國立交通大學

資訊科學與工程研究所

碩 士 論 文

結合頻譜分配與傳送機率於感知無線網路

Joint Spectrum Allocation and Transmission Opportunity for Cognitive Radio Networks

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中 華 民 國　九 十 九　年 八 月

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A Thesis

Submitted to Institute of Computer Science and Engineering

College of Computer Science

National Chiao Tung University

in partial Fulfillment of the Requirements

for the Degree of

Master

in

Computer Science

August 2009

Hsinchu, Taiwan, Republic of China

中華民國九十九年八月六日

Abstract

There are three main operator types and research subjects in cognitive radio systems, consisting of software define radio (SDR), channel sensing and channel management. In this paper, we focus on a channel-sensing and accessing and a synchronized channel-sensing and accessing for cognitive radio users in IEEE 802.11 wireless networks is proposed. The mechanism consists of two phases: fast channel sensing and channel vacating. A pair of cognitive radio users can search an available channel with the most success transmission probability from those available channels presently and further proceed to transmit data by fast channel sensing time-efficiently; proactive channel vacating is for the pair of cognitive radio users to be aware of the presence of primary users and vacate the occupied channel as quick as possible. We utilize the concept of channel hopping to reduce the average channel sensing time of cognitive radio users. Besides, we propose one equation to decide how to set TXQ (the bounded time interval during which a CR user can send as many frames as possible) by PU traffic load and make the caused interference to primary users within tolerable range. We further evaluate the performance of a considered cognitive radio network through simulations. From the simulation results, our proposed protocol can efficiently balance the tradeoff between throughput performance of a cognitive radio network and waiting time of primary users.

摘要

感知網路中目前可分成三個主要的運作模式和相關研究主題，包含軟體定義無線電、頻道感測和頻道管理。在本篇論文中，我們著重在頻道感測與頻道存取，提出了一套在 802.11 無線網路環境下感知網路中的同步頻道感測與存取。此套機制包含了兩種階段：快速頻道感測及釋放頻道。一對感知網路使用者可藉由快速頻道感測從目前可使用的頻道中，取得成功傳送機率高的頻道，進而傳送資料；主動釋放頻道是讓感知網路使用者察覺主要使用者要使用頻道時，能快速的釋放頻道給主要使用者，避免干擾。我們更利用頻道跳躍序以減少平均頻道感測時間。經由模擬值的結果，我們所提出的方法，可以有效的利用頻道及減少主要使用者的等待時間。

致謝

In the past two years as a master, I often felt dispirited in my learning, proposal or research and I was about to give up many times. Fortunately, many people give me a hand to overcome a lot of difficulties and accomplish my master thesis. I would like to express of my sincere thanks to my advisor, Professor Hsi-Lu Chao. Without advisor’s supervision and guidance, I could not to accomplish my master thesis. Without my advisor Professor Chen I cannot own these honors now.

Finally, I would like to thank my family, my upperclassmen, my classmen, my underclassmen, my friends and people who I knew in National Chiao Tung University. They all concern about my life, take care of me and encourage me timely. With your company, I have a lot of happiness during these two years. I show my appreciation for all of you.

LiHua Chao

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Chapter 1 Introduction

1.1 Background

Electromagnetic radio spectrum is one of the most valuable resources in wireless communications. With rapid increase of the wireless applications and products, unlicensed bands such as Industrial, Scientific and Medical (ISM) and Unlicensed National Information Infrastructure (UNII) have become over-crowded. On the other hand, a large portion of the assigned spectrum is used sporadically and a significant amount of the allocated spectrum remains under-utilized. Cognitive Radio (CR) [1], as a promising solution to efficiently utilize the unused spectrum, has become a hot research topic these days. The concept of CR techniques is that secondary (referred to as cognitive radio users, CR users) can temporarily borrow unoccupied channels owned by licensed users (referred as primary users, PUs) without interfering with primary users. Based on the scanned available channels, CR users can utilize available channels to communicate with each other. The technology of cognitive radio has been proved that it does enhance spectrum utilization [2,3,4].

Although the basic idea of cognitive radio is simple, the efficient design of cognitive radio networks (CRNs) imposes the new challenges that are not present in the conventional wireless networks. Specifically, identifying the time-varying channel availability imposes a number of nontrivial design problems to the medium access control (MAC) layer. One of the most difficult, but important, design problems is how the CR users decide when and which channel they should tune to in order to transmit/receive the CR users' packets without affecting the communications among the primary users. This problem becomes even more challenging in CRNs.

In order to use channels without affecting PUs, CR users must have the ability to measure, to sense, and to learn channel characteristics and availabilities [5]. Since primary users can claim the spectrum anytime, CR users should be able to identify the presence of primary users in time and vacate the occupied bands immediately to prevent/reduce the interference to primary users. Therefore, spectrum sensing, and spectrum accessing and vacating are two of the most crucial tasks to realize this technique. Spectrum sensing is the task for cognitive radio users to collect information about spectrum usage and existence of primary users; while spectrum accessing and vacating are the task for cognitive radio users to transmit data packets and vacate the occupied data channel to primary users as quick as possible.

Sensing the whole spectrum and exchanging massive control messages to select a best and available data channel is a time-inefficient channel access approach for cognitive radio users. The reason is the traffic behavior of primary users is unknown and unpredictable to CR users. Therefore, it may occur that a CR user records a sensed channel being idle and then keeps sensing other channels. Unfortunately, primary users come back to use the channel and that CR user also decides to select that channel. In such case, the CR user either interferes with primary users or re-senses channels.

The focus of this paper is to design a spectrum accessing and vacating mechanism with throughput improvement for cognitive radio users. In the following, we present our literature study, and elaborate our motivation and objectives.

1.2 Review of Related Studies

To form a CRN, Media Access Control (MAC) protocols are of great importance, especially in the way a CR user searches for free channels. Existing CRN MAC protocols searching free channel can be classified into two categories: single rendezvous or parallel rendezvous. The former is have a control channel as the rendezvous channel, and nodes can exchange all control information and negotiate parameters for data transmission on this channel; the latter, contrarily, do not need a common control channel. The basic idea of parallel rendezvous protocols is that nodes jump among different channels according to their own sequences and the control information is exchanged at different channels when nodes meet. Examples of single and parallel rendezvous schemes are [6-11] and [13-16], respectively. Some selected literature is briefly described in the following.

1.2.1 Single Rendezvous Approaches

Single rendezvous MAC protocols have a control channel as the rendezvous channel, and nodes can exchange all control information and negotiate parameters for data transmission on this channel. A hardware-constraint cognitive MAC (HC-MAC) was proposed in [6]. HC-MAC has a dedicated control channel to exchange RTS/CTS information. Considering limitations of sensing constraint and transmission constraint, the authors formulate an optimal stopping problem by considering sensing overhead and transmission limitation. The derived sensing time helps on a potential CR sender achieving its optimal expected throughput. The authors further integrate optimal sensing time and IEEE 802.11 DCF to form the designed HC-MAC mechanism. The drawback of HC-MAC is only one CR pair can do transmissions at a time. In other words, CR nodes which hear a cognitive-ready to send (C-RTS) or cognitive-clear-to-send on the control channel are frozen to send data. Therefore, the overall throughput of the cognitive radio network is reduced, especially when there are un-sensed unoccupied channels

In [7], there is a control channel being always available for CR users to exchange control information. Time is divided into beacon intervals, and each beacon interval is further divided into three phases: “channel selection”, “sensing”, and “data transmission”. A CR sender informs its intended receiver the selected data channel by ATIM (Ad Hoc Traffic Indication Message), and intended receiver will respond by transmitting an ATIM-ACK during channel selection phase. In sensing phase, a CR pair senses the availability of the selected data channel. In data transmission phase, to avoid collisions in channel selection phase, the RTS/CTS/DATA/ACK four-way handshake as in the IEEE 802.11 CSMA/CA protocol will be used to solve this problem. A CR user is designated to periodically broadcast beacons for all CR users achieving global synchronization. One characteristic of [7] is that CR users can transmit packets on not only data channels, but also the control channel. Therefore, CR users still have opportunities to send data when all data channels are utilized by primary users. The disadvantage of [7] is all CR users must achieve global synchronization. This assumption is a key challenge, especially when CR users form a multi-hop cognitive radio network. Another drawback of [7] is massive exchanges of control messages in channel selection phase. Though longer phase duration may resolve this issue, its side effect is channel utilization reduction.

The author of [8] proposes an Opportunistic Spectrum MAC (OS-MAC) which is a single transceiver based CR MAC mechanism. In OS-MAC, the authors propose a notion of a Secondary User Group (SUG) representing a set of users who want to communicate with each other. Only one CR user in an SUG can transmit at a time. In addition, time is divided to periods called Opportunistic Spectrum Period (OSP) which is comprised of three consecutive phases: select phase, delegate phase and update phase. In OS-MAC, each data channel always has one Delegate Secondary User (DSU) which is appointed among those CR users currently using the channel.

The DSUs will periodically switch to control channel to inform and get the channel information. After learning of the conditions of all data channels, each SUG selects and then switches to the best data channel for data communication. However, the membership of the CR users to the clusters is based on the assumption that each user already knows which cluster to join. As the clusters are formed based on group-communication needs, this is infeasible without exchanging detailed cluster information. Moreover, the CR delegate does not coordinate with the other clusters for efficient spectrum sensing, as each cluster operates independently without enforcing silent periods. Furthermore, there is no consideration of protection to the PUs either by adapting transmission, power control, among others

The authors in [9] propose a cross-layer based opportunistic multi-channel MAC protocol in wireless ad hoc network. This protocol assumes that each CR user is equipped with two transceivers; one is for dedicated control channel and the other for data channels. This protocol develops two channel sensing policies: random sensing policy (RSP) and negotiation-based sensing policy (NSP). In RSP, each secondary user randomly chooses one of the n licensed channels for sensing. Therefore, the chosen channels among all the secondary users are independent and identically distributed. In RSP, the more the number of secondary users is, the more likely the number of sensed channels is large. When the number of CR users is large enough, the CR users can sense all of the licensed channels. The authors also propose the negotiation-based sensing policy. The basic idea of the negotiation-based sensing policy is to let the secondary users know which channels are already sensed by their neighboring CR users, and then select the different channels to sense at the next time slot. However,

In [10], the C-MAC protocol is characterized by in-band signaling as it integrates the control channel in the super-frame structure It guarantees flexible control channel coverage and it is robust to PU activity through the use of backup channels. The main drawbacks of this work are the high control overhead due to beacon exchange and requirement of strict synchronization. The necessity for synchronization can be addressed in networks with special topologies, such as a cluster. Moreover, several different clusters representing different control channels may be integrated over time. This work may be limited in application as it assumes special topology formation, and is also affected in dynamically changing topologies. Besides, the selection and rendezvous pattern of rendezvous channels in multi-hop cases is still a challenging task in C-MAC.

The authors of [11] propose a synchronized channel sensing and access protocol (SSA) for cognitive radio users. The mechanism consists of two phases: fast channel accessing and proactive channel vacating. SSA utilizes the concept of channel hopping to reduce the average channel sensing time of cognitive radio users. Besides, through the designed vacating mechanism, cognitive radio users can create opportunities for primary users to claim the spectrum and thus minimize the caused interference to primary users. However, SSA does not elaborate how to decide the bounded time interval during which a CR user can send as many frames as possible and RTI (Ready-To-be-Interrupted). Moreover, the hopping sequences (h) generate randomly and need to relative prime with channel numbers.

1.2.2 Parallel Rendezvous Approaches

The common characteristic of parallel rendezvous approaches are hopping sequence and without control channel. In [13], the authors propose Multi-channel MAC (McMAC) protocol for multi-channel case initially and it works properly in the 802.15.4 based equipments. In McMAC, each node has its own unique sequence and the sequence is generated by a pseudo-random generator. The seed of the sequence is the node's own MAC address. The pseudo-random generator that is used in McMAC is the Park-Miller random number generator. Nodes in the McMAC network switch across the channels following their hopping sequences. The sequence of a node is broadcast and if other nodes want to communicate with a particular node, it should follow to the node's sequence and tune to the same channel to establish communication. However, this approach also has a higher protocol complexity and it requires one-hop neighbor pairs to synchronize.

The SSCH protocol proposed in [14] adopts multiple appointments to overcome the single control channel bottleneck. In SSCH, each node has its own hopping sequences determined by the channel and seed parameters. In each hopping, nodes broadcast its (channel, seed) to neighbors. When a sender wants to communicate with a receiver, the sender will try to get the hopping sequence of the intended receiver. Then the sender adopts the receiver's hopping sequence in order to increase the time they spend on the same channel. Afterward they can communicate with each other. After completing transmitting, the sender and the receiver go back to their own hopping sequence, respectively. It has been demonstrated that parallel rendezvous MAC protocols, like McMAC [13] and Slotted Seeded Channel Hopping (SSCH) [14] in a multi-channel wireless networks, generally outperform single rendezvous MAC protocols [12]. These protocols do not have bottleneck like in single rendezvous MAC protocols and they are all based on a single transceiver. However, to let this mechanism work, the sender learns the receiver's current sequences via a seed broadcast mechanism.

The authors of [15] extended McMAC from general multi-channel networks into CRNs. A channel-hopping based cognitive radio MAC mechanism (we called it as CH-MAC) was proposed in [15]. In [15], each CR user has its own channel hopping sequence, which is determined by a unique ID (e.g., MAC address). All CR users share the same hopping sequence generation function, and thus a potential CR sender can easily obtain the hopping sequence of its intended CR receiver. A CR user follows its own hopping sequence to monitor channels when it has no data to send. Otherwise, a CR sender follows the receiver's hopping sequence to do negotiation and data transmissions. The advantage of this approach is it does not need a dedicated control channel. However, for a potential CR sender, how to meet its intended CR receiver on a specific channel efficiently is not elaborated in [15].

In [16], the authors argue that in cognitive radio networks, the channels for PUs may have different maximum transmission power limits and the bandwidth which CR users can utilize may be different. Thus, the authors propose datarate-aware MAC (DRA-MAC) protocol which is to adjust the hopping sequence of CR users according to the data rates available for CR users in different channels, so that better channel utilization can be achieved. However, similar to [15], the disadvantage of [16] is not elaborated that how to meet its intended CR receiver on a specific channel efficiently. Another drawback of [16] is massive exchanges of control messages in varying hopping sequence.

1.3 Motivation and Objective

Based on our literature study and observation, existing work usually allows a CR sender sending one frame on the borrowed data channel. This is to avoid impacting on primary users and to provide fairness among CR users. However, when the traffic load of primary users is low, CR users consume the major portion of channel time on exchanging control messages. It inspires us to design a time-efficient channel sensing and vacating protocol which reduces the number of control frame exchanges, improves the throughput of a cognitive radio network (CRN), and supports fairness among all CR pairs. Similar to [11], we continue using a fast channel sensing mechanism to access channels and similar data transmission strategies. Different to [11], the first is that no method is proposed to decide how to set TXQ but our scheme proposes one equation to decide the value. The second is that hop sequence in [11] is produced randomly but our scheme proposes one equation to compute success transmission probability and further produces hop sequence.

Chapter 2

System Model and Assumptions

The adopted system architecture in this paper is shown in Fig. 2-1. Here we consider an IEEE 802.11-based service network, which consists of an access point (AP) and multiple primary users (PUs), as the primary network. The AP is responsible for channel assignments of PUs' transmissions. On the other hand, CR users operate in an ad hoc mode, and thus these CR users form a distributed cognitive radio network (CRN).

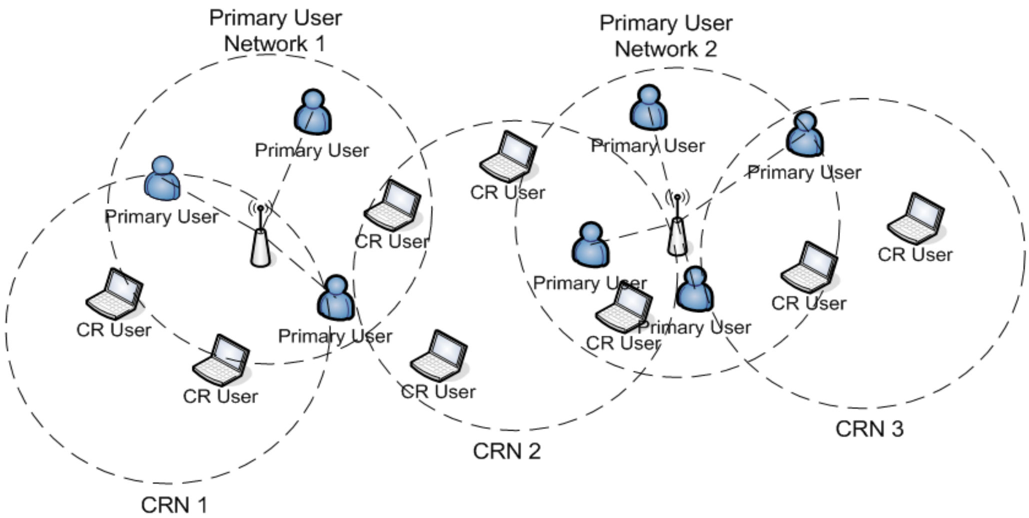


Figure 2-1 : The adopted system architecture consisting of primary users and CR users

In this CRN, we do not consider routing issue and thus all are single-hop transmissions, i.e., a pair of CR users can communicate only when they are one-hop neighbors. Besides, we make some assumptions:

1. Similar to [19, 20], each CR user equips only one transceiver, and it has the capability of sensing the presence of PUs on the channel switching to.
2. There is a dedicated channel for CR users to exchange control messages, and *N* data channels.

3. When a CR user is idle, it always listens to the control channel.
4. A pair of CR users can start to transmit data packets when they find a channel which is not currently occupied by PUs and other CR users.
5. CR users utilize CSMA/CA protocol to resolve collisions on the control channel.
6. AP can get PUs' traffic behavior on each dada channel and broadcast necessary information for CR users.

Chapter 3
The Proposed Synchronized Channel Sensing and Accessing Mechanism

In this chapter, we introduce our proposed synchronized channel sensing and accessing mechanism. Through the proposed mechanism, a pair of CR users can find and sense an unoccupied channel efficiently, and then transmit data frames on that channel. The characteristics of our proposed mechanism include:

1. It is a distributed algorithm, and thus each pair of CR users determines an unoccupied channel independently.
2. It is a reactive spectrum sensing scheme, and thus CR users sense data channels only when they have data to transmit.
3. Primary users can easily recognize that the overheard signals are sent by a primary user or a CR user.

3.1 Defined Control Frames and Parameters

In our approach, we define four control frames and three parameters. In the following, we use 802.11 MAC frames as an example to elaborate our protocol. However, the proposed mechanism can be applied to other contention-based wireless primary networks.

3.1.1 Control Messages

(1). Control-channel-Request-To-Send (CRTS): this control frame is utilized by a potential CR sender to inform the CR receiver its transmission intention. Besides, two parameters are included in the frame: initial selected data channel ID, and hopping sequence, both are introduced soon. CRTS is sent at the control channel only.

(2). Control-channel-Clear-To-Send (CCTS): this control frame is utilized for a CR receiver to reply its CR sender that it is idle and ready to sense the specified initial data channel. Similarly it is sent at the control channel only.

(3). Data-channel-Request-To-Send (DRTS): this control frame is utilized for a CR sender to inform its receiver that the sensed data channel is idle for itself.

(4). Data-channel-Clear-To-Send (DCTS): this control frame is for a CR receiver to reply its CR sender that it also senses the data channel idle. Upon receiving a DCTS frame, the CR sender can start to transmit data frames.

3.1.2 Parameters

(1). Hopping sequence (*H*): *H* is a $1 \times N$ vector which contains ID of data channel of a CR sender's next try. For example, the *H* consists of [h_1, h_2,…, h_N] and h_1 indicates the channel which has the highest probability of successful transmission. The *H* is a sequence sorted by equation (6) explained later.

(2). Transmission Quota (*TXQ*): the bounded time interval during which a CR user can send as many frames as possible. The impact of a large *TXQ* value is long searching time of finding an available idle channel for a CR user. In this paper, the unit of *TXQ* is frames. For example, *TXQ* is *m* frames indicates a CR sender can transmit at most *m* frames on a data channel. We propose one equation to set *TXQ* according to PU traffic load. CR user must use this equation to get *TXQ* call as *MaxTXQ*. The *MaxTXQ* means that each *TXQ* of CR pair should equal or less than it. The *MaxTXQ* sets as following:

$$MaxTXQ = \frac{BN\left(1 - \frac{\sum_{i=1}^{N} \lambda_{t_i}}{N}\right)}{B\left(\frac{TXtime}{\tilde{W} + C + TXtime}\right)} \qquad (1)$$

Symbol	Definition
N	The number of channels
B	Bandwidth
λ_{t_i}	Traffic load of PUs on channel *i*
TXtime	Spent time to transmit one frame
$\tilde{W}$	Sensing time
C	Spent time to transmit DRTS+DCTS+ 3SIFS + ACK

Table3-1: Notation

3.2 Production of Hopping Sequence

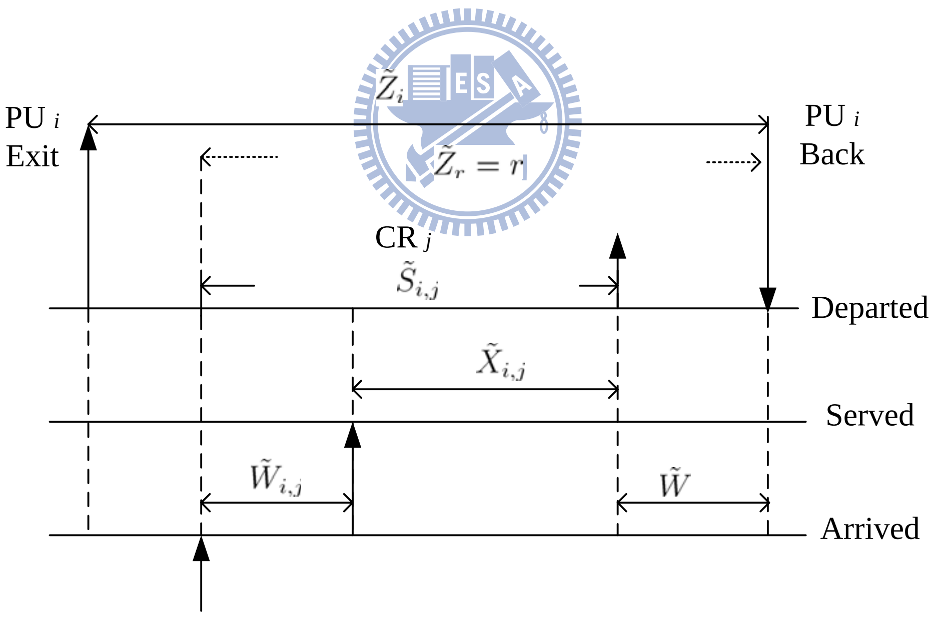


Figure. 3-1:The channel model

We follow signal rendezvous protocols which are dedicated channel for CR users to exchange control messages. The advantage of utilizing a dedicated control channel is it eliminates massive message exchanges for a pair of CR users to meet with each other and to send transmission invitation. Besides control channel, there are

N data channels. When a CR user is idle, it always listens to the control channel. There is a AP which is responsible for broadcast PUs' activities to CR users on control channel. However, we do not want that AP interfere with PUs. Thus, AP only broadcasts PUs' traffic load to inform CR users on control channel. Then we consider each PU_i uses a dedicated channel i. Then each CR user equips only one transceiver, and it has the capability of sensing the presence of PUs on the channel switching to.

We consider the spectrum sharing problem for spectrum overlay in a cognitive wireless network, where unlicensed users (i.e., CR users) opportunistically exploit the spectrum holes in licensed frequency bands. Specifically, CR users can only transmit data on channels if these channels are not being used by primary users. We consider a channel viewpoint to analyze the successful probability of CR user transmission and define several symbols as Table 3-2. As Fig. 3-1 shown, CR users have to sense channel and then transmit packets if channel is idle. Let $\tilde{S}_{i,j} = \tilde{W}_{i,j} + \tilde{X}_{i,j}$ which $\tilde{W}_{i,j}$ means sensing channel time and $\tilde{X}_{i,j}$ represents transmission time. We assume that $\tilde{W}_{i,j}$ and $\tilde{X}_{i,j}$ are following a random distribution. Then the sensing time distribution by the definition of [17] is as following:

$$\tilde{W}_{i,j} = \frac{1}{B\gamma_{i,j}^2}\left[4 + 4(\gamma_{i,j} + 1)\right]^2 \tag{2}$$

which B and $\gamma_{i,j}$ represent bandwidth and Signal-to-Noise (SNR) individually. $\tilde{W}$ is the reserved time for next CR use to sense successfully. To avoid PU disruption, channel *i* must be idle for at least $\tilde{S}_{i,j} = \tilde{W}_{i,j} + \tilde{X}_{i,j}$ time duration to guarantee CR *j*'s successful transmission, i.e., $\tilde{S}_{i,j} \leq \tilde{Z}_i$. In order to estimate more precisely, we consider $\tilde{Z}_r = r$ which means the duration that CR user *j* arrives till the time of PU*i* comes back. Let $P(\tilde{S}_{i,j} \leq \tilde{Z}_r)$ represent CR *j*'s success transmission probability on channel *i*.

Symbol	Definition
N	The number of channels
B	Bandwidth
$\gamma_{i,j}$	The signal-to-noise ratio (SNR) of CR *j* on channel *i*
λ_{p_i}	The arrival rate of PUs on channel *i* [set (1-λ_{t_i})]
μ_i	The channel service rate on channel *i* [set 1/λ_{t_i}]
λ_c	The arrival rate of CR users(set 1)
$\tilde{X}_{i,j}$	Transmission time of CR *j* on channel *i*
$\tilde{W}_{i,j}$	Sensing time CR *j* on channel *i*

Table 3-2: Notation

It is obviously that this system is M/G/1. With clearer explanation, as Fig.3-1 shown, if a CR user arrives to channel *i* when a PU *j* does not use, the CR user will sense this channel through $\tilde{W}_{i,j}$period. After sensing successfully, the CR user transmits data to its receiver during$\tilde{X}_{i,j}$ period. The $\tilde{X}_{i,j}$ depends on CR users traffic load. It is obviously that if CR users transmit successfully, $\tilde{S}_{i,j}$ must be less than$\tilde{Z}_i$. In order to calculate more precisely, we not only consider idle time interval $\tilde{Z}_i$ of PU *j* but also focus on $\tilde{Z}_r$ means the duration from a CR user arrives this channel to a PU uses this channel. Thus, we derive $\tilde{Z}_r$ distribution as following:

$$
\begin{aligned}
f_{\tilde{Z}_r}(r) &= \int_{z=r}^{\infty} f_{\tilde{Z}_r|\tilde{Z}_i}(r|\tilde{Z}_i = z)dF_{\tilde{Z}_i}(z) \\
&= \int_{z=r}^{\infty} \frac{d}{dr} P[\tilde{Z}_r < r|\tilde{Z}_i = z]dF_{\tilde{Z}_i}(z) \\
&= \int_{z=r}^{\infty} \frac{1}{z}\frac{zf_{\tilde{z}}(z)}{E[\tilde{z}]}dz \\
&= \frac{1}{E[\tilde{z}]}\int_{r}^{\infty} f_{\tilde{Z}}(z)dz \\
&= \frac{1}{E[\tilde{z}]}[1 - F_{\tilde{z}}(r)] \\
&= \frac{1 - F_{\tilde{z}}(r)}{E[\tilde{z}]}
\end{aligned} \tag{3}
$$

After that, we analyze $\tilde{S}_{i,j}$ through z-transform as following equations. We use $\tilde{S}$ to instead of$\tilde{S}_{i,j}$.

$$
\begin{aligned}
F^*_{\tilde{S}}(s) &= \frac{(1-z)(1-\rho)F^*_{\tilde{x}}(\lambda_c - \lambda_c z)}{F^*_{\tilde{x}}(\lambda_c - \lambda_c z) - z}\Big|_{z=\frac{\lambda_c - s}{\lambda_c}} \\
&= \frac{s(1-\rho)F^*_{\tilde{x}}(s)}{s - \lambda_c[1 - F^*_{\tilde{x}}(s)]}
\end{aligned} \tag{4}
$$

which $\rho = \lambda_c/\mu_i$ and μ_i is channel service rate. Then we assume the system is M/M/1 and thus $F^*_{\tilde{x}}(s) = \frac{\mu_i}{\mu_i + s}$. Next, we can rewrite equation (4)

$$
\begin{aligned}
F^*_{\tilde{s}}(s) &= \frac{s(1-\rho)\frac{\mu_i}{\mu_i+s}}{s - \lambda_c + \lambda_c\frac{\mu_i}{\mu_i+s}} \\
&= \frac{\mu_i(1-\rho)}{s + \mu_i(1-\rho)}
\end{aligned} \tag{5}
$$

The probability density function of $\tilde{S}$ is $f_{\tilde{S}}(t) = \mu_i(1-\rho)e^{-\mu_i(1-\rho)t}, t \geq 0$. Thus, we know the probability that a CR user transmits packet to other CR nodes successfully on channel *i* defined as $P(\tilde{Z}_r \geq \tilde{S})$ and derive as following:

$$
\begin{aligned}
P(\tilde{Z}_r \geq \tilde{S}) &= P(0 < \tilde{S} \leq r, r \leq \tilde{Z}_r < \infty) \\
&= \int_r^{\infty} P(0 < \tilde{S} \leq r) f_{\tilde{Z}_r(r)} dr \\
&= \int_r^{\infty} \int_0^r \mu_i(1-\rho)e^{-\mu_i(1-\rho)t} f_{\tilde{Z}_r}(r) dt dr \\
&= \int_r^{\infty} \mu_i(1-\rho) \left(\int_0^r e^{-\mu_i(1-\rho)t} dt \right) f_{\tilde{Z}_r}(r) dr \\
&= \int_r^{\infty} \mu_i(1-\rho) \left(\frac{-1}{\mu_i(1-\rho)} e^{-\mu_i(1-\rho)t}|_0^r \right) f_{\tilde{Z}_r}(r) dr \\
&= \int_r^{\infty} (1 - e^{-\mu_i(1-\rho)r}) f_{\tilde{Z}_r}(r) dr \\
&= \int_r^{\infty} f_{\tilde{Z}_r}(r) dr - \int_r^{\infty} e^{-\mu_i(1-\rho)r} f_{\tilde{Z}_r}(r) dr \\
&= \int_r^{\infty} \lambda_{p_i} e^{-\lambda_{p_i} r} dr - \int_r^{\infty} e^{-\mu_i(1-\rho)r} \lambda_{p_i} e^{-\lambda_{p_i} r} dr \\
&= e^{-\lambda_{p_i} r} - \frac{\lambda_{p_i}}{\lambda_{p_i} + \mu_i - \lambda_c} (e^{-(\lambda_{p_i} + \mu_i - \lambda_c)r}) \qquad (6)
\end{aligned}
$$

After equation (6), a CR user can calculate the successful transmission probability on each channel and the probability depends on PU traffic load and needed transmission time, i.e. *r*. Each CR user will calculate the probability of each channel and sort channel ID to its hopping sequences *H* according to probability values in decreasing order.

Our approach achieves long-term fairness on channel access among all CR pairs and improves the throughput of a cognitive radio network.

3.3 The proposed channel sensing and accessing algorithm

The proposed channel sensing and accessing algorithm for CR users consists of two phases: fast channel sensing and channel vacating.

3.3.1Fast Channel Sensing

When a CR sender, say CR_A, intends to transmit data to a CR receiver CR_B, it first checks the availability of CR_B by sending a CRTS on the control channel.

Hopping sequence H is encapsulated in the CRTS. The control channel access and collision resolution are based on the CSMA/CA mechanism. If CR_B is listening to the control channel and successfully receives the CRTS, it replies CR_A a CCTS. At this moment, CR_A and CR_B achieve synchronization and switch to channel $Ch(h_1)$ for channel sensing purpose.

When hopping to $Ch(h_1)$, both CR_A and CR_B listen to $Ch(h_1)$ for t time interval to avoid interfering on-going transmissions of PUs or CR users. Here we set t by equation(2). If $Ch(h_1)$ is still idle after t time, CR_A and CR_B exchange DRTS and DCTS as usual. Otherwise, CR_A and CR_B hop to the next data channel $Ch(h_2)$ and then sense again. The reason that CR_A and CR_B exchange DRTS and DCTS at the data channel is to avoid collisions when more than two pairs of CR users sensing the same data channel. The next sensed data channel is determined by sequence hop. The hopping sequence is repeated and each channel is sensed once per run. Fig.3.2 as example, The complete hopping sequence is [2, 5, 0, 3, 6, 1, 4, 7, 2, 5, 0, 3, 6, …].

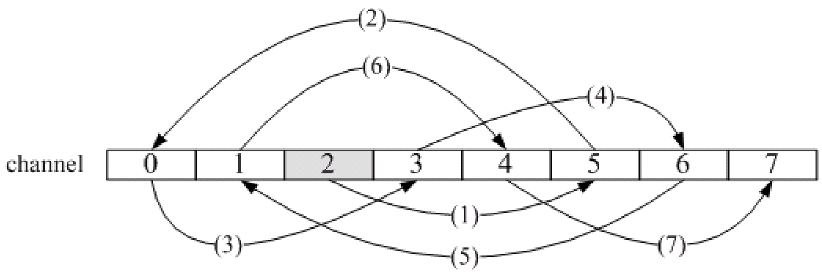


Figure3-2: An illustrative example of data channel hopping sequence: N=8, $Ch(h_1)$=2.

For a specific hopped data channel, say $Ch(h_i)$, there are four possible sensing results:

(1). $Ch(h_i)$ is idle for both CR_A and CR_B

In this case, CR_A sends a DRTS frame to CR_B immediately and then waits for

CR_A's reply. Upon successfully receiving the DCTS, CR_A starts to transmit data frames to CR_B. After successfully transmitting MAXTXQ data frames, CR_A and CR_B vacate the data channel and hop back to the control channel. Besides, CR_A can send at most MAXTXQ frames at that data channel. If there are still queued frames to send, CR_A and CR_B must switch to the control channel, and run the procedure of fast channel sensing again. The timetable of message exchanges is in Fig. 3-3(a).

(2). $Ch(h_i)$ is idle for CR_A but busy for CR_B

Similar to case 1, CR_A sends a DRTS frame to CR_B immediately. However, CR_B cannot successfully receive the DRTS and thus it does not reply a DCTS frame. After staying at $Ch(h_i)$ for T time interval, both CR_A and CR_B hop to $Ch(h_{i+1})$ simultaneously. T is the maximum time interval that CR_A and CR_B stay at $Ch(h_i)$, and it can be derived by CR_A and CR_B independently. It is obvious that $T \geq t + t_{DRTS} + 2SIFS + t_{DCTS}$, where t_{DRTS}, and t_{DCTS} are the transmission time for DRTC and DCTS frames. In this paper, we set $T \geq t + t_{DRTS} + 2SIFS + t_{DCIS}$. The timetable of message exchanges is in Fig. 3-3(b).

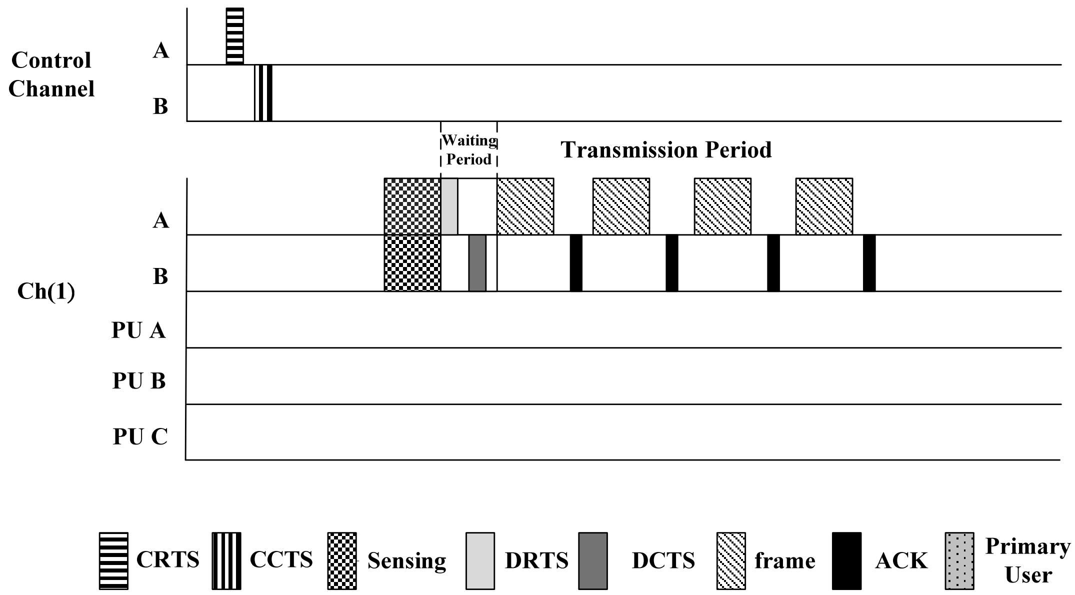
(3). $Ch(h_i)$ is busy for CR_A but idle for CR_B

Since $Ch(h_i)$ is busy for CR_A, CR_B does not transmit a DRTS frame. After waiting an amount of T time duration, both CR_A and CR_B hop to $Ch(h_{i+1})$. The timetable is Fig. 3-3(c).

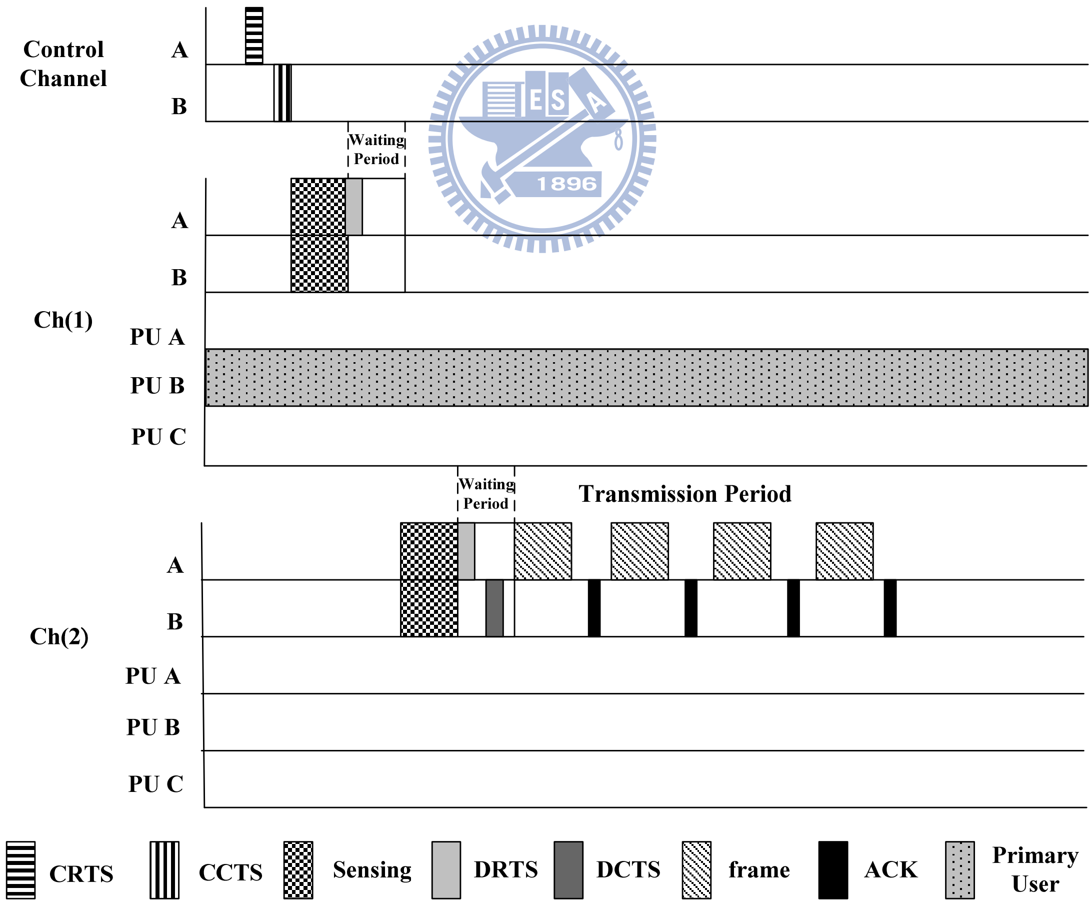
(4). $Ch(h_i)$ is busy for both CR_A and CR_B

Similar to case 3, CR_A and CR_B hop to $Ch(h_{i+1})$ after T time interval, and thus the timetable is as in Fig. 3-3(c).

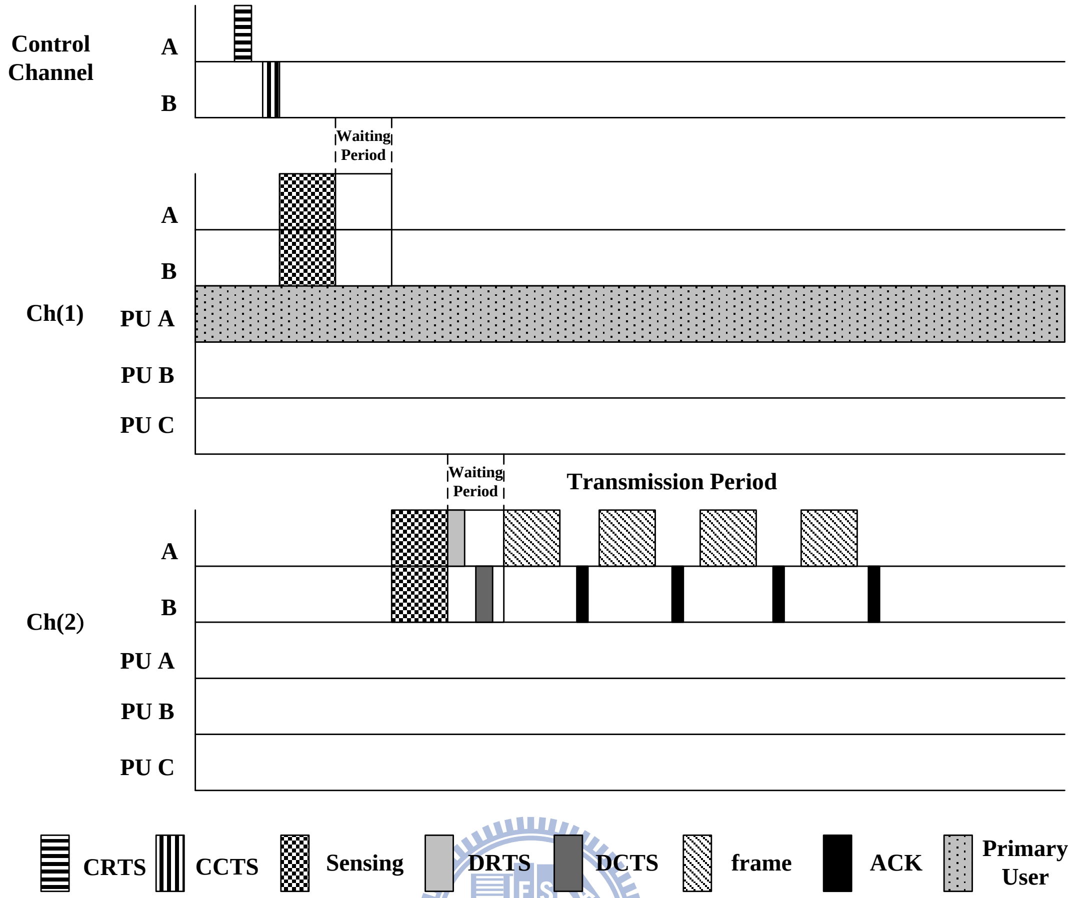
The process of data channel hopping and sensing does not terminate till CR_A and CR_B find one data channel which is not occupied by PUs and other CR users.



(a) Timetable of case 1: $Ch(1)$ is idle for both CR_A and CR_B



(b) Timetable of case 2: $Ch(1)$ is idle for CR_A but busy for CR_B



(c) Timetable of case 3 and case 4: *Ch*(1) is busy for CR_A but idle for CR_B and *Ch*(1) is busy for both CR_A and CR_B

Figure3-3: Explanation of message exchanges for fast channel sensing phase

3.3.2 Channel Vacating

In our mechanism, CR users will vacate data channel when they have accessed the data channel long enough (i.e., it has already transmitted *MaxTXQ* frames at that data channel), even if PUs come back to data channel. But because we set *MaxTXQ* by PU traffic load, the interference for PUs is acceptable.

The full process is showed as Fig.3-4.

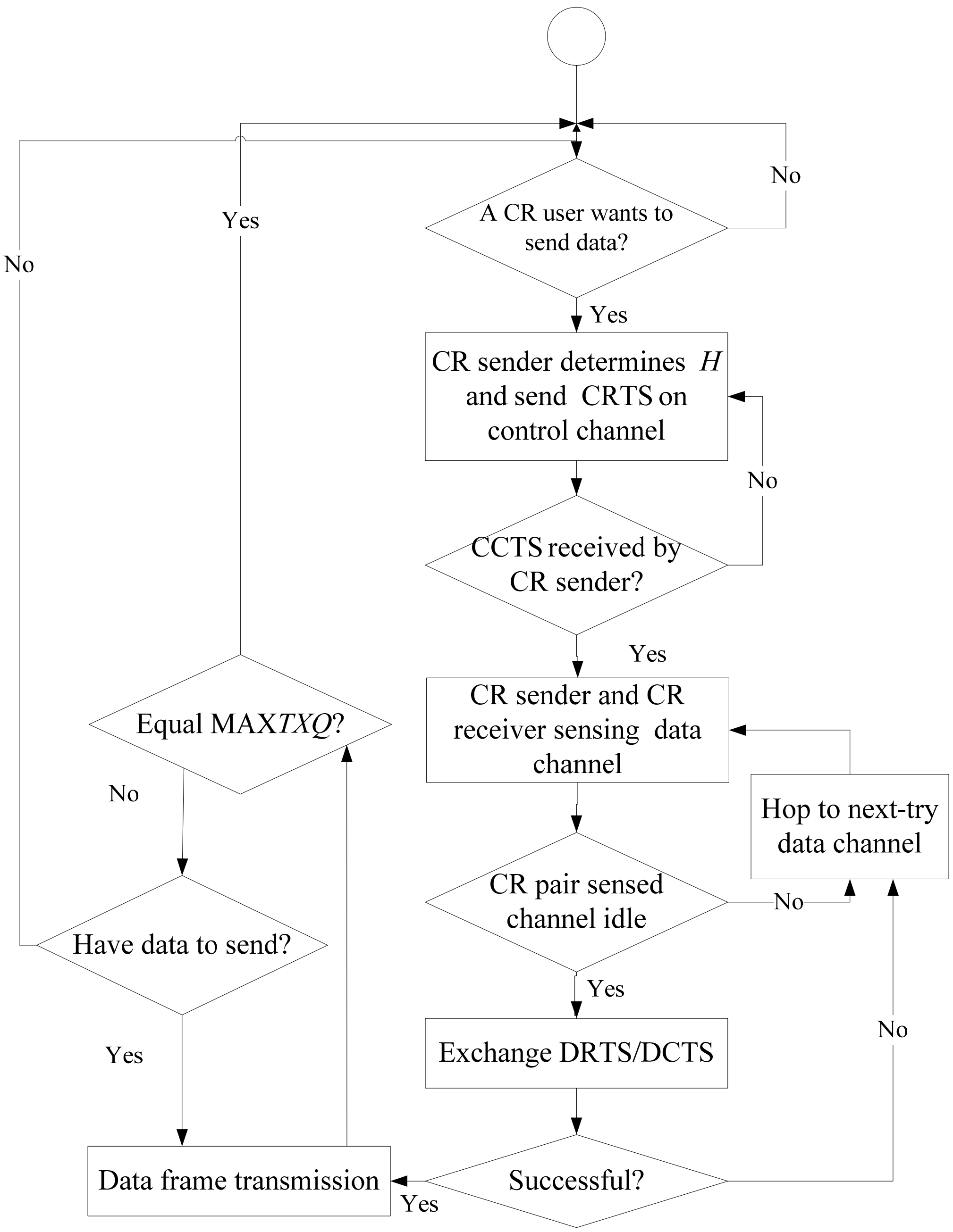


Figure3-4: The flowchart of proposed channel sensing and accessing mechanism

Chapter 4

Simulation Results

To evaluate the performance of the designed channel sensing and accessing algorithm presented in chapter 3, we develop a simulation program to discover the system throughput of a cognitive radio network, and the impact on primary users. We compared our approach with [7], i.e., OSA-MAC, with [11], i.e., SSA-MAC, with [15], i.e., CH-MAC and with [16], i.e., DRA-MAC. Again, we only consider single-hop flows of cognitive radio users.

Table4- 1 :Parameter settings of simulation

Parameter	Value
Frame size	2048bytes
Number of data Channels (*N*)	5
SIFS	0.01ms
DIFS	0.05ms
Simulation time	100s
Sensing time for a data channel	2ms

In this experiment, there are six channels: one is control channel, and the others are data channel. Each data channel is occupied by primary users with Poisson arrival distribution. Cognitive radio users are always backlogged. Settings of simulation parameters are the same as in Table 4-1. The throughput of a considered CRN is shown in Fig. 4-1. Here we set primary users' traffic load be 0.4, and vary the number of CR pairs from 1 to 16. We observed that our proposed mechanism outperforms other proposed approaches. The reason is, in our approach, a CR sender can transmit multiple frames (the maximum is *MaxTXQ* frames) without interruption from PU users when an available data channel is accessed. Contrarily, in SSA-MAC, because our proposed setting-*TXQ* method according to PU traffic load and then we get *MaxTXQ* 4, $TXOP_{CR}$ of SSA is set 4. Our proposed method outperforming SSA-MAC is the reason that our setting-*TXQ* method depends on PU traffic load and we provide no opportunity for PU users to interrupt CR users' transmission in this data channel. Despite no interruption opportunities, our method affects PU users within tolerable range. In OSA-MAC, the reason is that a CR sender only transmits one frame at a time and it spends too much time in phase one and OSA-MAC is synchronous protocol so it performs worst. In DRA-MAC, it is also synchronous protocol which results in reducing opportunities to access data channel. The difference between DRA-MAC and CH-MAC is that DRA-MAC adjusts hopping sequence according to each channel's datarate, so DRA-MAC outperforms CH-MAC. This result thanks to the no interruption, less collision and longer accessing time makes our approach's throughput get better. The throughput of PU users is shown in Fig. 4-2. We observed that five methods affect PU traffic slightly.

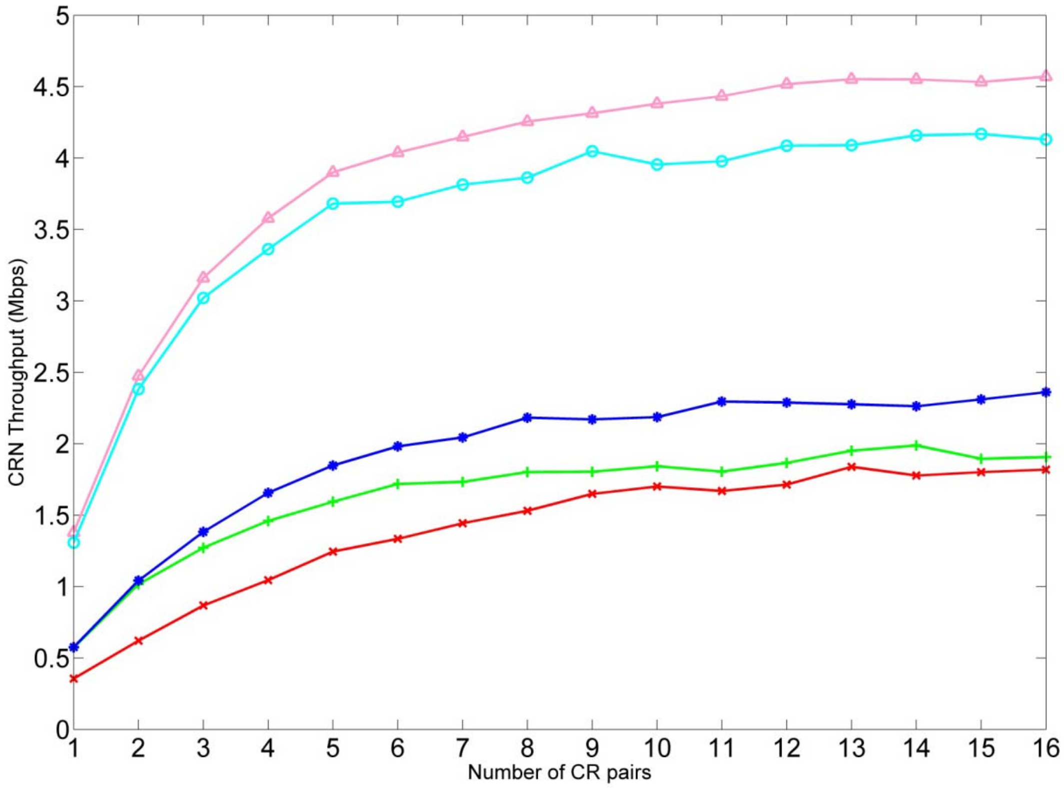


Figure4-1: CRN throughput vs. the number of CR pairs, upon PUs utilizing 40% bandwidth

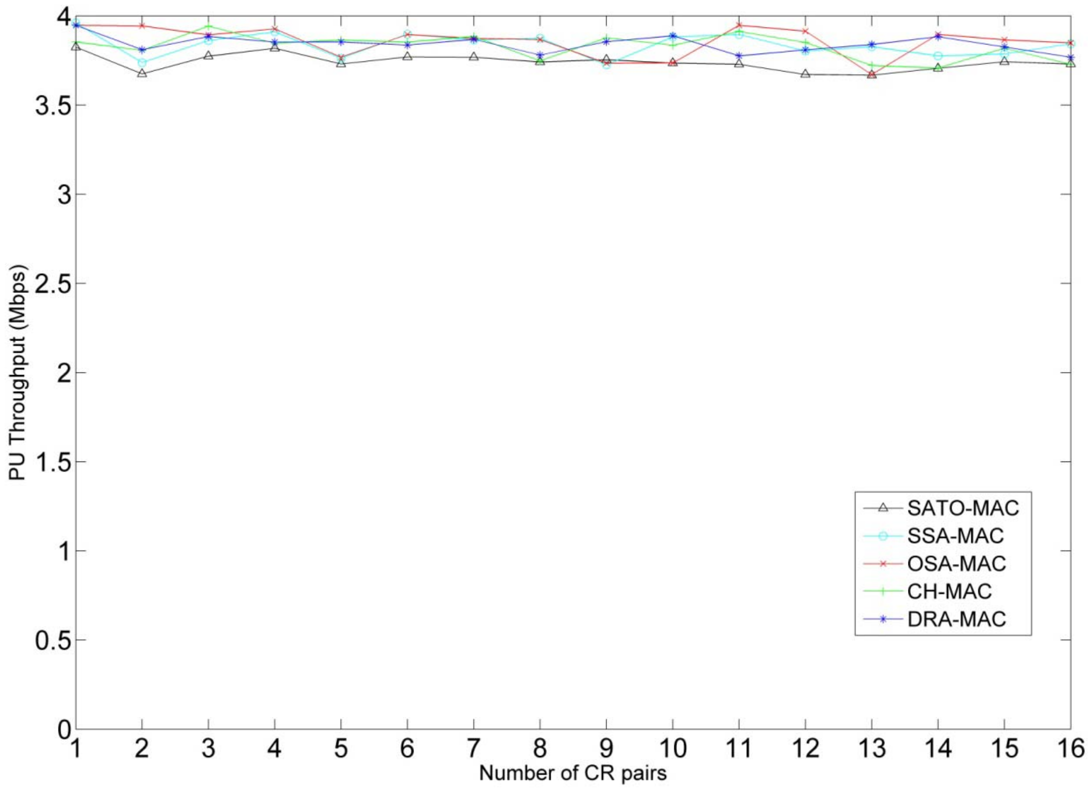


Figure 4-2 : PU throughput vs. the number of CR pairs, upon PUs utilizing 40% bandwidth

Followed, we investigate the impact of primary users' traffic load on CR users' throughput, and the result is shown in Fig. 4-3. Here we set the number of CR pairs be 15, and vary primary users' traffic load. For example, 0.6 traffic load indicates that primary users generate packets to utilize 60% bandwidth in total. Our proposed mechanism achieves a higher throughput than other methods, except SSA-MAC when primary users' traffic load is larger than 0.54. Because our proposed mechanism proposes setting-*MaxTXQ* method, when traffic load varies from 0.1 to 0.9, *MaxTXQ* varies from 6 to 1. When traffic load is 0.6, *MaxTXQ* is 2 so SSA-MAC outperforms our mechanism with $TXOP_{CR}$ =4. Specifically, the CRN throughput of our algorithm is zero when PUs utilize all bandwidth; contrarily, OSA-MAC still has 0.57 Mbps throughput and performs better when PU traffic load is higher. The reason is that in OSA-MAC, CR users are able to send data frames on not only data channels, but also the control channel. Thus CR users can send frames on the control channel, even if they cannot borrow data channels from PUs. The throughput of PU users is shown in Fig. 4-4. We observe that five methods perform similarly.

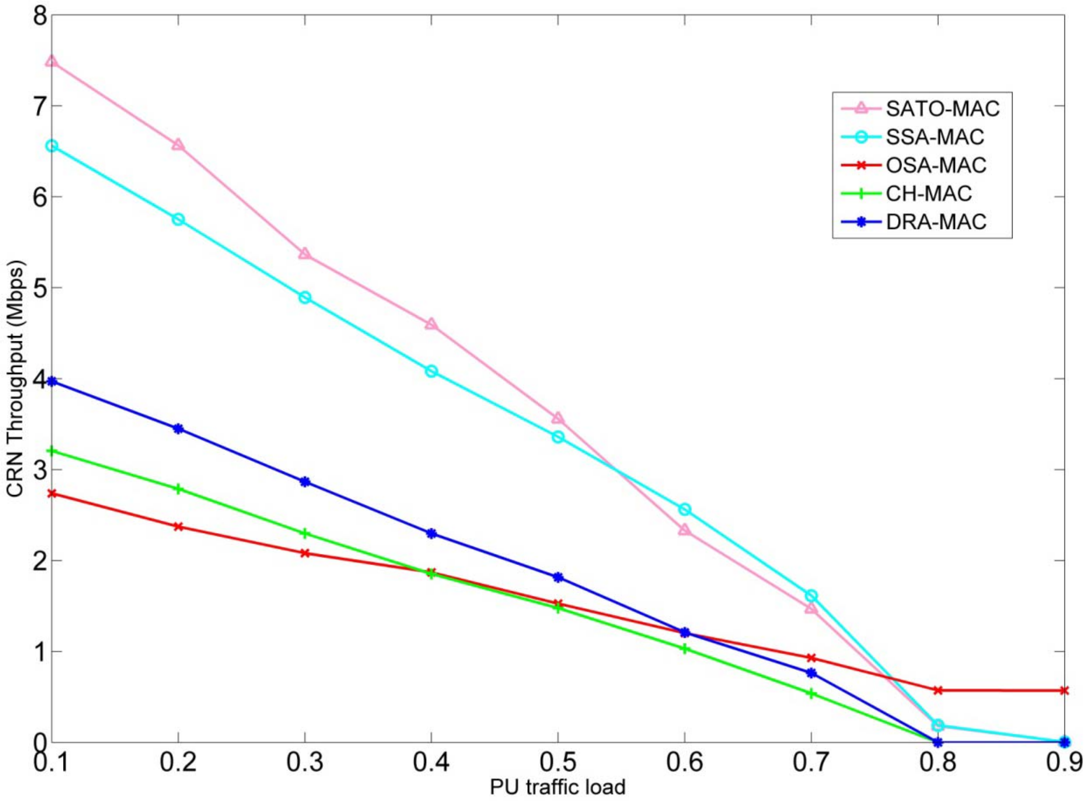


Figure 4-3: The throughput of a CRN vs. PUs' traffic load, upon 15 CR pairs

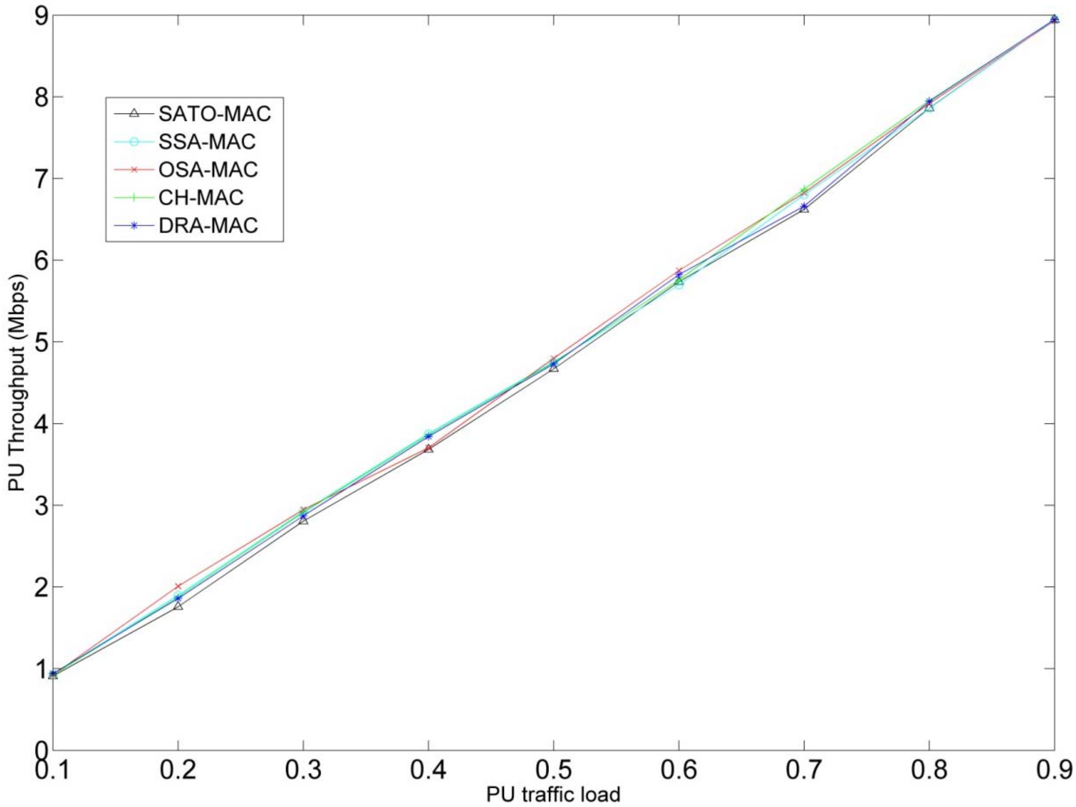


Figure 4-4: The throughput of PU vs. PUs' traffic load, upon 15 CR pairs

Though a CRN has a good throughput performance upon a large *MaxTXQ* value, the side-effect is long searching time for CR users, as shown in Fig. 4-5. In Fig. 4-5, the average searching time of five methods increases as the number of CR pair increases. Our approach and SSA-MAC is asynchronous so both have lower searching time than other approaches. In addition, the average searching time of OSA-MAC is longer than that of our approach when the number of CR pairs is few. The reason is OSA-MAC consists of three phases, and all CR users are synchronized when executing each phases. In other words, though a CR user has already sensed an unoccupied data channel and finish its one-frame transmission, it cannot start channel selection phase immediately. Instead, it waits for the beacon of next beacon interval. However, when the number of CR pair increases, OSA-MAC has a lower average searching time compared to our approach. This is because, for OSA-MAC, a CR sender only transmits one data frame when occupying a data channel and could use control channel as data channel in phase 3. However, the average searching time of DRA-MAC and CH-MAC have longer than other approaches because they are synchronous and couldn't use control channel as data channel. In Fig. 4-6, specifically, a large *MaxTXQ* value indicates that a CR user can transmit more data packets before vacating the occupied data channel and thus other CR users will spend much more time on data channel sensing. With lower PU traffic load, because our approach with larger *MaxTXQ* than SSA-MAC, our approach has longer searching time. OSA-MAC has a shortest average searching time with reason as above mentioned. DRA-MAC and CH-MAC both have longer searching time with reason as above mentioned.

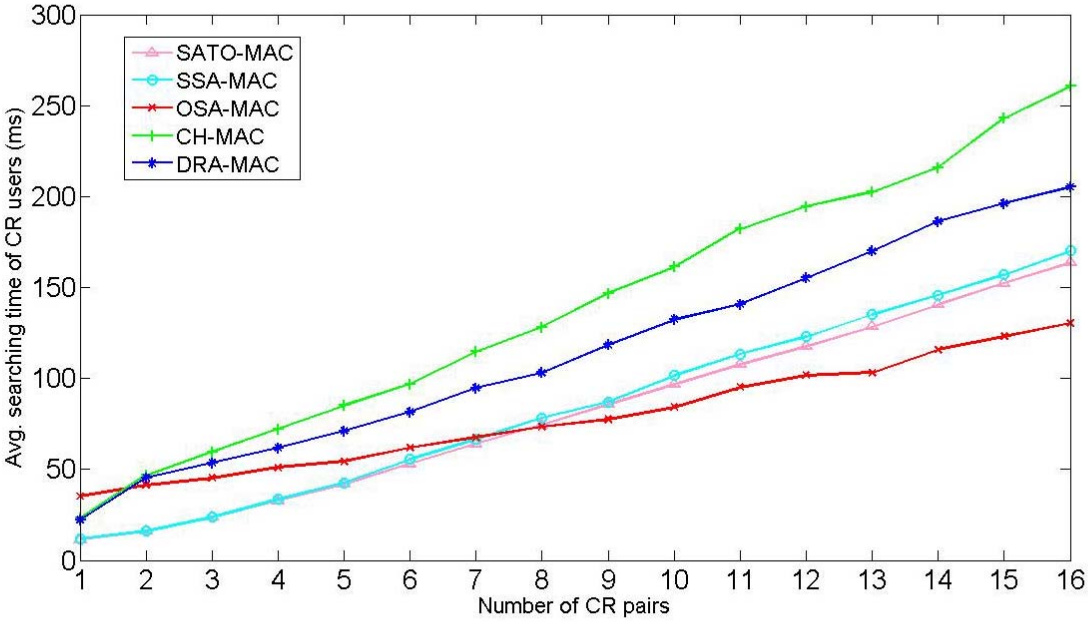


Figure 4-5: Average searching time of CR users vs. the number of CR pairs, upon PUs utilizing 40% bandwidth

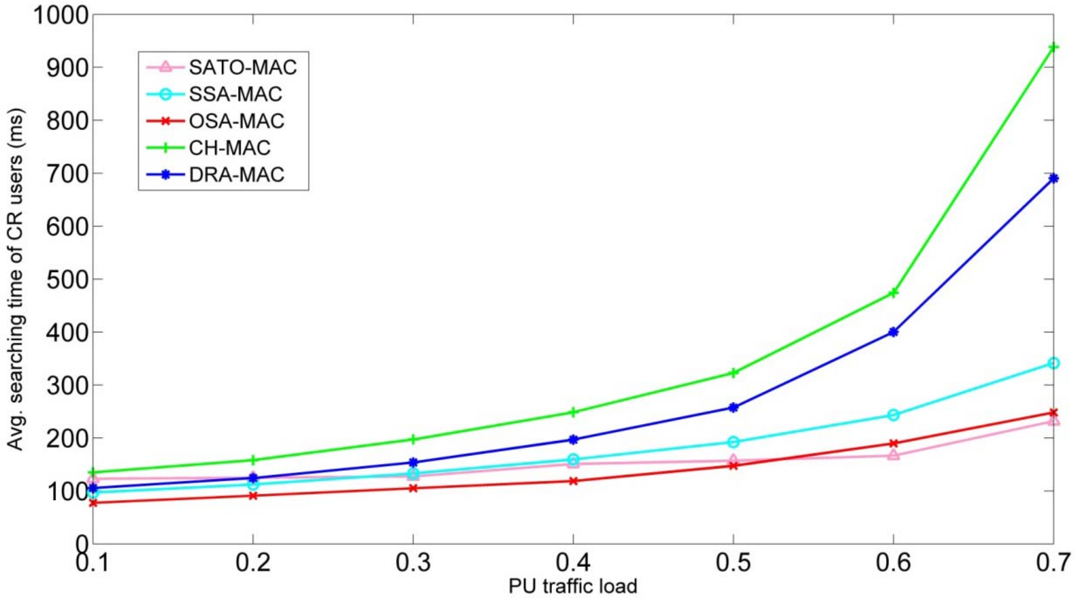


Figure 4-6: Average searching time of CR users vs. PUs' traffic load, upon 15 CR pairs

In Fig. 4-7, because of no interruption mechanism and transmitting more data packets when CR users occupying the data channel, the waiting time of our approach is longer than other approaches. But according to [21], the tolerable waiting time of PUs is 2s so the simulation results are acceptable. Because of having control channel as data channel in phase 3, OSA-MAC has lower waiting time of PU. DRA-MAC and CH-MAC both have fewer opportunities to access data channel so waiting time of them are shorter than our approach and SSA-MAC. In Fig. 4-8, the reasons are mentioned as above.

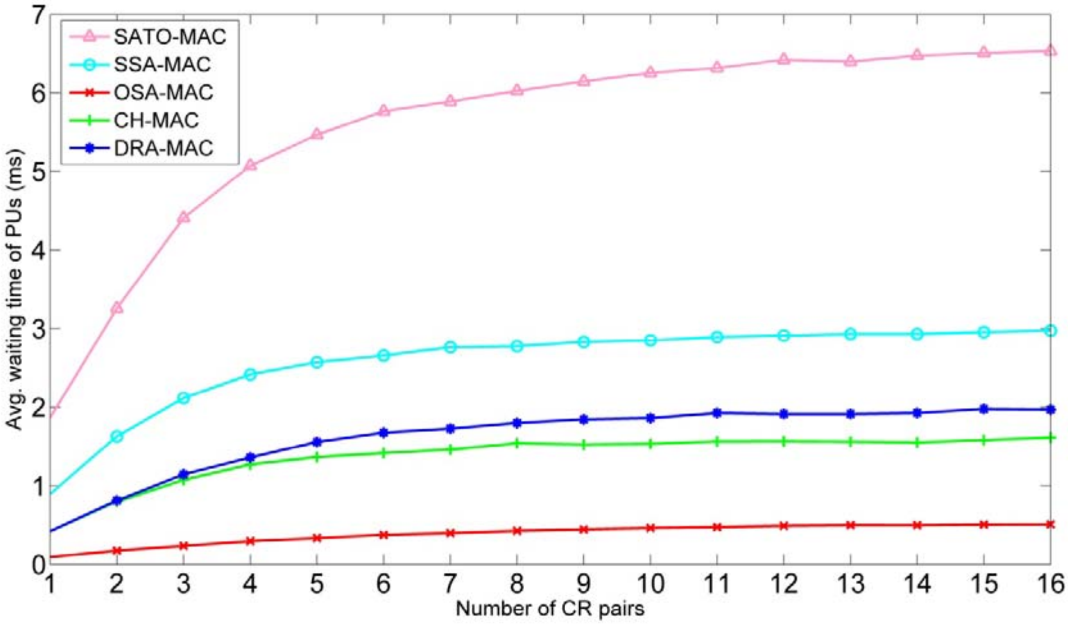


Figure 4-7: Average waiting time of PU users vs. the number of CR pairs, upon PUs utilizing 40% bandwidth

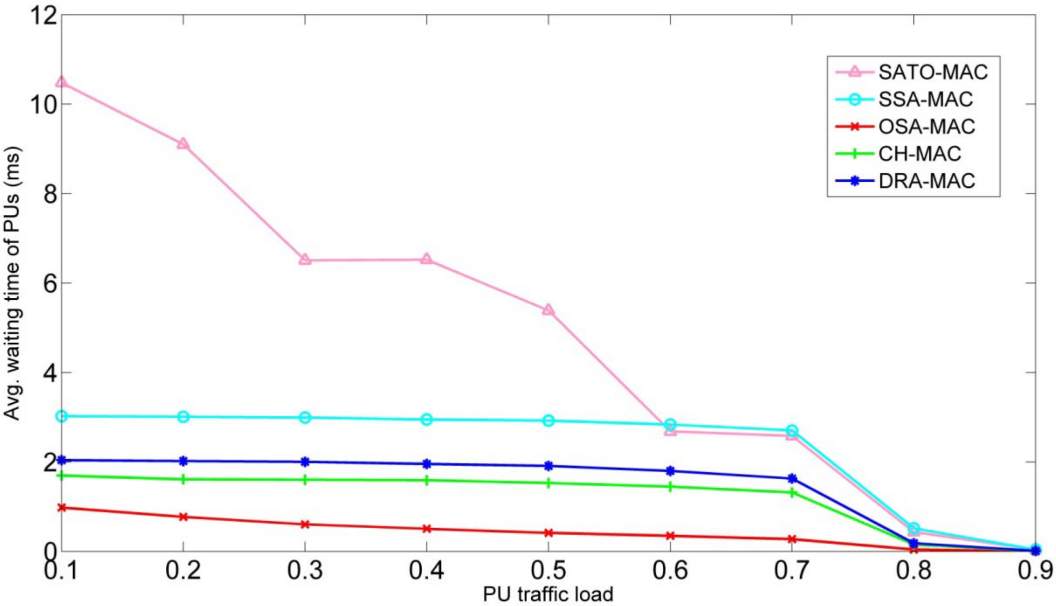


Figure 4-8: Average waiting time of PU users vs. PUs' traffic load, upon 15 CR pairs

We then observe the impact of frame size on the performance of primary users, and the simulation results are shown in Figs.4-9 and 4-10. Here we set the number of CR pairs be 15 and PU traffic load be 0.4. As frame size varies, *MaxTXQ* varies from

11 to 4.It is straightforward that when frame size increases, the CRN throughput increases significantly. Contrarily, the throughput of PUs decreases slightly, and the decrement is less than 1.88%, as shown in Fig. 4-9. Again, thanks to the no interruption mechanism which lengthens the average waiting time of primary users which still is acceptable according to [21], as shown in Fig. 4-10.

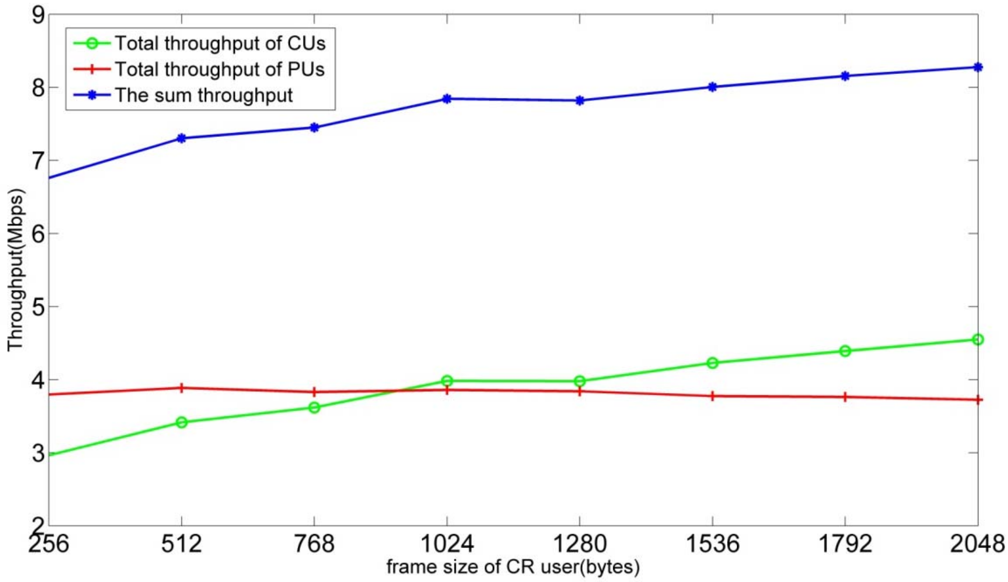


Figure 4-9: Throughputs of PUs and CR users vs. CR frame size, upon 15 CR pair

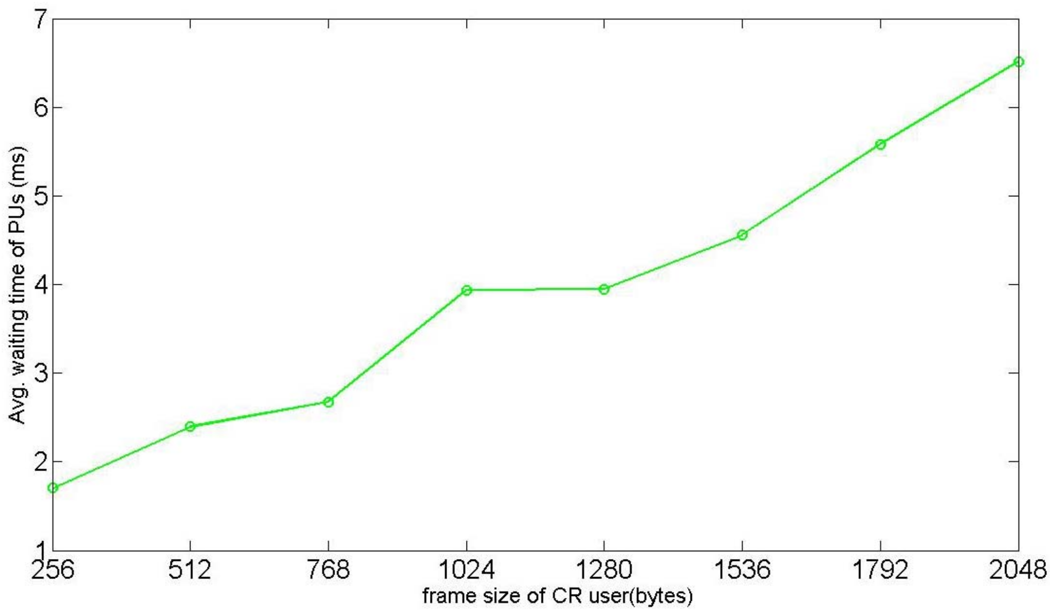


Figure 4-10: The average waiting time of PUs vs. CR frame size, upon 15 CR pairs

Then we present the performance of channel utilization of CR users. This experiment is to show the degree of channel utilization with different PU traffic load. We set the number of data channels be five, and CR pairs be 15. Fig. 4-11 is the throughput performance. When PU traffic load is under 0.5, the channel utilization of available bandwidth achieves over 73% and when PU traffic load becomes larger and larger, the channel utilization of available bandwidth varies from 63% to 4.9%. Because we propose setting-*TXQ* method by PU traffic load, even if PU traffic load varies, the channel utilization of available bandwidth mostly achieves over 71%. But with higher PU traffic load, CR users have fewer opportunities to access data channel so the channel utilization of available bandwidth degrades, especially as PU traffic load is 0.8 and 0.9.

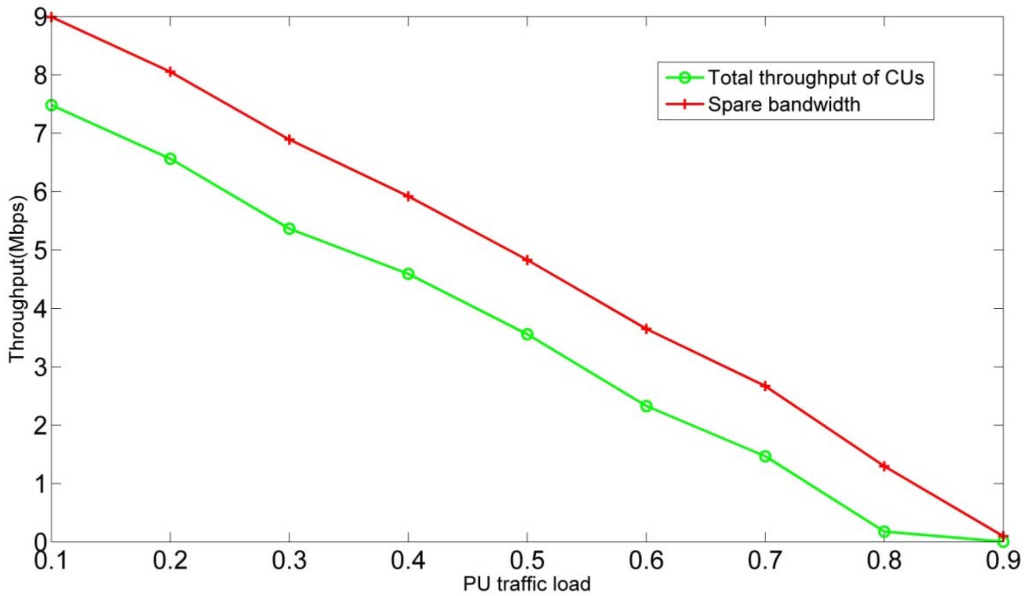


Figure 4-11: Throughput vs. PU traffic load, upon N=5, and 15 CR pairs

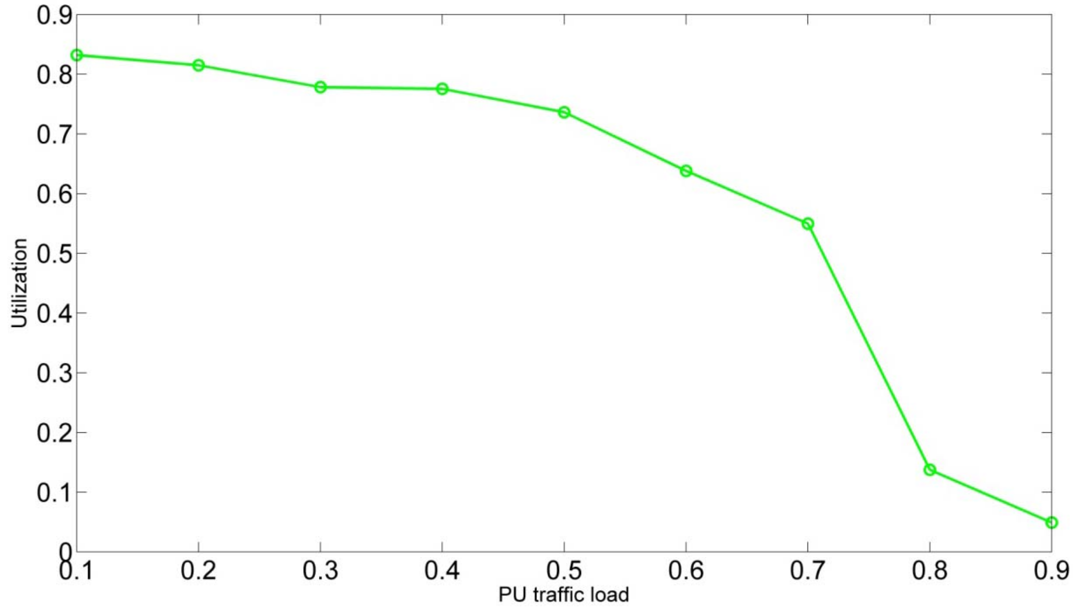


Figure 4-12: Channel utilization vs. PU traffic load, upon *N*=5, and 15 CR pairs

Chapter 5

Conclusion and Future Work

In this paper, a synchronized channel sensing and accessing mechanism for cognitive radio users has proposed. This mechanism consists of two phases: fast channel sensing and channel vacating. We propose the method to decide hopping sequence according to successful transmission probability for using these data channels fully and also propose the method to decide *MaxTXQ* according to PU traffic load.Computer simulation was conducted to demonstrate the superior performance of our protocol over that of other approaches although waiting time is higher than other, but it is acceptable. In the future, we hope that this mechanism apply to multi-hop or add QoS consideration. In multi-hop, relay node could use the equation to decide hopping sequence to make the best channel used fully. In QoS, we could consider various desired bandwidth of CR user, and assign different *TXQ* for meeting QoS.

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