number LCs).
- *EOT:* The bit sequence that informs the end of token.

P M	destination ID	NoC	NoAC	NoN	utilization	channel occupation	destination node occupation	e o t

Figure 4.2 : Token Structure

4.2 Token Based Protocol for the Control Channel

The proposed protocol makes data transmission parallel to the token transmission so data transmission does not affect the THT. Every SU holds the token just if they need an LC to start their connection with the destination. Therefore, the TRT (T_c) is predictable and shorter as shown is equation (4.1).

$$T_c = \sum_{i=0}^{N} T_{ij} \tag{4.1}$$

where N is the number of SUs in the network and T_{ij} is the transmission time of the token from node i to node j. The transmission of the token is related to the length of the token (L_T), bit rate of the control channel (R_c) and propagation delay (τ).

$$T_{ij} = \frac{L_t}{R_c} + \tau \tag{4.2}$$

Propagation delay can be ignored since nodes are considered to be close to each other.

4.2.1 Protocol operation on the control channel

The nodes in the network (SUs) have requests from upper layers, which are waiting in their queue. When a request reaches to the top of the queue, the node starts to wait for the token to arrive by listening to the control channel. As soon as the token is captured, the SU checks the *NoAC* field to see if there is any available LCs for data transmission. If there is one, or more, the channel with lowest utilization is selected according to the *utilization* subfield of the token. The bit reserved for the selected LC in the *channel occupation* field is changed to OCCUPIED and *NoAC* is decreased by one (Figure 4.3). Also, destination SU should be informed about the connection so *destination node occupation* field is updated. Sender writes the number of the selected LC to the six bits subfield reserved for the intended node.

not_occupied	occupied	occupied	----------------	not_occupied
channel 0	*channel 1*	*channel 2*		*channel M*

Figure 4.3 : A view of *channel occupation* field of token at a random time

After capturing an LC, second transceiver tunes to that channel and prepares to send data packages. The procedure of this other MAC layer issue will be explained in section 4.2.2.

If token arrives during an ongoing connection, it is transmitted immediately without holding. However, if a token arrives after connection ends then SU checks the *NoAC* field. If there is no available LC left, the SU releases its own to give subsequent SUs a chance to capture an LC. In the case of available channels, the SU controls its request queue; if there is a request waiting, the current selected LC is not changed but the subfield of the destination node in *destination node occupation* field is updated if it is necessary. Previous destination's subfield is updated to be NOT_OCCUPIED and current destination's subfield is updated with the current selected LC. The behavior of SU is explained with a flowchart in Figure 4.4.

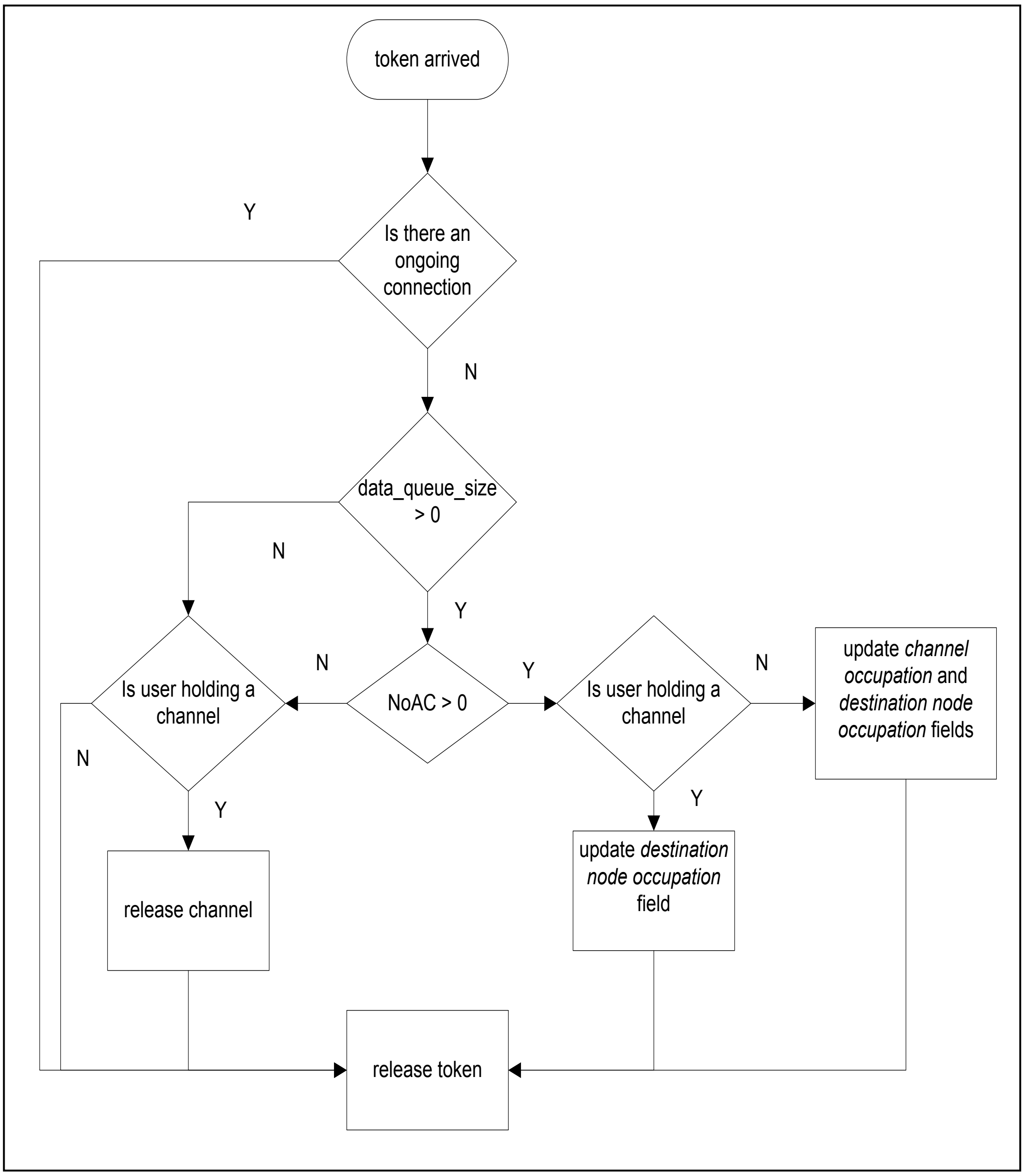

Figure 4.4 : Flowchart for behavior of secondary users on control channel

In order to release a channel after ending a connection, SU has to wait for the token to arrive. When it arrives, the subfield of the channel to be released is modified as NOT_OCCUPIED in *channel occupation* field and *NoAC* is increased by one.

4.2.2 Data transmission on licensed data channels

The thesis proposes a protocol for control channel, which is a part of the MAC layer. The MAC layer protocols should also have the ability to organize data transmission along with control data transmission. However, in cognitive systems with dedicated control channel; licensed channels and control channel are not dependent so there is no need for a specific sub-protocol for data transmission on LCs. The proposed control channel protocol is generic and can be used with different types of spectrum sensing and management protocols which are responsible for data transmission operations in cognitive networks. In order to perform our simulations and proper evaluation of the LC utilization, we created a protocol to organize SU behavior on LCs too.

The important rule of cognitive radio networks is to disturb primary user as low as possible. In our protocol, package length of SUs is limited (T_{su}^{max}) to keep interference, if occurs, at a minimum level. Limit T_{su}^{max} should be much shorter than typical PU connection durations. Even though the transmission of a PU starts at the middle of a SU package transmission, disturbance will be T_{su}^{max} at a maximum. However, limiting the length of packages is not enough by itself to reduce disturbance since if SU packages are consecutive, total length of them will exceed T_{su}^{max}. Therefore, before every package transmission SU should listen to the LC and make sure that no PU is active on it for a specific duration. This duration is idle waiting time (T_w) of SUs. As soon as SU detects the LC to be idle for T_w duration, it starts to send its package. Figure 4.5 shows this behavior of SUs on LCs.

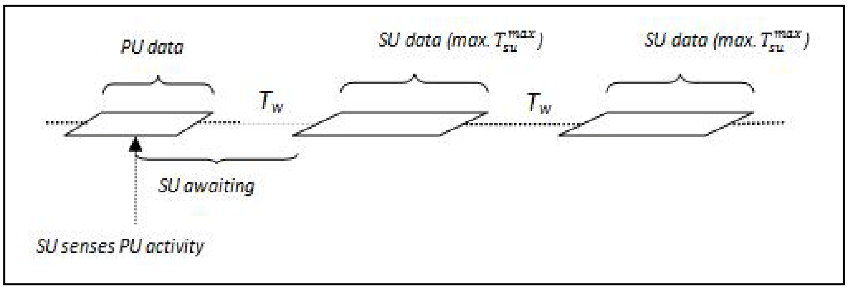

Figure 4.5 : Secondary user behavior on licensed channel

On the other hand, the protocol should protect SUs too since waiting for PU to end its conversation can cause excess access delays. Secondary users have a waiting limit (L_{su}) and after this limit is exceeded, SU tries to find itself a new LC. Although changing channel causes a loss of time too, it is known that PU connections are very long compared to SUs'. That is why; handoff becomes a better choice than waiting for PU to leave. In proposed protocol, SUs cannot change their current LC without capturing the token so when L_{su} is exceeded and token arrives, the disturbed SU would try to change its current channel. Figure 4.6 shows that behavior of secondary users on licensed data channels.

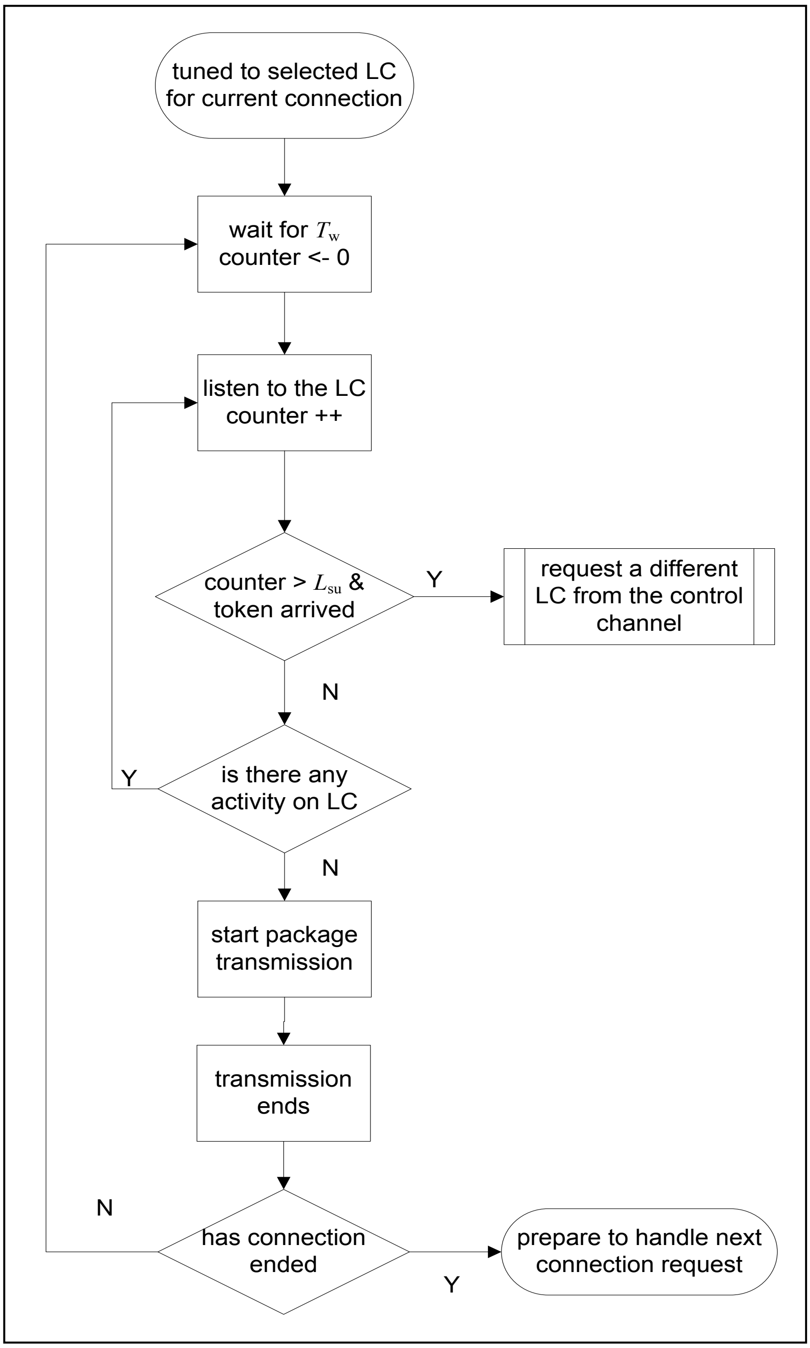

Figure 4.6 : Flowchart for behavior of secondary users on licensed data channel

5. SIMULATION

5.1 Simulation Environment

The network consists of N secondary users and M licensed channels. Primary users are active on the licensed channels with utilization γ and secondary users are active with utilization ζ. All secondary users are sender nodes so N nodes try to get reply from the control channel during simulation.

The token starts from a SU and all nodes are visited in a specific order. There are no priorities for SUs since the purpose of the protocol is not priorities. The protocol should enhance the performance of the control channel and be fair. All link failures (control or licensed channels) are neglected. There is no time-to-live (TTL) defined for the data packages since maximum response delays were observed in simulation results.

5.1.1 Request pattern of secondary and primary users

Primary users are the licensed users who have priority on licensed channels. The purpose of the cognitive radio systems is to provide a better usage of underutilized licensed channels so the PU activity on the LCs that the protocol runs would be an ON/OFF Markov chain behavior. The channels are sometimes busy with the PU activity but mostly they are empty. That is an important parameter for the simulation which was mentioned as PU utilization (γ_i) above and can be represented as in (5.1).

$$\gamma_i = \frac{\mu_i}{\mu_i + \lambda_i} \tag{5.1}$$

where μ_i is the busy duration of a channel and λ_i is the idle duration of a channel. The definition of SU utilization ζ is the same. When ζ is equal to 0.1 for a SU, the arrival rate of request to the queue of that SU is enough to keep the channel busy for the 10% of total channel time. Requests for both user types are independent and identically distributed. Request arrivals are Poisson random processes and connection durations are exponential. Even though there might be longer connections, it is assumed that SUs do fragmentation so that they won't exceed T_{su}^{max} .

5.1.2 Simulation parameters

There were some parameters to be determined before executing simulations. These parameters were selected to give best performance of the proposed protocol.

Table 5.1 : Simulation parameters

Parameters	Values
R_c (Bit rate of control channel)	1 Mbps
R_d (Bit rate of a licensed channel)	1 Mbps
PHY header	128 bits
T_{su}^{max}	10 ms
Lsu	1 ms
T_w	200 μs

The maximum interference time is determined as 10 ms so PU connections have a longer mean package length. The number of secondary users is always equal to or less than number of licensed channels (N≤ M) since response delay will be affected if there are not enough licensed channels. We only want to observe the response delay in a normal operation of the network. As it will be explained in the next section, our proposed protocol is compared with a CSMA/CA based protocol. In a situation where there aren't enough LCs for SUs (M < N), the calculation of the response delay differs between protocols. The CSMA/CA based protocol does not make a request to the control channel when there are no available LCs. Thus, there is no response delay to be evaluated. On the other hand, the token based protocol always have a response from the control channel even if the response is negative (there are no available LCs). In conclusion, the comparison of response delays when number of LCs is smaller than number of SUs (M < N) is not fair.

5.2 CSMA/CA Design

We designed a modified CSMA/CA protocol for cognitive radios to compare our results. The modifications made are four-way handshakes instead of two-way and handoffs caused by disturbance of the SUs caused by PUs. Four-way handshakes are necessary since sender and receiver should share the selected LC information besides RTS and CTS packages. The handoff procedure is the same as the proposed protocol; the sender tries to change its channel, if any available, by starting the four-way handshakes on control channel if it gets disturbed. The difference is there is no need to wait for token to arrive. Other aspects of sharing control information are the same as the CSMA/CA protocol introduced in IEEE 802.11 standard.

Behavior of the SUs on LCs is the same as the proposed protocol too. The parameters of both protocols adjusted to be similar to make fair comparisons.

5.3 Results

As mentioned many times the purpose of the protocol is to enhance the control channel performance; thus achieve shorter response delays. (Response delay is the duration of the interval between the time a request is received and the time an LC is captured.) For this reason, a highly loaded network was created with either increasing the number of SUs or increasing the utilization of the SUs. A CSMA/CA protocol was also tested and results were compared with it. In addition, the final utilization of the channels was observed to show that proposed token protocol not only enhances spectrum sharing but also helps spectrum management.

In the first simulation, the effect of the increase in the number of SUs was observed where $\gamma = 0.1$ and $\zeta = 0.9$.The results in Figure 5.1 show the average response delays of the control channel for both protocols.

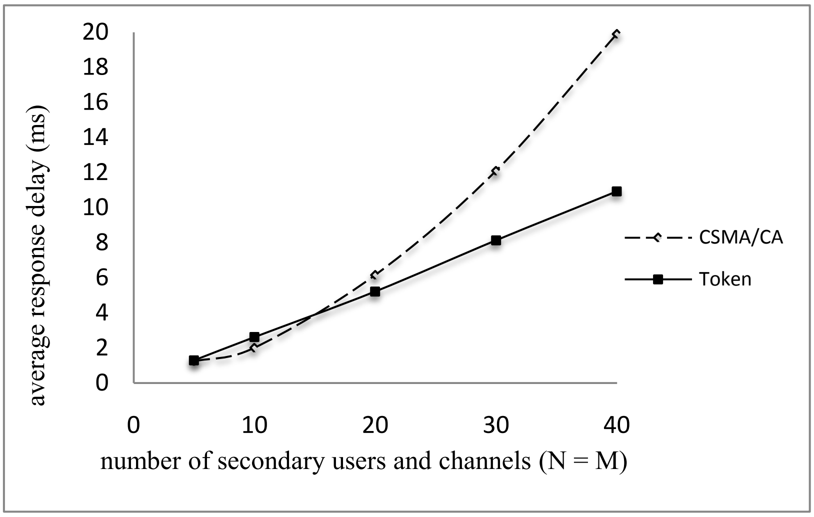

Figure 5.1 : The average response delays of the control channel

Average response delays increase linearly in token based protocol, which is expected since the TRT increases linearly as well. However, CSMA/CA protocol shows an exponential increase because of the high collision rate and binary exponential back-off procedure. The results in Figure 5.2, shows the maximum response delays seen in both protocols. The results in previous and this figure confirm the claim of the thesis about the short response delays expected with the use of token based scheme.

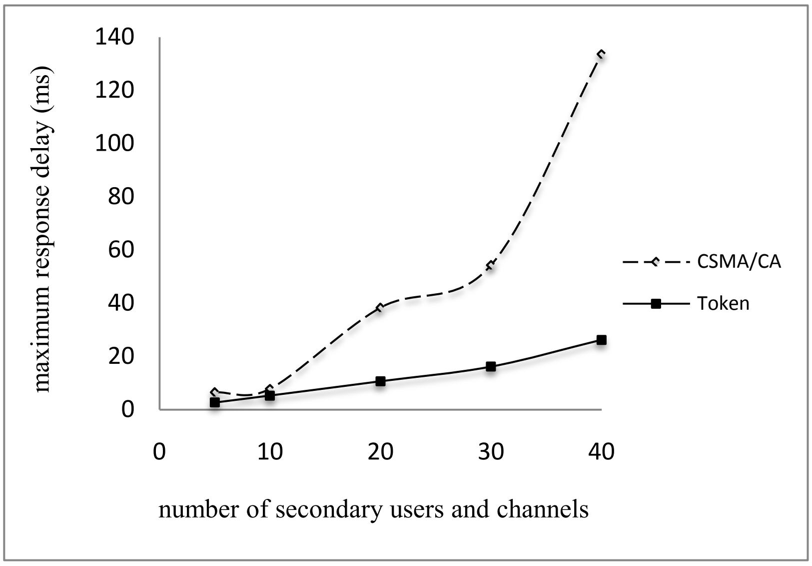

Figure 5.2 : Maximum response delays of the control channel

Maximum response delay stays limited in token based protocol since every user has a chance to capture a channel for every TRT. The maximum response delay of CSMA/CA increases rapidly and long delays are not acceptable since SUs have limited time to occupy a channel. The results in Figure 5.3 show the total utilization of the licensed channels (utilization by only SUs).

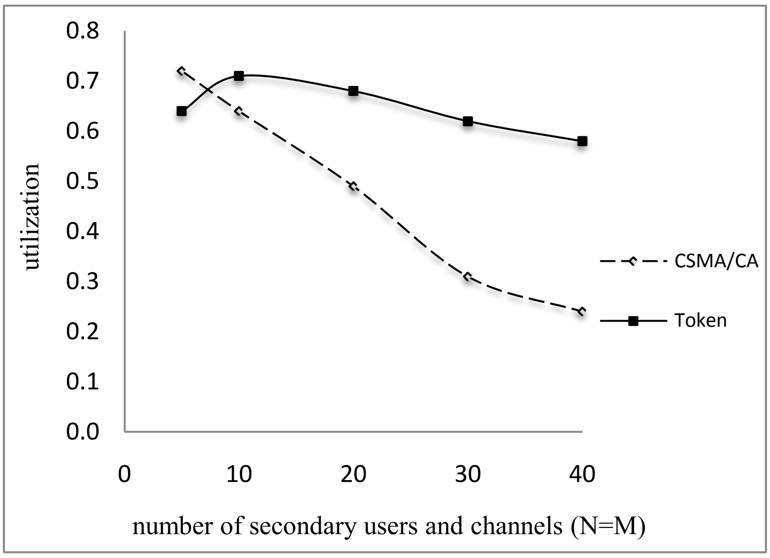

Figure 5.3 : Aggregate utilization of secondary users on licensed data channels

As seen in the figure above, as the number of the SUs increases in the network, utilization of the LCs is better with the token based protocol. CSMA/CA shows better results with low number of users since collisions are minimal. As the number of SUs increase, increasing collision rate and inadequate spectrum management drops the utilization of LCs. Token based protocol shows a mild decrease in utilization since spectrum management is better and response delays are limited.

In the second simulation, the same results were observed but this time, instead of increasing the number of SUs, their utilizations were increased. The parameter values: $\gamma = 0.1$, N = 30 and M = 30. The results in Figure 5.4 shows the average response delays as ζ increases.

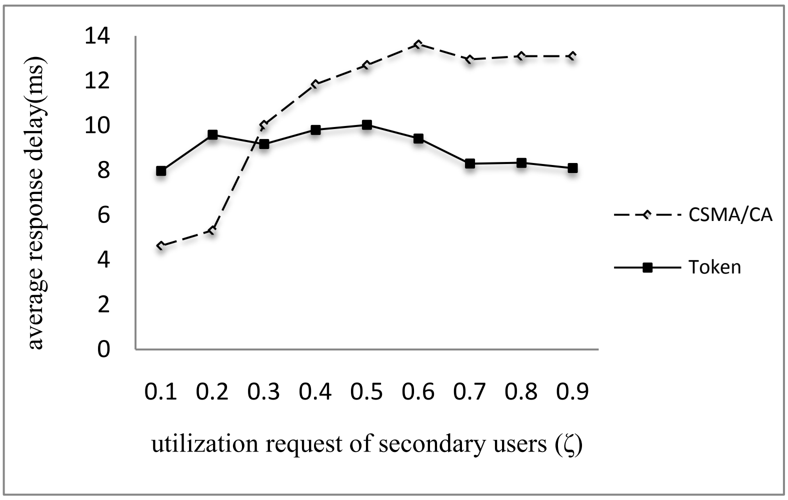

Figure 5.4 : The average response delays of the control channel as ζ increases

As expected, the CSMA/CA protocol gives better results in low loads. Token based protocol shows a more stable response delay; thus, it only gets effected by the increase in the number of users as in the previous simulation. High utilization of users affects it moderately. The second result of second simulation is the maximum response delays of both protocols. The result above and in Figure 5.5 confirm that token based scheme has lower and predictable response delays.

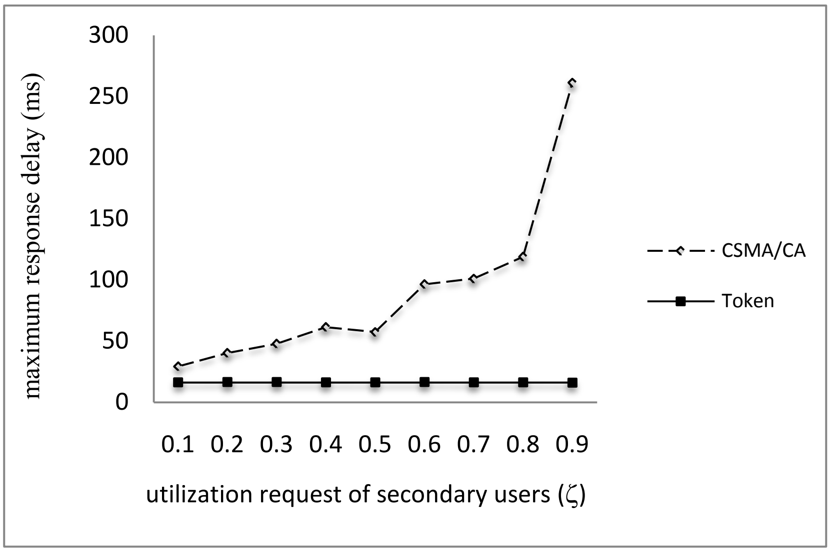

Figure 5.5 : Maximum response delays of the control channel as ζ increase

It is seen that maximum response delay of the token based protocol is almost static and predictable to users since the maximum response delays converge to the TRT.

The results in Figure 5.6 show the utilization of LCs as the utilization of the SUs' increase.

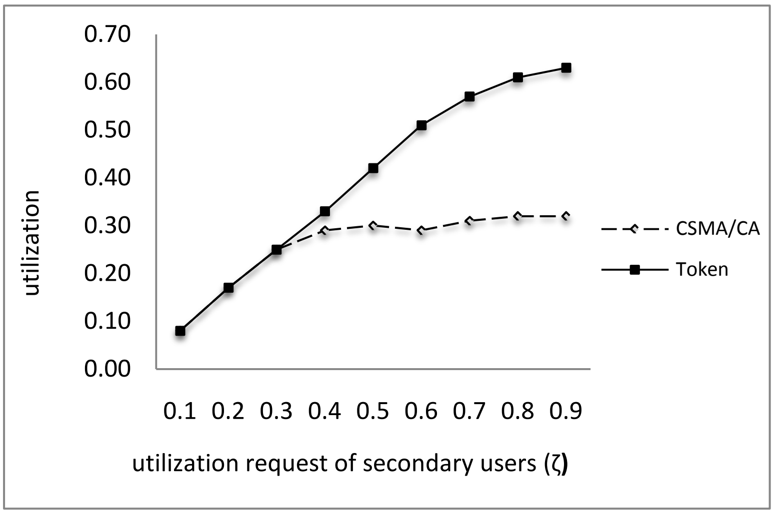

Figure 5.6 : Aggregate utilization of secondary users on licensed data channels as ζ increases

The results show that token based protocol is better at replying user requests at high loads. The CSMA/CA protocol becomes saturated after $\zeta \cong 0.3$. Two previously mentioned factors; high collision rate and bad spectrum management cause low utilization. SU that are using CSMA/CA protocol make decisions about the busy duration of a LC according to the RTS/CTS packages that they hear from the control channel. This prediction has its disadvantages in cognitive radio systems since the behavior of SU is unsteady. However, in token based protocol the busy duration of a LC is from the time it is seen as captured inside the token until the time it is seen released inside the token. There is no confusion and no prediction for SUs.

The last simulation observes utilization and access delay as the utilization of the PUs increase in the network. Access delay is different from the response delay. In cognitive radio networks, a response from the control channel means that a SU successfully captured a channel. However, SU cannot immediately start transmission on that LC since it has to avoid interference with PUs. Therefore, there is an access delay caused by the obstacles in the LCs, which is the duration that starts with the arrival of a request and goes on until the actual beginning of the transmission on LC. The increase in the PU utilization (γ) is expected to affect access delay in a bad manner since busy LC will cause data transmission to be delayed and requests to control channel –caused by handoffs- to increase.

The parameters of the simulation are N = 30, M = 30 and $\zeta = 0.9$. Figure 5.7 shows average access delays as γ increases. Token based protocol has shorter access delays, which proves that proposed protocol is better at handling frequent requests to control channel. CSMA/CA protocol also has the disadvantage of repeated handoffs. As PU utilization increases, thus LC becomes busier, SU try to change their current channels with the ones that they consider freer. However, in a situation where all the LCs are occupied handoffs cause longer access delays since the cost of an handoff is high. On the other hand, token based protocol also has the same handoff procedure but with a difference that SUs have to wait for the token to arrive to make a handoff. Therefore, SU give more chance to their current channel and save from the cost of handoffs. Figure 5.8 supports the explanations above and show that token based protocol also enhances total LC utilization of SUs.

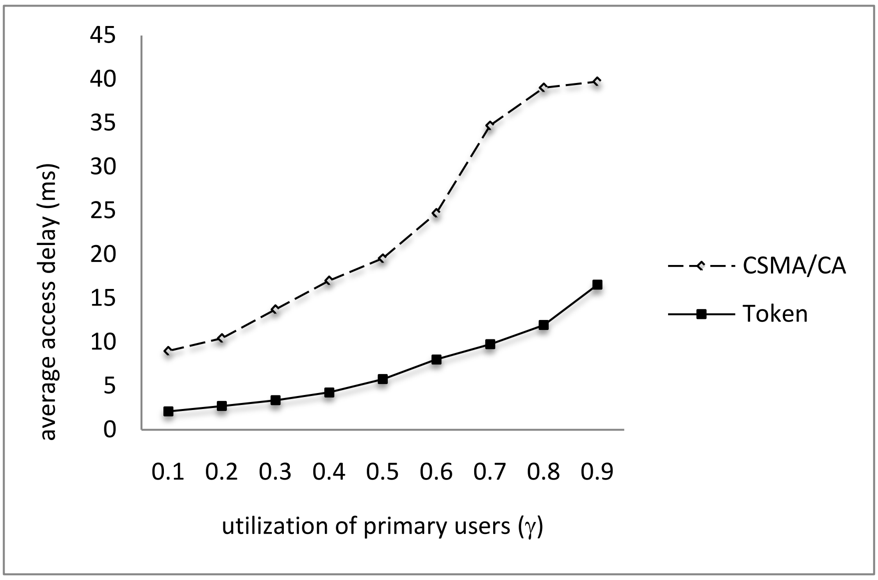

Figure 5.7 : The average access delays of both protocols as γ increases

The results in Figure 5.8 show the channel utilization of both protocols. Token based protocol has better utilization at all levels of PU utilization.

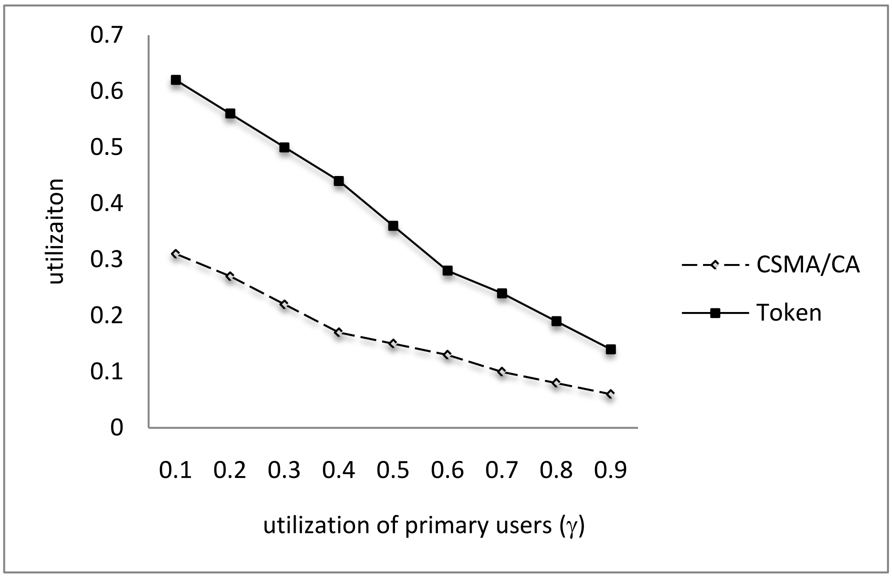

Figure 5.8 : Aggregate utilization of secondary users on licensed data channels as γ increases

6. CONCLUSION

In this thesis, a token based control channel protocol for cognitive radio networks was introduced. Control channel protocols are important for spectrum sharing functionality of cognitive radios. They should prevent saturation on control channel since response delays of the packages should be as short as possible. Cognitive radios are considered for critical applications like military and public safety so long delays and saturation could cause vital problems in communication. That is why a more solid and predictable token based protocol was proposed in this thesis. Many of the researches done for spectrum sharing use carrier sensing protocols so the results of the simulation was compared with a CSMA/CA protocol.

The proposed protocol uses two transceivers but this is not considered as an extra cost since hardware costs get more affordable day by day. Working on control channel and data channels at the same time makes protocol more flexible and less time consuming.

In wireless networks with single channel, token based protocols has the disadvantage of long TRT. Asynchronous traffic is prevented when TRT starts to get longer. However, in multi-channel systems like cognitive radio TRT stays almost the same at every rotation, which makes the protocol even more predictable and solid.

Simulation results showed that the proposed protocol is better in utilization of the spectrum and for response delays. Utilization is not only affected by control channel saturation but also by the wrong choice of data channels. Since proposed protocol carries all global network information inside the token, secondary users makes less faulty decisions about the spectrum.

6.1 Future Work

In the proposed spectrum sharing protocol, it was assumed that the virtual token ring has a static structure and arrivals or departures do not happen. Those abilities could be a future work especially to work with mobile nodes. Token rings generally covers a small group of user to prevent long TRT. Even though proposed protocol has lower concerns in this problem area, multi-ring abilities can be studied to gain larger coverage.

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