國立交通大學

網路工程研究所

碩 士 論 文

在 802.11 無線網路下感知網路中同步感測頻道與使用之研究

Synchronized Channel Sensing and Accessing for Cognitive Radio Users in IEEE 802.11 Wireless Networks

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Abstract

One of the most challenging issues in cognitive radio systems is channel sensing and channel accessing. In this paper, 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 proactive channel vacating. Fast channel sensing is for a pair of cognitive radio users to search an available channel 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, through the designed interruption mechanism, cognitive radio users can create opportunities for primary users to claim the spectrum and thus minimize the caused interference to primary users. We further analyze and evaluate the performance of a considered cognitive radio network through a two-dimensional Markov chain and simulations. From the analytical and simulation results, our proposed protocol can efficiently balance the tradeoff between throughput performance of a cognitive radio network and waiting time of primary users to claim channels.

Abstract

有許多新的議題在感知網路中被討論，其中一項就是頻道感測與頻道存取。在本篇論文中，我們提出了一套在 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：快速頻道感測及主動釋放頻道。快速頻道感測是針對一對感知網路使用者找尋可使用的頻道；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。我們更進一步利用二維馬克夫鍊去分析且評估感測網路之效能。經由理論值與模擬值的結果，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 course of the past two years, many people help me to accomplish my master thesis. I would like to express of my sincere thanks to my advisor, Professor His-Lu Chao and Dr. Tsai in the Industrial Technology Research Institute cheered me on when I was about to give up. Without their supervision and perspicacious advices, this thesis could not be completed. Without my advisor Professor Chao I cannot own these honors now.

Finally, I would like to thank my family, my upperclassmen, my underclassmen, and my friends. They all concern about my life and take care of me. Because of your company, I have a lot of happiness during these two years. I show my appreciation for all of you.

TakChon Lou

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Chapter 1

Introduction

1.1 Background

As more and more versatile multimedia services emerge in the market, it becomes obvious that the spectrum is much scarcer and thus the current frequency allocation schemes cannot accommodate the needs of all services. Cognitive radio [1] is a promising technique to alleviate the problem of spectrum shortage. The concept of cognitive radio is that unlicensed users (referred to as cognitive radio users, CR users) can access the spectrum owned by licensed users (referred as primary users, PUs), while they cannot interfere with primary users when exploiting the spectrum. Thus to realize the technique of cognitive radio, a cognitive radio user must have the ability to measure, to sense, and to learn channel characteristics and availabilities [2]. In addition, primary users can claim the spectrum anytime when they have data to send, thus cognitive radio 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.

The focus of this paper is to design a spectrum sensing and accessing mechanism for cognitive radio users in 802.11-based networks. Spectrum sensing is the task for cognitive radio users to collect information about spectrum usage and existence of primary users; while spectrum accessing is the task for cognitive radio users to transmit data packets efficiently and vacate the occupied data channel to primary users as quick as possible. In the following, we introduce some existing work studying these two issues, and then elaborate our motivation and objectives.

1.1 Review of Related Studies

Based on the way a CR user searches for free channels, existing spectrum sensing schemes can be classified into two categories: proactive and reactive. The former is periodic basis, and a CR user continuously searches for unoccupied channels, and maintains a table to record the characteristics of sensed channels (such as signal-to-noise value, and occupancy), even it has no data to send currently; the latter, contrarily, is on-demand basis and a CR user searches for unoccupied channels only when it has data frames to transmit. Examples of proactive and reactive spectrum sensing schemes are [3, 4] and [5, 6, 7, 8, 9, 10], respectively. Some selected literature is briefly described in the following.

1.2.1 Proactive approaches

Proactive schemes mainly mean that a CR user needs to sense all channels continuously regardless of having data to transmit or not. In particular, in [3], a statistical channel allocation MAC protocol, named SCA-MAC, is proposed. In SCA-MAC, all CR users sense spectrum continuously and periodically. Moreover, a control channel is reserved for CR users to initiate transmissions through exchanging Control-channel-Request-To-Send (CRTS) and Control-channel-Clear-To-Send (CCTS) packets. The potential transmission opportunities, which are sensed by the CR receiver, are contained in the CCTS packet. Upon successfully exchanging CRTS and CCTS, the pair of CR users tune their transceivers to the agreed channels for data transmissions. The major advantage of SCA-MAC is a CR user can utilize multiple continuous unoccupied-channels to transmit data, and thus it reduces the total transmission time efficiently and improves the successful delivery rate. However, the disadvantages include (i) data channel selection is based on the recorded statistics of the CR receiver, and the designated spectrum hole may not be idle for the CR sender; (ii) to sense multiple continuous available channels is time consuming; and (iii) how to achieve synchronization is not addressed.

Instead of dedicating the control channel to control message exchanges, [4] utilizes two radios to do channel sensing (named listening radio) and data transmission (named data radio). The CR user which initiates to form a cognitive radio network divides channel time interval into N time slots, and N is the number of channels. The listening radio keeps sensing channels sequentially and each CR user records neighboring information and available channels. When a CR sender wants to send data, it randomly selects a common channel to send control frames at the specified time slot. Although this protocol can well exploit available channel resources, its implementation is complicated and hardware-constrained because each

CR user needs to be equipped two transceivers and globally synchronized. Besides, CR users would exchange massive packets which is bandwidth consuming.

1.2.2 Reactive approaches

In [5], there is a dedicated channel which is always available for CR users to exchange control information. Each beacon interval is divided into three phases: “channel selection”, “sensing”, and “data transmission”. Channel selection phase is for a CR user to inform its intended receiver the selected data channel. Sensing phase is for the CR pair to sense the availability of the selected data channel. The CR sender starts to transmit data packets in data transmission phase when the selected data channel is sensed idle. To achieve globe synchronization, one CR user is designated to periodically broadcast beacons. One characteristic of [5] is that CR users can transmit packets on not only data channels, but also the control channel, and thus it achieves high channel utilization. However, [5] has the same disadvantage as [4] that all CR users achieve global synchronization. This assumption is a key challenge, especially when all CR users form a multihop cognitive radio network. Another drawback of [5] 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.

A hardware-constraint cognitive MAC (HC-MAC) was proposed in [6]. 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 for a potential CR sender achieves optimal expected throughput. The authors further integrate optimal sensing time and IEEE 802.11 DCF to form HC-MAC mechanism. The drawback of HC-MAC is only one CR pair can do transmissions at a time. In other words, when a CR pair is transmitting data frames, other CR nodes which heard the C-RTS or C-CTS on the control channel are frozen until the transmissions finish. Thus, the overall throughput of the cognitive radio network is reduced, especially when there are un-sensed unoccupied channels.

A channel-hopping based cognitive radio MAC mechanism was proposed in [7]. Each CR user has its own channel hopping sequence, which is determined by its 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 hopping sequence to monitor on that channel, unless it has data to send. A CR sender follows the receiver's hopping sequence to negotiate with and transmit data to the receiver. 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 [7].

1.3 Motivation and objective

Through sensing the whole spectrum and exchanging massive control messages with each other to determine a best and available channel is a time-inefficient way for cognitive radio users. The reason is that the traffic behavior of primary users is unpredictable. Therefore, it may occur that primary users come back to claim the spectrum when CR users are sensing channels and exchanging control messages and are not yet transmitting data. The worst case is that one channel was sensed idle by a CR sender, the CR sender is negotiating with other CR users to avoid channel conflicts, and primary users want to utilize the channel. In such case, the CR sender should do channel sensing and negotiation again. It inspires us to design an time-efficient channel sensing and accessing protocol which can reduce exchanges of control messages as many as possible. In addition, existing literature (e.g., [3,4,5,6,7]) assumed CR users are aware of the presence of primary users and will vacate occupied channels as quick as possible. In fact, from the viewpoints of physical and MAC layers, primary users are not able to distinguish the overheard signals are sent by primary users or by CR users. However, detailed detection/interruption mechanisms were not proposed in literature. Therefore, we employ an interruption mechanism for primary users to be able to claim channels.

Chapter 2

System Model and Assumptions

The adopted system architecture in this paper is shown in Fig. 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. Note that our approach can be extended to implement in an ad hoc network as well. 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).

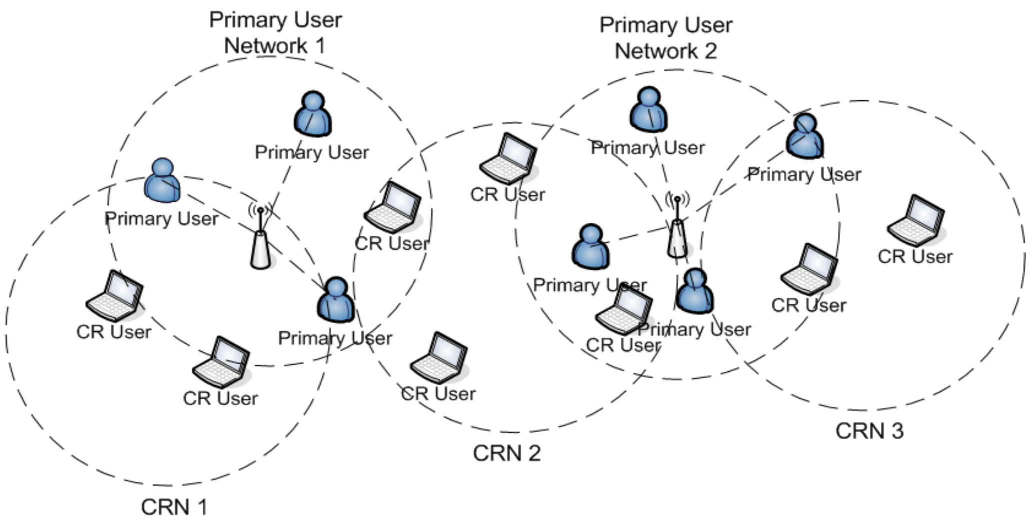


Figure 2-1 **:** The adopted system architecture consisting of primary users and CR

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 [11, 12], 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.

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.
4. An interruption function is incorporated in our approach for primary users asking CR users to vacate the borrowed channels.

3.1 Newly defined control frames and parameters

In our approach, we define three control frames and four 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 New Control Messages

(1). RTS_{CR}: 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 increment-per-hop, both are introduced soon. RTS_{CR} is sent at the control channel only.

(2). CTS_{CR}: 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). Ready-To-be-Interrupted (RTI): this control frame is sent by a CR sender after receiving a data ACK from the CR receiver and is for one-hop neighboring primary users to claim the data channel, if they have data to send.

3.1.2 New Parameters

(1). Initial selected data channel ID (denoted as $Ch(1)$): it is randomly selected by a CR sender, and is the first data channel that the pair of CR users will switch to do channel sensing. $Ch(1)$ is a positive integer, and $1 \leq Ch(1) \leq N$.

(2). Increment-per-hop (h): it is randomly generated by a CR sender to derive the ID of next-try data channel. h must satisfy: (i) h is less or equal to the number of data channels (i.e., N), and (ii) h and N are relative primes. For example, when N=8, h could be 1, 3, 5, and 7. The reason of N and h being relative primes is to avoid many CR pairs sensing the same subset of data channels.

(3). $TXOP_{CR}$: the bounded time interval during which a CR user can send as many frames as possible. The impact of a large $TXOP_{CR}$ value is long sensing time of finding an available idle channel for a CR user. In this paper, the unit of $TXOP_{CR}$ is frames. For example, $TXOP_{CR}$ is m frames indicates a CR sender can transmit at most m frames on a data channel.

(4). $SIFS_{CR}$: the small time gap between a RTI and the next data frame. This short time interval is providing opportunities for PUs to claim channels. When a PU wants to send data at a channel, and hears a RTI control frame, it replies with a RTS and then the CR sender vacates the channel immediately. If there are multiple RTSs sent within $SIFS_{CR}$ and collisions occur, the CR sender detects the presence of PUs and still returns the occupied data channel. $SIFS_{CR}$ is long enough for a PU to send a RTS (i.e., $SIFS_{CR} > t_{RTS}$). In this paper, we set $SIFS_{CR}=10\times SIFS$. However, it is adjustable to improve throughput performance.

3.2 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 proactive channel vacating.

3.2.1 Fast 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 $\mathrm{RTS_{CR}}$ on the control channel. Both the randomly generated $Ch(1)$ and h are encapsulated in the $\mathrm{RTS_{CR}}$. 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 $\mathrm{RTS_{CR}}$, it replies CR_A a $\mathrm{CTS_{CR}}$. At this moment, CR_A and CR_B achieve synchronization and switch to channel $Ch(1)$ for channel sensing purpose.

When hopping to $Ch(1)$, both CR_A and CR_R listen to $Ch(1)$ for t time interval to avoid interfering on-going transmissions of PUs or CR users. Here we set t be 2ms. If $Ch(1)$ is still idle after t time, CR_A and CR_B exchange RTS and CTS as usual. Otherwise, CR_A and CR_B hop to the next data channel and then sense again. The reason that CR_A and CR_B exchange RTS and CTS 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 (1).

$$Ch(i+1) = (Ch(i)+h) \bmod N, i \geq 1, \tag{1}$$

where i indicates the i^{th} channel hopping, and N is the number of data channels. Using Fig. 2 as an example, the number of data channel N is 8 (numbered 0-7); $Ch(1)$ and h are 2 and 3, respectively. Therefore, the pair of CR users will first sense channel 2. If channel 2 is busy, they will further sense channel 6 (because [(2+3) mod 8]=5). The complete hopping sequence is [2, 5, 0, 3, 6, 1, 4, 7, 2, 5, 0, 3, 6, …]. We observed that the hopping sequence is repeated and each channel is sensed once per run. In Chapter 5, we will evaluate the impact of different hopping generation functions on system performance.

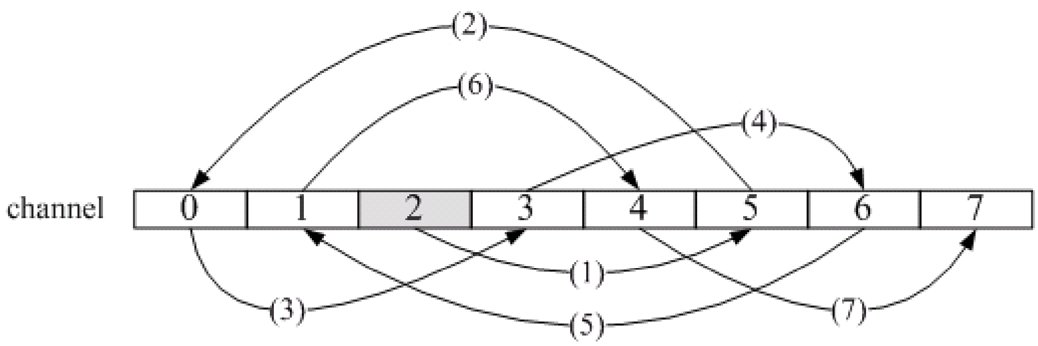


Figure 3-1 : An illustrative example of data channel hopping sequence: N=8, $Ch(1)$=2, h=3.

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

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

In this case, CR_A sends a RTS frame to CR_B immediately and then waits for CR_A's reply. Upon successfully receiving the CTS, CR_A starts to transmit data frames to CR_B. After successfully transmitting a data frame, CR_A broadcasts a RTI to one-hop neighboring PUs and waits for $SIFS_{CR}$ so that PUs can claim the channel. Upon receiving RTS sent by a PU, CR_A and CR_B vacate the data channel and hop back to the control channel. Besides, CR_A can send at most $TXOP_{CR}$ 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. 3-2(a).

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

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

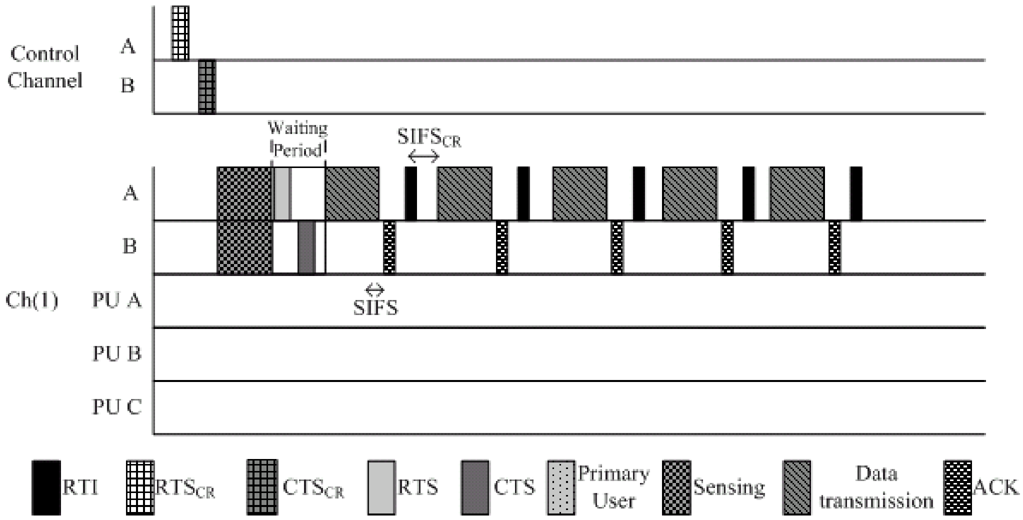
(3). $Ch(i)$ is busy for CR_A but idle for CR_B

Since $Ch(i)$ is busy for CR_A, CR_B does not transmit a RTS frame. After waiting an amount of T time duration, both CR_A and CR_B hop to $Ch(i+1)$. The timetable is Fig. 3-2(c).

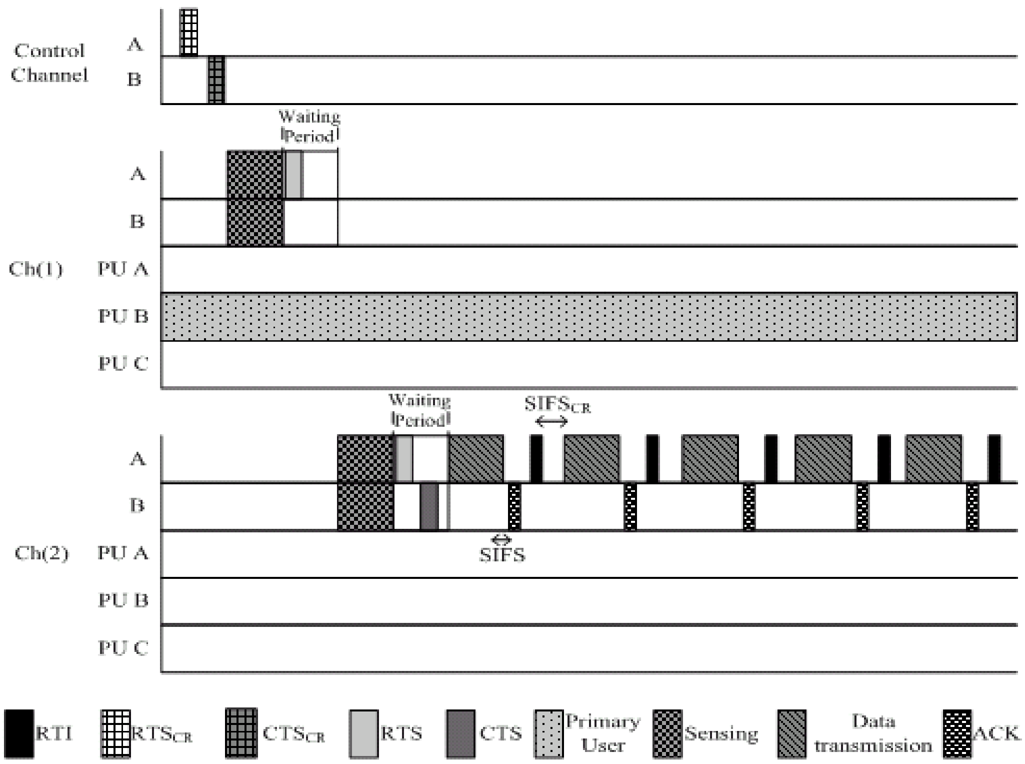
(4). $Ch(i)$ is busy for both CR_A and CR_B

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

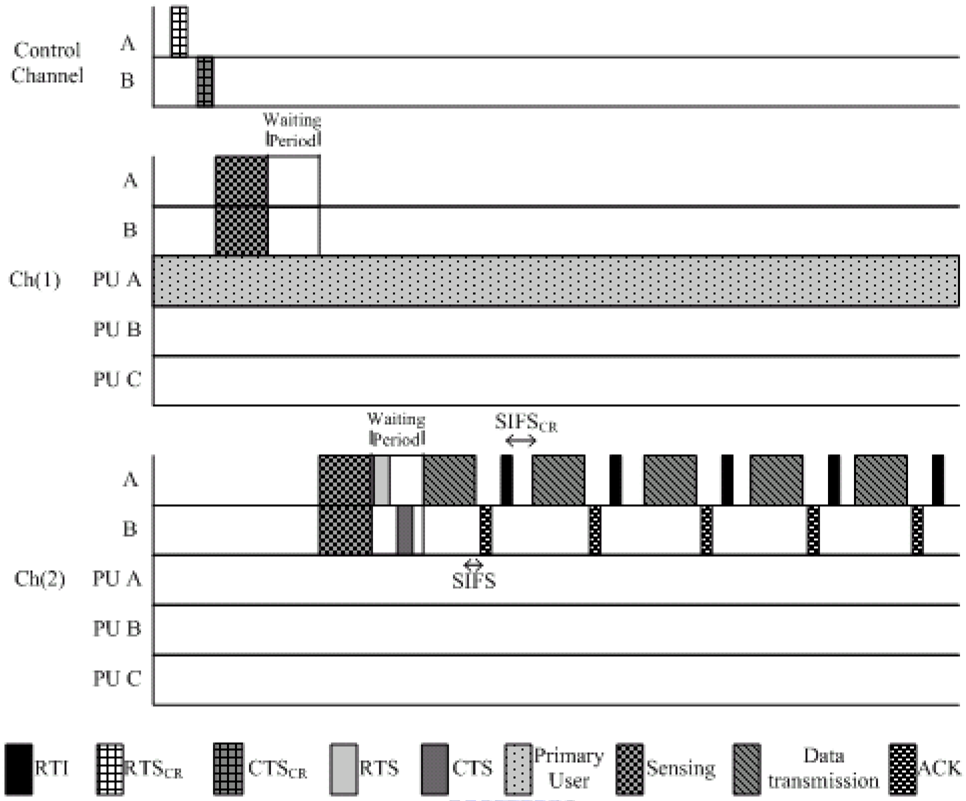
The process of data channel hopping and sensing does not terminate till CR_A and CR_B find one data channel which is not occupied by PUs and other CR users.



(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

Figure 3-2 : Explanation of message exchanges for fast channel sensing phase

3.2.2 Proactive channel vacating

There are two situations for a CR pair to vacate the occupied data channel: one is they have accessed the data channel long enough (i.e., it has already transmitted $TXOP_{CR}$ frames at that data channel), and the other is PUs want to claim that data channel. For the former, the CR sender and receiver stop transmitting/receiving data frames and then hop back to the control channel, as described in Chapter 3.2.1. Our phase 2 design focuses on the latter. To be aware of the presence of potential primary senders, there must be a mechanism for potential primary senders to interrupt the transmissions of a CR pair. The design challenges of this interruption mechanism are twofold: how does a potential primary sender recognize that the data channel is occupied by a CR pair or other primary users, and how to make a CR pair to automatically return the borrowed data channel. We elaborate our interruption mechanism in the following. Both challenges are dealt with RTI control frame.

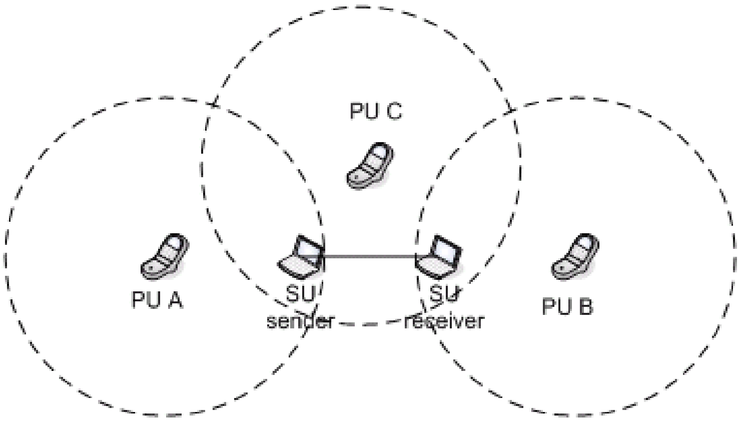


Figure 3-3 : An illustrative example for explanation of fast channel sensing phase

After transmitting a data frame and successfully receiving the ACK, a CR transmitter sends a RTI frame and then waits for $SIFS_{CR}$ long. Within this time duration, potential primary senders are able to send RTS to its intended primary receiver. Upon receiving RTS messages, the CR sender/CR receiver knows the presence of primary users, and they will hop to the control channel. There are three possible actions after a CR sender transmitting a RTI:

(1) Case 1: the potential primary sender is a neighbor of the CR sender, while it is not a neighbor of the CR receiver

In Fig. 3-3, PU_A is such a potential primary sender. PU_A sends a RTS frame upon receiving RTI frame. The CR sender then stops transmitting data and hops back to the control channel. In the meantime, the CR receiver does not receive further data frames, and thus is aware that the CR sender must be interrupted by a potential primary sender. The CR receiver hops back to the control channel, too. If the CR sender still has data for the CR receiver, it generates a new initial data channel ID and increment-per-hop, and sends communication invitation on the control channel. The corresponding timetable of message exchanges is in Fig. 3-4(a).

(2) Case 2: the potential primary sender is a neighbor of the CR receiver, but it is not a neighbor of the CR sender

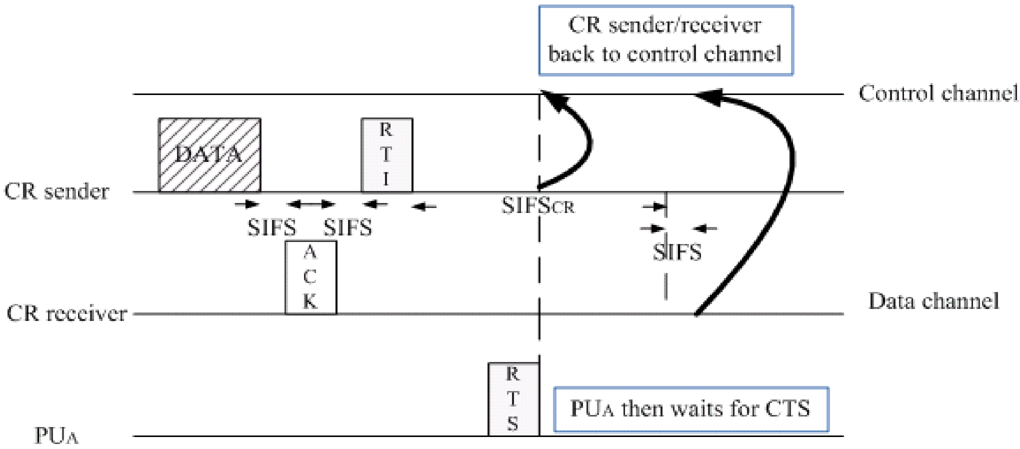
Again in Fig. 3-3, PU_B is such a potential primary sender. When the CR sender sends a RTI frame, the CR receiver is idle for $SIFS_{CR}$ long. Since $t_{SIFS_{CR}}$ is longer than t_{DIFS}, thus PU_B can send a RTS frame to its receiver. At this time, the CR receiver is aware of the presence of a primary sender. The CR receiver hops back to the control channel. Though the CR sender keeps sending data frames, it does not receive any ACKs from the CR receiver. Therefore, the CR sender vacates the occupied data channel and hops back to the control channel, too. The corresponding timetable of message exchanges is in Fig. 3-4(b).

(3) Case 3: the potential primary sender is a neighbor of the CR sender and the CR receiver

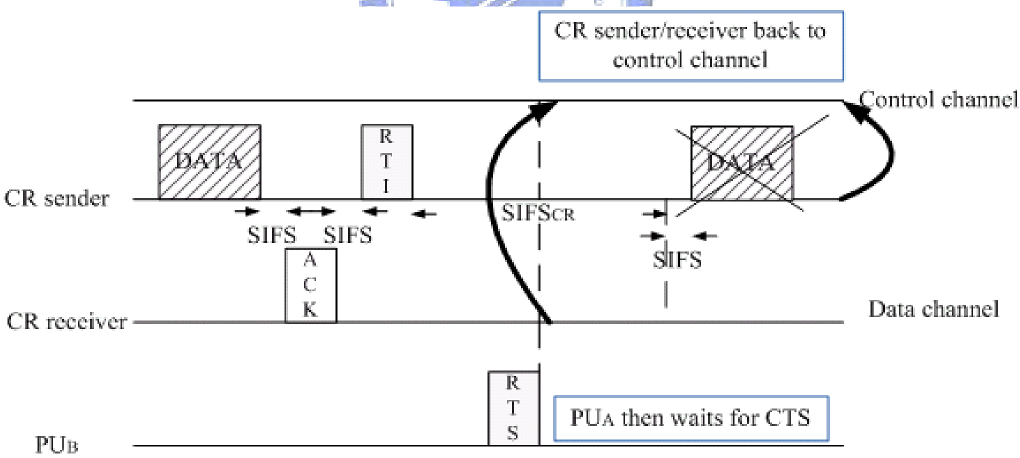
PU_C is such a potential primary sender shown in Fig. 4. Both the CR sender and the CR receiver receive the RTS frame sent by PU_C, and then hop back to the control channel. The corresponding timetable of message exchanges is in Fig. 3-4(c).

The detailed flow chart of our proposed channel sensing and accessing mechanism is summarized in Fig. 3-5.

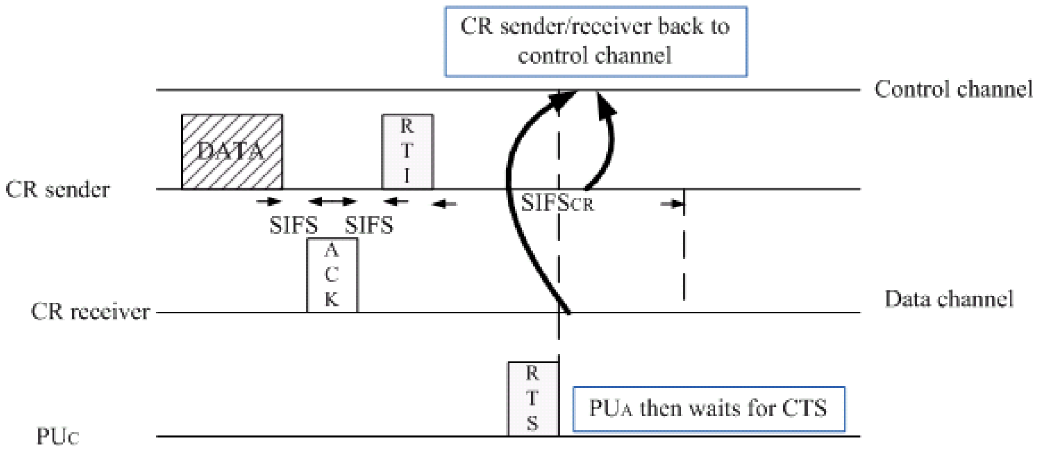
Here is a little discussion. In this paper, it considers that there is no retransmission mechanism for CR users, and if there is no ACK replied by CR receiver because of the packet loss, the CR pair will also think that the channel is claimed back by PU, although it is not true. Because of these situations, if there has retransmission mechanism for CR users, the CR receiver may reply a NACK in case of the receiver does not receive the data frame correctly. If the CR sender receiver the NACK, that means it is just a packet loss occur, it is not a PU cliam back the data channel, then it will do the retransmission of frame.



(a) Timetable of case 1: PU_A is a neighbor of CR sender



(b) Timetable of case 2: PU_B is a neighbor of CR receiver



(c) Timetable of case 3: PU_C is a neighbor of CR sender and CR receiver

Figure 3-4 : Explanation of message exchanges for proactive channel vacating phase

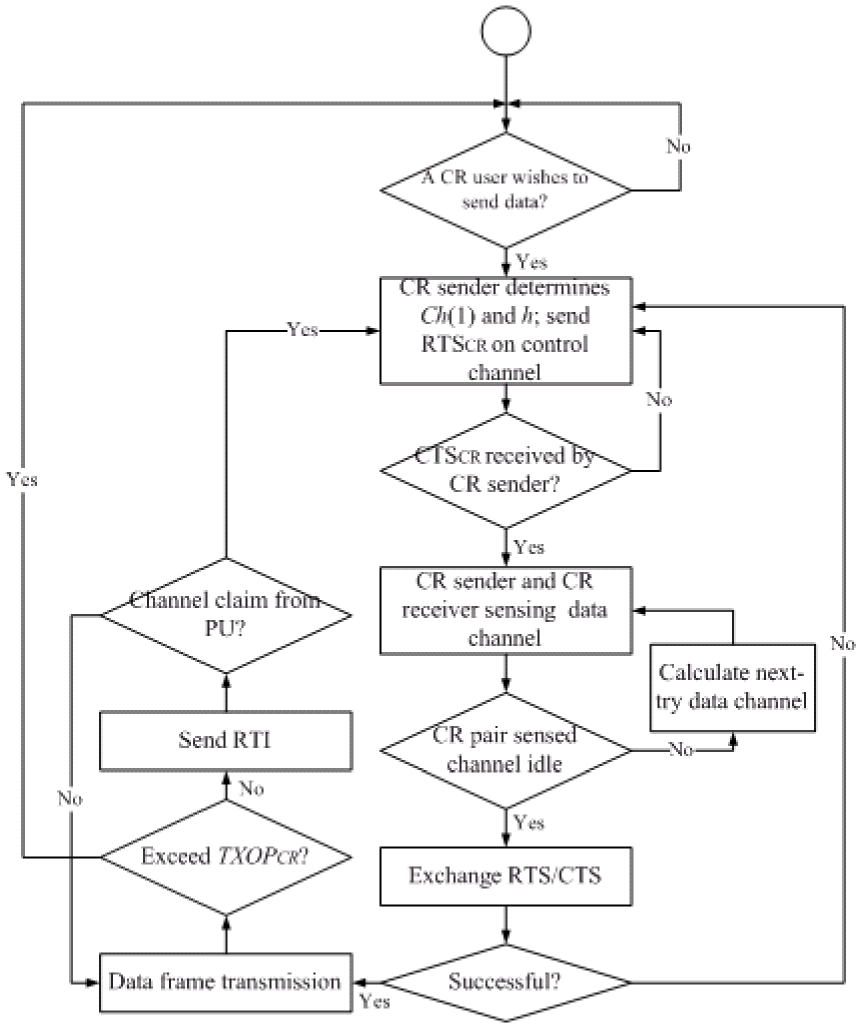


Figure 3-5 : The flowchart of proposed channel sensing and accessing mechanism

Chapter 4

Performance Analysis

In this chapter, we model the process of channel occupation of our approach as a continuous-time Markov Chain, and then analyze our approach. We assume there are *N* data channels and *C* pairs of cognitive radio users. The probability of channel selection of primary users is uniform distribution. Though randomly selecting an initial data channel ID and an increment-per-hop, we assume each data channel has the same probability to be sensed. Therefore, we assume that the probability of data channel selection for cognitive radio users is uniform distribution, too. The traffic arrival rates of primary and cognitive radio users are λ_p and λ_c respectively which are both the Poisson distribution. Beside, the corresponding service time of primary and cognitive radio users is exponential distribution with rates μ_p and μ_c. In this Markov Chain, states are described by an integer set (*i*, *j*, *k*), where *i* is the number of channels occupied by primary users, *j* is the number of channels that are occupied by cognitive radio users, and *k* is an event indicator. If *k* equals to 1, it indicates that a primary user is trying to sense and access a data channel, which is occupied by a CR user. In such case, the primary user waits for a RTI frame to claim the channel; otherwise, *k* equals to 0, which means no interruption occurs. Besides, the number of free channels is (*N*-*i*-*j*). For example, state (2, 1, 1) denotes that there are three busy data channels: two is occupied by primary users and one is occupied by a pair of CR users. In addition, a primary user is trying to access the data channel been currently occupied by that CR pair.

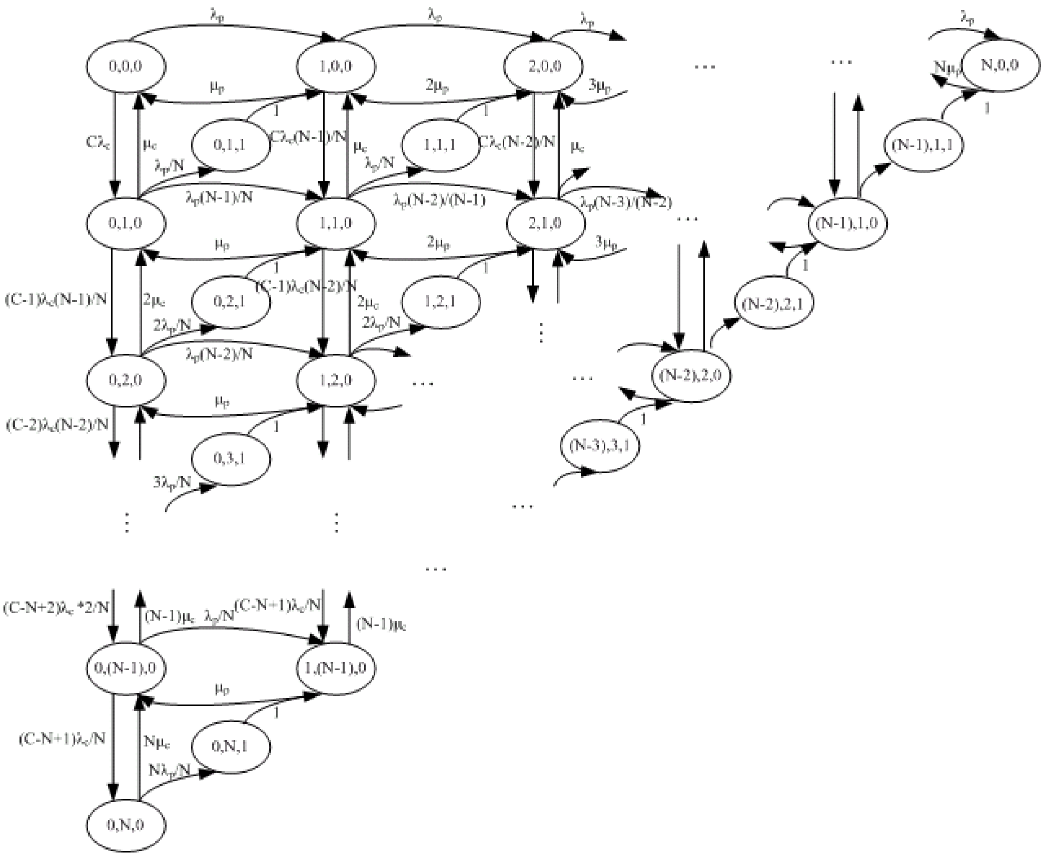


Figure 4-1 **:** Two-dimensional finite Markov chain utilized to analyze the throughput performance of a cognitive radio network

The state transition diagram is shown in Fig. 4-1. Let *P*(*i*, *j*, *k*) denote the steady-state probability. When considering primary users' arrivals and departures, state (*i*, *j*, 0) may transit to states (*i*-1, *j*, 0), (*i*+1, *j*, 0), or (*i*, *j*, 1) followed by (*i*+1, *j*-1, 0). The probabilities of state transitions from (*i*, *j*, 0) to (*i*-1, *j*, 0) and (*i*+1, *j*, 0) are $i\mu_p$ and $\lambda_p \frac{N-i-j}{N-i}$, accordingly. The state transition from (*i*, *j*, 0) to (*i*, *j*, 1) indicates that a primary user is trying to access the data channel occupied by a pair of CR users, and thus triggers an interruption with probability $\lambda_p \frac{j}{N}$. In such case, the interrupted cognitive radio user must return the occupied data channel to the primary user. Therefore, probability of state transition from (*i*, *j*, 1) to (*i*+1, *j*-1, 0) is 1.

Considering CR users' arrivals and departures, state $(i, j, 0)$ may transit to state $(i, j+1, 0)$ and state $(i, j\text{-}1, 0)$ with probability $(C-j)\lambda_c \frac{N-i-j}{N}$ and $j\mu_C$, respectively. Note that $\frac{(N-i-j)}{N}$ is the probability that a new pair of CR users sense an idle channel.

For a specific steady state, according to the principle of flow conservation that input flow rates equal the output flow rates, we derive the corresponding balance equations, as follows.

For those states whose $i = k = 0$, and $0 \leq j \leq N-1$,

$$\begin{aligned} &p(0,j,0)\left(\frac{(C-j)(N-j)}{N}\lambda_c + \lambda_p + j\mu_c\right) \\ &= p(0,j-1,0)\left(\frac{(C-j+1)(N-j+1)}{N}\lambda_c\right)(1-\sigma(j)) \\ &+ p(0,j+1,0)(j+1)\mu_c + p(i+1,j,0)\mu_p \end{aligned} , \tag{2}$$

where $\sigma(j) = \begin{cases} 1, & j = 0 \\ 0, & elsewhere \end{cases}$.

Besides, for those states whose $i \neq 0$, and $(i+j) \leq N-1$, k=0, we derive

$$\begin{aligned} &p(i,j,0)\left(i\mu_p + \frac{(C-j)(N-i-j)}{N}\lambda_c + \lambda_p + j\mu_c\right) = p(i,j+1,0)(j+1)\mu_c \\ &+ p(i+1,j,0)(i+1)\mu_p + p(i-1,j+1,1) + p(i-1,j,0)\left(\frac{N-j}{N}\lambda_p\right)(1-\sigma(i)) \\ &+ p(i,j-1,0)\left(\frac{(C-j+1)(N-i-j+1)}{N}\lambda_c\right)(1-\sigma(j)) \end{aligned} , \tag{3}$$

where $\sigma(i) = \begin{cases} 1, & i = 0 \\ 0, & elsewhere \end{cases}$.

Further, the derived equation of state $(0, N, 0)$ is

$$p(0,j,0)(\lambda_p + j\mu_c) = p(0,j-1,0)\frac{C-N+1}{N}\lambda_c.$$

(4)

For those states whose $i \neq 0, k = 0, i \neq N$, $(i + j) = N$,

$$p(i,j,0)(i\mu_p + j\mu_c) = p(i,j-1,0)\frac{(C-j)(N-i-j)}{N}\lambda_c$$
$$+p(i-1,j+1,1) + p(i-1,j,0)\frac{N-i-j}{N-i}\lambda_p \quad . \tag{5}$$

Finally, for $i = N$, $j = 0$, we know

$$p(i,0,0)(i\mu_p) = p(i-1,1,1) + p(i-1,0,0)\lambda_p$$

(6)

For the transient states that $k = 1$, $0 \leq i \leq N-1, 1 \leq j \leq N$,

$$p(i,j,1) = p(i,j,0)\frac{j}{N-i}\lambda_p. \tag{7}$$

Then, the interrupted probability (denoted as $P_{interrupted}$) of CR users equals to the sum of total interrupted states, i.e.,

$$P_{interrupted} = \sum_{i=1}^{N}\sum_{j=0}^{N} p(i,j,1). \tag{8}$$

From Eqs. (2)-(8), we know

$$\sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{1} p(i,j,k) = 1. \tag{9}$$

Thus the total throughput of primary users (denoted as T_{PU}) is

$$T_{PU} = B\sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{1} ip(i,j,k). \tag{10}$$

By applying matrix operations, we can solve all state probabilities. The throughput performance of CR users (which is the metric we are interested in and is denoted as T_{CR}) is given as

$$T_{CR} = B\sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{1} jp(i,j,k). \tag{11}$$

Chapter 5

Simulation and Analytic Results

To evaluate the performance of the designed channel sensing and accessing algorithm presented in chapter 3 and to validate the analytic model presented in chapter 4, 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 [5], i.e., OSA-MAC, and with [7], i.e., Channel-hopping based MAC. Again, we only consider single-hop flows of cognitive radio users.

We first compare the CRN throughput of analytic and simulation results upon the same parameter settings (listed in Table 1). We vary the number of data channels from 1 to 3. Besides, we assume CR users are always backlogged, and thus the arrival rates of primary users and cognitive radio users are 0.4 and 1, respectively. The service rate of primary users is 0.667. The CRN throughput is shown in Fig. 5-1. Though the analytic and simulation results are almost consistent, there exists discrepancy. The maximum error, which occurs at N=1 and C=15, is less than 6% ((3.17-3)/3.17 = 5.3%). There are two reasons, one is our analytic model does not take sensing time into consideration, while it is an overhead in our simulation. Another one is about the channel selection. In our analytic mode, it considers that the probability of choosing each channel is even, that means if there is N data channel, the probability of choosing each channel is all equal to 1/N. But in simulation, because of the randomly choosing *Ch(1)* and *h*, the probability of choosing each channel may not be even. It effects on the spending time on sensing idle channel.

Table 1. Parameter settings of simulation

Parameter	Value
Frame size	2048bytes
Number of data Channels (*N*)	5
SIFS	0.01ms
$SIFS_{CR}$	0.1ms
DIFS	0.05ms
Simulation time	100s
Sensing time for a data channel	2ms

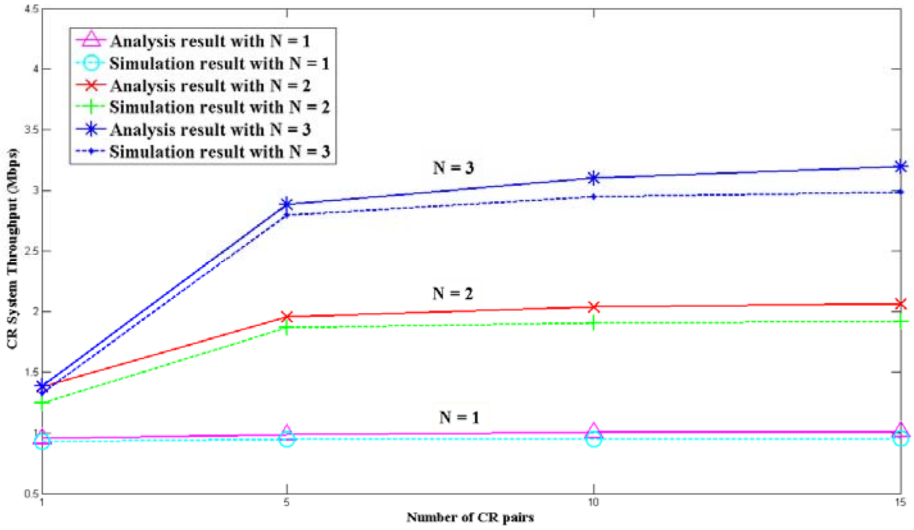


Figure 5-1 : The analysis and simulation throughput performance of a CRN

Next, we compare the performance of our mechanism, OSA-MAC and Channel-hopping based MAC. 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 1. The throughput of a considered CRN is shown in Fig. 5-2. We observed that our proposed mechanism outperforms OSA-MAC. The reason is, in our approach, a CR sender can transmit multiple frames (the maximum is $TXOP_{CR}$ frames) when an available data channel is sensed. Contrarily, in OSA-MAC, a CR sender only transmits one frame at a time. Note that our approach still performs better than OSA-MAC upon $TXOP_{CR}$=1. The reason is that the sensing time our approach is shorter than that of OSA-MAC. On the other hand, our approach performs is worse than Channel-hopping based MAC when $TXOP_{CR}$ = 1. It is because it doesn't have to exchange control message to negotiating about the potential sensing channel. But when $TXOP_{CR}$ >=2, our approach will be better than his. This result thanks to the interrupt mechanism, less collision and longer accessing time makes our approach's throughput get better. We further investigate the impact of $TXOP_{CR}$ on primary users. We found that it has no impact on the throughput performance of primary users, shown in Fig. 5-3. Thanks to the designed interruption mechanism so that primary users can claim borrowed data channels in time.

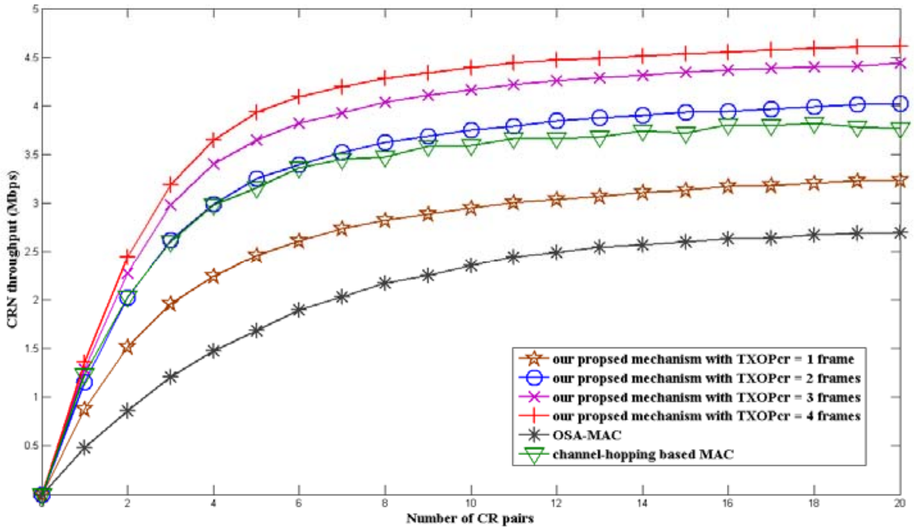


Figure 5-2 : The simulation throughput performance of a CRN

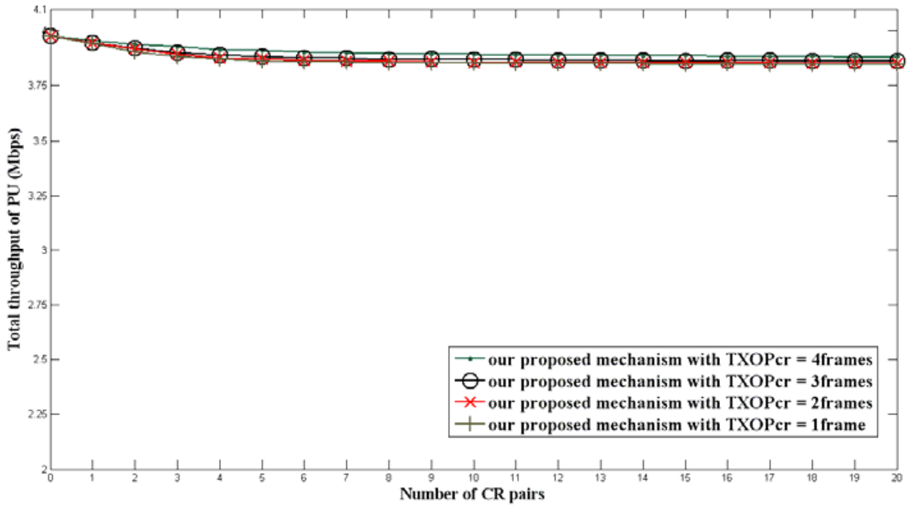


Figure 5-3 : PU throughput vs. the number of CR pairs, upon PUs utilizing 40% bandwidth

Followed, we investigate the impact of primary users' traffic load on CR users' throughput, and the result is shown in Fig. 5-4. Here we set the number of CR pairs be 15, and vary primary users' traffic load from 0.1 to 1. For example, 0.2 traffic load indicates that primary users generate packets to utilize 20% bandwidth in total. Our proposed mechanism achieves a higher throughput than OSA-MAC, except when primary users' traffic load is larger than 0.85. Specifically, the CRN throughput of our algorithm is zero when PUs utilize all bandwidth; contrarily, OSA-MAC still has 0.77 Mbps throughput. The reason is 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.

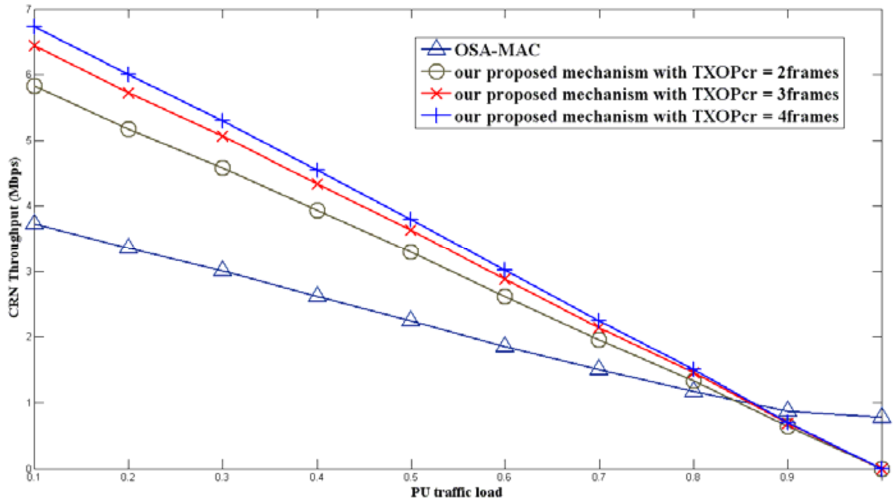


Figure 5-4 : The throughput of a CRN vs. PUs' traffic load, upon 15 CR pairs

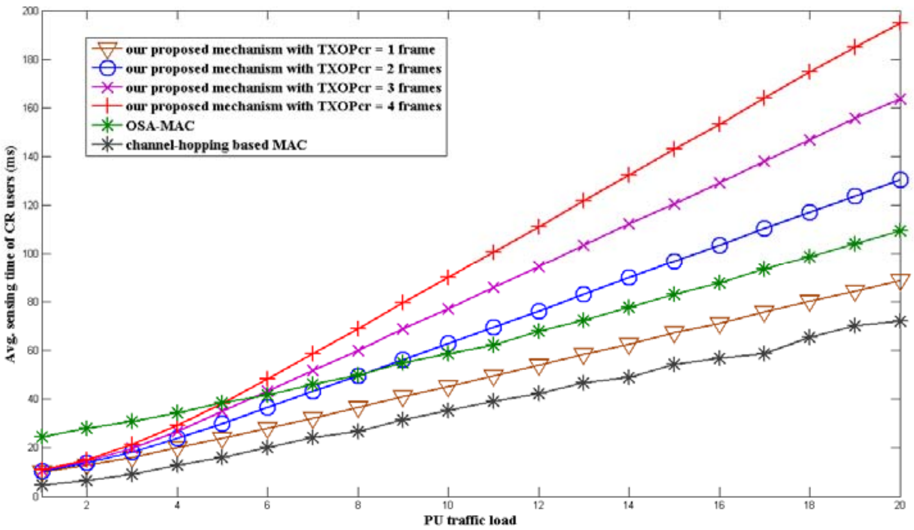


Figure 5-5 : Average sensing time of CR users vs. the number of CR pairs upon PUs utilizing 40% bandwidth

Though a CRN has a good throughput performance upon a large $TXOP_{CR}$ value, the side-effect is long sensing time for CR users, as shown in Fig. 5-5. In Fig. 5-5, the average sensing time of OSA-MAC and our approach increases as the number of CR pair increases. Specifically, a large $TXOP_{CR}$ 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. In addition, the average sensing 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 sensing time compared to our approach. This is because, for OSA-MAC, a CR sender only transmits one data frame when occupying a data channel.

From Figs. 5-2 and 5-5, we observe that there is a trade-off between CRN throughput and data channel sensing time. If most of the CR traffic load is non-real time data type, the major performance evaluation metric is "throughput". Thus a large $TXOP_{CR}$ value results in a high throughput performance and is a suitable parameter setting. However, if some CR traffics are real time data type, a small $TXOP_{CR}$ value is better to achieve QoS requirement.

We then observe the impact of frame size on the performance of primary users, and the simulation results are shown in Figs. 5-6 and 5-7. Here we set the number of CR flows be 15. 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 1.25%, as shown in Fig. 5-6. Again, thanks to the designed interruption mechanism which shortens the average waiting time of primary users to claim data channels, as shown in Fig. 5-7.

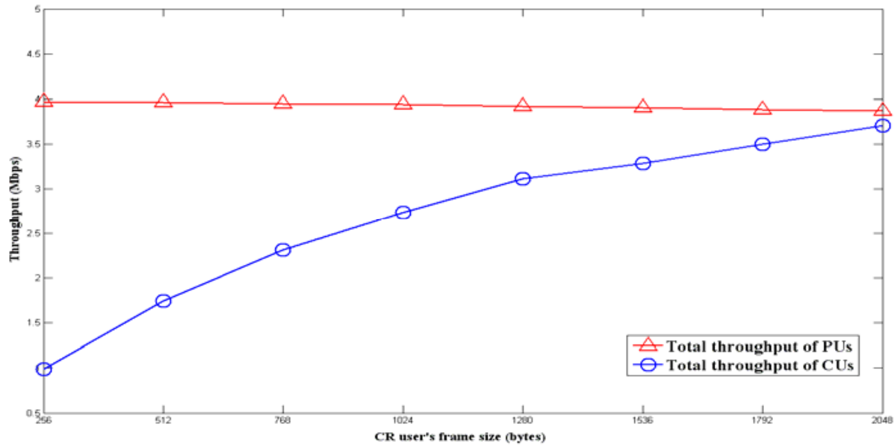


Figure 5-6 : Throughputs of PUs and CR users vs. CR frame size, upon 15 CR pair

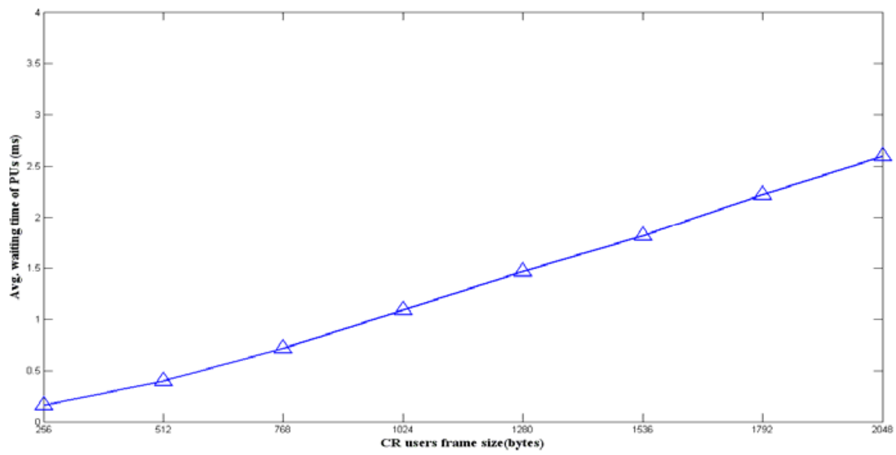


Figure 5-7 : The average waiting time of PUs vs. CR frame size, upon 15 CR pairs

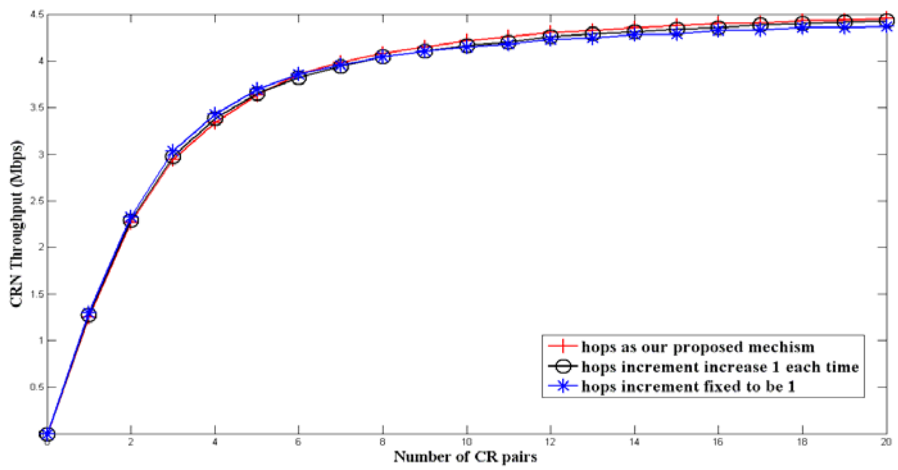


Figure 5-8 : Throughput of a CRN vs. number of CR pairs of various generation functions

Followed, we compare the throughput performance of various generation functions of hopping sequence. Specifically, the initial channel $Ch(1)$ is intact for all generation functions, and each generation function has its own increment-per-hop pattern. In this experiment, we examine three increment-per-hop patterns. The first approach is fixed increment-per-hop (denoted as "fixed-*h*" and it is adopted in our proposed channel sensing mechanism), and the next hopped data channel is $Ch(i+1)=[(Ch(i)+h) \bmod N]$. The second approach is linear increment-per-hop (denoted as "linear-*h*"), and the next hopped channel is $Ch(i+1)=[(Ch(i)+h+(i-1)) \bmod N)]$. The last approach does not utilize increment-per-hop and the next hopped channel is $Ch(i+1)=[(Ch(i)+1)) \bmod N]$. We denote the third approach "without-*h*". For example, the number of data channels N is 5 (numbered from 0 to 4), the initial channel ID is 3, and initial increment-per-hop is 2. The channel hopping sequences of fixed-*h*, linear-*h*, and without-*h* are [3, 0, 2, 4, 1, 3, 0, 2, 4, 1, …], [3, 1, 0, 0, 1, 3, 1, 0, 0, 1, …], and [3, 4, 0, 1, 2, 3, 4, 0, …]. The throughput performance is in Fig. 5-8. We found data channel hopping sequence do not impact on CRN throughput. It is expectable that fixed-*h* and without-*h* perform similarly, and the reason is that for both generating functions, a CR user senses every data channel once per run, while with different order. It is interesting that for linear-*h*, a CR user only senses three out of five data channels, while still performs similarly to others. Thus we conclude no matter "sensing all channels per run" or "sensing subset of channels per run," our designed mechanism performs similarly.

Then we present the performance of channel utilization, including PUs and CR users. This experiment is to show the improvement degree of channel utilization. We set the number of data channels be five, and primary users utilize 40% bandwidth. Fig. 5-9 is the throughput performance of $TXOP_{CR}$ =2, and Fig. 5-10 is that of $TXOP_{CR}$ =4.

When the number of CR pairs is larger than 10, the overall channel utilization achieves over 75% (7.5Mbps/10Mbps=0.75) and the corresponding improvement degree of channel utilization contributed by CR users is 46% (3.5Mbps/7.5Mbps), as shown in Fig. 5-11. When $TXOP_{CR}$ =4, the channel utilization further increases to 85%, and the throughput of CR users even higher than that of PUs.

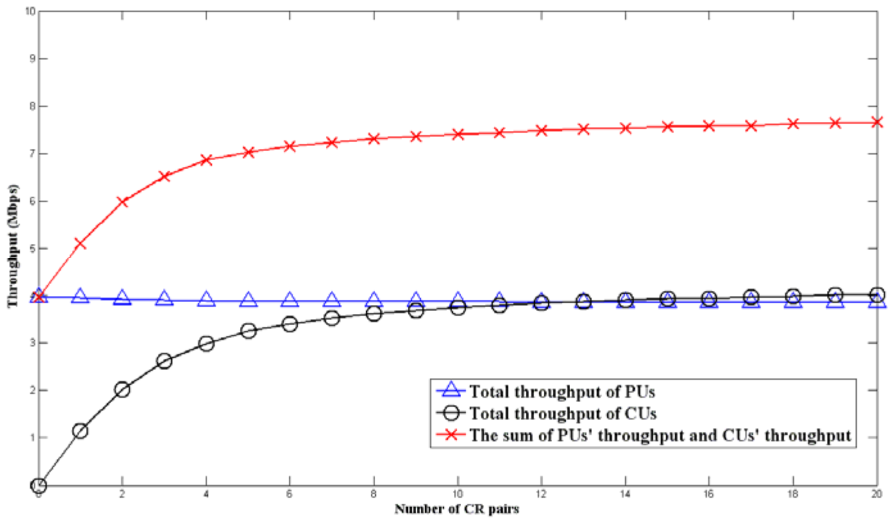


Figure 5-9 : Channel utilization vs. number of CR pairs, upon $TXOP_{CR}$ = 2 frames, N=5, PUs utilizing 40% bandwidth

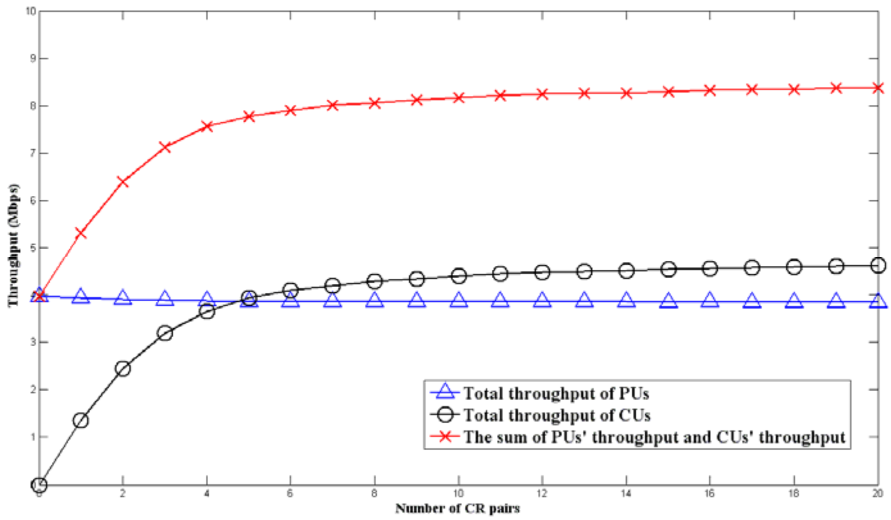


Figure 5-10 : Channel utilization vs. number of CR pairs, upon $TXOP_{CR}$ = 4frames, N=5, PUs utilizing 40% bandwidth

Then, we examine how RTI messages impact on primary users. Without transmitting RTI messages periodically by CR users, primary users cannot interrupt CR users' transmissions as quick as possible. Instead, a primary user cannot start to transmit data packets till the ongoing transmission is completed. In such case, $TXOP_{CR}$ value does impact on PUs' throughput performance. A large $TXOP_{CR}$ value indicates that PUs must wait for a long time to claim data channels, and thus PUs' throughput decreases, as shown in Fig. 5-11. On the other hand, the throughput of CR users increases as $TXOP_{CR}$ value increases, as what we expected. On the other hand, without RTI, CR users in our proposed mechanism utilize more bandwidth and have higher throughput performance, as shown in Fig 5-12.

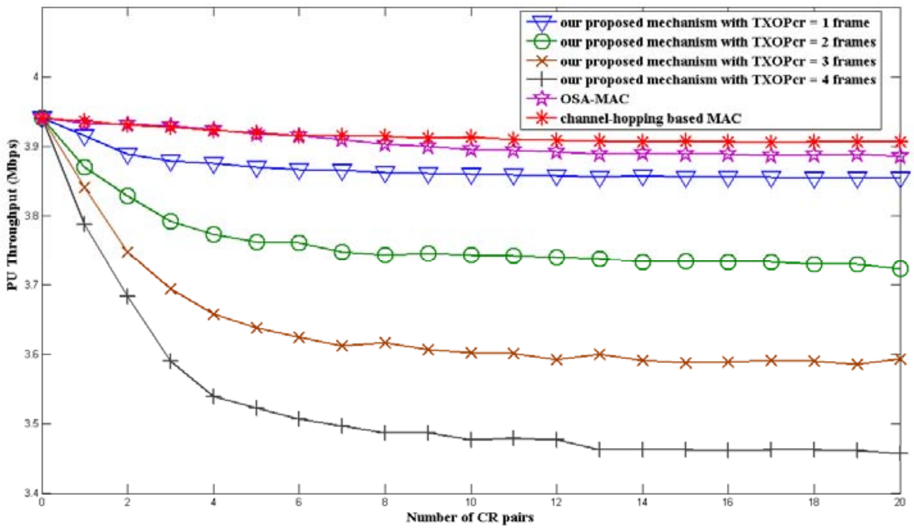


Figure 5-11 : Throughput of PUs vs. number of CR pairs without RTI, upon N=5, PUs utilizing 40% bandwidth

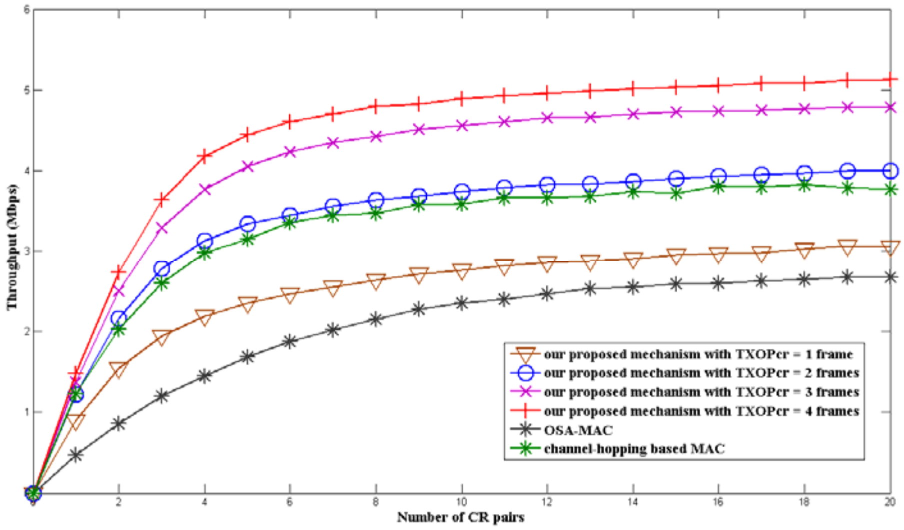


Figure 5-12 : Throughput of CR users vs. number of CR pairs without RTI, upon *N*=5, PUs utilizing 40% bandwidth

Finally, we consider that if the packet error in the network is getting high, whether it causes a high traffic load on the control channel. So, we will show how does the packet error rate matters to the number control frames on the control channel. In Fig. 5-13, we could see that the number of control frames on control channel will increase as the packet error rate increases. It is because when a packet error is occurred, the CR receiver will not reply an ACK, and the CR pairs would think the channel is claimed back of PU, so the CR pair will switch back to the control channel and exchange the RTS_{CR}/CTS_{CR} again. It makes more control frames exchanged on the control channel as the packet error is rate getting higher, as shown in Fig. 5-13.

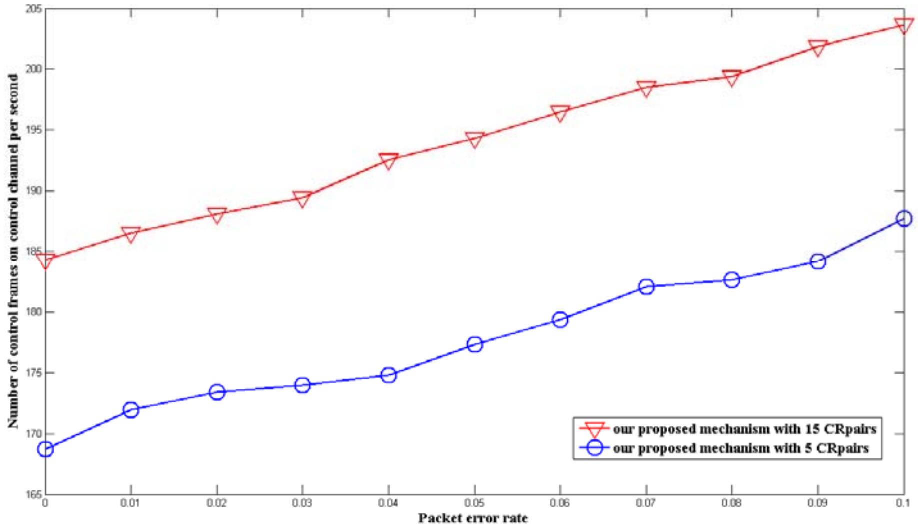


Figure 5-13 : Number of control frames sent on control channel vs. packet error rate, upon N=5, PUs utilizing 40% bandwidth

Chapter 6

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 proactive channel vacating. One unique design in our protocol is interruption mechanism, which is achieved by employing RTI control frames. Through the assistance of RTI, we balance the tradeoff between throughput performance of a CRN and PUs' channel claiming time. Indeed, primary users may not be able to identify RTI frame due to CR users operating in a dissimilar network system. This problem can be easily solved through adjusting the value of $SIFS_{CR}$ to make primary users "believe" channels are idle and are able to send transmission invitations to intended receivers. Then the function of RTI frame is to let the neighbor of CR user know the channel is not be released, the channel is just waiting for primary user to claim it back. Also for the receiver side, the ACK is having the same function to RTI here. An analytical model was developed to evaluate the theoretical performance of our protocol. Computer simulation was conducted to demonstrate the superior performance of our protocol over that of OSA-MAC.

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