University of Alberta

Design of Asynchronous Cooperative Spectrum Sensing Scheme and Wideband Dynamic Spectrum Access Algorithm for Cognitive Radio Networks

by

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Abstract

Dynamic spectrum access (DSA) is a promising solution for mitigating the problem of crowded radio spectrum and enhancing the utilization efficiency of spectrum resources, making it a hot research topic. In DSA, spectrum sensing is crucial and cooperative spectrum sensing (CSS) is confirmed as a promising technology that can combat the wireless channel fading problem. Most current works have assumed that secondary users (SUs) are synchronous with the primary users' (PUs) network. However, on one hand, the SUs may not have information about the PUs' communication protocols. On the other hand, communications among PUs are not based on synchronous operation in some systems. In order to address such problems, an asynchronous CSS scheme is proposed. Based on this scheme, the DYWAMIT, a contention-based wideband DSA algorithm, is proposed. Performance analysis and simulations are conducted to evaluate the proposed scheme and algorithm. Some important future research challenges are highlighted.

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Chapter 1

Introduction

Wireless communications technology which can utilize the electromagnetic radio spectrum (frequencies lower than around 300 GHz, or equivalently, wavelengths longer than about 1 mm) as a communication medium, has attracted the interest of a large number of telecommunication researchers. The usage of wireless radio spectrum resources and the regulation of radio emissions are coordinated by national regulatory bodies such as the Federal Communications Commission (FCC) in the USA and Industry Canada (IC) in Canada. The FCC and IC assign the spectrum to some specific license holders, also known as *primary users* (PUs), on a long-term basis for large geographical regions. Over time, with the rapid development of new wireless devices and applications, this fixed spectrum assignment policy has resulted in the spectrum scarcity problem.

1.1 Cognitive Radio

The spectrum scarcity problem is not due to the physical shortage of the spectrum, but due to the severe under-utilization of a large portion of the licensed spectrum. The inefficient usage of the limited spectrum promoted the development of dynamic spectrum access (DSA) techniques, where users who have no spectrum licenses, also known as *secondary users* (SUs), are allowed to use the unused licensed spectrum temporarily [1].

New DSA schemes are expected to mitigate the problem of crowded electromagnetic radio spectrum and significantly enhance the utilization efficiency of existing spectrum resources compared with static spectrum allocation [2]. Cognitive radio (CR) technology is considered as an effective approach to realize such DSA schemes. The essence of CR is that SUs can dynamically access licensed spectrum in an opportunistic way, on the premise that legacy communication activities operating in the licensed spectrum are not interfered with [3]. The available spectrum resources in the space, frequency and time domains for SUs are dubbed “spectrum holes”.

A CR differs from the conventional radio devices in that it can equip users with *cognitive capability* and *reconfigurability* [4]. Cognitive capability refers to the ability to sense and gather information from surrounding environment, such as information about transmission frequency, bandwidth, power, modulation, etc. [4]. With this capability, SUs can identify the best available spectrum. Reconfigurability refers to the ability to rapidly adapt the operational parameters according to the sensed information in order to achieve the optimal performance [4]. Through using the spectrum in an opportunistic way, CR enables SUs to sense which portion of the spectrum are available, select the best available channel, coordinate spectrum access with other users, and vacate the channel when a PU reclaims the spectrum usage right.

In CR, there is one standard called IEEE 802.22 [5], the first CR wireless regional area network standard. This standard allows broadband access to be provided in sparsely populated areas that cannot be economically served by wire line means, or other wireless solutions at higher frequencies, by using cognitive radio techniques to allow operation on a noninterfering basis in the VHF/UHF TV broadcast bands.

In the implementation of DSA, there are mainly four issues as follows [6]

- Spectrum sensing: the essential task of monitoring the primary activities and detecting “spectrum holes”.

- Spectrum access: capturing the best available channel to meet the SUs’ communication requirements and quality of service requirements, without harmful interference to the PUs.

- Spectrum sharing: providing fair spectrum scheduling method among coexisting SUs.

- Spectrum mobility: vacating the spectrum when the PU reappears; maintaining seamless communication requirements during transitions to the better channel.

The works in this thesis aim at addressing the first three problems. It is true that when constructing practical CR networks, minimizing the effect of spectrum handover on SUs' communication should be seriously taken into account. However, the maintenance scheme in the Link-layer of the secondary network is not our focus, which will not be discussed in this thesis.

1.2 Spectrum Sensing

In CR networks, spectrum sensing is a rather crucial functionality which achieves the key task of locating vacant bandwidth portions for active SUs [3]. The challenge for a reliable sensing method is when the primary received signal is very weak or deeply faded/shadowed [7].

Usually, spectrum sensing techniques can be categorized into three groups, energy detection [8], coherent detection [9] and cyclostationary feature detection [10]. The energy detection strategy simply compares the output of the energy detector, i.e. the energy of the received signal, with a threshold which depends on the noise floor [8]. Some of the challenges with energy detection include selection of the threshold, inability to differentiate interference from primary users and noise, and poor performance under low signal-to-noise (SNR) values.

If some knowledge about the features of the primary signal such as the modulation type, bandwidth, pulse shaping, etc. are available at the CR receiver, a coherent detection or cyclostationary feature detection can be exploited in order to have more robust sensing [9], [10]. To be specific, in coherent detection, also known as matched filter detection, we can decide on the presence of primary activities if the maximum SNR is acheived at the output of the matched filter. The main advantage of matched filter detection is the short time to achieve a certain probability of false alarm or probability of misdetection [11]. However, matched filter detection requires CR to demodulate received signals and moreover, since CR needs receivers for all signal types, the implementation complexity is impractically large [7]. Cyclostationary feature detection detects PUs by exploiting the cyclostationary features of the received signals [12]. Cyclostationary features are caused by the periodity in the signal or in its statistics like mean and autocorrelation [13]. This detection algorithm can differentiate noise from PUs' signals, and achieve more accurate detection. This is a result of the fact that noise is wide-sense stationary (WSS) with no correlation while modulated signals are cyclostationary with spectral correlation due to the redundancy of signal periodicities [14].

However, due to its low computational (and hence implementation) complexities and its fast detection ability, energy detection is widely deployed as the underlying detection scheme, as well in this thesis.

1.3 Motivations

Current research on cooperative spectrum sensing (CSS) is mostly based on the assumption that the SUs are synchronous with the PUs in the Media Access Control (MAC)-layer. In other words, the MAC-layer time slots in the secondary network are clocked the same as those in the primary network. Although the knowledge of the slot structures of primary networks can help SUs not to generate interference to the PUs, guaranteeing accurate slot time synchronization among the PUs and SUs is a time and energy consuming issue. On the other hand, if the SUs have no access to the PUs' slot timing information, they cannot access primary bands employing such synchronous schemes, because the SUs' unsynchronized accesses will cause interference to the PUs. It is also possible that communications among PUs are not based on synchronous protocols [15]. Considering these problems, we proposed an asynchronous CSS scheme and obtained the optimal sensing period for this scheme in Chapter 3. Our scheme will no longer require SUs to synchronize with the PUs, enabling the SUs to cognitively and asynchronously access primary channels even without knowing the communication protocols of the PUs [16].

Wideband spectrum sensing is one of the main requirements of an effective and practical CR system, because the wideband spectrum sensing has the ability to help identifying multiple transmission opportunities for SUs, and also enable improved design of other CR functionalities such as spectrum mobility and spectrum management [17]. Since most communication systems are based on half-duplex (such as WiFi, TD-SCDMA), and full-duplex requires transmitting and receiving information simultaneously whose hardware implementation is difficult, we consider the SUs build a half-duplex network in the thesis. In the synchronous scenario, after the SUs detect available primary channels at the beginning of one time slot, they can share the channel through time division multiple access (TDMA) until the end of the current time slot.

However, when it comes to the asynchronous scenario, the half-duplex SUs (which means the SUs cannot sense while they transmit information), have no knowledge about when the PUs will return. Since the PUs will return with a higher probability during the latter part of one time slot, in a fully distributed cognitive radio network, it is possible that all the SUs may contend for the earlier part of one time slot, which may lead to severe conflicts among the SUs, making the asynchronous DSA problem even more challenging. To tackle the aforementioned challenges, we proposed in Chapter 4 a contention-based asynchronous wideband DSA algorithm, called DYWAMIT which is a set of comprehensive and effective solutions for the application scenario when the SUs are confronted with unknown PUs' behaviors [18].

1.4 Related Works and Challenges

In [19], [20], [21], [22], [23], [24], [25], [26], some fundamental problems of synchronous CSS schemes are discussed, including MAC-layer protocol design, sensing parameters calculation (sensing time and sensing period), data fusion type selection, derivation of detection/false alarm probability, etc. To summarize, there are two theoretical methods usually used, *optimization theory* and *game theory*. References [19] and [20] adopt the probability of detecting PUs as the optimization objective, while the goal of [21] and [22] is to maximize the SUs' channel throughput. The works [23], [24], [25], [26] mainly focus on fairness problems in CSS from a game theoretical view. Reference [27] proposed an asynchronous CSS method and a sliding-window algorithm. There, however, the term "asynchronous" refers to the communication format of the secondary network, i.e. the SUs are asynchronous with each other within their own network. In our work, the term means that the SUs are asynchronous with the PUs, but all SUs are synchronous, which is different from the scheme discussed in [27]. The focus of [27] is to avoid overhead caused by time synchronization among SUs, while our motivation is that SUs need not maintain synchronization with PUs when sensing or accessing primary channels. In [28], [29], [30], the asynchronous CSS topic among independent SUs has been discussed, instead of the CSS scheme considered in our work.

There are rather limited previous works when it comes to wideband spectrum sensing. Reference [31] proposed a wideband sensing-time-adaptive joint detection framework where the wideband spectrum, or multiple narrowband chanels is sensed jointly. In [32] the sensing time setting for a multi-user wideband case with CSS was investigated using convex optimization. Work in [33] used a wavelet transformation to estimate the power spectral density (PSD) of the received signal and decompose it into nonoverlapping subbands that are characterized by irregularities in frequency. There are also some results on the application of compressive sensing to wideband sensing [34], [35], [36].

Several decentralized opportunistic MAC protocols [37], [38], [39], [40], [41], [42], [43], [44] have been proposed in the literature. Reference [37] developed an analytical model to investigate the performance of a decentralized MAC protocol, but considered only a single spectrum band. Reference [38] proposed decentralized MAC protocols with the employment of request-to-send (RTS) / clear-to-send (CTS) frames to identify a spectrum opportunity, but the analysis is confined to a single SU scenario. In [39], cognitive MAC has been analyzed for multiple SUs, but requires the synchronization of both SUs and PUs. In [40], a multi-channel MAC protocol, which focuses only on the Global System for Mobile Communications (GSM) cellular networks was proposed. Reference [41] proposed and analyzed opportunistic multi-channel MAC protocols for cognitive radio based wireless ad hoc networks, in which two different channel sensing policies called the random sensing policy and the negotiation based sensing policy are proposed, and the tradeoff between throughput and delay was revealed. Reference [42] proposed a CSMA/CA (carrier sense multiple access/collision avoid)-based cognitive MAC protocol using statistical channel allocation, in which the SUs select the channel having the highest successful transmission probability to send packets. However, the computational complexity for determining the successful transmission probabilitites increases rapidly as the number of primary channels increases. Reference [43] proposed a two-level opportunistic spectrum access strategy, in which the spectrum sensing time is optimized to control the total traffic rate of the secondary network at the first level, and two MAC protocols called the slotted cognitive radio ALOHA (CR-ALOHA) and cognitive-radio-based carrier-sensing multiple access (CR-CSMA) are developed to deal with the packet scheduling of the secondary network at the second level. In [44], the authors investigated the joint optimal sensing and distributed MAC protocol design problem for CR networks, and derived the normalized throughput of the proposed MAC protocols, and determined their optimal configuration for throughput maximization.

However, those aforementioned strategies are all synchronous schemes which rely on two basic assumptions; the first is that the primary network is based on time-slotted communication protocols; the second is that the SUs are aware of the PUs' time clock in advance. The asynchronous CSS scheme proposed in Chapter 3 does not require the SUs to be synchronous with the PUs' network, enabling the SUs to cognitively and asynchronously access primary channels even without knowing the communication protocols of the PUs. Based on the research model of Chapter 3, which only targeted at single-band (narrowband) sensing, we propose in Chapter 4 a contention-based wideband DSA algorithm, in which SUs who intend to access the primary channels should compete for available ones.

1.5 Contributions

Our contributions in this project are five-fold.

- We propose an asynchronous CSS scheme.
- We propose an asynchronous wideband DSA algorithm, called DYWAMIT, among multiple SUs.
- We analyze the performance of the proposed DSA algorithm, incorporating channel sensing analysis and contention analysis.
- We analyze the average throughput of the SUs of the proposed asynchronous CSS scheme and the DYWAMIT algorithm and achieve the optimal sensing period.
- We present numerical results to evaluate the performance of the proposed scheme and algorithm, and maximize the throughput of the SUs with the optimal configuration.

1.6 Thesis Outline

The thesis is organized as follows. In Chapter 2, we first present the basic system model and then explain some background knowledge on renewal theory. In Chapter 3, we introduce the asynchronous CSS scheme, which is followed by the presentation of the asynchronous wideband DSA algorithm, called DYWAMIT, among multiple SUs, in Chapter 4. Finally, Chapter 5 concludes this thesis while giving some suggestions and potential future research directions.

Chapter 2

General System Model

In this chapter, we first present the channel state model and then explain periodic sensing in CR.

2.1 Channel State Model

The ultimate goal of spectrum sensing is to verify the availability of primary channels. A channel state model is needed to illustrate the channel's availability. In the asynchronous situation, there is no time slot in the primary channels from the viewpoint of the SUs. Instead, each primary channel just alternatively switches between the ON state and the OFF state. The ON state means the channel is being occupied by some PU, while the OFF state represents a "spectrum hole" for SUs, as shown in Fig. 2.1.

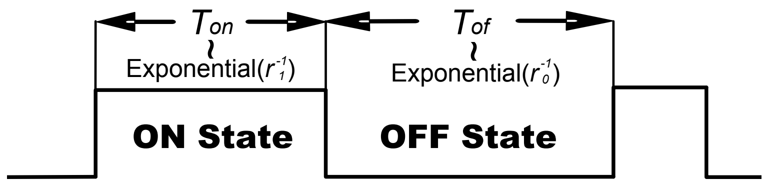

Figure 2.1. The ON-OFF channel model.

Different ON states are regarded as memoryless and mutually independent, as in [45]. These properties also hold true for OFF states. As discussed in [37], [46], [47], we assume that the length of one ON/OFF state $T_{\text{ON}}/T_{\text{OF}}$[1] obeys

[1]The footnote "of" in T_{of}, and P_{of}, F_{of}, f_{of} thereafter, all mean "OFF state"

the exponential distribution with parameter r_1 /r_0, viz.

$$T_{on} \sim 1 - e^{-t/r_1} \tag{2.1a}$$

$$T_{of} \sim 1 - e^{-t/r_0}. \tag{2.1b}$$

Thus, the channel usage by one PU can be modeled as an ON-OFF process, as shown in Fig. 2.1. Regarding the estimation of r_1 and r_0, [45] provides an effective maximum likelihood estimator, as well as the confidence intervals and the robustness of the estimator.

The *forward recurrence time* of the OFF state F_{of} refers to the duration from the SUs' sensing point (the time point when the SUs begin to sense the current channel) to the end of the OFF state [48], as shown in Fig. 2.2. Since the length of one OFF state T_{of} obeys the exponential distribution with

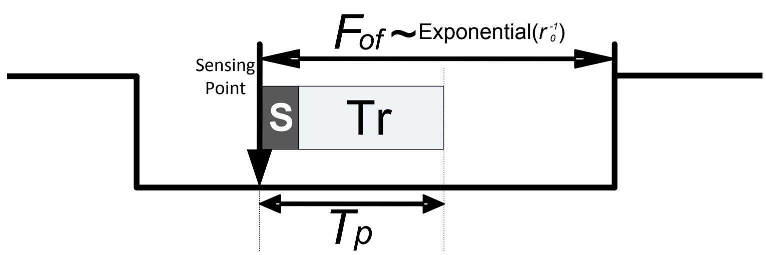

Figure 2.2. The *forward recurrence time* of the OFF state.

parameter r_0 and different OFF states are regarded as memoryless, the *forward recurrence time* of the OFF state $F_{of}(t)$ still obeys the exponential distribution with parameter r_0. This property also holds true for the *forward recurrence time* of the ON state.

2.2 Periodic Sensing

Once the SUs have an opportunity for transmission, they may tune its transmission parameters to access the channel. However, they should continue sensing the spectrum every T_p seconds in order to vacate the channel when the PU reappears. This is due to the fact that the secondary network is half-duplex which means the SUs cannot sense a channel and transmit in the same channel simultaneously. The sensing period T_p, containing the *sensing state* and the *transmission state*, determines the maximum time that the SU disregards the PU's activity and may impose harmful interference on the primary network, and may also decrease the SUs' average throughput. On the other hand, a large value of T_p increases the SUs' opportunity to access the underutilized spectrum. Therefore, the relationship between the SUs' average throughput and the sensing period T_p needs to be investigated.

Fig. 2.3 represents the frame structure considered for the periodic spectrum sensing. Each frame consists of one *sensing state* and one *transmission state*. T_p is considered small relative to the average length of one ON/OFF state of the channel r_1 and r_0 (i.e. $T_p << r_1$ and r_0).

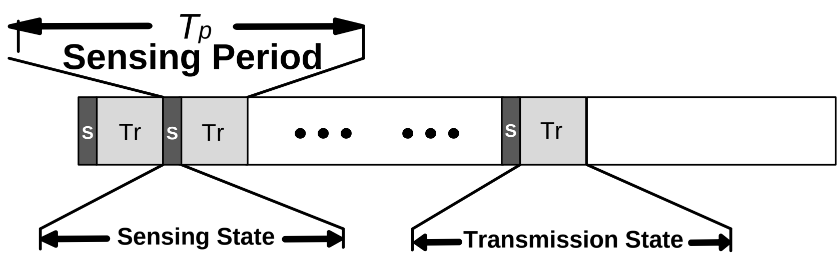

Figure 2.3. The frame structure of periodic spectrum sensing.

2.3 Summary

In this chapter, we presented the channel state model and the periodic sensing used in this study.

Chapter 3

A Novel Asynchronous Cooperative Spectrum Sensing Scheme

In this chapter[1], we first present the complete system model and then discuss cooperative spectrum sensing (CSS) based on energy detection. This leads to the introduction of the proposed asynchronous CSS scheme. We also derive the average throughputs of the SUs, accounting for the asynchronism between the SUs and the PU, for four cases of practical interest.

3.1 System Model

In this scheme, for analytical convenience, there is only one channel and one PU in the primary network. In the secondary network, a coordinator among M cooperative SUs is employed to collect the sensing results from other active SUs, decide the availability of the primary channel and allocate the available primary channel to different groups of SUs.

Recall that the term "asynchronous" here does not refer to the communication scheme among SUs. Instead, it means that the system clock of the secondary network is asynchronous with that of the primary network. The secondary network is still assumed to be a synchronous system and time is divided into slots with the same length. At the beginning of each slot, active SUs sense the primary channel with time T_s and sampling rate λ, as shown

[1]The results in this chapter have been presented at the IEEE International Conference on Communications (ICC) 2013, held in Budapest, Hungary [16]

in Fig. 3.1. Energy detection is employed in the sensing process. T_s and λ are specified values, which are determined by the configuration of the SUs' PHY-layer hardware.

After sensing, the SUs report their own sensing results to the coordinator of the secondary network, which will then decide whether the channel is in the ON or OFF state.

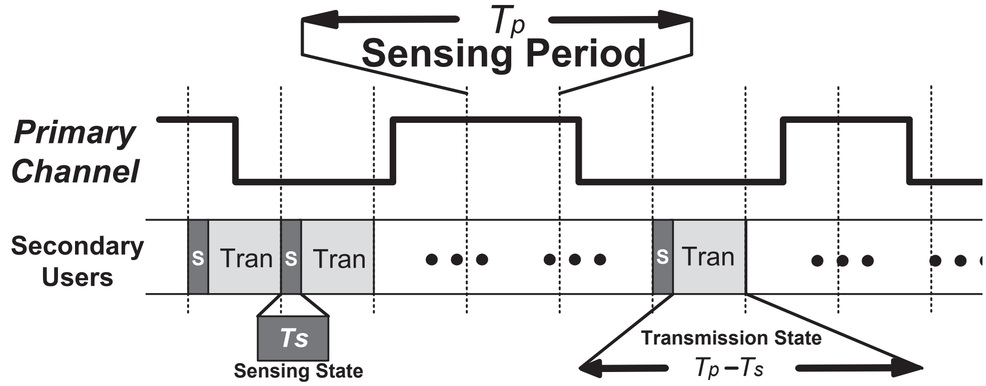

Figure 3.1. The asynchronous cooperative spectrum sensing scheme.

3.2 Cooperative Spectrum Sensing (CSS)

Fading/shadowing environment is an obstacle in achieving preferable performance of spectrum sensing. To solve this problem, cooperative spectrum sensing (CSS) scheme has been proposed recently, which requires multiple SUs to simultaneously sense one primary channel and share their sensing results after sensing. This cooperative scheme has been corroborated to enhance the probability of detecting the PUs greatly [19, 20, 21, 22, 23, 24, 25, 26]. Usually, there are two methods for information sharing in cooperative spectrum sensing: *distributed method* and *centered method*. The former refers that the SUs separately sense the channel and broadcast the sensing results one by one within a small region according to some pre-defined protocol. While in the *centered method*, the SUs report their sensing results to a so-called coordinator node who plays a key role in combining all local spectrum sensing information and deciding the channel state. In this chapter, the *centered method* is adopted, and in Chapter 4, the *distributed method* is adopted. We need to mention that CSS is conducted within a small region, which means the cooperative SUs are homogeneous in the same geographical area. There are many ways of information integration in CSS, we consider the most common and easiest way where the SUs' sensed information is summed and divided by the total number of cooperative SUs.

The performance of spectrum sensing is usually evaluated by two parameters, the detection probability and the false alarm probability. The former, denoted by P_d, is the probability that if there are primary activities, the SUs can detect them successfully. The latter, denoted by P_f, represents the probability that if there are no primary activities, the SUs falsely decide that PUs are active. Under hypothesis $\mathcal{H}_0$ and $\mathcal{H}_1$, the primary channel is in the OFF and ON state, respectively. The received signals under $\mathcal{H}_0$ and $\mathcal{H}_1$ at the secondary receiver are given by

$$\begin{aligned} \mathcal{H}_0: \quad & y_m[n] = u_m[n], && n = 1, 2, ..., \lambda T_s \\ \mathcal{H}_1: \quad & y_m[n] = s_m[n] + u_m[n], && m = 1, 2, ..., M \end{aligned} \tag{3.1}$$

where the subscript m refers to the mth SU, $[n]$ denotes the nth sample, y_m is the mth SU's received signal, u denotes the background noise which is assumed as circular symmetric complex Gaussian (CSCG) [21] with mean zero and variance σ^2 and $s[n]$ are the primary signals received by SUs which are considered $i.i.d$ random processes with means zero and variances σ_p^2.

Thus, for the mth SU, the energy statistic of the sensed signal in the primary channel Y_m is

$$Y_m = \frac{1}{\lambda T_s} \sum_{n=1}^{\lambda T_s} \Big| y_m[n] \Big|^2. \tag{3.2}$$

Then, all SUs send their sensed results Y_m to the coordinator, which has been dubbed the "soft decision" [1] method in CSS. The overall energy statistic of the primary channel Y is calculated as

$$\begin{aligned} Y &= \frac{1}{M} \sum_{m=1}^{M} Y_m \\ &= \frac{1}{\lambda M T_s} \sum_{m=1}^{M} \sum_{n=1}^{\lambda T_s} \Big| y_m[n] \Big|^2. \end{aligned} \tag{3.3}$$

The coordinator compares Y with a predetermined threshold Y_{th} to decide whether primary activities exist. We express the coordinator's decision results by $\mathcal{D}_0$ and $\mathcal{D}_1$

$$\begin{aligned}
\mathcal{D}_0: \quad & Y < Y_{th}, \quad \text{decide no primary activity exists} \\
\mathcal{D}_1: \quad & Y \geq Y_{th}, \quad \text{decide primary activities exist.}
\end{aligned}$$

If the coordinator determines that the channel is available, it will assign it to the active SUs for transmitting packets. On the contrary, if the coordinator discovers that the PU returns to the channel, the SUs assigned to that channel will be informed to cease the communication immediately. Therefore, our sensing scheme is based on the *overlay approach* for sharing spectrum with PUs [49]. It should be emphasized that the main topic of this chapter is to propose an asynchronous CSS scheme and find its optimal sensing period. We do not consider spectrum allocation by the coordinator. Nevertheless, our spectrum sensing scheme is independent of any spectrum allocation scheme and can work well with any of them.

Then we can get expressions for P_d and P_f according to [21]

$$\begin{aligned}
P_d &= \Pr[\mathcal{D}_1|\mathcal{H}_1] \\
&= \Pr[Y \geq Y_{th}|\mathcal{H}_1] \\
&= Q\left(\left(\frac{Y_{th}}{\sigma^2} - \text{SNR}_p - 1\right)\sqrt{\frac{\lambda M T_s}{2\text{SNR}_p + 1}}\right) \qquad (3.4)\\
P_f &= \Pr[\mathcal{D}_1|\mathcal{H}_0] \\
&= \Pr[Y \geq Y_{th}|\mathcal{H}_0]. \\
&= Q\left(\left(\frac{Y_{th}}{\sigma^2} - 1\right)\sqrt{\lambda M T_s}\right) \qquad (3.5)
\end{aligned}$$

where $\text{SNR}_p = \frac{\sigma_p^2}{\sigma^2}$ is the average SNR of the primary signal received by SUs and $Q(x)$ is the Gaussian Q-function defined as [19]

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{+\infty} \exp(-\frac{t^2}{2})dt \qquad (3.6)$$

where $Q(0) = 0.5$ and $Q(x)$ is a decreasing function.

One of the most important issues in DSA is to ensure the PUs' quality of service (QoS) by controlling the interference from the SUs. This can be achieved by putting constraints on P_d, which is regulated by the PUs, i.e., $P_d \geq P_d^{th}$. This threshold is a system design constraint for the SUs, in the sense that they should adjust their system parameters to fulfill the PUs' requirement.

In a real system, the detection probability P_d should be at least larger than 0.5 and the false alarm probability P_f should be at least smaller than 0.5. From (3.4) and (3.5), the loosest constraints $P_d > 0.5$ and $P_f < 0.5$ are equivalent to the following inequality according to the two features of $Q(x)$

$$\sigma^2 < Y_{th} < \sigma^2(1 + \mathrm{SNR}_p)$$

or

$$1 < \frac{Y_{th}}{\sigma^2} < 1 + \mathrm{SNR}_p. \tag{3.7}$$

This loosest constraint can allow us to set rational parameters for $\frac{Y_{th}}{\sigma^2}$ and SNR_p easily in the simulation.

3.3 Asynchronous CSS

In the OFF state, if the coordinator can successfully decide there is no primary activity with probability P_{of} where,

$$P_{of} = 1 - P_f \tag{3.8}$$

SUs assigned to the channel will communicate with each other in the *transmission state* under interference from only CSCG background noise. Therefore, the SUs' achievable date rate in this case, R_0, according to the Shannon upper bound, is

$$R_0 = \mathbb{E}\Bigg(\log\Big(1 + \mathrm{SNR}_s\Big)\Bigg) \tag{3.9}$$

where SNR_s denotes the SNR of secondary signals at a secondary receiver.

In the ON state, if the coordinator falsely decides there is no primary activity with probability P_{on} where,

$$P_{on} = 1 - P_d \tag{3.10}$$

the secondary receiver will be interfered by the primary sender's transmission in addition to CSCG background noise. Thus, R_1 can be calculated as

$$R_1 = \mathbb{E}\left(\log\left(1 + \frac{\mathrm{SNR}_s}{\mathrm{SNR}_p + 1}\right)\right). \tag{3.11}$$

3.3.1 Average Throughput Analysis

In our proposed sensing scheme, owing to the asynchronism between the SUs and the PU, there are four different cases, S_{00}, S_{01}, S_{10} and S_{11} according to different beginnings and endings of the SUs' for one sensing period, shown in Fig. 3.2. We discuss the average throughput of each case in turn. We need to stress that since $T_p << r_0$ and r_1 as discussed in Section 2.2, cases where the SUs' one sensing period contains two or more ON/OFF states and the transition from OFF to ON or ON to OFF in one sensing state rarely happen.

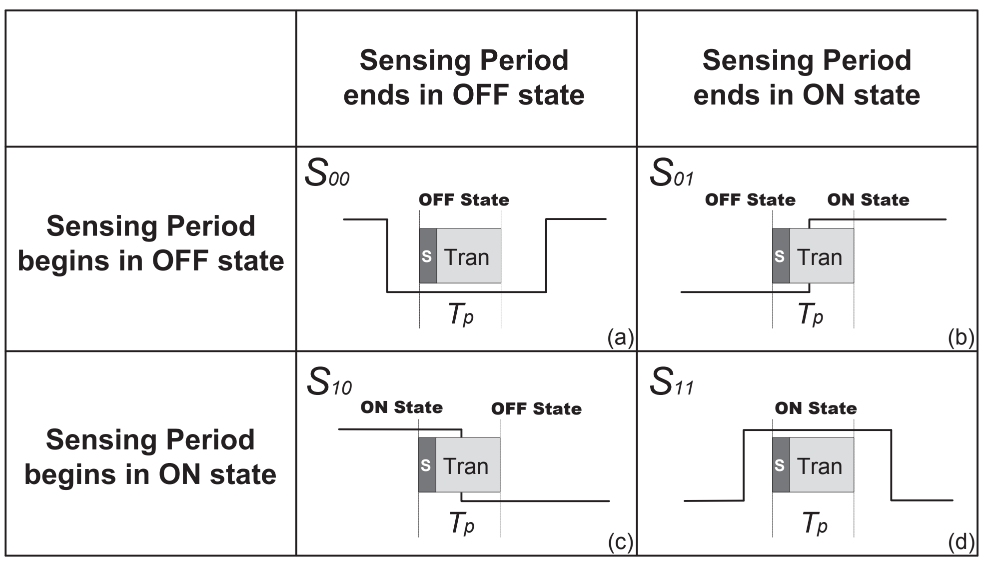

Figure 3.2. Four different cases of asynchronism between SUs and PU.

- **Case** S_{00}

In this case, the SUs' one sensing period T_p wholly falls into the OFF state of the channel. This happens when T_p begins in the OFF state and is shorter than the SUs' *forward recurrence time* of the OFF state F_{of}. According to Section 2.1, F_{of} still obeys the exponential distribution with parameter r_0 as is the case for the OFF period. Therefore, we can obtain the occurrence probability of S_{00} as

$$\begin{aligned}\Pr[S_{00}] &= \mu_0 \Pr\Big(F_{of} \geq T_p\Big) \\ &= \mu_0 \int_{T_p}^{+\infty} \frac{1}{r_0} e^{-\frac{f_{of}}{r_0}} df_{of} \\ &= \mu_0 e^{-\frac{T_p}{r_0}} \end{aligned} \tag{3.12}$$

where $\mu_0 = \frac{r_0}{r_0+r_1}$ is the occurrence probability of the OFF state. Thus, the average throughput of the SUs in this case is

$$R_{00} = P_{of} \cdot \frac{T_p - T_s}{T_p} \cdot R_0. \tag{3.13}$$

- **Case** S_{01}

This case designates that the SUs' one sensing period T_p begins in the OFF state of the channel and ends in the ON state. Similar to the analysis in case S_{00}, the occurrence probability of case S_{01} is

$$\begin{aligned}\Pr[S_{01}] &= \mu_0 \Pr\Big(0 \leq F_{of} \leq T_p\Big) \\ &= \mu_0 \int_{0}^{T_p} \frac{1}{r_0} e^{-\frac{f_{of}}{r_0}} df_{of} \\ &= \mu_0 \Big(1 - e^{-\frac{T_p}{r_0}}\Big). \end{aligned} \tag{3.14}$$

In this case, the average throughput of the SUs contains two parts, one without the existence of a PU and another with the existence of a PU expressed by

$$\begin{aligned}R_{01} &= P_{of} \cdot \frac{F_{of} - T_s}{T_p} \cdot R_0 + P_{on} \cdot \frac{T_p - F_{of}}{T_p} \cdot R_1 \\ &= \frac{1}{T_p} \cdot \Big((R_0 P_{of} - R_1 P_{on}) F_{of} + (P_{on} R_1 T_p - P_{of} R_0 T_s)\Big). \end{aligned} \tag{3.15}$$

It can be seen from eq. (3.15) that the variable F_{of} makes R_{01} also become a random variable instead of a deterministic value like R_{00} (T_p is considered as a fixed parameter in the analysis of average throughput). The expected value of R_{01} can be derived as

$$\mathbb{E}(R_{01}) = \frac{1}{T_p} \cdot \Big((R_0 P_{of} - R_1 P_{on}) \mathbb{E}_{[0 \le F_{of} \le T_p]} F_{of} + (P_{on} R_1 T_p - P_{of} R_0 T_s) \Big) \tag{3.16}$$

where $\mathbb{E}_{[0 \le F_{of} \le T_p]} F_{of}$ is the expected value of F_{of} over the interval $[0 \le F_{of} \le T_p]$. We need to normalize F_{of} over the interval $[0 \le F_{of} \le T_p]$ first, namely

$$F_{of} \sim \frac{1}{r_0} e^{-\frac{f_{of}}{r_0}} \qquad (0 \le f_{of} \le +\infty)$$

$$\Big\downarrow \ \textbf{Normalization over } [0 \le F_{of} \le T_p]$$

$$F_{of} \sim \frac{\frac{1}{r_0} e^{-\frac{f_{of}}{r_0}}}{\int_0^{T_p} \frac{1}{r_0} e^{-\frac{f_{of}}{r_0}} df_{of}} = \frac{\frac{1}{r_0} e^{-\frac{f_{of}}{r_0}}}{1 - e^{-\frac{T_p}{r_0}}} \qquad (0 \le f_{of} \le T_p).$$

Then eq. (3.16) becomes

$$\begin{aligned}\mathbb{E}(R_{01}) &= \frac{1}{T_p} \cdot \left((R_0 P_{of} - R_1 P_{on}) \int_0^{T_p} f_{of} \cdot \frac{\frac{1}{r_0} e^{-\frac{f_{of}}{r_0}}}{1 - e^{-\frac{T_p}{r_0}}} df_{of} + (P_{on} R_1 T_p - P_{of} R_0 T_s) \right) \\ &= \frac{1}{T_p} \cdot \left(\frac{(R_0 P_{of} - R_1 P_{on}) \cdot \left(r_0 - (T_p + r_0) e^{-\frac{T_p}{r_0}} \right)}{1 - e^{-\frac{T_p}{r_0}}} + (P_{on} R_1 T_p - P_{of} R_0 T_s) \right).\end{aligned} \tag{3.17}$$

- **Case** S_{10}

Case S_{10} happens when the SUs' one sensing period T_p begins in the ON state of the channel and ends in the OFF state. Similar to the analysis in case

S_{01}, the occurrence probability of case S_{10} is

$$\begin{aligned}\Pr[S_{10}] &= \mu_1 \Pr\Big(0 \leq F_{on} \leq T_p\Big)\\ &= \mu_1\Big(1 - e^{-\frac{T_p}{r_1}}\Big)\end{aligned} \tag{3.18}$$

where F_{on} is the SUs' *forward recurrence time* of its ON state which also obeys the exponential distribution with parameter r_1 as does the ON period and $\mu_1 = \frac{r_1}{r_0+r_1}$ is the occurrence probability of the ON state.

In this case, the average throughput of the SUs also contains two parts, one with the existence of a PU and another without the existence of a PU expressed by

$$\begin{aligned}R_{10} &= P_{on} \cdot \frac{F_{on} - T_s}{T_p} \cdot R_1 + P_{of} \cdot \frac{T_p - F_{on}}{T_p} \cdot R_0\\ &= \frac{1}{T_p} \cdot \Big((R_1 P_{on} - R_0 P_{of})F_{on} + (P_{of} R_0 T_p - P_{on} R_1 T_s)\Big).\end{aligned} \tag{3.19}$$

As for case S_{01}, through normalization, the probability density function ($p.d.f$) of T_p over $[0 \leq F_{on} \leq T_p]$ can be obtained and then we can get

$$\begin{aligned}\mathbb{E}(R_{10}) = \frac{1}{T_p} \cdot \Bigg(&\frac{(R_1 P_{on} - R_0 P_{of}) \cdot \Big(r_1 - (T_p + r_1)e^{-\frac{T_p}{r_1}}\Big)}{1 - e^{-\frac{T_p}{r_1}}}\\ &+ (P_{of} R_0 T_p - P_{on} R_1 T_s)\Bigg).\end{aligned} \tag{3.20}$$

- **Case** S_{11}

In this case, the SUs' one sensing period T_p wholly falls into the ON state of the channel. As for case S_{00}, the occurrence probability of case S_{11} is

$$\begin{aligned}\Pr[S_{11}] &= \mu_1 \Pr\Big(F_{on} \geq T_p\Big)\\ &= \mu_1 e^{-\frac{T_p}{r_1}}.\end{aligned} \tag{3.21}$$

The average throughput of SUs of this case is

$$R_{11} = P_{on} \cdot \frac{T_p - T_s}{T_p} \cdot R_1. \tag{3.22}$$

3.3.2 Optimal Sensing Period T_p^*

The SUs' average throughput under each case S_j ($j = 00, 01, 10, 11$) can be expressed by

$$\mathbb{E}\big(R\big) = \sum_{j=00}^{11} \Pr[S_j]\mathbb{E}\big(R_j\big) \tag{3.23}$$

As discussed in Section 2.2, the determination of the optimal value of the sensing period T_p^* is a trade-off. We construct a constrained optimization equation, namely eq. (3.24) to address this problem. It can be shown that the objective function is nondecreasing in T_p within the constrained region, so the objective function should achieve its maximum value at the maximum feasible T_p, that is $0.2r_0$ or $0.2r_1$. The detailed proof will be presented in Chapter 4. The solution is

$$T_p^* = \operatorname{Arg\,max}\ \mathbb{E}\big(R\big) \tag{3.24}$$
$$\text{s.t.} \quad \begin{cases} T_s < T_p << r_0 \\ T_s < T_p << r_1 \end{cases}$$

or

$$\text{s.t.} \quad \begin{cases} T_s < T_p \leq 0.2r_0 \\ T_s < T_p \leq 0.2r_1 \end{cases}$$

3.4 Numerical Results

In the previous sections, we discussed the proposed asynchronous CSS scheme. Numerical results are presented in this section. The relevant parameters used in the evaluation are listed in Table 3.1.

3.4.1 Detection Probability and False Alarm Probability

Fig. 3.3 shows the detection probability P_d and the false alarm probability P_f versus the SNR of the primary signals received by the SUs, SNR_p, for different values of the ratio of decision threshold to noise variance, $\frac{Y_{th}}{\sigma^2}$, with $M = 10$ SUs. Note that a small change in $\frac{Y_{th}}{\sigma^2}$ has a big effect on the value of decision

TABLE 3.1

NUMERICAL PARAMETERS FOR PERFORMANCE EVALUATION

Parameter	Value	Description
T_s	1 ms	Sensing time of each sensing period
λ	100 kHz	Sampling rate
SNR_s	10 dB	SNR of secondary signal received by SUs
$\mu_0 = \Pr[\mathcal{H}_0]$	0.8	Probability of the OFF state
$\mu_1 = \Pr[\mathcal{H}_1]$	0.2	Probability of the ON state
r_0	2.4 s	Average length of OFF state
r_1	0.6 s	Average length of ON state

threshold. It can be seen that P_d increases with increase of SNR_p while P_d and P_f decrease together with increase in $\frac{Y_{th}}{\sigma^2}$. Note that when the value of SNR_p is large enough, say increasing beyond -8 dB, the detection probability P_d is almost one. So increasing M further will only give a decrease on P_f, not an increase on P_d.

3.4.2 Maximized Average Throughput of SUs

Fig. 3.4 shows the SUs' maximized average throughput versus SNR_p for different numbers of SUs, M, with $\frac{Y_{th}}{\sigma^2} = 1.05$. The results are calculated from eq. (3.24). One can see that the maximized average throughput decreases when SNR_p increases initially but levels off at a floor value if SNR_p increases further. The reason is as follows. A higher SNR_p influences the sensing throughput tradeoff in two ways. First, the detection probability P_d is increased, which results to a decrease of the probability of the coordinator deciding on the absence of primary activities, P_{on}, in the ON state of the channel. Second, the conditional achievable throughput in the ON state of the channel, R_1, is decreased. Initially the secondary receiver suffers interference from the PU's transimission in the ON state of the channel, which results in reduced average throughput. When SNR_p exceeds a certain value, P_d is almost 1 and P_{on} is almost 0, which cause SNR_p to have little further effect on the SUs' average throughput. Moreover, since more cooperative SUs can help improve P_d and reduce P_f, the SUs' average throughput is larger when the number of SUs, M, is larger.

Fig. 3.5 shows SUs' maximized average throughput versus the number of

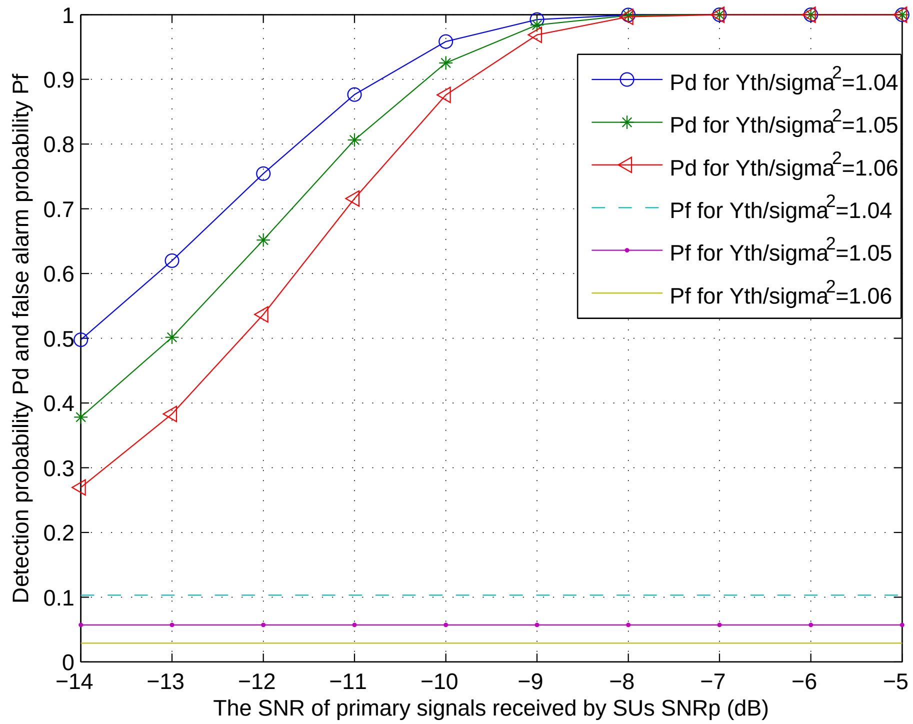

Figure 3.3. The detection probability and false alarm probability versus SNR_p for different decision thresholds with $M = 10$.

cooperative SUs, M, for different values of $\frac{Y_{th}}{\sigma^2}$ with SNR_p = -10 dB. We can verify that cooperative spectrum sensing does outperform the noncooperative case when $M = 1$, and see more clearly that the SUs' average throughput keeps ascending with increasing number of SUs. As we mentioned before, as $\frac{Y_{th}}{\sigma^2}$ increases, P_f decreases, which means that they have more opportunities to discover available idle channels leading to their increasing throughput.

3.5 Summary

In this chapter, we first proposed a novel asynchronous CSS scheme for SUs. Based on the ON/OFF primary channel model and the detection and false alarm probability, the SUs' average throughput of each asynchronous case was analyzed. Finally, we constructed and solved an optimization problem to find the optimal sensing period of this scheme by maximizing the SUs' average throughput.

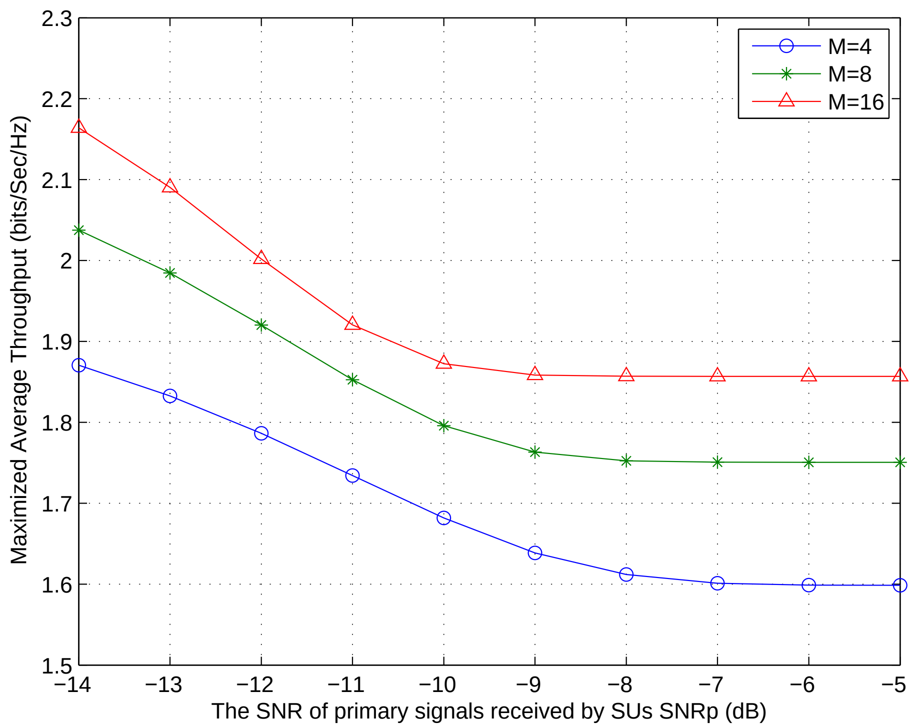

Figure 3.4. The maximized average throughput of the SUs versus SNR_p for different numbers of SUs, M, with $\frac{Y_{th}}{\sigma^2} = 1.05$.

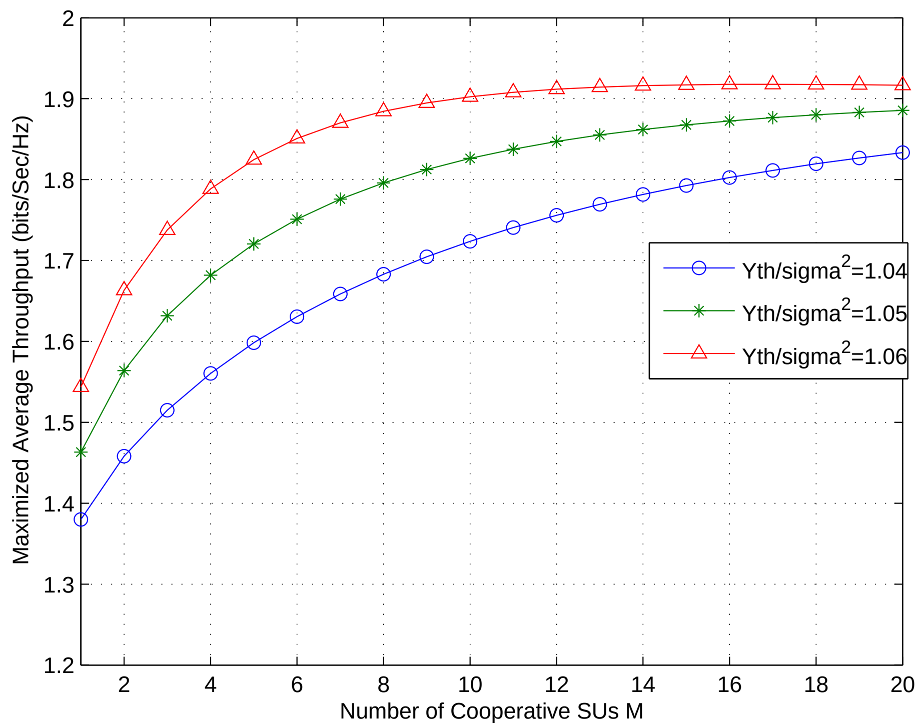

Figure 3.5. The maximized average throughput of the SUs versus M for different values of $\frac{Y_{th}}{\sigma^2}$ with SNR_p = -10 dB.

Chapter 4

DYWAMIT: A Contention-Based Asynchronous Wideband Dynamic Spectrum Access Algorithm

In this chapter[1], we first present the relevant system model and then review the features of the so called DYWAMIT: Dynamic Wideband Access Mobile Information Technology. This leads to the performance analysis of DYWAMIT, which will be very useful for designing practical cognitive radio wireless networks.

4.1 System Model

In the system, the expression PU refers to the mobile/fixed users in *licensed* digital TV bands or users of cellular networks, while the SUs are *unlicensed* wireless devices. Fig. 4.1 below shows the network entity. It is assumed that there is a wideband channel which is divided into J non-overlapping narrowband subchannels (i.e. J independent primary channels) in total in the primary network. The PUs' mutual communications are based on their own protocols, not known by the SUs. In the secondary network, the M cooperative SUs build a half-duplex multihop network. Considering that the SUs are usually small-sized and power-limited mobile terminals, we assume each SU

[1]The results in this chapter have been accepted by the IEEE Global Communications Conference (GLOBECOM) 2013 [18]

is equipped with only one antenna that can be tuned to any combination of J primary channels, which can be implemented by OFDM (Orthogonal Frequency Division Multiplexing) techniques [50]. There is a control channel in the secondary network, which is used for exchanging sensing results and primary channels contention. Although the SUs have their own control channel, they still need to dynamically access the primary "spectrum holes" to acquire more bandwidth for high-speed multimedia transmission.

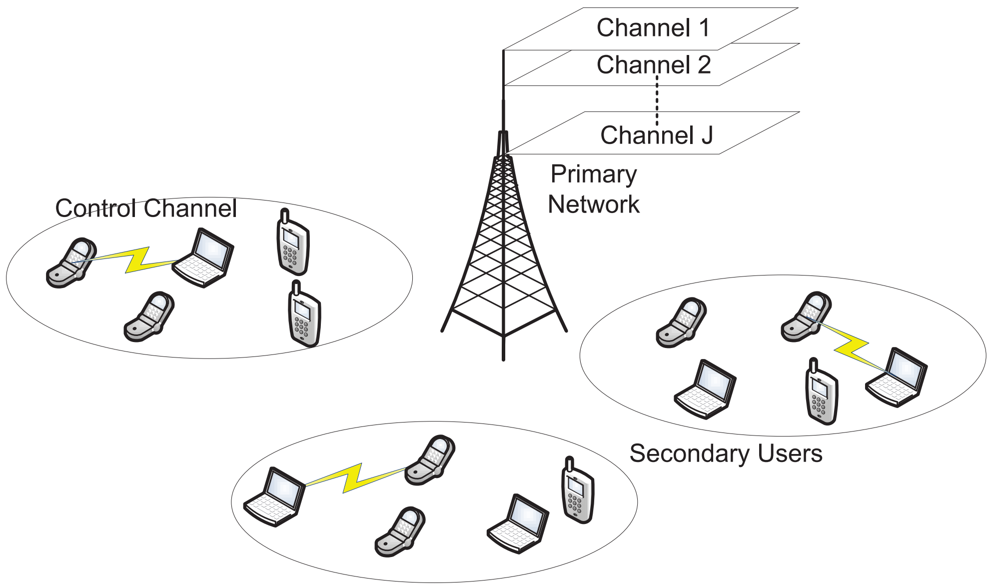

Figure 4.1. The network entity.

4.2 The DYWAMIT Scheme

DYWAMIT sets up five states for the SUs' activity, an observation state, sensing state, sharing state, contention state and transmission state. Fig. 4.2 illustrates the state transition diagram.

In the observation state, the SUs alternatively sleep and wake up to monitor all channels, estimating and updating the ON-OFF parameters of them. How to concretely control the lengths of sleeping and awake periods to maximally save power consumption is not our focus, and will not be discussed in this thesis.

It is assumed that each SU is equipped with only one antenna and that they can just sense one channel at one time; there is no capability to simultaneously sense two or multi-channels. Thus, in the spectrum sensing state, the active SUs sense primary channels in sequence using the energy detection method. After the spectrum sensing state, the SUs share the sensing information in the sharing state.

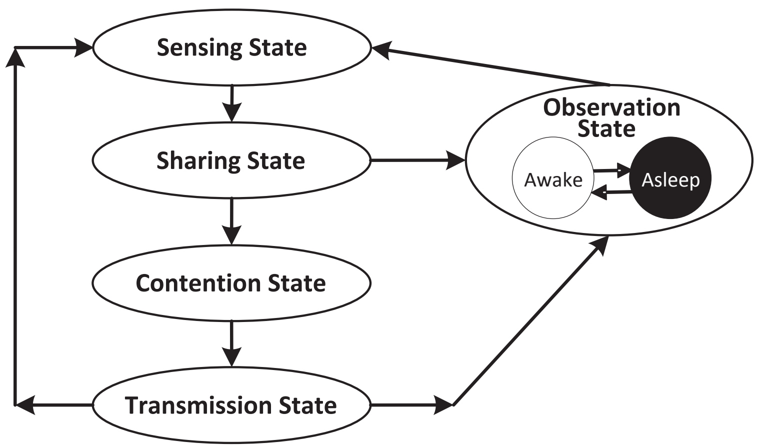

Figure 4.2. The SUs' state transition diagram.

In DYWAMIT, the active SUs who do not plan to access the primary network should also participate in the CSS and reporting of states in order to enhance the detection probability. These altruistic SUs will not need any channel in the transmission state, which can be seen from the state transition diagram in Fig. 4.2. They return to the observation state instead of trying to access any channel. So in the contention state, the SUs who intend to access the primary network should compete among each other for available channels through RTS/CTS.

The so-called "asynchronous DSA" of DYWAMIT dose not mean that the SUs are asynchronous with each other. Instead, it means that the system clock of the secondary network is asynchronous with that of the primary network. In DYWAMIT, the secondary network is still assumed to be a synchronous system and time is divided into slots with the same length. Fig. 4.3 below shows the difference between the traditional synchronous schemes and our newly defined asynchronous scheme. The particular synchronous scheme among the SUs is irrelevant for the subsequent analysis.

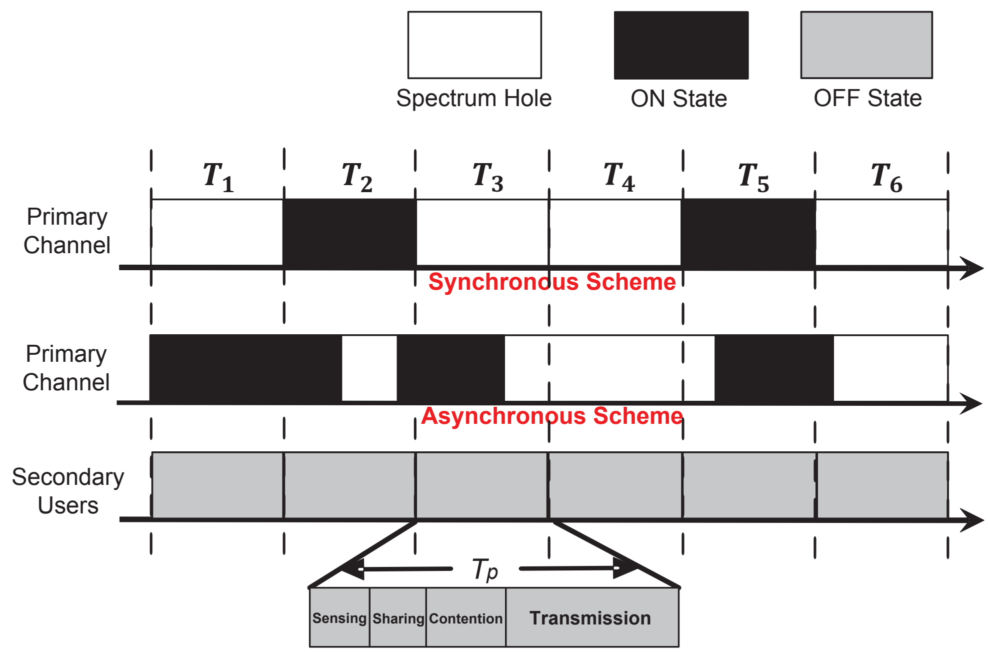

Figure 4.3. Comparison between the traditional synchronous schemes and the proposed asynchronous scheme.

4.2.1 Channel Sensing

At the beginning of each sensing period, active SUs sense primary channels one by one with dwell time T_s on each channel and sampling rate λ, as shown in Fig. 4.4. Energy detection is employed in the sensing process, as in Chapter 3, for each primary channel. T_s and λ are specified values, which are determined by the configuration of SUs' PHY-layer hardware.

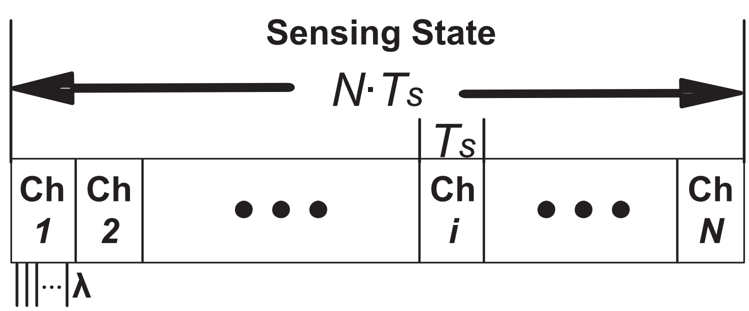

Figure 4.4. The sensing state.

We use $\mathcal{H}_0^{(i)}$ and $\mathcal{H}_1^{(i)}$ to express one primary channel being in the OFF and ON state, respectively. The received signals under $\mathcal{H}_0^{(i)}$ and $\mathcal{H}_1^{(i)}$ at the secondary receiver are given by

$$\mathcal{H}_0^{(i)} : y_m^{(i)}[n] = u_m^{(i)}[n], \qquad n = 1, 2, ..., \lambda T_s \tag{4.1a}$$

$$\mathcal{H}_1^{(i)} : y_m^{(i)}[n] = s_m^{(i)}[n] + u_m^{(i)}[n], \quad m = 1, 2, ..., M \tag{4.1b}$$

where the superscript (i) denotes channel i, the subscript m refers to the mth SU, $[n]$ denotes the nth sample, $y_m^{(i)}$ is the mth SU's received signal in channel i, $u^{(i)}$ denotes the background noise which is also assumed to be CSCG with mean zero and variance $\sigma^{(i)2}$, and $s^{(i)}[n]$ are the primary signals received by SUs which are considered $i.i.d$ random processes with means zero and variances $\sigma_p^{(i)2}$.

Thus, for the mth SU, the energy statistic, $Y_m^{(i)}$, of the sensed signal in the ith channel is

$$Y_m^{(i)} = \frac{1}{\lambda T_s} \sum_{n=1}^{\lambda T_s} \left| y_m^{(i)}[n] \right|^2. \tag{4.2}$$

It is obvious that the overall channel sensing time $T_{cs} = J \cdot T_s$ is proportional to the total number of the sensed primary channels. When there are many primary channels to sense, i.e. J is large, the sensing state may be too long. In order to reduce the cost of spectrum sensing, the SUs only sense N channels out of all J primary channels in DYWAMIT. Note that the N sensed channels are randomly chosen by each SU to aviod the situation where some channels are heavily sensed while some channels are never sensed. However, too small N may lead to the situation that intended SUs can not obtain enough available primary channels, which leads to waste of the spectrum bands. Therefore, an appropriate N is required for DYWAMIT algorithm. In the performance analysis section, we will show the relationship between N and the number of idle channels detected by the SUs.

4.2.2 Information Sharing

After the sensing state, all SUs exchange sensing information $Y_m^{(i)}$ in the information sharing state on their control channel. The information sharing state is divided into M sub-slots each with dwell time T_{sh}. Thus the total information sharing state time is $T_{is} = M \cdot T_{sh}$. The MAC-layer broadcasting frame of DYWAMIT is shown in Fig. 4.5. At the beginning the packet control field indicates the protocol version, the type of data packet, the packet counter and so on. The TA field contains the address of the transmitter sending the broadcasting frame. The numbers of channels are different for global and partial sensing. The main payload field (totally $2N$ bytes) contains the sensing information, i.e. the detected energy of each primary channel. A 32-bit CRC (cyclic redundancy check code) is used in the end to detect errors. If certain error is detected, that frame will be discarded accordingly.

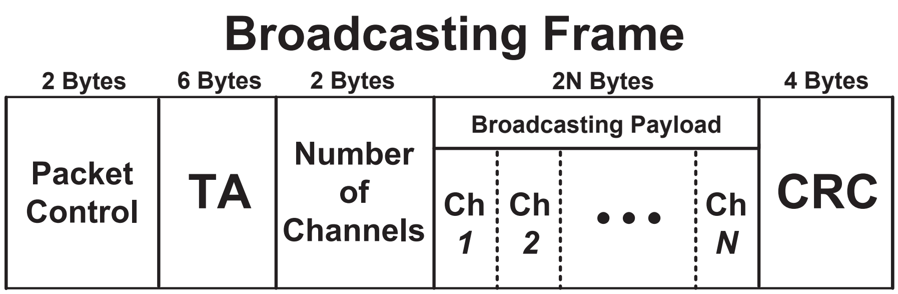

Figure 4.5. The broadcasting frame.

Thus, the overall energy statistic of the ith channel, $Y^{(i)}$, is calculated as

$$\begin{aligned} Y^{(i)} &= \frac{1}{M}\sum_{m=1}^{M} Y_m^{(i)} \\ &= \frac{1}{\lambda M T_s}\sum_{m=1}^{M}\sum_{n=1}^{\lambda T_s}\left|y_m^{(i)}[n]\right|^2. \end{aligned} \tag{4.3}$$

The SUs compare $Y^{(i)}$ with a predetermined threshold $Y_{th}^{(i)}$ to decide whether primary activities exist. We express the decision results by $\mathcal{D}_0^{(i)}$ and $\mathcal{D}_1^{(i)}$

$$\begin{aligned} &\mathcal{D}_0^{(i)}: \quad Y^{(i)} < Y_{th}^{(i)}, \quad \text{decide no primary activity exists} \\ &\mathcal{D}_1^{(i)}: \quad Y^{(i)} \geq Y_{th}^{(i)}, \quad \text{decide primary activities exist.} \end{aligned}$$

Also, we can get expressions for P_d and P_f for each channel i [21]

$$\begin{aligned}
P_d^{(i)} &= \Pr[\mathcal{D}_1^{(i)}|\mathcal{H}_1^{(i)}] \\
&= \Pr[Y^{(i)} \geq Y_{th}^{(i)}|\mathcal{H}_1^{(i)}] \\
&= Q\left(\left(\frac{Y_{th}^{(i)}}{\sigma^{(i)2}} - \text{SNR}_p^{(i)} - 1\right)\sqrt{\frac{\lambda M T_s}{2\text{SNR}_p^{(i)}+1}}\right) \qquad (4.4)
\end{aligned}$$

$$\begin{aligned}
P_f^{(i)} &= \Pr[\mathcal{D}_1^{(i)}|\mathcal{H}_0^{(i)}] \\
&= \Pr[Y^{(i)} \geq Y_{th}^{(i)}|\mathcal{H}_0^{(i)}]. \\
&= Q\left(\left(\frac{Y_{th}^{(i)}}{\sigma^{(i)2}} - 1\right)\sqrt{\lambda M T_s}\right) \qquad (4.5)
\end{aligned}$$

where $\text{SNR}_p^{(i)} = \frac{\sigma_p^{(i)2}}{\sigma^{(i)2}}$ is the average SNR of the primary signal received by the SUs.

4.2.3 Contention

In the contention state, the SUs who have not successfully competed for available channels must keep monitoring the control channel to be informed about which channels have been reserved by other intended SUs. Thus, on one hand, these SUs will not try to compete for channels already reserved in the remaining contention time. On the other hand, the design of the contention state also avoids the situation that two different pairs of SUs agree on one same primary channel at one time, which will lead to collisions in the transmission state. Therefore, DYWAMIT divides the contention state into L contention slots with dwell time T_{ct} for each slot as shown in Fig. 4.6. This configuration can guarantee that there is only one pair of SUs negotiating at any one slot.

The contention state is implemented on the control channel. DYWAMIT employs a CSMA/CA mechanism to detect contentions among the SUs. At the beginning of each contention state, intended SUs select a contention slot **randomly** from those L contention slots. Then it will transmit a RTS frame with the requested channel information to its destination SU, then begin waiting for a CTS packet with the agreed channel information from its destination SU. The MAC-layer RTS/CTS frames are shown in Fig. 4.7 where the RA field contains the address of the intended immediate receiver. The transmission times of the RTS frame and CTS frame are T_{RTS} and T_{CTS}, respectively.

Fig. 4.6 also illustrates the CSMA/CA process. If the source SU receives

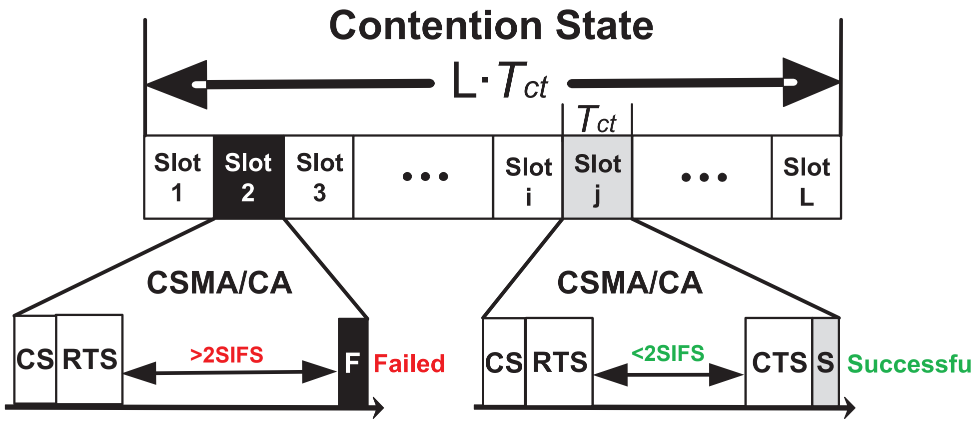

Figure 4.6. The contention state.

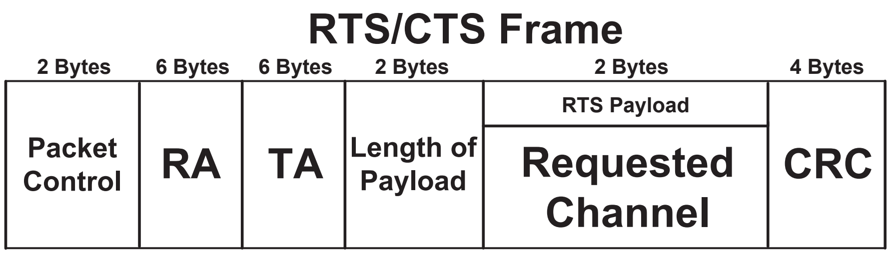

Figure 4.7. The RTS/CTS frame.

the CTS frame correctly within 2SIFS (short inter-frame space), this contention will be considered as successful. Then, this pair of SUs will reserve that assented channel and other SUs will not try to compete for that channel later. Note that each SU can only reserve one available primary channel, i.e., once the SU successfully competes for one channel, it will not compete for other channels during the following contention slots. SIFS, defined in IEEE 802.11 [51], is the small time interval between the data frame and its acknowledgement, and it is the smallest of all inter frame spaces. They are used for the highest priority transmissions enabling stations with this type of information to access the radio link first. On the contrary, if the source SU fails to get any response from its intended destination SU, it will regard this contention as a failure and **randomly** re-select another slot to contend until the contention is successful or the whole contention state is over. Thus, the duration of one contention slot T_{ct} can be calculated as

$$T_{ct} = T_{\text{RTS}} + 2\text{SIFS} + T_{\text{CTS}} \tag{4.6}$$

and the total contention time is

$$T_c = L \cdot T_{ct}. \tag{4.7}$$

4.2.4 Overall DYWAMIT Algorithm

Having the descriptions of the five states of DYWAMIT given above, we can summarize the detailed DYWAMIT algorithm by the pseudo codes in Algorithm 1, which illustrates one SU's activity within one sensing period T_p. The meanings of the relevant variables in the algorithm are listed in Table 4.1 below. Note that a control channel is required to implement the DYWAMIT algorithm. First, in the information sharing state, the SUs need to exchange their channel sensing results on the control channel. Second, in the contention state, the SUs need to compete for available channels, also on the control channel, including RTS/CTS information exchange.

TABLE 4.1
THE MEANINGS OF THE VARIABLES IN THE ALGORITHM

Flag	Description
state_flag	current state of a SU: five states
BroadFrame	structure of the SU's broadcasting frame
tran_over_flag	whether the SU has finished data transmission
been_slots	how many slots have been contended
selc_slot	the selected slot
contend_suc_flag	whether the SU has successfully competed

4.3 Performance Analysis

Although the DYWAMIT algorithm has now been explicitly presented, there are still three technical issues to resolve, namely,

- How to determine the number of channels sensed by each SU, N?
- How to determine the number of the total contention slots L?
- How to determine one sensing period T_p, which represents how often the SUs re-sense the primary channels?

In this section, we will study these problems through performance analysis.

Algorithm 1 The DYWAMIT algorithm in detail

```
Initialize state_flag == SENSING;
if state_flag == SENSING then
    BroadFrame.ch_num = N;
    for i = 1 to BroadFrame.ch_num do
        Detect the energy of channel i: Y_m^(i);
        BroadFrame.payload[i] = Y_m^(i);
    end for
    state_flag == SHARING;
end if
if state_flag == SHARING then
    Receive and analyze the Broadcasting Frame;
    if tran_over_flag == 0 then
        state_flag == CONTENTION;
    else
        state_flag == OBSERVATION;
    end if
end if
if state_flag == CONTENTION then
    been_slots = 1; contend_suc_flag = 0;
    while been_slots ≤ L && contend_suc_flag == 0 do
        selc_slot = randomly selected slot from 1 to L;
        Send an RTS frame to the destination SU;
        if The CTS frame is received within 2SIFS then
            contend_suc_flag == 1;
            state_flag == TRANSMISSION;
        end if
        been_slots++;
    end while
    state_flag == OBSERVATION;
end if
if state_flag == TRANSMISSION then
    Communicate with the receiver SU on the agreed channel;
    state_flag == SENSING;
end if
if state_flag == OBSERVATION then
    Periodically wake up to estimate channels parameters;
    state_flag == SENSING.
end if
```

4.3.1 Channel Sensing Analysis

According to DYWAMIT, in the channel sensing state, each SU randomly senses N channels out of a total J primary channels due to hardware and time constraints. We assume that all the primary channels have the same spectrum utilization μ_1 for convenience of analysis. Although M SUs can totally sense $M \cdot N$ channels and $M \cdot N >> J$, some idle channels may not be discovered due to the randomness. In this subsection, we theoretically analyze the average number of sensed idle channels when given the number of SUs, M, the number of channels sensed by each SU, N, and the primary channels' spectrum utilization μ_1. Based on the analysis, we can determine an appropriate value for N.

Since the utilizations of the primary channels are mutually independent, the distribution of the number of idle channels, which is the probability that there are i idle channels among J primary channels, $p_I(i)$, follows the binomial distribution,

$$p_I(i) = \binom{J}{i}(1-\mu_1)^i \cdot \mu_1^{J-i}, 0 \leq i \leq J. \tag{4.8}$$

Then the expected number of idle channels, $\mathbb{E}[I]$, is given by

$$\mathbb{E}[I] = \sum_{i=0}^{J} i \cdot p_I(i). \tag{4.9}$$

Or more directly, $\mathbb{E}[I]$ can be calculated as [52]

$$\mathbb{E}[I] = (1-\mu_1) \cdot J. \tag{4.10}$$

The distribution of the number of sensed idle channels among N chosen channels by a SU, i.e., the probability that there are si sensed idle channels among N sensed channels by a SU, $p_{SI}(si)$, follows the binomial distribution

$$p_{SI}(si) = \binom{N}{si}(1-\mu_1)^{si} \cdot \mu_1^{N-si}, 0 \leq si \leq N. \tag{4.11}$$

Then, the expected number of sensed idle channels among N chosen channels by a SU is

$$\mathbb{E}[SI] = \sum_{si=0}^{N} si \cdot p_{SI}(si) \tag{4.12}$$

or

$$\mathbb{E}[SI] = (1-\mu_1)\cdot N. \tag{4.13}$$

Combining (4.10) and (4.13), we can see that the probability that an idle channel among all the idle channles is sensed by a SU, p_{ia}, is

$$\begin{aligned} p_{ia} &= \frac{\text{Number of Sensed Idle Channels by a SU}}{\text{Number of Idle Channels}} \\ &= \frac{\mathbb{E}[SI]}{\mathbb{E}[I]} \\ &= \frac{N}{J}. \end{aligned} \tag{4.14}$$

Since whether one idle channel is sensed by one SU is independent of other SUs, the probability that a random idle channel is sensed by at lease one SU is

$$p_{sd} = 1-(1-p_{ia})^M. \tag{4.15}$$

Moreover, whether one idle channel is sensed by the SUs is independent of other idle channels. Thus, given the total number of idle channels $I = i$, the conditional probability that there are sim sensed idle channels by M SUs, follows the following binomial distribution,

$$p_{SIM}(sim|i) = \begin{cases} \binom{i}{sim}(p_{sd})^{sim}\cdot(1-p_{sd})^{i-sim} & 0 \le sim \le i \\ 0 & i < sim \le J. \end{cases} \tag{4.16}$$

Then according to the total probability formula [52], the number of the sensed idle channels by M SUs follows

$$p_{SIM}(sim) = \sum_{i=sim}^{J} p_{SIM}(sim|i)\cdot p_I(i), 0 \le sim \le J \tag{4.17}$$

where $p_I(i)$ is given in (4.8). Thus, the average number of sensed idle channels by M SUs can be calculated using

$$\mathbb{E}[SIM] = \sum_{sim=0}^{J} sim\cdot p_{SIM}(sim). \tag{4.18}$$

By substituting (4.8)-(4.17) into (4.18), we can obtain an expression for the average number of sensed idle channels by M SUs when each SU senses N channels. As we will see in the simulation, the more channels each SU senses, the more idle channels can be sensed. Therefore, according to the system design requirement, i.e., the smallest number of sensed idle channels $\mathbb{E}[SIM]_{min}$, we can calculate the minimum number of channels sensed by each SU, N_{min}, using (4.18).

4.3.2 Contention Analysis

According to the DYWAMIT design, in the channel contention state, each SU randomly chooses one contention slot to compete for available primary channels. Since each contention slot can only support one pair of SUs exchanging RTS/CTS information, conflicts may appear when two pairs of SUs are trying to exchange RTS/CTS information in the same contention slot. In this subsection, we analyze the relationship between the number of contention slots, L, and the average number of successful SUs. In the asynchronous situation, "success" means one certain slot is selected by only one SU and no PU comes back in the whole contention state time.

First, since each SU ramdomly chooses one contention slot among L slots, the probability of one certain slot being selected is $\frac{1}{L}$. Moreover, since selection of one contention slot by one SU is independent of other SUs, the probability of one certain slot being selected by only one SU, denoted by p_a, is

$$\begin{aligned} p_a &= \binom{M}{1} \cdot \left(\frac{1}{L}\right)^1 \cdot \left(1 - \frac{1}{L}\right)^{M-1} \\ &= \frac{M}{L} \cdot \left(1 - \frac{1}{L}\right)^{M-1}. \end{aligned} \tag{4.19}$$

Secondly, the probability of some PU coming back within L contention slots, denoted by p_b, is the probability that the length of the contention period is longer than the forward recurrence time of the OFF state, F_{of}. We get from Section 2.2 that F_{of} has the same distribution as T_{of}. In such a case, we have

$$\begin{aligned} p_b &= \Pr(0 \le F_{of} \le LT_{ct}) \\ &= \int_0^{LT_{ct}} \frac{1}{r_0} e^{-\frac{t}{r_0}} dt \\ &= 1 - e^{-\frac{LT_{ct}}{r_0}}. \end{aligned} \tag{4.20}$$

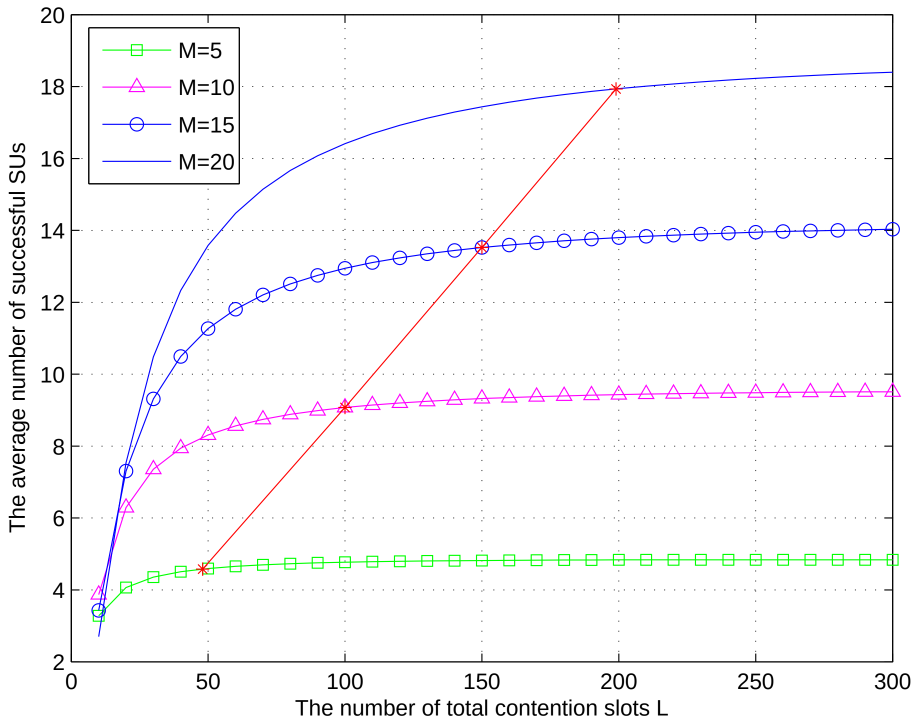

Figure 4.8. The average number of successful SUs versus the number of total contention slots, L, for different numbers of SUs, M. The straight line gives the quiescent points for different values of M.

Then the probability of no PU coming back in the whole contention state, denoted by p_c, is

$$\begin{aligned} p_c &= 1 - p_b \\ &= e^{-\frac{LT_{ct}}{r_0}}. \end{aligned} \tag{4.21}$$

In the asynchronous situation, it is obvious that there is a larger probability of the PUs' coming back in later slots and thus a smaller probability for the SUs to contend successfully. Let S denote the number of successful SUs, then the average number of successful SUs is calculated as

$$\begin{aligned} \mathbb{E}[S] &= p_a \cdot L \cdot p_c \\ &= M\left(1 - \frac{1}{L}\right)^{M-1} e^{-\frac{LT_{ct}}{r_0}}. \end{aligned} \tag{4.22}$$

Fig. 4.8 shows the average number of successful SUs, $\mathbb{E}[S]$, versus the total number of contention slots, L, for different numbers of SUs, M. $\mathbb{E}[S]$ increases with the increase of L, leading to an increase of the SUs' average throughput because more sensed idle channels can be exploited by the SUs. However, a too large number of contention slots leads to a too long contention interval T_c, and thus much less transmission time T_{tr} for a given sensing period T_p. This will affect the average throughput of the SUs negatively. Therefore, an appropriate number of contention slots L must be determined for different numbers of SUs, M.

Also, we can see from Fig. 4.8 that the average number of successful SUs shows a saturation effect and increases slowly when the number of total contention slots L exceeds a certain number. This means increasing L further will not bring much benefit on the number of successful SUs and will cause unnecessary contention time cost instead. Let us denote the increasing rate (or gradient) of $\mathbb{E}[S]$ as I_s. Mathematically, when I_s is approaching 0, the saturation is attained. Note that the greater L is, the closer I_s approaches to 0, while the higher contention cost will be incurred. In such a case, we can set a threshold I_{th}, which represents the minimum useful increasing rate of the number of successful SUs, in order to help find a favorable value of L. The physical meaning of the I_{th} is that when the gradient of $\mathbb{E}[S]$ reaches I_{th}, it is considered that the number of successful SUs reaches saturation and there is no need to further increase the number of contention slots L. We proceed by examining the first derivative of the average number of successful SUs,

$$\begin{aligned}\frac{d\mathbb{E}[S]}{dL} = M\Bigg(& (M-1)\cdot\frac{(1-\frac{1}{L})^{M-2}}{L^2}e^{-\frac{LT_{ct}}{r_0}} \\ & -\frac{T_{ct}}{r_0}\cdot(1-\frac{1}{L})^{M-2}e^{-\frac{LT_{ct}}{r_0}}\Bigg)\end{aligned} \tag{4.23}$$

where L is much larger than 1 and $\frac{T_{ct}}{r_0}\cdot L$ is very small (note that although Fig. 4.8 is plotted using $T_{ct} = 0.1$ ms and $r_0 = 1.5$, the result only changes a little which can be ignored when we change the value of r_0 in the applicable regime), so $(1-\frac{1}{L})^{M-2} \approx 1$, $(1-\frac{1}{L})^{M-1} \approx 1$ and $e^{-\frac{LT_{ct}}{r_0}} \approx 1$. Then (4.23) becomes

$$\frac{d\mathbb{E}[S]}{dL} \approx M\left(\frac{M-1}{L^2} - \frac{T_{ct}}{r_0}\right) \tag{4.24}$$

and the previously mentioned condition on the threshold becomes

$$\frac{d\mathbb{E}[S]}{dL} \approx M\left(\frac{M-1}{L^2} - \frac{T_{ct}}{r_0}\right) \geq I_{th} \tag{4.25}$$

or

$$L \leq \sqrt{\frac{M-1}{\frac{I_{th}}{M} + \frac{T_{ct}}{r_0}}}. \tag{4.26}$$

From Fig. 4.8 we can see that when $M = 10$, the average number of succesful SUs tends to increase slowly after $L = 100$. Using (4.25), we can get the threshold $I_{th} = 0.0083$. Finally, we can get a quiescent point for different numbers of SUs M shown in Table 4.2 in the number of contention slots, L. The straight line in Fig. 4.8 shows quiescent points for different values of M. The quiescent point, or Q-point, or the operating point of a device, is the steady-state voltage or current at a specified terminal of an active device (such as a transistor) with no input signal applied. Here in the thesis, the quiescent points mean the appropriate number of contention slots L for different numbers of cooperative SUs, M.

TABLE 4.2
QUIESCENT POINTS FOR DIFFERENT NUMBERS OF SUs M

M	L	M	L
2	15	12	120
3	27	13	130
4	37	14	140
5	48	15	150
6	59	16	160
7	69	17	170
8	79	18	179
9	90	19	189
10	100	20	199
11	110	21	208

4.3.3 Optimal Sensing Period Analysis

Based on the research model of Chapter 3, first, owing to the asynchronism between the SUs and PUs, there are four different cases, S_{00}, S_{01}, S_{10} and S_{11} according to different beginnings and endings of the SUs' for one sensing period, shown in Fig. 4.9.

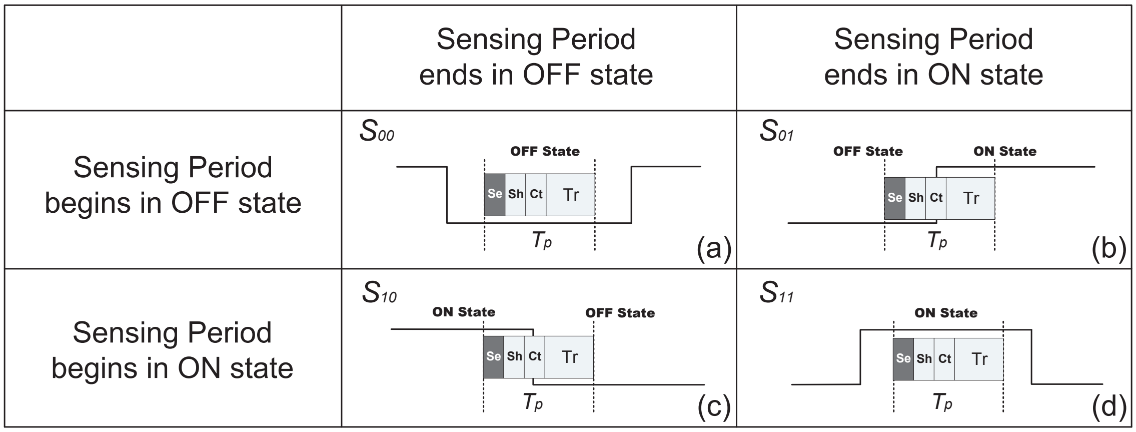

Figure 4.9. Four different cases of asynchronism between SUs and PUs.

Secondly, the occurrence probabilities of the four cases are the following four equations, respectively

$$\Pr[S_{00}] = \mu_0 e^{-\frac{T_p}{r_0}} \tag{4.27}$$

$$\Pr[S_{01}] = \mu_0 \Big(1 - e^{-\frac{T_p}{r_0}}\Big) \tag{4.28}$$

$$\Pr[S_{10}] = \mu_1 \Big(1 - e^{-\frac{T_p}{r_1}}\Big) \tag{4.29}$$

$$\Pr[S_{11}] = \mu_1 e^{-\frac{T_p}{r_1}} \tag{4.30}$$

where $\mu_0 = \frac{r_0}{r_0+r_1}$ is the occurrence probability of the OFF state and $\mu_1 = \frac{r_1}{r_0+r_1}$ is the occurrence probability of the ON state.

Thirdly, the average throughput of the SUs in each case is

$$R_{00} = P_{of} \cdot \frac{T_p - T_{pr}}{T_p} \cdot R_0 \tag{4.31}$$

$$\mathbb{E}(R_{01}) = \frac{1}{T_p} \cdot \Bigg(\frac{(R_0 P_{of} - R_1 P_{on}) \cdot \left(r_0 - (T_p + r_0) e^{-\frac{T_p}{r_0}} \right)}{1 - e^{-\frac{T_p}{r_0}}} + (P_{on} R_1 T_p - P_{of} R_0 T_{pr}) \Bigg) \quad (4.32)$$

$$\mathbb{E}(R_{10}) = \frac{1}{T_p} \cdot \Bigg(\frac{(R_1 P_{on} - R_0 P_{of}) \cdot \left(r_1 - (T_p + r_1) e^{-\frac{T_p}{r_1}} \right)}{1 - e^{-\frac{T_p}{r_1}}} + (P_{of} R_0 T_p - P_{on} R_1 T_{pr}) \Bigg) \quad (4.33)$$

$$R_{11} = P_{on} \cdot \frac{T_p - T_{pr}}{T_p} \cdot R_1 \quad (4.34)$$

where $T_{pr} = T_{cs} + T_{is} + T_c$ is the preparation time, the sum of the channel sensing time, information sharing time and contention time, and $T_{cs} = NT_s$, $T_{is} = MT_{sh}$, and the transmission time in one sensing period, T_{tr}, is $T_{tr} = T_p - T_{pr}$; $P_{of}^{(i)} = 1 - P_f^{(i)}$ is the probability that SUs can successfully decide there is no primary activity in the OFF state of channel i, and $P_{on}^{(i)} = 1 - P_d^{(i)}$ is the probability that SUs falsely decide there is no primary activity in the ON state of channel i; $R_0^{(i)} = \mathbb{E}\left(\log\left(1 + \mathrm{SNR}_s^{(i)}\right) \right)$ is the conditional throughput of SUs in the ON state of channel i where $\mathrm{SNR}_s^{(i)}$ denotes the SNR of secondary signals at a secondary receiver, and $R_1^{(i)} = \mathbb{E}\left(\log\left(1 + \frac{\mathrm{SNR}_s^{(i)}}{\mathrm{SNR}_p^{(i)} + 1}\right) \right)$ is the conditional throughput of SUs in the OFF state of the channel. Note that "i" is omitted in (4.31)-(4.34).

At this time, we can now express the SUs' average throughput in channel i under each case $S_j^{(i)}$ $(j = 00, 01, 10, 11)$ by

$$\mathbb{E}\big(R^{(i)}\big) = \sum_{j=00}^{11} \Pr[S_j^{(i)}] \mathbb{E}\big(R_j^{(i)}\big) \quad (4.35)$$

and the SUs' average throughput $\mathbf{C}(T_p)$ in all J channels and under all cases can be obtained as

$$\mathbf{C}(T_p) = \frac{\mathbb{E}[SIM] \cdot \mathbb{E}\big(R^{(i)}\big)}{J} \tag{4.36}$$

where the average number of sensed idle channels $\mathbb{E}[SIM]$ is given by (4.18).

We now construct a constrained optimization equation, namely (4.37) to address this problem.

$$T_p^* = \text{Arg}\max\ \mathbf{C}(T_p) \tag{4.37}$$

$$\text{s.t.}\quad \begin{cases} T_{pr} < T_p << r_0^{(i)} \\ T_{pr} < T_p << r_1^{(i)} \qquad\qquad (i = 1, 2, ..., N) \end{cases}$$

or

$$\text{s.t.}\quad \begin{cases} T_{pr} < T_p \leq 0.2 r_0^{(i)} \\ T_{pr} < T_p \leq 0.2 r_1^{(i)} \qquad\qquad (i = 1, 2, ..., N). \end{cases}$$

We prove the following theorem.

Theorem 1: The function $\mathbf{C}(T_p)$ is nondecreasing in T_p in the constrained region.

Proof: To prove this result, we need to compute the first derivative of $\mathbf{C}(T_p)$. Since $\mathbb{E}[SIM]$ and J both don't contain T_p and are positive, we get rid of them for convenience when conducting the derivation. Thus, we compute the first derivative of $\mathbb{E}\big(R\big)$ as

$$\begin{aligned} \frac{d\mathbb{E}\big(R\big)}{dT_p} &= \frac{\mu_0}{x^2} \cdot \Big((a-b) r_0 \big(1 - e^{-\frac{x}{r_0}}\big) + bT_{pr} - (a-b) e^{-\frac{x}{r_0}} x\Big) \\ &+ \frac{\mu_1}{x^2} \cdot \Big((b-a) r_1 \big(1 - e^{-\frac{x}{r_1}}\big) + aT_{pr} - (b-a) e^{-\frac{x}{r_1}} x\Big) \end{aligned} \tag{4.38}$$

where $a = R_1 P_{on}$ and $b = R_0 P_{of}$.

Since $e^{-\frac{T_p}{r_0}} \approx 1 - \frac{T_p}{r_0}$ when $T_p << r_0$, and $e^{-\frac{T_p}{r_1}} \approx 1 - \frac{T_p}{r_1}$ when $T_p << r_1$, (4.38) becomes

$$\frac{d\mathbb{E}\big(R\big)}{dT_p} \approx \mu_0 \cdot \Big(\frac{a-b}{r_0} + \frac{bT_{pr}}{x^2}\Big) + \mu_1 \cdot \Big(\frac{b-a}{r_1} + \frac{aT_{pr}}{x^2}\Big). \tag{4.39}$$

Since $\mu_0 = \frac{r_0}{r_0 + r_1}$ and $\mu_1 = 1 - \mu_0$, we can get the relation $\frac{r_0}{r_1} = \frac{\mu_0}{\mu_1}$. According to [45], we set $r_0 = 3\mu_0$ and $r_1 = 3\mu_1$ in the simulation. Then (4.39) becomes

$$\frac{d\mathbb{E}(R)}{dT_p} \approx \frac{(\mu_0 b + \mu_1 a)T_{pr}}{x^2} > 0 \tag{4.40}$$

which proves *Theorem 1*.

According to *Theorem 1*, the objective function $\mathbf{C}(T_p)$ should achieve its maximum value at the maximum feasible value of T_p, that is $0.2r_0$ or $0.2r_1$.

4.4 Numerical Results

In the previous sections, we studied the proposed DYWAMIT algorithm. Numerical results are presented in this section to illustrate the performance of the algorithm. The parameters used in the evaluation are listed in Table 4.3. Note that T_{sh} in the following table represents the transmission time of one SU's broadcasting frame. The more the SUs, the longer the total information sharing state time T_{is}. T_{RTS} and T_{CTS} are determined by the lengths of RTS and CTS frames divided by the system's data rate, here we use $T_{\text{RTS}} = T_{\text{CTS}} = 24$ μs. The time interval of SIFS is emplyed from IEEE 802.11a [51].

TABLE 4.3
NUMERICAL PARAMETERS FOR PERFORMANCE EVALUATION

Parameter	Value	Description
J	30	Number of primary channels
T_s	1 ms	Sensing time of each channel
λ	100 kHz	Sampling rate
SNR_p	-10 dB	SNR of primary signal received by SUs
SNR_s	10 dB	SNR of secondary signal received by SUs
T_{sh}	0.1 ms	Transmission time of one SU's broadcasting frame
T_{RTS}	24 μs	Transmission time of RTS frame
T_{CTS}	24 μs	Transmission time of CTS frame
SIFS	16 μs	Time interval for short interframe space

4.4.1 Average Number of Sensed Idle Channels

Fig. 4.10 shows the average number of idle channels sensed by $M = 10$ cooperative SUs versus the spectrum utilization of primary channels μ_1 (from

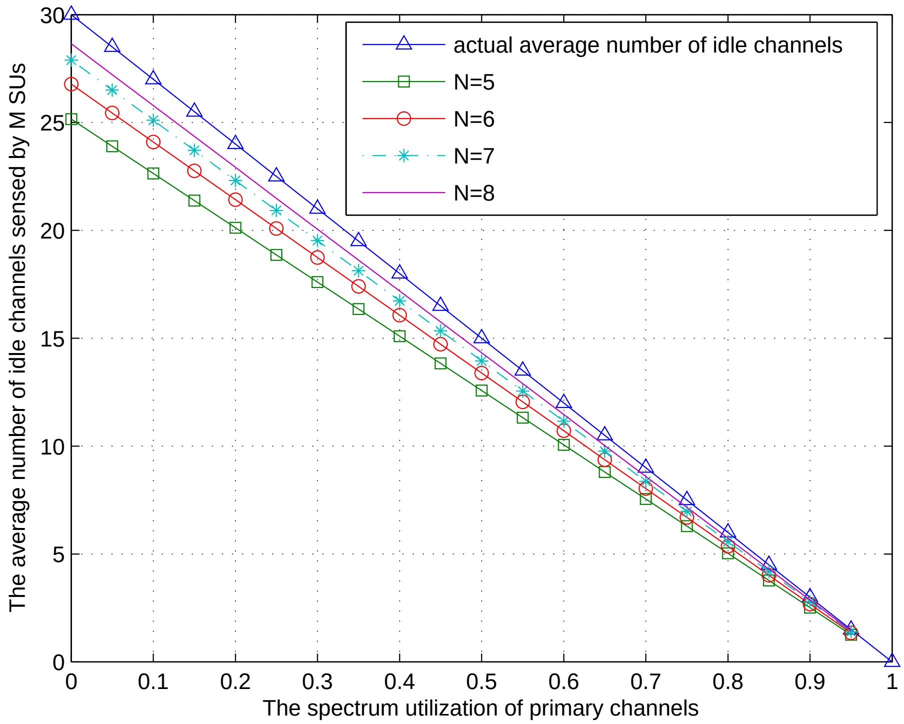

Figure 4.10. The average number of idle channels sensed by $M = 10$ SUs for different numbers of primary channels sensed by one SU, N.

0 to 1) for different numbers of channels sensed by one SU, N, with the total number of primary channels, $J = 30$. The average number of sensed idle channels decreases linearly with the increase of μ_1. This is expected, since as μ_1 increases, the total number of idle channels decreases. Since the SUs only sense parts of primary channels, the average number of idle channels sensed by them is always less than the actual number of idle channels. And since as N increases, the total number of channels sensed by the M SUs also increases, the average number of idle channels sensed by them also increases and is closer to the actual number of idle primary channels. For example, when $\mu_1 = 0.4$, the average numbers of sensed idle channels with $N = 5$, 6, 7 and 8 channels are 15.1, 16.1, 16.7 and 17.2, respectively, while the actual number of idle channels is 18. Although each SU only senses a very limited number of primary channels (from 5 channels to 8 channels) compared with the total number of primary channels (30 channels), all the SUs can know the presence of most idle channels through information sharing.

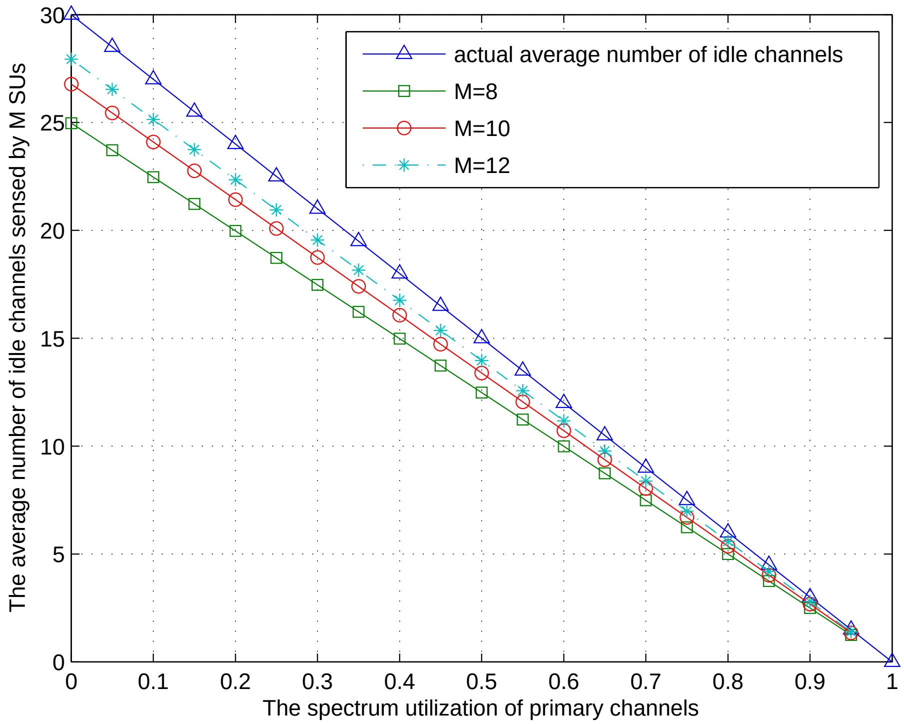

Figure 4.11. The average number of idle channels sensed by different numbers of cooperative SUs, M, when $N = 6$ channels are sensed by one SU.

Fig. 4.11 shows the average number of idle channels sensed by different numbers of cooperative SUs, M, versus the spectrum utilization of primary channels μ_1 when $N = 6$ channels are sensed by one SU with the total number of primary channels $J = 30$. As M increases, the total number of sensed idle channels also increases. This is expected, because the total number of channels sensed by the SUs increases, as M increases. For example, when $\mu_1 = 0.4$, the average numbers of idle channels sensed by $M = 8$, 10 and 12 SUs are 15.0, 16.1 and 16.8, respectively.

4.4.2 Maximized Average Throughput of SUs

Fig. 4.12 shows the maximized average throughput of $M = 2$ SUs versus the spectrum utilization of primary channels, μ_1, for different numbers of primary channels sensed by one SU, N, with the total number of primary channels, $J = 30$, and $\frac{Y_{th}}{\sigma^2} = 1.05$. From Fig. 4.12, we get that as μ_1 increases, the maximized average throughput decreases. This is expected, since as μ_1 gets

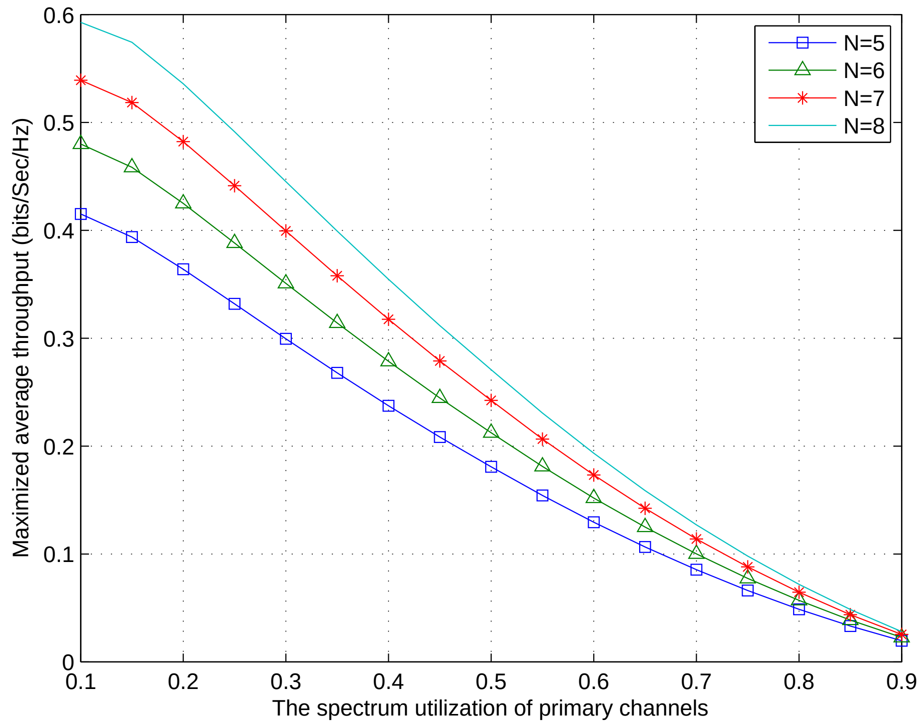

Figure 4.12. The maximized average throughput of $M = 2$ SUs versus μ_1, for different values of N, with $\frac{Y_{th}}{\sigma^2} = 1.05$.

larger, the number of idle channels which can be utilized by the SUs decreases. What's more, as N increases, the total number of sensed idle channels by $M = 2$ SUs also increases, which leads to an increase of the SUs' maximized average throughput.

Fig. 4.13 shows the M SUs' maximized average throughput versus the number of cooperative SUs M, for different numbers of primary channels sensed by one SU, N, with the spectrum utilization of primary channels, $\mu_1 = 0.5$, and $\frac{Y_{th}}{\sigma^2} = 1.05$. Since more cooperative SUs can not only help decrease the false alarm probability, but also increase the total number of sensed idle channels, the SUs' average throughput keeps increasing with an increasing number of SUs. In addition, the SUs' maximized average throughput also increases as N increases, which is consistent with the results in Fig. 4.12, for different values of M.

Fig. 4.14 shows the SUs' maximized average throughput versus the number of cooperative SUs, M, for different values of $\frac{Y_{th}}{\sigma^2}$, with the spectrum utilization

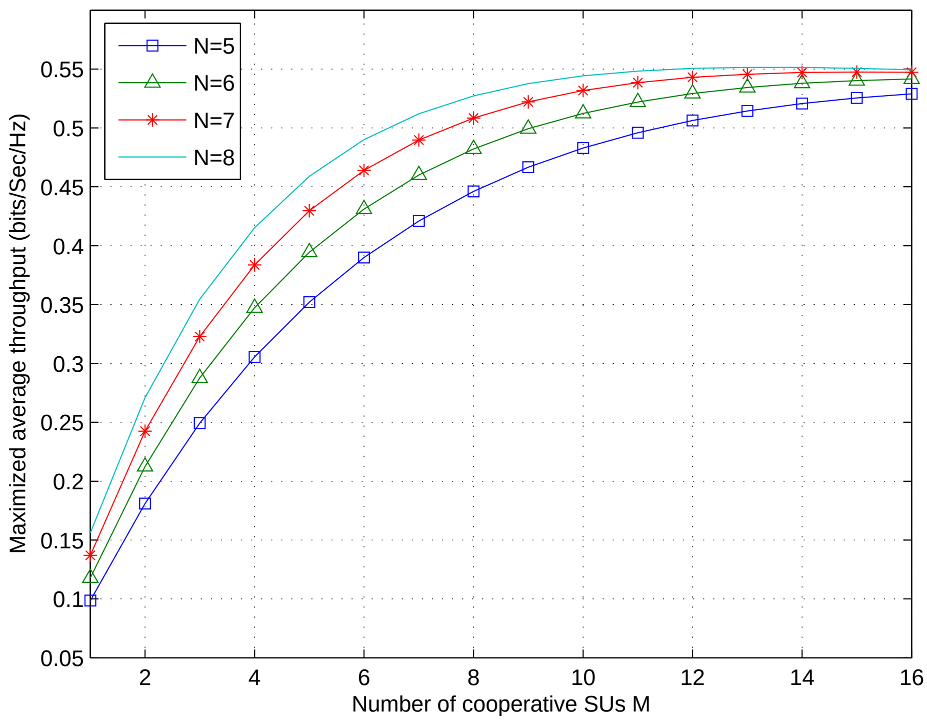

Figure 4.13. The SUs' maximized average throughput versus M, for different values of N, with $\mu_1 = 0.5$, $\frac{Y_{th}}{\sigma^2} = 1.05$.

of primary channels, $\mu_1 = 0.5$, and the number of primary channels sensed by one SU, $N = 6$. As $\frac{Y_{th}}{\sigma^2}$ increases, the SUs' false alarm probability P_f decrease, which means that they have more opportunities to discover available idle channels leading to their increasing throughput.

These observations provide important practical guidelines for designing different desired parameters, such as the number of SUs, the channel utilization of PUs, etc., for cognitive radio wireless networks.

4.5 Applications of asynchronous spectrum sensing and access

In this section, we describe some application scenarios for the asynchronous spectrum sensing and access in both civilian and military sectors, including cognitive WiFi and cognitive urban sensor networks and cognitive tactical networks.

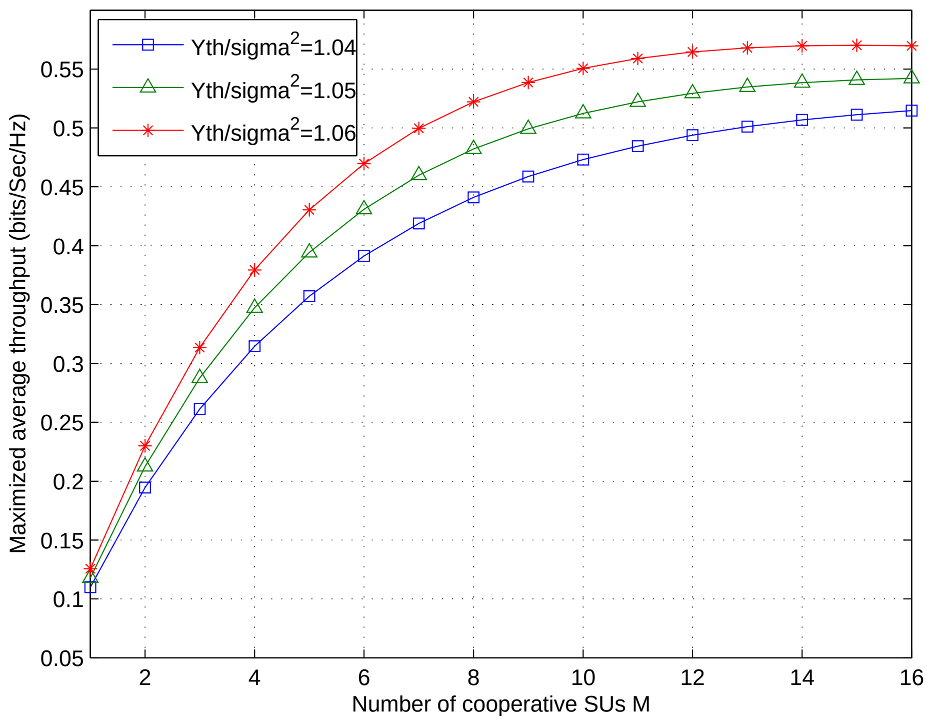

Figure 4.14. The SUs' maximized average throughput versus M, for different values of $\frac{Y_{th}}{\sigma^2}$, with $\mu_1 = 0.5$, $N = 6$.

4.5.1 Cognitive WiFi

Current WiFi technology is working on the unlicensed 2.4 GHz band. As the unlicensed bands are becoming more and more crowded, researchers have begun to study the cognitive solutions so that WiFi can work as SUs on the licensed spectrums [53]. It is important to recognize that different countries have various, differing regulations regarding the usage of different licensed spectrums, which makes the synchronization with the communication systems on the licensed spectrums extremely challenging. Therefore, an asynchronous cognitive WiFi solution becomes more adaptive and practical. The schemes discussed in this thesis can be directly adopted in such asynchronous cognitive WiFi systems. First, the proposed asynchronous spectrum sensing schemes can supplement the traditional CSMA/CA protocol by dynamically controlling the length of total carrier sensing time, and the carrier sensing time of each primary channel. Second, the proposed asynchronous spectrum access mechanism provides a distributed MAC-layer protocol, which can substitute for the traditional contention-window based protocol in current WiFi technology. Hence, enabled by our proposed schemes, the asynchronous cognitive WiFi technology will be a promising application in the near future.

4.5.2 Cognitive urban sensor networks

Urban pollution in developing countries has become increasingly severe with the fast urbanization process and rapid economic growth. For instance, Beijing, one of the largest cities in China, suffered from 124 heavy-fog days during the year 2012. Recently, authors in [54] designed an urban mobile sensor network, called "CabSense", which is a taxi-based mobile sensing system to create detailed pollution maps for urban areas. During the deployment of the "CabSense" system, one of the most restrictive problems was the scarce unlicensed spectrum resources. This problem is acute especially in metropolitan areas with extremely high population and building densities, such as Beijing. In such a case, enabling the urban sensor network with cognitive radio functionality will be an ideal solution. However, based on the field investigation at Beijing, it is extremely difficult for the urban mobile sensing systems (acting as SUs) to synchronize with the PUs (e.g., TV bands) due to the high mobility of the system and the high dynamics of spectrum environment in such high-density cities. Therefore, the asynchronous spectrum sensing and access schemes proposed in this thesis can better integrate into the cognitive urban sensor network.

4.5.3 Cognitive tactical networks

In the military sector, the concept of tactical networks emerges as a real-time media to exchange information among commanders, soldiers and military equipments. The tactical network is characterized by high dynamics, hierarchical structure and heterogeneity of radio communications. Current research shows that future tactical networks also require cognitive functions across the protocol stack to exploit scarce spectrum and dynamically adaptation functions and configuration settings [55]. The existing synchronous spectrum sensing and access schemes require synchronization among all the tactical network elements, which is contrary to the basic features of tactical networks. Under the complex battlefield radio environment, the asynchronous solutions would be highly favorable. The proposed asynchronous spectrum sensing and access framework in this article can be well adopted to model the cognitive tactical network. One open issue is that the hierarchical structure should be taken into account when designing the asynchronous cognitive tactical network.

4.6 Summary

In this chapter, we proposed a contention-based asynchronous wideband dynamic spectrum access algorithm, called DYWAMIT. In particular, with this scheme, the SUs need not synchronize with the PUs when dynamically accessing primary channels. We studied the problems of how to conduct competitions between SUs and how to determine the number of contention slots and the sensing period. For the sensing state, the average number of sensed idle channels was analyzed and simulated. For the contention state, the relationship between the number of successful SUs and the number of contention slots was investigated and quiescent points for different numbers of SUs were determined. Furthermore, a constrained optimization problem maximizing the SUs' average throughput was formulated to achieve the optimal sensing period. These results will be of particular interest when implementing practical cognitive radio networks. Finally, some application scenarios for the asynchronous spectrum sensing and access in both civilian and military sectors were described.

Chapter 5

Conclusion and Future Research Directions

5.1 Conclusion

Motivated by the need and importance of asynchronous spectrum sensing in cognitive radio networks, we proposed a novel asynchronous cooperative spectrum sensing (CSS) scheme and an asynchronous wideband dynamic spectrum access (DSA) algorithm. In Chapter 3, an asynchronous CSS scheme was presented, which no longer requires SUs to synchronize with the PU, enabling the SUs to cognitively and asynchronously access primary channels even without knowing the communication protocols of the PU. Subsequently, we derived the average available opportunistic throughput capacity of the secondary network for four cases of interest, accounting for the asynchronism between the SUs and the PU. Furthermore, we formulated the scheme as an optimization of the sensing period, in which we optimized the average secondary network opportunistic throughput capacity within a constrained sensing period range.

Extending the results in Chapter 3, which only targeted at single-band (narrowband) sensing, a contention-based asynchronous wideband DSA algorithm was presented in Chapter 4. More specifically, a state transition diagram was constructed to describe one SU's activities during one sensing period. In the sensing state, all the SUs cooperatively sense the channels in order to enhance the detection probability and then exchange the sensing results in the sharing state. In order to avoid spectrum waste, the intended SUs compete for available channels among each other through RTS/CTS in the contention state followed by a transmission state. In line with evaluating the performance of the proposed algorithm, the average number of sensed idle channels by the SUs was analyzed, the relationship between the number of successful SUs and the number of contention slots were all investigated; quiescent points for different numbers of SUs were determined. Furthermore, a constrained optimization problem maximizing the SUs' average throughput was formulated to achieve the optimal sensing period and the objective function was proved to be nondecreasing in the constrained region. The effectiveness of the proposed algorithm was also confirmed through numerical simulations. This research can provide helpful insights into the MAC protocol design in cognitive radio networks. Finally, some application scenarios for the asynchronous spectrum sensing and access in both civilian and military sectors were described.

In summary, this work presented an asynchronous CSS scheme and an asynchronous wideband DSA algorithm, each suitable for specific applications.

5.2 Future Research Directions

Since it represents a fundamental study on designing asynchronous spectrum sensing and access frameworks, this work can be extended (or can be considered as a basis for other studies) in several ways, a number of which are stated below.

1) In this thesis, the average SNR of the primary signals received by the SUs, SNR_p, are determined through making the detection probability and false alarm probability in a rational region, and is constant. Since SNR depends on the channel model, we can modify the SNR model and consider the Rayleigh fading channel model. On the other hand, we can investigate further about the relationship between the SUs' average throughput, the detection threshold P_d^{th}, and the related system parameters.

2) In this study, it was assumed that all the primary channels have the same spectrum utilization μ_1. This assumption facilitates the analysis. However, diversity channel situations exist in practical cognitive radio networks. So considering different values of spectrum utilization for different primary channels could be considered as an another potential research direction.

3) In this research, it was assumed that one SU randomly chooses N channels from J primary channels. This assumption also facilitates the analysis. However, on one hand, based on the research direction in 2), another possible

potential research direction is to choose the N channels that enjoy the smallest spectrum utilizations μ_1, not randomly, to increase the secondary transmission opportunities. However, on the other hand, N channels may not be necessary in some situations. In line with this, one can minimize the required number of channels-to-sense while constraining the secondary opportunistic throughput loss.

4) In our problem formulation in Subsection 4.3.3, the determination of the number of contention slots in Subsection 4.3.2 may lead to some performance loss. Another interesting topic is to jointly consider the sensing period and the number of contention slots as optimization variables. The solution of this optimization problem is an important issue for further research.

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