Narrowband Cooperative Spectrum Sensing in Cognitive Networks

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Abstract

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Qingjiao Song

With the increase of different types of wireless devices, the radio frequency (RF) spectrum will not longer large enough to accommodate these increased devices for communication in the future under the traditional fixed spectrum access (FSA) policy. Therefore, cognitive radio (CR), which provides devices flexible spectrum access, has been proposed to solve this scarcity problem in RF spectrum. The ability of CR depends largely on its spectrum sensing since it provides device access to one spectrum band while avoiding interference to other devices. However, the results from single spectrum sensing is not reliable in real communication condition due to various fading effects. Thus, designing an efficient cooperative spectrum sensing scheme a significant task.

In this thesis, two cooperative narrowed spectrum sensing schemes, multi-selective cooperation and selective-cooperation, will be proposed. Multi-selective cooperation, an improved version from selection combining (SC), is based on ordered statistics of the reporting links between the cooperative nodes and fusion center where the links with high signal-to-noise ratios (SNRs) are selected as reliable reporting links. Furthermore, we examine the optimum *N-out-of-K* rule of our scheme under different detection threshold and SNR. Another new scheme, selective-cooperation, is proposed based on multi-selective cooperation and it selects the links, whose SNRs are larger than fusion center's, as reliable reporting links. The performance of both new schemes are compared to other existing schemes in-terms of the probability of detection and probability of false alarm over independent identity distributed (i.i.d) and independent non-identical distributed (i.n.d) Rayleigh fading channels. Both simulations and analytical results show that the multi-selective scheme outperforms some traditional schemes, i.e selection combining, general *N-out-of-K* rule and square-law selection (SLS) under different system parameters. Simulations and analytical results also show that the performance of the selective-cooperation scheme gets further improvement compared with multi-selective scheme and it outperforms some traditional schemes, i.e. square-law combining (SLC), under different communication environments.

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Qingjiao Song

To my parents and my family for their love and great support

Contents

List of Figures

Nomenclature

χ^2_{2q}	A central chi-square (χ^2) distribution with $2q$ degrees of freedom [6]
$\chi^2_{2q}(2\gamma)$	A noncentral chi-square (χ^2) distribution with $2q$ degrees of freedom and a non centrality parameter 2γ [6]
$\delta(dB)$	Standard deviation of $10log_{10}\omega$
η	The Nakagami parameter
γ	Signal-to-noise ratio
$\Gamma(.)$	Gamma function
$\Gamma(.,.)$	Incomplete gamma function
$\gamma^{(k)}$	The signal-to-noise ratio in k_{th} in the U set
λ	Detection threshold
$\overline{\gamma}$	The average of signal-to-noise ration
$\overline{P_{d}}^{(j)}_{(PD=h)}$	The average of probability of detection of $f^{(j)}_{PD=h}$
$\overline{P_d}^{(k)}$	The average of probability of detection of $f^{(k)}$
$\overline{P_d}^{(z_1,z_2\ldots,z_N)}$	The average of probability of detection of $f^{(z_1,z_2\ldots,z_N)}$
$\overline{P_{d}}^{(i,j)}_{(PD=h)}$	The average of joint probability of detection of $f^{(i,j)}_{PD=h}$
ϱ	The Rician parameter

ζ	Channel gain
$a(t)$	the additive white Gaussian noise (AWGN)
$d(t)$	Received signal at the energy detection system
e^x	Exponential function
E_s	Primary signal energy
$F(x)$	Cumulative distribution function of x
$f(x)$	Probability density function of x
$f^{(k)}$	Probability density function of the signal-to-noise ratio in k_{th} in the U set
$f^{(z_1,z_2...,z_N)}$	Joint probability density function of any N signal-to-noise ratios in the S_K set
$f^{(i,j)}_{PD=h}$	Joint probability density function of i_{th}, j_{th} signal-to-noise ratios in the S_h set under the condition that P-D link's signal-to-noise ratio in h_{th}
$f^{(j)}_{PD=h}$	Probability density function of signal-to-noise ratios in j_{th} in the S_h set under the condition that P-D link's signal-to-noise ratio in h_{th}
H_0	Primary signal is absent
H_1	Primary signal is present
$I_v(.)$	The v_{th}-order modified Bessel function of the first kind
K	Multi-selective scheme selects K links as report links
K_{opt}	Optimal K in multi-selective scheme given total error bound
L	The number of links in cognitive network including the links from primary user to relays and link from primary user to destination
N	Among K report links, final decision is made when N or more links make consistent local decisions

N_{01}	AWGN one-sided power spectral density
N_K^{opt}	Optimal N for each given K in multi-selective scheme
P_d	Probability of detection
P_f	Probability of false alarm
P_h	The overall probability of detection in S_h set
P_m	Probability of miss detection
P_{common}^N	The sum of the average of probability of detection of any N signal-to-noise ratios in the S_K set
$P_{common}^{PD=h}$	The sum of all joint probability of detection in the S_h set
q	Time bandwidth product
$Q_q(.,.)$	The q_{th}-order generalized Marcum-Q function
R_{L,τ,x_1}	A set of all combinations of $L-\tau$ indices chosen from the different set $\{1,2,...L\}-\{x_1\}$
$s(t)$	Primary signal
S_h	Sub-set of U in selective-cooperation scheme
S_K	Sub-set of U in multi-selective scheme
T	Observation interval time
U	Strictly decreasing set of L links' SNRs after ordering
V	Decision statistic at the energy detection system
V'	Normalized decision statistic
W	Signal bandwidth

Chapter 1

Introduction

This thesis focuses on the cooperative spectrum sensing in narrow-band in the cognitive radio networks. Cognitive radio, a flexible spectrum assignment technique, has already been proposed to enhance the efficiency of spectral utilization in cellular networks because of the intension of current spectral utilization. Spectrum sensing is a crucial portion in cognitive radio that enables users in such networks, also called secondary users, to utilize some spectrum holes while refraining from making interference to primary users in cellular networks. Many works have been studied in spectrum sensing schemes under independent identical distributed (i.i.d) fading channels currently, but few of them are related to spectrum sensing schemes under independent non-identical distributed (i.n.d) fading channels. Thus, this thesis will propose two new spectrum sensing schemes (selective-cooperation spectrum sensing, and multi-selective cooperation spectrum sensing) by using order-statistics to improve spectrum sensing performance, then analyze these two schemes over i.i.d and i.n.d conditions. Both schemes have better spectrum sensing performance than some current spectrum sensing schemes.

1.1 Motivation

The precious radio frequency (RF) spectrum is allocated by government spectrum regulators. In order to support various types of wireless devices and different kinds of services without interfering, spectrum regulators adopt a traditional fixed spectrum access (FSA) policy, which assigns each band of RF spectrum with particular bandwidth to wireless primary users. However, with the increase of new wireless products, especially the widely usage of machine-to-machine products [8] in the future, the spectrum demand is constantly increasing while, in several counties, most of the available spectrum has been fully utilized, which evidently shows that spectral resource will no longer be enough for new wireless products by using FSA police. On the other hand, a primary user is wasting its allocated spectrum when it is assigned a certain spectrum, but actually unused it. Recent researches on the measurements of actual spectrum utilization in Fig. 1.1 also have shown that only some portions of the whole spectrum have been highly used while large portions of them are severely under-utilized. For instance, the spectrum between 30 MHz and 3 GHz in New York, the maximal occupancy has been measured to be 13.1%, while the average occupancy from six locations is 5.2% [9].

To resolve the spectral scarcity problem mentioned above, cognitive radio (CR) is proposed to advance spectral usage [10]. The federal communications commission (FCC) allows secondary user (SU) to enter into one spectrum band when the primary user (PU) does not use its band after adopting CR techniques [1]. As Fig. 1.2 shows, cognitive radio is designed to sense, detect surrounding PUs' state: 1) when PU is absent, SU reuses PUs' spectrum hole. 2) when PU is present, SU retreats from the PU spectrum hole. Thus, spectrum sensing is a critical part for a SU operation since all other SU's activities depend on the sensing result. Up to now, researchers have developed several local techniques to improve spectrum sensing performance [11–13]. However, these local techniques are not always reliable and can not provide a satisfactory detection performance when multipath and shadowing effects exist [14]. In many other wireless networks, relays have been introduced to solve the multipath and shadowing effects [15], [16]. In this front, cooperative spectrum sensing techniques are presented to mitigate multipath and shadowing effects efficiently in CR because of the increase of spatial diversity in CR [17–22]. Currently numerous cooperative spectrum sensing schemes have been designed over i.i.d fading channels [11–14, 21, 23–27]. But i.i.d is an ideal communication condition that relays are assumed to be nearby to each other, few of these works consider the performance of cognitive network over i.n.d fading channels. In practice, i.i.d condition turns into i.n.d condition when relays are far away from each other as in heterogeneous networks. In [28] and [29], i.n.d fading channels are analyzed in cooperative spectrum sensing by combining all relay links' SNRs in probability of detection calculation, regardless of the relay link's condition. In fact, the performance can be improved if a relay link's condition is taken into consideration. In recent work [30] [31] and [32], order-statistics is introduced to spectrum sensing in SU over i.i.d fading channels in detection threshold. However, order-statistics have not been considered as a method to access the comparison of relay's condition over i.n.d fading channels. Besides, designers of a cooperative spectrum sensing scheme should consider bandwidth usage for sharing the spectrum sensing data while improving spectrum sensing performance.

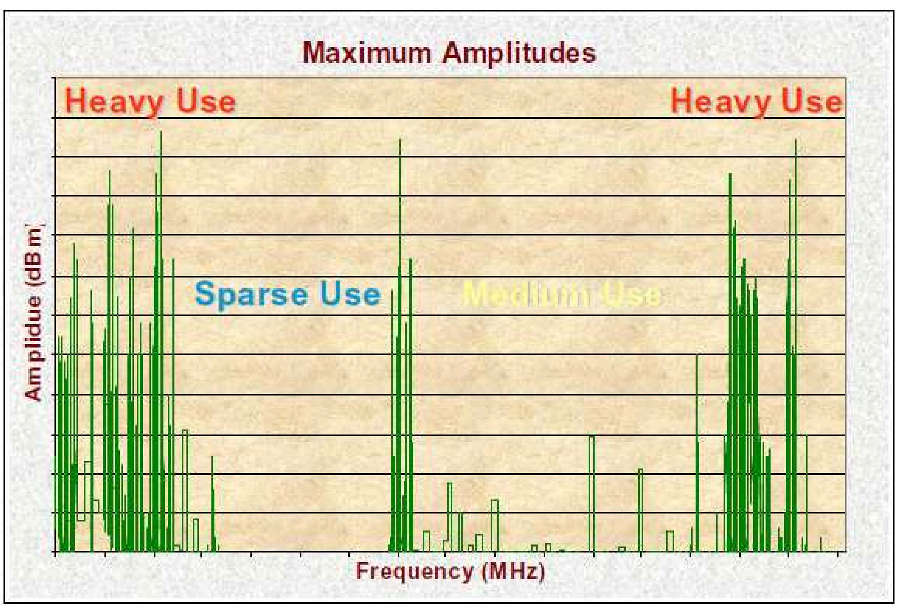

Figure 1.1: Spectrum allocation and spectrum usage measured from [1]

1.2 Objectives and Contributions

1.2.1 Objectives

The aim of this thesis is to analyze the performances of some current cooperative spectrum sensing schemes and propose two novel cooperative spectrum sensing schemes which further improve the detection performance of spectrum sensing. More specifically, the thesis has the following objectives:

To analyze the detection performances of some current cooperative spectrum sensing schemes over i.i.d fading channels and i.n.d fading channels.

To propose two novel cooperative spectrum sensing schemes, multi-selective cooperation and selective cooperation, based on a balance between accuracy of spectrum detection and bandwidth usage for sharing the spectrum sensing data. These two schemes spectrum sensing performances are further improved by the introduction of order-statistics in the comparison of relay's condition.

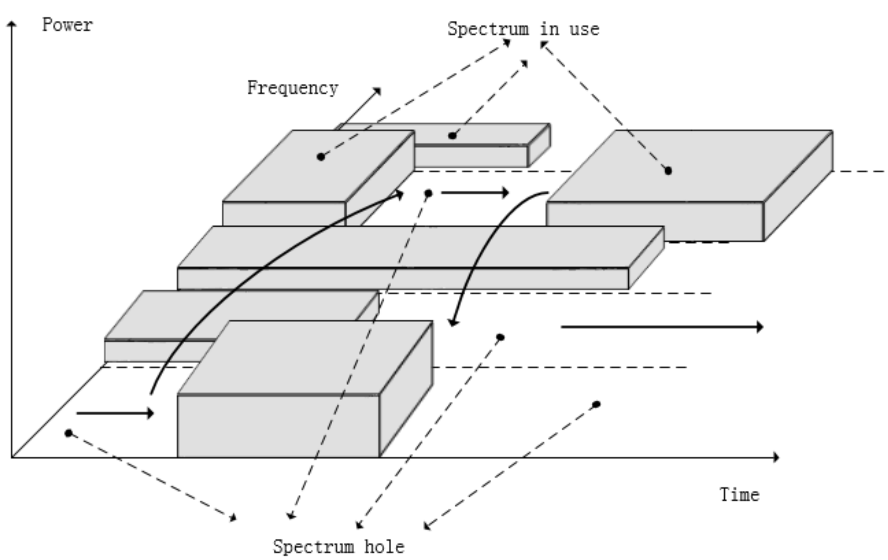

Figure 1.2: The concept of how to access spectrum hole dynamically [2]

1.2.2 Key Contributions

The main contributions of this thesis can be summarized as follows:

Expressions of the probability of detection over i.n.d Rayleigh fading channels are derived under different cooperative energy detection schemes, i.e. selective combining (SC) [6], square-law combining (SLC) [7], and square-law selection (SLS) [7]. The detection performances are simulated and analyzed under different cooperative energy detection schemes.

A new cooperative energy detection scheme, named multi-selective cooperation which is an improved version from SC, is proposed in this thesis. The probability expressions of detection of the multi-selective scheme are deduced over both i.i.d and i.n.d Rayleigh fading channels. Selective-cooperation theoretical performance applied by these expressions matches well with simulations. For achieving best performance, optimization analysis of the multi-selective scheme is also proposed. Simulation and theoretical results show the proposed multi-selective scheme offers much improvement in detection compared with SC over both i.i.d and i.n.d Rayleigh fading channels. Also, its performance is better than SLS performance over these channels. Since our proposed scheme uses *N-out-of-K* rule, it also help to reduce bandwidth consumption.

Another new cooperative energy detection scheme, named selective-cooperation, is proposed in this thesis. The expressions of energy detection of selective cooperation are derived over both i.i.d and i.n.d Rayleigh fading condition. Selective-cooperation theoretical performance is analyzed and shown to be in good agreement with simulations. Compared with SLC, SLS and SC, our proposed scheme has three advantages: 1) better energy detection performance in low signal-noise-radio (SNR); 2) requiring few cooperative relays to achieve accurate spectrum sensing; 3) saving bandwidth for sharing the spectrum sensing data.

To best of our knowledge, it is the first time to adopt order-statistics for relay's condition comparison in the cooperative spectrum over i.n.d fading channels.

1.3 Thesis Outline

Other remaining chapters of this thesis are organized as follows:

Chapter 2

This chapter introduces the capabilities and tasks of cognitive radios. Then, some traditional spectrum sensing schemes and classification method of cooperative spectrum sensing schemes from literatures are presented.

Chapter 3

This chapter introduces the structure of energy detection and its performance over Rayleigh, Nakagami, Rician and shadowedd fading channels, respectively. The probability expressions of false alarm and detection of some current cooperative schemes, i.e. SC, SLC and SLS, over both i.i.d and i.n.d Rayleigh fading channels are then introduced. The detection performance of these cooperative schemes is analyzed over both i.i.d and i.n.d.

Chapter 4

This chapter proposes our multi-selective scheme. The proposed scheme's mechanism is presented and the probability expressions of false alarm and detection of multi-selective scheme will then be derived over both i.i.d and i.n.d Rayleigh fading channels. The comparison between multi-selective scheme and other current schemes is presented and analyzed later. For the detection performance improvement, the optimization of the multi-selective scheme are discussed over i.i.d and i.n.d Rayleigh fading channels.

Chapter 5

This chapter proposes a second selective-cooperation scheme. The schemes mechanism is presented and the probability expressions of false alarm and detection of the multi-selective scheme will then be derived over both i.i.d and i.n.d Rayleigh fading channels. The detection performance comparison between SC, SLC, SLS and selective-cooperation is presented.

Chapter 2

Literature Review

Cognitive radio technology offers opportunistic access to a PU's spectrum band that is unused temporarily, and avoids interference to PU when PU reuses the spectrum [1, 3, 4, 10, 33–36]. In this chapter, we present the background of cognitive radio to see how it works in detail firstly. Since spectrum sensing is a crucial portion in its network, the local spectrum sensing techniques' introduction will be presented later. Due to the severe effects of multi-path fading and shadowing, sensing results from local secondary user are not precise anymore. Therefore, cooperative spectrum sensing techniques are introduced for robust detection [21, 23, 24].

In this chapter, Section 2.1 presents the capabilities and tasks of cognitive radios. Section 2.2 presents a review the development of spectrum sensing schemes. This section first introduces single spectrum sensing techniques, and then generally presents the classification method of cooperative spectrum sensing schemes.

2.1 Cognitive Radio

Cognitive radio is proposed by J.Mitola III in [10] firstly, and later officially defined as [37]:

A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with environment in which it operates.

Two major features in cognitive radio are extracted according to the definition above: Cognitive capability and reconfigurability [1].

- Cognitive capability: One cognitive radio senses an unused spectrum in the surroundings, then smartly selects optimal spectrum and appropriate parameters to access this spectrum via cognitive capability. This process can be described as a cycle with three main operations: spectrum sensing, spectrum analysis and spectrum decision [1], as Fig.2.1 shows.

  Spectrum sensing: In cognitive network, one cognitive radio captures some information from spectrum bands seeking for available spectrum holes. Also, the cognitive radio should keep monitoring spectrum bands and retreat from these holes when primary users want to reuse their spectrum.

  Spectrum analysis: The surrounding spectrum bands' characteristics are extracted and estimated from the information captured via spectrum sensing.

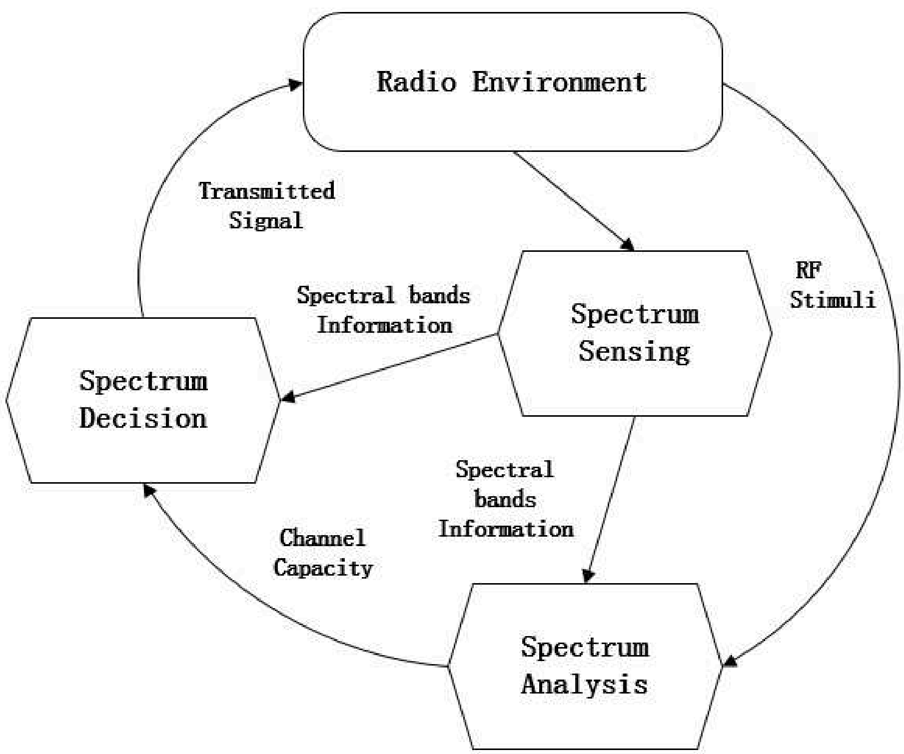

Figure 2.1: The process of cognitive radio described as a cognitive cycle [1]

Spectrum decision: An optimal spectrum hole is chosen for SU transmission according to the results from the spectrum analysis operation. Meanwhile, the cognitive radio will also intelligently choose suitable parameters, e.g., transmission mode , data rate, and bandwidth needed in transmission, for transmission in current communication environment.

- Reconfigurability: reconfigurability is another characteristic of cognitive radio enabling cognitive radio changes its parameters to adapt to a dynamic communication environment [1]. Some parameters introduced in the following are considered mostly in cognitive network.

  Operating frequency: It is available for cognitive radio to change the operating frequency for optimal transmission in a dynamic environment and protecting PU activity.

  Modulation: In order to adapt to SU's transmission requirements and channel conditions, a cognitive radio is available to adjust its modulation scheme.

  Transmission power: For the mitigation of interference and power efficiency enhancement, cognitive radio allows power reconfiguration based on power constraint or limit required in the networks.

  Communication technology: In heterogeneous networks, cognitive radio will adjust itself and be used in different types of communication systems with its interoperability .

2.2 Spectrum Sensing Techniques

In this section, we focus on the spectrum sensing techniques introduction because most of the functions in the cognitive radio are relied on spectrum sensing. Currently, spectrum sensing schemes are divided into two categories: narrowband spectrum sensing and wideband spectrum sensing. Since this thesis focuses on narrowband spectrum sensing schemes, these schemes are introduced in detail in the following. Narrowband spectrum sensing schemes are classified as shown in Fig.2.2. Most of the spectrum sensing schemes are aimed to detecting a active PU transmitter nearby the cognitive radio [33]. Among transmitter detection schemes, three classical schemes are introduced: matched filtering detection [38] [39], energy detection [13, 35, 40, 41] and cyclostationary feature detection [12].

Because of multipath fading, shadowing and the hidden terminal problem [1], detection in spectrum sensing may be significantly affected. Thus, researchers have proposed cooperative spectrum sensing techniques to weaken these effects [3] [4].

2.2.1 Classical Spectrum Sensing

In this section, three classical spectrum sensing schemes are introduced. Generally, the performances of these three schemes depend largely on communication surroundings.

Matched Filter Detection

The optimal detection about additive noise's status is matched filter detection if cognitive radio has PU signal's information because this detection maximises signal-to-noise ratio (SNR)[38] [39]. Also, matched filter detection reduces observation time by coherent detection. The structure of a matched filter detection is present in Fig.2.3. But coherent detection requires a prior information about the PU signal, e.g. pulse shape, packet format and modulation type, as a template for correlating with received signal and also needs carrier

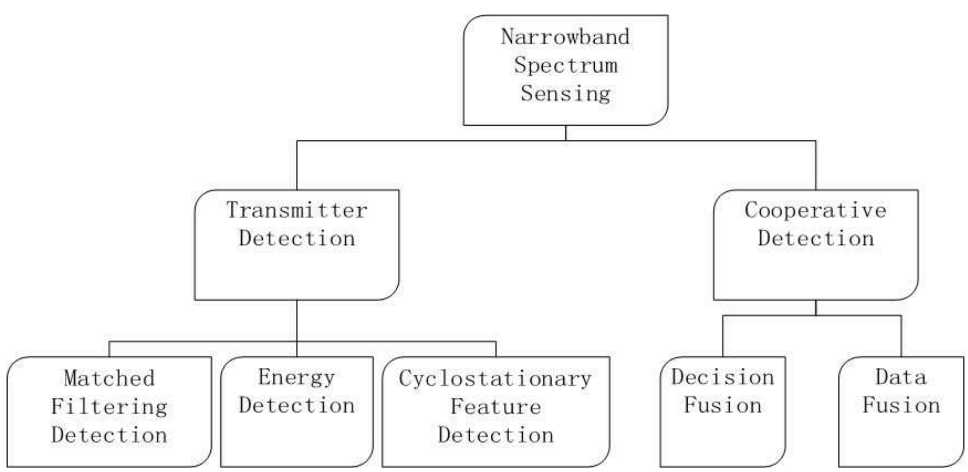

Figure 2.2: The classification of narrowband spectrum sensing schemes [3]

synchronisation and timing devices for signal processing. Thus, matched filter detection is more complexity compared with other classical detection schemes and it performs poorly when coherent detection knows few prior information obtained from PU's signal.

Energy Detection

Energy detection will be optimal detection schemes when secondary user does not have the information of PU signal [42]. Since energy detection adopts non-coherent detection method, it does not require the complicated processing as matched filter detection requires. Fig.2.4 presents the structure of energy detection. Bandpass filter (BPF) first selects a centre frequency to receive signal from interested bandwidth [3] [43] [44] and then, the received signal is measured by a magnitude squaring device. Integrator, which controls the observation time, sums up all the received signals after squaring device measure during the observation time. Then the receiver compares the sum with predetermined threshold to estimate PU activity. Although energy detection can be performed without prior information obtained from PU's signal, and requires low implementation complexity, it performs poorly under low SNR conditions and cannot distinguish between signal of PU from signal of other secondary user. Also, noise level uncertainty results in energy detection poor performance since energy detection requires the knowledge of noise power.

Cyclostationary Feature Detection

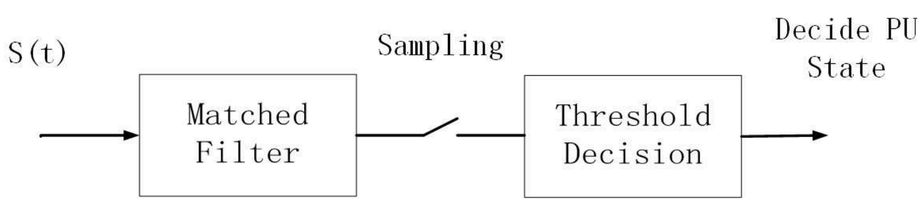

Figure 2.3: Spectrum sensing of matched filter [4]

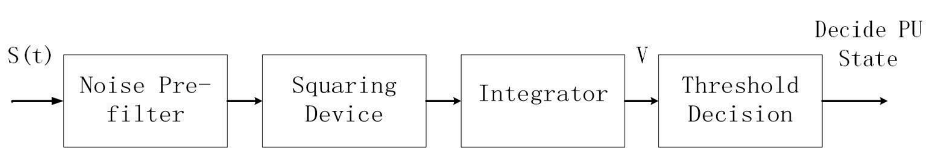

Figure 2.4: Spectrum sensing of energy detection [4]

Cyclostationary feature detection is proposed to overcome energy detection disadvantage where it cannot distinguish between different types of signals. Cyclostationary detection receiver detects the signal of PU via exploiting the cyclostationary features in the PU signal [38] [45]. A block diagram of cyclostationary feature detection is present in Fig.2.5. Mostly, PU transmitted signals are modulated signals, which are modulated by pulse train, cyclic prefixes, or repeating spreading. Because of these modulated signals' autocorrelation, they are regarded as cyclostationary. Cyclostationary feature detection adopts cyclic correlation function for detecting PU signal with a certain modulation type with additive noise. After obtaining partial information of the PU signal, cyclic correlation function can distinguish certain modulated PU signals from other modulated signals and noise because different types of modulated signals exploit different cyclic characteristics and wide-sense stationary additive noise has no correlation. However, there are two disadvantages in this detection technique. First, this detection technique requires partial information of the PU signal. Second, high cost of computation because of the introduction of cyclic correlation function.

2.2.2 Cooperative Spectrum Sensing

Since relays help networks increase spatial diversity [46] [47], cooperative spectrum sensing mitigates shadowing and hidden terminal problem effects. For example, in a distributed network as shown Fig.2.6, each SU observes PU activity independently, and forwards its received data or local decision to the SU, also regarded as destination. The destination is the SU who wants to utilize PU spectrum through report channel. Then the destination combines all the data or local decisions from other secondary users (relays) and its own received data or local decision to final decide on PU's activity. Up to now, researchers have designed several types of cooperative spectrum sensing schemes, i.e. *N-out-of-K* rule,

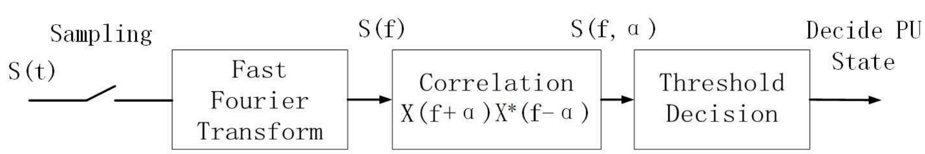

Figure 2.5: Spectrum sensing of cyclostationary feature detection [4]

maximal ratio combining (MRC) [48], square-law combining (SLC) [7], square-law selection (SLS) [7], and selection combining (SC) [6]. Based on the type of information transmitted in report channels, cooperative spectrum sensing schemes are classified into data fusion and decision fusion. Based on the methods to achieve cooperative sensing, cooperative spectrum sensing schemes have two models: parallel fusion model and game theoretical model.

Cooperation Fusion

Data Fusion: When secondary user relays received signal directly to destination without any further processing, the destination will receive these signal as reference when making final decision on PU status. If the destination knows well about the channel state information (CSI) between PU and the secondary users, MRC is the optimal scheme for spectrum sensing [49]. If the destination has partial CSI, which mostly considered as SNR in spectrum sensing case, between PU and the secondary users, selection combining is the best choice.

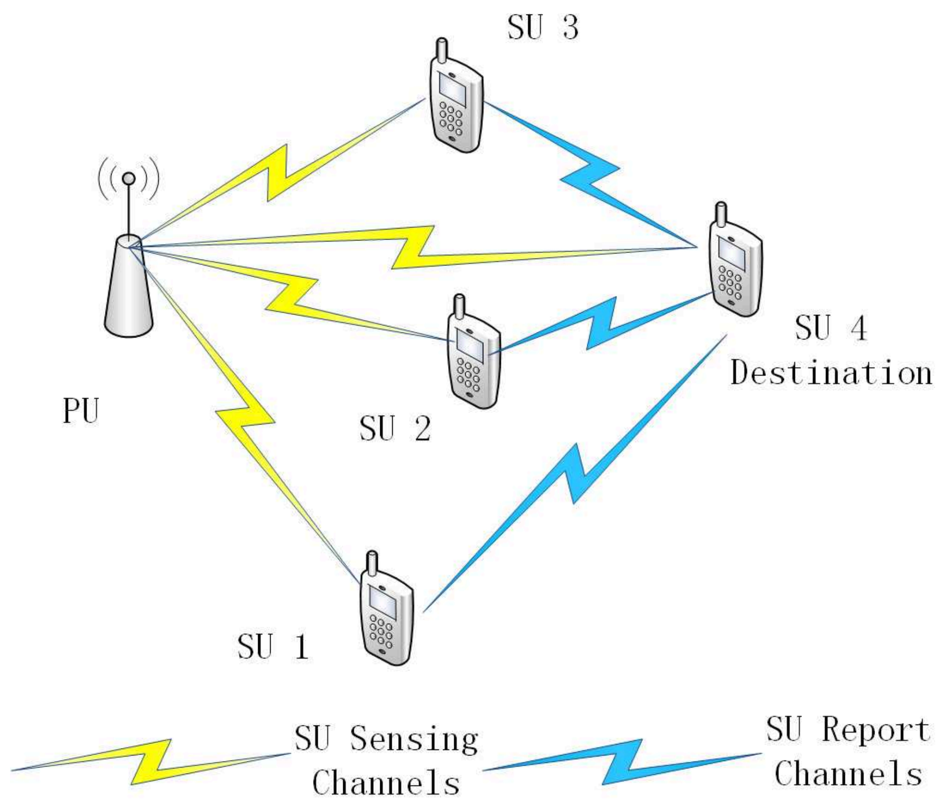

Figure 2.6: An example of distributed cognitive network. Destination makes final decision by combining other SUs' observed data or local decisions through report channels and its own observed data or local decision through sensing channel.

In practice, it is difficult to have perfect CSI at the destination, which makes MRC non-practical. When energy detection is employed in selection combining, each secondary user requires independently to send SNR and energy vectors to destination. This requires much bandwidth for report channels. Thus, SLC and SLS [6] [7] are proposed for bandwidth saving. In SLC and SLS schemes, secondary user only needs to send energy vector to destination, which saves nearly half of the bandwidth compared with the case of selection combining.

Decision Fusion: Different from data fusion model, in decision fusion model, each secondary user estimates received PU signal and takes local decision on the status of PU, independently. Then the destination combines local decisions from secondary users and its own local decision making a binary decision on PU's status. The decision fusion also known as *N-out-of-K* rule [14], including OR, AND and Majority rules. Suppose k represents the number of secondary users and destination, the destination with *N-out-of-K* rule makes final decision that PU is present when n or more local decisions show that PU is present.

Cooperation Models

Cooperation structure, also called cooperation model [50], should consider how to group secondary users, how to combine local observations for making final decisions on PU activity are made. Currently, there exists two common cooperation models: parallel fusion (PF) model and game theoretical model.

Parallel Fusion Model: Each SU has the same priority and should sense PU signal, report its received signal to the other SU. Thus, distributed cognitive network is a special case of parallel fusion model. For example, as Fig.2.6 shown, SU4 makes its final binary decision based on its local sensing and sensing data from other SUs via report channels. Thus, parallel fusion model requires SUs to be synchronized. Due to parallel fusion model's simple structure, data fusion and decision fusion are derived from this model.

Game Theoretical Model: In game theoretical model, secondary users are regarded as a set of players. Depending on the rules of the game, secondary users may have different performance. Based on game theoretical model, many game rules are developed [51] [5]. For example, in a coalitional game [5], secondary users are divided into groups freely, called coalitions, based on their estimation about the communication surroundings. As Fig.2.7 shows, SU1, SU2 and SU3, belong to the same coalition 1, will sense the same specified PU1 spectrum. Then SU1 and SU2 will sense local data to SU3, which temporarily works as a local fusion center in coalition in this coalition, to make final decision. However, these coalitions are self-organized and not fixed, each secondary user joins or leaves freely depending on its utility value, which accounts for the tradeoff between receiving high probability of detection and energy cost incurred. Thus, cognitive networks achieve high probability of spectrum detection and spectrum management by introducing game coalitional.

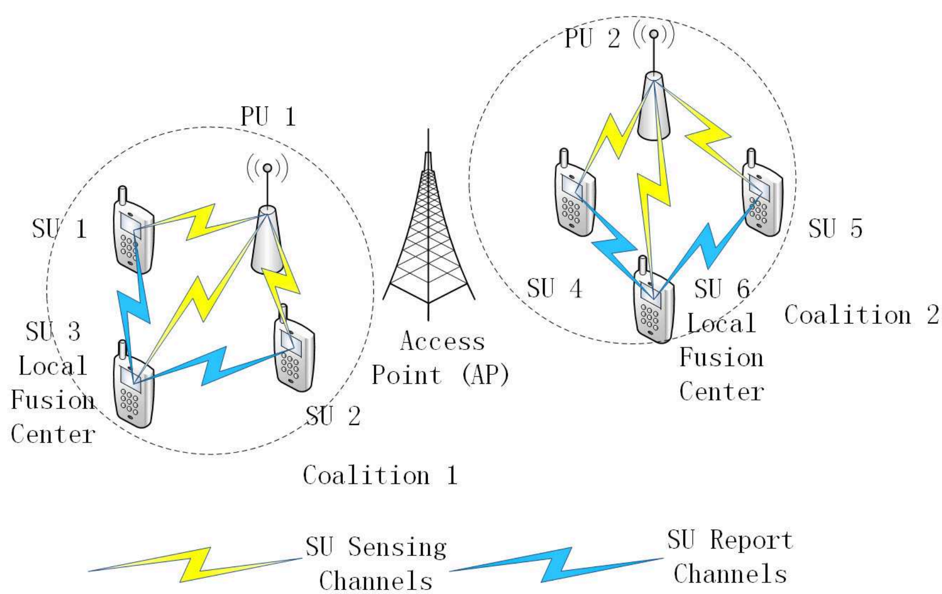

Figure 2.7: Cooperative spectrum sensing via hedonic coalition formation [5].

Chapter 3

Cooperative Spectrum Sensing

Energy detection is the main focus in this thesis since it has simple structure and low implementation complexity. Due to different types of fading channels, energy detection has different performance. On the other hand, cooperative energy detection schemes are designed to combat shadowing effect and hidden terminal problem. Many cooperative energy detection schemes, such as MRC, SC, SLC, SLS and *N-out-of-K* rule, are derived. Since MRC is required to know well about CSI, which maybe not be practical in real channels, this thesis focuses on the introduction of SC, SLC and SLS.

This chapter will present basic energy detection system at first, and then simulate, analyze its performance over several varieties of fading channels, i.e. Nakagami-m fading channels, Rician fading channels, shadowing fading channels. Later, the detection expressions of SLS, SLC, SC and *N-out-of-K* rule over both i.i.d and i.n.d Rayleigh fading channels are introduced. Then we simulate SLS, SLC, SC, *N-out-of-K* rule over both i.i.d and i.n.d channels. The analysis and conclusions will be presented after the simulation.

3.1 Basic Energy Detection System

The basic energy detection system is shown in Fig.2.4 consisting of bandpass filter (BPF), squaring device, integrator and threshold comparison device. BPF is introduced for filtering noise in order to switch noise from limitless band to band-limited, flat spectral density. The received signal, $d(t)$, is limited bandwidth by BPF, passes squaring device for measuring its energy and followed by integrator which in charge of observation interval time T for measuring calculated energy during time T.

The primary signal, $s(t)$, is transmitted between PU and SU over a wireless fading channel. This fading channel has channel gain, represented as ζ. At the energy detection system, received signal, $d(t)$, is considered as a binary hypothesis that follows: H_0 (representing the absence of PU) and H_1 (representing the presence of PU) and is expressed as [14]

$$d(t) = \begin{cases} a(t), & H_0, \\ \zeta s(t) + a(t), & H_1. \end{cases} \tag{3.1}$$

where $a(t)$ represents the additive white Gaussian noise (AWGN).

When the PU is absent (H_0), $d(t)$ only has $a(t)$, where $a(t)$ will be expressed as

$$a(t) = \sum_{g=-\infty}^{\infty} a_g sinc(2Wt - g), \tag{3.2}$$

where $a_g \sim N(0, N_{01}W)$ with one-sided power spectral density N_{01}. Since noise at the detector passes through BPF, whose bandwidth is W, the noise variance is expressed as $N_{01}W$.

After integration as Fig.2.4 shows, the test, also called decision statistic, V is written as [7]

$$V = \int_0^T a^2(t)dt = \frac{1}{2W} \sum_{i=1}^{2q} a_g^2, \tag{3.3}$$

where $q = TW$. In order to normalize V, we define

$$b_g = \frac{a_g}{\sqrt{N_{01}W}}. \tag{3.4}$$

The normalized decision statistic $V^{'}$ is expressed as

$$V^{'} = \sum_{i=1}^{2q} b_g^2 \tag{3.5}$$

Because energy detector is non-coherent, $V^{'}$ can be viewed as the sum of $2q$ variables, which following Gaussian distribution independently with normalized, unit variance and zero mean. Thus, $V^{'}$ is described as a central chi-square (χ^2) distribution with $2q$ degrees of freedom [6].

The similar process and expression of energy detection are given when PU is present (H_1). The received signal $d(t)$ includes received signal $s(t)$ and AWGN $a(t)$.

$$s(t) = \sum_{g=-\infty}^{\infty} s_g sinc(2Wt - g), \tag{3.6}$$

We define the signal energy and instantaneous SNR as E_s, γ respectively.

$$E_s = \int_0^T s^2(t)dt \tag{3.7}$$

$$\gamma = \frac{E_s}{N_{01}} \tag{3.8}$$

Thus, similar expression can be derived from (3.4) and (3.5) with the replacement of n_g by $n_g + s_g$. The normalized decision statistic $V^{'}$ is expressed as

$$V^{'} = \sum_{i=1}^{2q} (\frac{a_g + s_g}{\sqrt{N_{01}W}})^2. \tag{3.9}$$

The decision statistic $V^{'}$ follows a noncentral χ^2 distribution with $2q$ degrees of freedom and a non centrality parameter 2γ [6]. Hence, the decision statistic will be described as [6]

$$V^{'} = \begin{cases} \chi_{2q}^2, & H_0, \\ \chi_{2q}^2(2\gamma), & H_1. \end{cases} \tag{3.10}$$

The probability density function (PDF) of $V^{'}$ is described as [7]

$$f_{V'}(y) = \begin{cases} \frac{1}{2^q\Gamma(q)} y^{u-1} e^{-\frac{y}{2}}, & H_0, \\ \frac{1}{2}\frac{y}{2\gamma}^{\frac{q-1}{2}} e^{-\frac{2\gamma+y}{2}} I_{q-1}(\sqrt{2\gamma y}), & H_1. \end{cases} \tag{3.11}$$

In (3.11), $\Gamma(.)$ represents the gamma function [52, Section 8.31], $I_v(.)$ is described as v_{th}-order modified Bessel function of the first kind [52, Section 8.43]. The decision statistic $V^{'}$ then compares with a threshold value λ in threshold comparison device making a binary decision on PU: PU is present ($V^{'} > \lambda$); PU is absent ($V^{'} < \lambda$) [6]. The energy detector's probabilities of false alarm (P_f) and detection (P_d) are expressed by [6]

$$P_d = P_r\left(V^{'} > \lambda \,\middle|\, H_1 \right), \tag{3.12}$$

$$P_f = P_r\left(V^{'} > \lambda \,\middle|\, H_0 \right), \tag{3.13}$$

The (3.13) can be derived by (3.11) [7]

$$P_f = \frac{\Gamma(q, \frac{\lambda}{2})}{\Gamma(q)}, \tag{3.14}$$

where $\Gamma(.)$ represents gamma function, and $\Gamma(.,.)$ is regarded as the incomplete gamma function.[6]

The (3.12) can be obtained from (3.11) by using the cumulative distribution function (CDF) of $V^{'}$,

$$P_d = 1 - F_{V'}(y) = Q_q(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{3.15}$$

where $F_{V'}(y)$ represents the CDF of $V^{'}$, $Q_q(.,.)$ represents the q_{th} order generalized Marcum-Q function given by [53]

$$Q_q(\sqrt{2\gamma}, \lambda) = \frac{1}{\sqrt{2\gamma}^{q-1}} \int_{\lambda}^{\infty} t^q e^{-\frac{(\sqrt{2\gamma})^2+t^2}{2}} I_{q-1}(\sqrt{2\gamma}t)dt. \tag{3.16}$$

According to [54], (3.15) can be simplified and rewritten as

$$Q_q(\sqrt{2\gamma}, \sqrt{\lambda}) = e^{\frac{\lambda}{2}} \sum_{i=0}^{q-1} \frac{(\frac{\lambda}{2})^i}{i!} + e^{-\frac{\lambda}{2}} \sum_{n=q}^{\infty} \frac{(\frac{\lambda}{2})^n}{n!} (1 - e^{-\gamma} \sum_{k=0}^{n-q} \frac{\gamma^k}{k!}). \tag{3.17}$$

3.2 Energy Detection Performance

3.2.1 Rayleigh Fading Channels

The channel between PU and SU is modeled as Rayleigh fading channels, the SNR's (γ) PDF is following an exponential distribution given as [6]

$$f(\gamma) = \frac{1}{\overline{\gamma}} exp(-\frac{\gamma}{\overline{\gamma}}), \tag{3.18}$$

where $\overline{\gamma}$ represents the average SNR in local channels. The average P_d over Rayleigh fading channels is derived by averaging (3.15) over (3.18),

$$\overline{P_d} = \int_0^{\infty} Q_q(\sqrt{2\gamma}, \sqrt{\lambda}) \frac{1}{\overline{\gamma}} exp(-\frac{\gamma}{\overline{\gamma}}) d\gamma \tag{3.19}$$

By using [53, Eq(30)], (3.19) can be expressed as [6]

$$\overline{P_d} = e^{-\frac{\lambda}{2}} \sum_{n=0}^{q-2} \frac{1}{n!} (\frac{\lambda}{2})^2 + (\frac{1+\overline{\gamma}}{\overline{\gamma}})^{q-1} \left[e^{-\frac{\lambda}{2(1+\overline{\gamma})}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{q-2} \frac{1}{n!} \frac{\lambda\overline{\gamma}}{2(1+\overline{\gamma})} \right] \tag{3.20}$$

3.2.2 Nakagami Fading Channels

The channel between PU and SU is modeled as Nakagami fading channels, the SNR's (γ) PDF is following an exponential distribution given as [6]

$$f(\gamma) = \frac{1}{\Gamma(\eta)} (\frac{\eta}{\overline{\gamma}})^{\eta} \gamma^{\eta-1} exp(-\frac{\eta\gamma}{\overline{\gamma}}), \quad \gamma \geq 0, \tag{3.21}$$

where η represents the Nakagami parameter.

The average P_d over Nakagami fading channels is derived by averaging (3.17) over (3.21) [55].

$$\overline{P_d} = e^{\frac{\lambda}{2}} \sum_{i=0}^{q-1} \frac{(\frac{\lambda}{2})^i}{i!} + e^{-\frac{\lambda}{2}} \sum_{n=q}^{\infty} \frac{(\frac{\lambda}{2})^n}{n!} \Big(1 - \frac{1}{\Gamma(\eta)} \Big(\frac{\eta}{\overline{\gamma}}\Big)^{\eta} \sum_{k=0}^{n-q} \frac{\int_0^{\infty} e^{-\frac{\eta+\overline{\gamma}}{\overline{\gamma}}\gamma} \gamma^{k+\eta-1} d\gamma}{k!}\Big). \tag{3.22}$$

By using [52, Eq(3.351-3)], (3.22) can be rewritten as [55]

$$\overline{P_d} = e^{\frac{\lambda}{2}} \sum_{i=0}^{q-1} \frac{(\frac{\lambda}{2})^i}{i!} + e^{-\frac{\lambda}{2}} \sum_{n=q}^{\infty} \frac{(\frac{\lambda}{2})^n}{n!} \Big(1 - \Big(\frac{\eta}{\eta+\overline{\gamma}}\Big)^{\eta} \sum_{c=0}^{n-q} \Big(\frac{\overline{\gamma}}{\eta+\overline{\gamma}}\Big)^{c} \frac{(\eta+c-1)!}{\Gamma(\eta) c!}\Big). \tag{3.23}$$

When $\eta = 1$, the Nakagami fading channel becomes to Rayleigh fading channel and (3.23) is reduced to (3.20). In other words, Rayleigh fading is one condition of Nakagami fading given $\eta = 1$.

3.2.3 Rician Fading Channels

Over Rician fading channels, the SNR's (γ) PDF is following an exponential distribution given as [6]

$$f(\gamma) = \frac{\varrho+1}{\overline{\gamma}} exp\Big(-\varrho - \frac{(\varrho+1)\gamma}{\overline{\gamma}}\Big) I_0\Big(2\sqrt{\frac{\varrho(\varrho+1)\gamma}{\overline{\gamma}}}\Big), \quad \gamma \geq 0, \tag{3.24}$$

where ϱ represents the Rician parameter. The average P_d over Rician fading channels is derived by averaging (3.17) over (3.24) written as

$$\overline{P_d} = e^{\frac{\lambda}{2}} \sum_{i=0}^{q-1} \frac{(\frac{\lambda}{2})^i}{i!} + e^{-\frac{\lambda}{2}} \sum_{n=q}^{\infty} \frac{(\frac{\lambda}{2})^n}{n!} (1 - \frac{(\varrho+1)e^{-\varrho}}{\overline{\gamma}} \sum_{c=0}^{n-q} \frac{\int_0^{\infty} e^{-\frac{(\varrho+1+\overline{\gamma})\gamma}{\overline{\gamma}}} \gamma^c I_0(2\sqrt{\frac{\varrho(\varrho+1)\gamma}{\overline{\gamma}}}) d\gamma}{c!}). \tag{3.25}$$

3.2.4 Shadowed Fading Channels

Since shadowed fading always attach to other fading channels mentioned above, this thesis focuses on one special case that channels are combined by Rayleigh fading and shadowed fading. Based on (3.15), the probability of miss detection over AWGN is written as

$$P_m = 1 - P_d = 1 - Q_q(\sqrt{2\gamma}, \sqrt{\lambda}). \tag{3.26}$$

where P_m is the probability of miss detection rewritten as [56], [57]

$$P_m(\gamma) = \sum_{n=q}^{\infty} \zeta(n) \sum_{c=0}^{n-q} e^{-\gamma} \frac{(\gamma)^c}{c!} \tag{3.27}$$

with

$$\zeta(n) = e^{-\frac{T}{2}} (\frac{\lambda}{2})^2 \frac{1}{n!} \tag{3.28}$$

The shadowed fading channels follow lognormal distribution and the PDF is given by [49],

$$f_{shadowed}(\omega) = \frac{\varepsilon_0}{\sqrt{2\pi}\delta\omega} e^{(-\frac{(10log_{10}\omega)^2}{2\delta^2})}, \qquad \omega \geq 0 \tag{3.29}$$

where $\varepsilon_0 = \frac{10}{ln(10)}$, δ(dB) is the standard deviation of $10log_{10}\omega$ [58]. As the PDF of Rayleigh fading channels, f_{Ray}, is given in (3.18), the PDF of SNR in shadowed-Rayleigh fading channel is given as [49]

$$f(\gamma) = \int_0^{\infty} \frac{1}{\omega} f_{Ray}(\frac{\gamma}{\omega}) f_{Shadowed}(\omega) d\omega \qquad \gamma \geq 0 \tag{3.30}$$

Thus, the average probability of miss detection, P_m, over shadowed fading Rayleigh fading is derived by averaging (3.15) over (3.29)

$$\overline{P}_m = \int_0^{\infty} P_m(\gamma) f(\gamma) d\gamma. \tag{3.31}$$

In high SNR scenario, the average probability of miss detection, P_m, is written as [58]

$$\overline{P}_m(\overline{\gamma}) = \frac{1}{\overline{\gamma}} e^{(\frac{\delta^2}{2\varepsilon_0^2})} (\frac{\lambda}{2} + 1 - q + \Phi_0), \tag{3.32}$$

where

$$\Phi_0 = \frac{(q-1-\lambda/2)\Gamma(q-1,\lambda/2) + (\lambda/2)^{q-1}e^{(-\lambda/2)}}{\Gamma(q-1)}. \tag{3.33}$$

3.2.5 Simulation Results

This section focuses on simulation of energy detection performance over various fading channels mentioned above where the receiver operating characteristic (ROC) curves are given [52]. Without loss of generality, for simulation convenient, we suppose that the one-sided bandwidth W is 1000Hz, the observation time T is 0.005s, the time bandwidth product q is 5, the average SNR $\overline{\gamma}$ is 10dB over both Nakagami and Rician fading channels, respectively. Since Rayleigh fading is one condition of Nakagami fading given $\eta = 1$, we will consider the simulation of energy detection over Rayleigh fading. We will simulate energy detection over shadowed-Rayleigh fading channels versus the average SNR $\overline{\gamma}$ since the probability of energy detection over shadowed-Rayleigh fading channels is only effective under high average SNR scenario.

The performance of energy detection over Nakagami fading channels is shown in Fig.3.1 under different Nakagami parameters. If $\eta = 1$, Nakagami fading reduces to Rayleigh fading. As Fig.3.1 shows, energy detection performance is improved when Rician parameter K increases since the ratio of signal dominant power, represented by K, is increased. Compared with the performance over Nakagami fading and Rician fading, as Fig.3.3 shown, shadowed fading largely affects energy detection performance.

3.3 Cooperative Spectrum Sensing

This section focuses on the introduction of SLS, SLC, SC and *N-out-of-K* rule over i.i.d Rayleigh fading channels. Later, the probability of detection of SLS, SLC, SC and *N-out-of-K* rule will be introduced or derived over i.n.d Rayleigh fading channels. Simulation results and conclusions will then be followed.

3.3.1 *N-out-of-K* Rule

N-out-of-K rule includes OR rule, Majority rule, and AND rule [14]. OR rule is presented when $N = 1$, AND rule is presented when $N = K$, and Majority rule is presented when

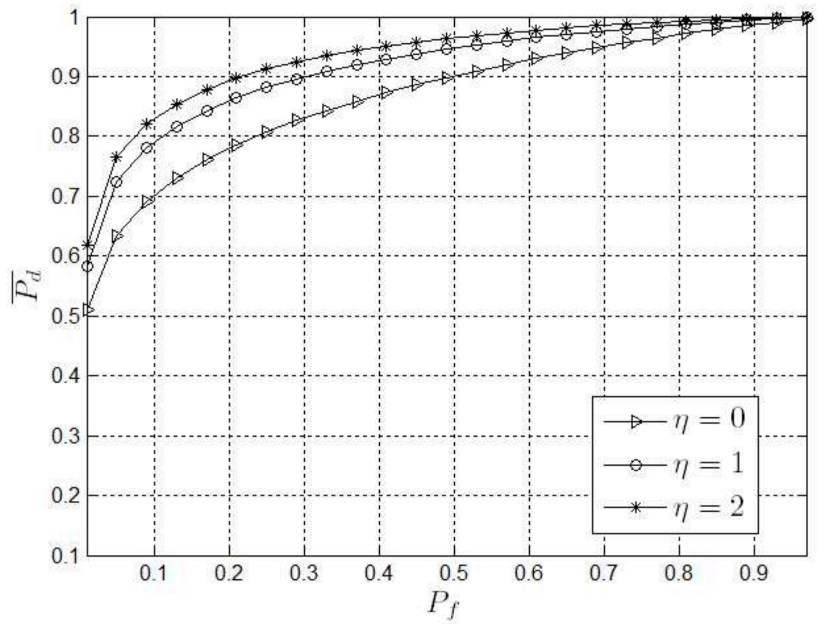

Figure 3.1: ROC curves over Nakagami fading channel with various η, $\overline{\gamma} = 10dB$, $q = 5$.

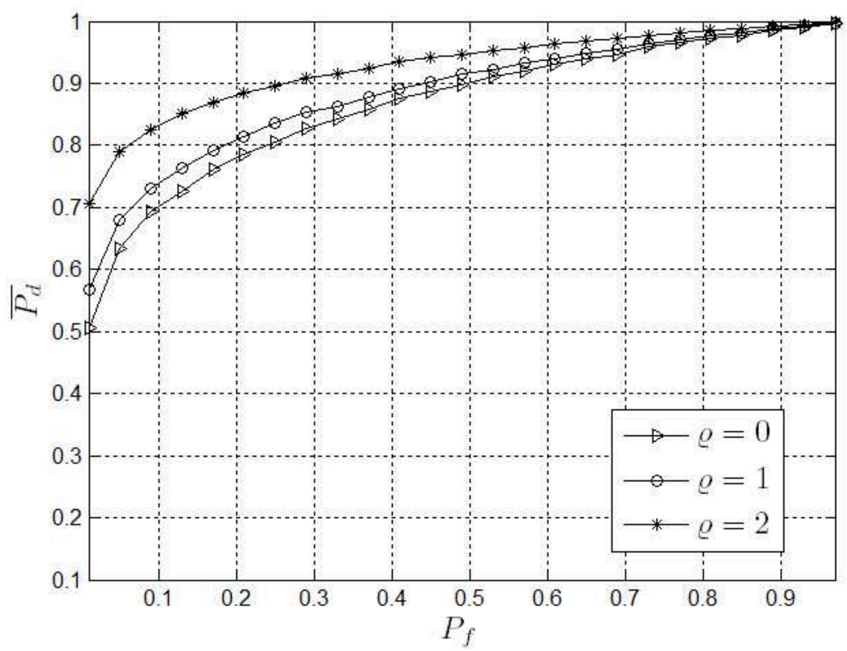

Figure 3.2: ROC curves over Rician fading channel with various ϱ, $\overline{\gamma} = 10dB$, $q = 5$.

$N = \lceil K/2 \rceil$. The probability of false alarm and detection are given by [14]

$$Q_f = \sum_{i=N}^{K} \binom{K}{i} (P_f)^i (1 - P_f)^{K-i}, \tag{3.34}$$

$$Q_d = \sum_{i=N}^{K} \binom{K}{i} (P_d)^i (1 - P_d)^{K-i}. \tag{3.35}$$

where P_f, P_d represent the probability of false alarm and detection in the single secondary user or destination, respectively, Q_f, Q_d represent the total probability of false alarm and detection in cognitive networks.

3.3.2 Square-Law Selection

In this scheme, the relay having maximum decision statistic $V'_{SLS} = max(y'_1, ..., y'_L)$ will be selected [59]. When cognitive networks over i.i.d Rayleigh fading channels, SLS corresponding $\overline{P_d}$ and $\overline{P_f}$ are given as [7]

$$\overline{P_f}_{SLS} = 1 - \left[1 - \frac{\Gamma(q, \frac{\lambda}{2})}{\Gamma(q)}\right]^L \tag{3.36}$$

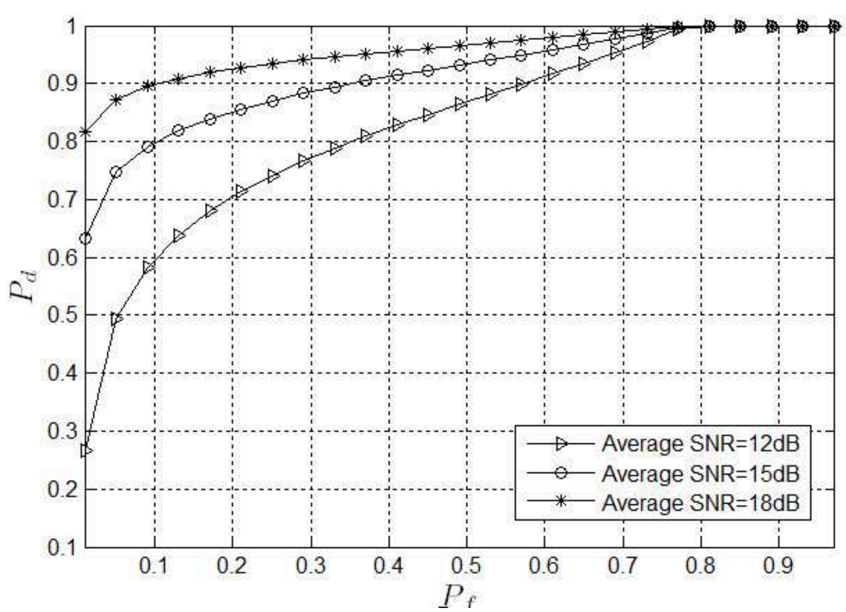

Figure 3.3: ROC curves over shadowed fading channel with various average SNR $\overline{\gamma}$, $q = 5$.

$$\overline{P_{dSLS}} = 1 - \prod_{i=1}^{L}(1 - \overline{P_{dR}}(\overline{\gamma_i}, q)) \tag{3.37}$$

where $\overline{P_{dR}}(\overline{\gamma_i}, q)$ represents the i_{th} channel's probability of detection in (3.20), $\overline{\gamma_i}$ represents the average SNR in i_{th} channel.

Under i.n.d Rayleigh fading channels condition, SLS corresponding expressions of $\overline{P_d}$ and $\overline{P_f}$ have the same formation in the case of i.i.d.

3.3.3 Square-Law Combining

SLC's thoery is based on combining the outputs from the square-law devices (doing the operation of square-and-integrate in relay), denoted as $\{V_i^{'}\}_{i=1}^{L}$ to yield a decision statistic $V_{SLC}^{'} = \sum_{i=1}^{L} V_i^{'}$ [7]. Over i.i.d Rayleigh fading channels, the PDF of SNR, γ, under square-law combining is equate to the PDF expression over single Nakagami fading channels (3.21) while replacing η by L and replacing $\overline{\gamma}$ by $L\overline{\gamma}$ as

$$f(\gamma) = \frac{1}{\Gamma(L)}(\frac{1}{\overline{\gamma}})^L \gamma^{L-1} exp(-\frac{\gamma}{\overline{\gamma}}), \quad \gamma \geq 0. \tag{3.38}$$

Thus, $\overline{P_d}$ under square-law combining is derived by averaging (3.15) over (3.46). Therefore, the corresponding $\overline{P_d}$ and $\overline{P_f}$ over i.i.d Rayleigh fading channels are expressed as [7]

$$\overline{P_{f\,SLC}} = \frac{\Gamma(Lq, \frac{\lambda}{2})}{\Gamma(Lq)} \tag{3.39}$$

$$\overline{P_{dSLC}} = A_1 + \beta^L e^{-\frac{\lambda}{2}} \times \sum_{i=1}^{q-1} \frac{\frac{\lambda}{2}^i}{i!} {}_1F_1(L; i+1; \frac{\lambda(1-\beta)}{2}) \tag{3.40}$$

where $\beta = (2L)/(2L + 2L\overline{\gamma})$, ${}_1F_1(.;.;.)$ is the confluent hypergeometric function [52], and

$$A_1 = e^{-\frac{\lambda\beta}{2L}} \left(\beta^{L-1} L_{L-1}\Big(\frac{-\lambda(1-\beta)}{2}\Big) + (1-\beta)\sum_{i=0}^{L-2} \beta^i L_i\Big(\frac{-\lambda(1-\beta)}{2}\Big) \right) \tag{3.41}$$

with $L_i(.)$ being the Laguerre polynomial of degree i [52].

When cognitive networks over i.n.d Rayleigh fading channels, the PDF of SNR γ under square-law combining is written as [60]

$$f(\gamma) = \frac{1}{\Gamma(L)}(\frac{L}{\overline{\gamma}_{SLC}})^L \gamma^{L-1} exp(-\frac{L\gamma}{\overline{\gamma}_{SLC}}), \quad \gamma \geq 0, \tag{3.42}$$

where $\overline{\gamma}_{SLC} = \sum_{i=1}^{L} \overline{\gamma}_i$ is regarded as sum of all channels' average SNR. Thus, the $\overline{P_d}$ over i.n.d Rayleigh fading channels is similar to (3.23) with m replaced by L, $\overline{\gamma}$ replaced by $\overline{\gamma}_{SLC}$, and q replaced by Lq, yielding

$$\overline{P_d} = e^{\frac{\lambda}{2}} \sum_{i=0}^{Lq-1} \frac{(\frac{\lambda}{2})^i}{i!} + e^{-\frac{\lambda}{2}} \sum_{n=Lq}^{\infty} \frac{(\frac{\lambda}{2})^n}{n!} \Big(1 - \Big(\frac{L}{L+\overline{\gamma}_{SLC}}\Big)^L \sum_{c=0}^{n-Lq} \Big(\frac{\overline{\gamma}_{SLC}}{L+\overline{\gamma}_{SLC}}\Big)^c \frac{(L+c-1)!}{\Gamma(L)c!}\Big). \tag{3.43}$$

Since fading channel does not affect the occurrence of false alarm, $\overline{P_f}$ over i.n.d Rayleigh fading channels is as the same as (3.39).

3.3.4 Selection Combining

Selection combining is a special cooperative sensing technique as the destination selects the relay with highest SNR (P-R channels). Over i.i.d Rayleigh fading channels, the PDF of SNR, γ, under selection combining is given by [6]

$$f(\gamma) = \frac{L}{\overline{\gamma}}(1 - e^{-\gamma/\overline{\gamma}})^{L-1} e^{-\gamma/\overline{\gamma}} \tag{3.44}$$

The probability of detection $\overline{P_d}$, is expressed via integrating (3.15) over (3.52) as [53],

$$\overline{P_d} = L \sum_{i=0}^{L-1} \frac{(-1)^i}{i+1} \binom{L-1}{i} \overline{P_{dR}}\Big(\overline{\gamma}/(i+1)\Big) \tag{3.45}$$

where $\overline{P_{dR}}\Big(\overline{\gamma}/(i+1)\Big)$ is obtained in (3.20) by replacing γ with $\gamma/(i+1)$. The probability of false alarm, $\overline{P_f}$, is as the same as (3.14) because it is independent from Rayleigh fading.

Over i.n.d Rayleigh fading channels, the PDF of SNR γ is expressed as

$$f(\gamma) = \sum_{x_1=1}^{L} f_{x_1}(\gamma) \sum_{R_{L,1,x_1}} \prod_{j=2}^{L} F_{x_j}(\gamma) \tag{3.46}$$

where $R_{L,1,x_1}$ is the set including total possible combinations of $L-1$ members chosen from the difference set $\{1, 2, ...L\} - \{x_1\}$, $f_{x_1}(\gamma)$ represents the PDF of the SNR in x_{1th} link given by (3.18) and $F_{x_j}(\gamma)$ represents the cumulative distribution function (CDF) of γ in $x_{j_{th}}$ link given as

$$F(\gamma_{x_j}) = 1 - e^{-\gamma_{x_j}/\overline{\gamma_{x_j}}}. \tag{3.47}$$

For $\prod_{j=2}^{L} F_{x_j}(\gamma)$, it will be further simplified as

$$\prod_{j=2}^{L} F_{x_j}(\gamma) = \sum_{w=0}^{L-1} (-1)^w \sum_{2 \le b_1 < b_2 < ... < b_w \le L} \prod_{p=1}^{w} e^{-\frac{\gamma}{\overline{\gamma_{x_{np}}}}}. \tag{3.48}$$

Therefore, the PDF of SNR, γ, will be written as [61]

$$f(\gamma) = \sum_{x_1=1}^{L} \frac{1}{\overline{\gamma_{x_1}}} \sum_{S_{L,x_1}} \sum_{w=0}^{L-1} (-1)^w \sum_{2 \le b_1 < b_2 < ... < b_w \le L} e^{-\mu_w \gamma} \tag{3.49}$$

with

$$\mu_w = \sum_{p=1}^{w} \frac{1}{\overline{\gamma_{x_{np}}}} + \frac{1}{\overline{\gamma_{x_1}}}. \tag{3.50}$$

Thus, $\overline{P_d}$ under selection combining is derived by averaging (3.15) over (3.57) by the usage of [53] yielding

$$\begin{aligned}\overline{P_d} = &\sum_{x_1=1}^{L} \frac{1}{\overline{\gamma_{x_1}}} \sum_{R_{L,1,x_1}} \sum_{w=0}^{L-1} (-1)^w \times \\ &\sum_{2 \le b_1 < b_2 < \ldots < b_w \le L} \frac{1}{\mu_w} exp(-\frac{\lambda}{2}) \times \\ &\Bigg\{ \Big(\frac{\mu_w + 1}{\mu_w}\Big)^{q-1} \Bigg[exp\Big(\frac{\lambda}{2\mu_w + 2}\Big) - \sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2\mu_w + 2}\Big)^t \Bigg] + \\ &\sum_{t=0}^{q-2} \frac{1}{t!} (\frac{\lambda}{2})^t \Bigg\}.\end{aligned} \tag{3.51}$$

Over i.n.d Rayleigh fading channels, the probability of false alarm $\overline{P_f}$ is equate to (3.14).

3.3.5 Simulations and Conclusions

Without loss of generality, for simulation convenient, we assume that the one-sided bandwidth W is 1000Hz, the observation time T is 0.005s, the time bandwidth product q is 5, the number of SU, L, is 6. In i.i.d Rayleigh fading case, the average SNR $\overline{\gamma}$ is 5dB. In the i.n.d case, the average SNR $\overline{\gamma}$ among L SUs range from 3dB to 8dB .

As Figs.3.4, 3.5 shown, SLC performs better than other cooperative schemes due to its high diversity advantage combining the information from all the cooperative SUs. Since SLS probability of detection in (3.45) is the same as the OR probability of detection in (3.43), SLS performs as well as OR does. The difference between OR and SLS is only in their operation mechanism: cooperative SUs send 1-bit local decision to destination in OR rule while cooperative SUs sending obtained data to destination. Considering bandwidth usage, OR rule is more bandwidth efficient than SLS. Although SC is based on data fusion from the SU with highest SNR for final decision, SC still performs a little bit worse than SLS because SC lacks high diversity.

In order to allow SC high diversity gain and improve its detection performance, we propose an improved cooperative scheme, named multi-selective cooperation in the next chapter, where the proposed scheme requires SUs to send 1bit local decision for improved bandwidth efficiency.

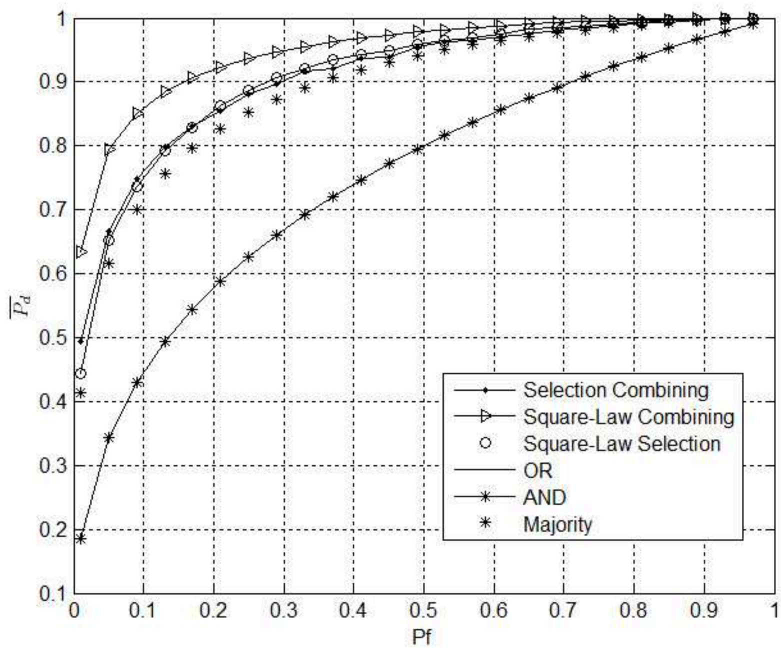

Figure 3.4: Complementary ROC curves for SC, SLC, SLS, Or, And, and Majority over i.i.d Rayleigh fading channels,$\overline{\gamma} = 5dB$,$L = 6$.

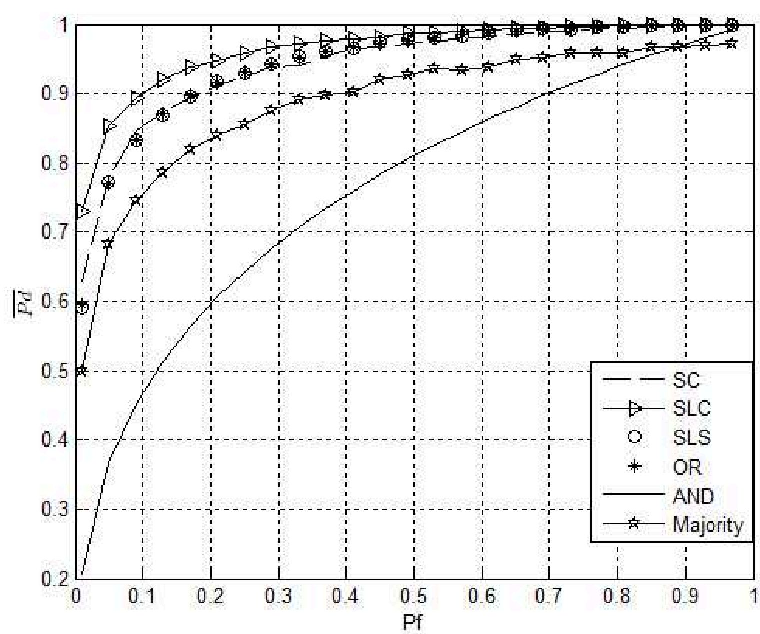

Figure 3.5: Complementary ROC curves for SC, SLC, SLS, Or, And, and Majority over i.n.d Rayleigh fading channels, $L = 6$,$\overline{\gamma}$ varies from 3dB to 8dB.

Chapter 4

Multi-Selective Cooperation

This chapter focuses on the improvement of selection combining scheme. Instead of selecting one node with highest SNR as final decision node, multi-selective cooperation suggests cognitive networks accept several nodes represented by K with high SNR to make final decision on whether PU exists or not. The comparison between multi-selective scheme and some cooperative energy detection schemes over i.i.d Rayleigh fading channels and i.n.d Rayleigh fading channels respectively is presented. In order to find the optimum number of selected node K that achieve the maximum probability of detection in the cognitive network, optimization analysis over both i.i.d Rayleigh fading channels and i.n.d Rayleigh fading channels are proposed later in this chapter.

The multi-selective cooperation is based on distributed cognitive networks as shown in Fig.4.1. We consider a cooperative cognitive network where at any time a secondary user (SU) can be a source, relay, or destination. The number of links including the P-R (primary to relay) and P-D (primary to destination) is denoted by L. Also to simplify the analysis, we first consider the R-D (relay to destination) links are error-free. Then we relax this assumption by modeling the R-D links as AWGN channels. This assumption can be justified in scenarios where the destination and relays are in the vicinity of each other forming a cluster.

4.1 Bandwidth Usage for Sharing the Spectrum Sensing Data

For SLS and SLC, relays send their decision statistic y_i to destination for sharing the spectrum sensing data while SC scheme requires relays send both local SNR_{pr} status information and y_i to destination. Thus, SC require more bandwidth for sharing the spectrum sensing data compared with SLC and SLS. On the other hand, multi-selective-cooperation scheme requires relays send local SNR_{pr} status information and 1-bit local decision to destination. In comparison with SLS and SLC, selective-cooperation requires nearly the same bandwidth as SLS and SLC do for sharing the spectrum sensing data.

To assess the performance of our detection scheme, in what follows, we derive this scheme's expressions and analyze the overall probabilities of false alarm and detection.

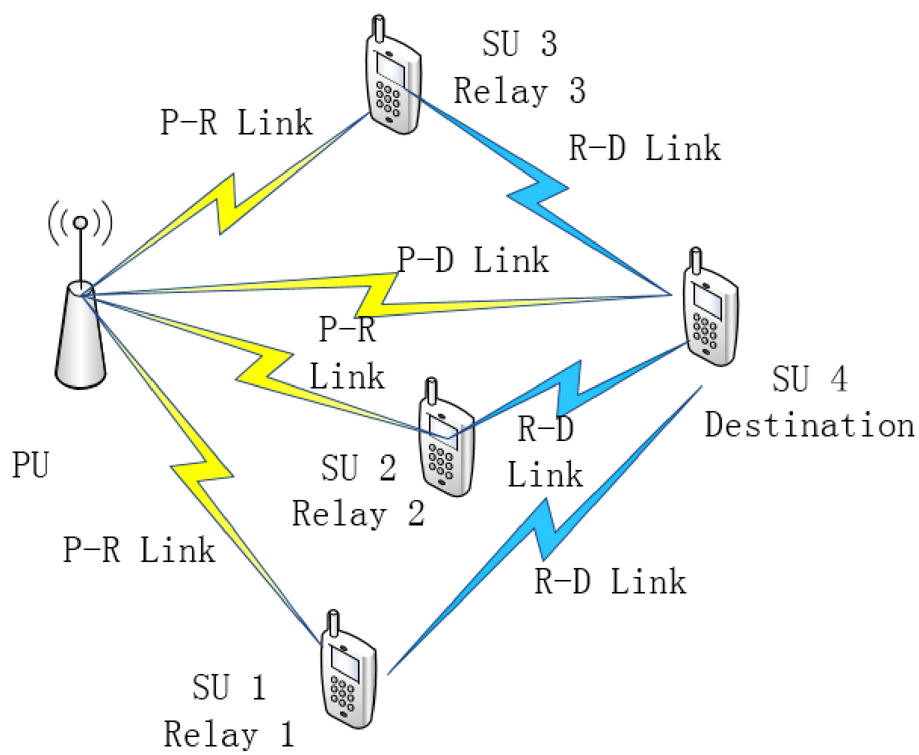

Figure 4.1: The cognitive network model of multi-selective cooperation.

4.2 Probability of False Alarm and Detection

4.2.1 Probability of False Alarm

Under the multi-selective cooperation scheme, the destination selects K links with the highest SNRs for final decision. However, in the case of H_0 in (3.1), the detector receives decision statistic from noise alone. Therefore, under H_0, the destination picks K links randomly irrespective of the SNRs. The overall probability of false alarm incorporating the *N-out-of-K* rule over i.i.d and i.n.d Rayleigh fading channels is given by

$$Q_f = \sum_{j=N}^{K} \binom{K}{j} {P_f}^j (1 - P_f)^{K-j}. \tag{4.1}$$

4.2.2 i.i.d Rayleigh Fading Channels

Over i.i.d Rayleigh fading channels, the probability density function (PDF) and cumulative distribution function (CDF) of the SNR γ, are given by [49]

$$f(\gamma) = \frac{1}{\overline{\gamma}} e^{-\gamma/\overline{\gamma}} \tag{4.2}$$

$$F(\gamma) = 1 - e^{-\gamma/\overline{\gamma}}. \tag{4.3}$$

The destination first orders the R-D and P-D links in-terms of their SNRs to form the set $U = \{\gamma^{(1)}, \gamma^{(2)}, ..., \gamma^{(L)}\}$, considered strictly decreasing set. The destination then selects the K $(1 \leqslant K \leqslant L)$ links corresponding to the K highest SNRs as reporting links from set U to form the sub-set $S_K = \{\gamma^{(1)}, \gamma^{(2)}, ..., \gamma^{(K)}\}$ as the one that represents these reporting links. In what follows, the PDF of $\gamma^{(k)}$ $(1 \leqslant k \leqslant K)$ in the set U and the joint PDF of the elements in the set S_K are first evaluated and then used to derive the probability of detection.

Since the multi-selective scheme selects K links from set U as report links, we need to derive the PDF of the $\gamma^{(k)}$ $(1 \leqslant k \leqslant K)$ in the set U. As the SNRs of the L links are i.i.d, the probability of any link being in the $\gamma^{(k)}$ in the set U is equal to $(1/L)$ and the corresponding

PDF of the SNR is given by [62]

$$\begin{aligned} f^{(k)}(\gamma^{(k)}) &= L\binom{L-1}{k-1}F^{L-k}(\gamma^{(k)})[1-F(\gamma^{(k)})]^{k-1}f(\gamma^{(k)}) \\ &= \frac{L!}{(k-1)!(L-k)!}F^{L-k}(\gamma^{(k)})[1-F(\gamma^{(k)})]^{k-1}f(\gamma^{(k)}) \end{aligned} \tag{4.4}$$

where $F(\gamma^{(k)})$ and $f(\gamma^{(k)})$ are given respectively by (4.2) and (4.3) with $F(\gamma^{(k)})$ representing the CDF of any link's SNR smaller than $\gamma^{(k)}$ in the set U. Since the multi-selective scheme adopts *N-out-of-K* rule in the set S_K, we derive the joint PDF of any N elements, regarded as $z_1, z_2, ..., z_N$, in the set S_K. According to (4.4), this joint PDF, represented by $\{\gamma^{(z_1)}, \gamma^{(z_2)}, ..., \gamma^{(z_N)}\}$ $(1 \leqslant z_1 < z_2, .., < z_N \leqslant K; 1 < N \leqslant K)$ for $\gamma^{(z_1)} > ... > \gamma^{(z_N)}$, $f^{(z_1,z_2...,z_N)}(\gamma^{(z_1)}, ..., \gamma^{(z_N)})$, is given by [63]

$$\begin{aligned} f^{(z_1,z_2...,z_N)} = & \frac{L!}{(z_1-1)!(z_2-z_1-1)!...(L-z_N)!} \\ & \times [1-F(\gamma^{(z_1)})]^{z_1-1}f(\gamma^{(z_1)})\times \\ & [F(\gamma^{(z_1)})-F(\gamma^{(z_2)})]^{z_2-z_1-1}f(\gamma^{(z_2)}) \\ & ... \times F^{L-z_N}(\gamma^{(z_N)})f(\gamma^{(z_N)}) \end{aligned} \tag{4.5}$$

Considering the probability of detection of $\gamma^{(k)}$, from (3.15) and (4.4), and by making the change of variable $x = \sqrt{2\gamma}$, one can show that

$$\begin{aligned} \overline{P_d}^{(k)} &= \int f_k(\gamma^{(k)})Q_q(\sqrt{2\gamma^{(k)}}, \sqrt{\lambda})d\gamma^{(k)} \\ &= \frac{L!}{(k-1)!(L-k)!}\sum_{i=0}^{L-k}\frac{(-1)^i}{k+i}\binom{L-k}{i}\overline{P_{dR}}\Big(\frac{\overline{\gamma}}{k+i}\Big) \end{aligned} \tag{4.6}$$

where $\overline{P_{dR}}$ is given by (3.20) with replacing $\overline{\gamma}$ by $\frac{\overline{\gamma}}{k+i}$.

Now, the joint probability of detection corresponding to $f^{(z_1,z_2\dots,z_N)}$ in the set U is given by (3.15) and (4.5) as

$$\begin{aligned}\overline{P_d}^{(z_1,z_2\dots,z_N)} = &\int_{\gamma^{(z_1)}}^{\infty} \dots \int_{0}^{\gamma^{(z_N)}} \Big[f^{(z_1,z_2\dots,z_N)}(\gamma^{(z_1)},\dots,\gamma^{(z_N)}) \times \\ &Q_q\Big(\sqrt{2\gamma^{(z_N)}},\sqrt{\lambda}\Big)\dots Q_q\Big(\sqrt{2\gamma^{(z_1)}},\sqrt{\lambda}\Big)\Big] d\gamma^{(z_N)}\dots d\gamma^{(z_1)}\end{aligned} \tag{4.7}$$

Finally, the total probability of detection is evaluated using (4.6) and (4.7).

Since the multi-selective scheme selects K links with highest SNRs as final reporting links from the set U, the probability of detection is equal to the overall probability of detection in the set S_K. Now adopting the *N-out-of-K* rule for the overall probability of detection in the set S_K (i.e., signal is present when at least any N of the reporting links from $\gamma^{(1)}$ to $\gamma^{(K)}$ having detected the PU signal), the joint probability of any N elements in the set S_K has been derived in (4.7). Note that after ordering, the elements in S_K are dependent on each other. Therefore, the overall probability of detection of N elements in S_K is given by

$$Q_d = \begin{cases} \Big(\sum_{S_{K,N}} \overline{P_d}^{(z_1,z_2,\dots,z_N)}\Big) - P_{common}^{N} & \text{if } N < K \\ \overline{P_d}^{(z_1,z_2,\dots,z_N)} & \text{if } N = K \end{cases} \tag{4.8}$$

where $S_{K,N}$ is the set including total possible combinations of N members chosen from the set S_K. For example, when $K=3$ and $N=2$, $S_{K,N} = \Big\{(\gamma^{(1)},\gamma^{(2)}),(\gamma^{(1)},\gamma^{(3)}),(\gamma^{(2)},\gamma^{(3)})\Big\}$. $\overline{P_d}^{(z_1,z_2,\dots,z_N)}$ represents the joint probability of any N elements, regarded as $\{\gamma^{(z_1)},\gamma^{(z_2)},\dots,\gamma^{(z_N)}\}$, in the $S_{K,N}$ set. Also $\overline{P_d}^{(z_1,z_2,\dots,z_N)}$ is calculated using (4.7) when $N>1$. For the case of $N=1$ corresponding to the OR rule, $\overline{P_d}^{(z_1,z_2,\dots,z_N)}$ is calculated using (4.6). In (4.8), P_{common}^{N} represents the joint probability of detection of the $N+g$ ($1 \leqslant g \leqslant K-N$) elements in the S_K set for the *N-out-of-K* rule with $N \leqslant N+g \leqslant K$. For instance, when $K=3$ and $N=1$, $P_{common}^{N} = \overline{P_d}^{(1,2)} + \overline{P_d}^{(1,3)} + \overline{P_d}^{(2,3)} - \overline{P_d}^{(1,2,3)}$. In general, the expression of P_{common}^{N} is written as

$$P_{common}^{N} = \begin{cases} \sum_{g=1}^{K-N} \sum_{S_{K,N+g}} (-1)^{(g+1)} \overline{P_d}^{(z_1,z_2,\dots,z_{N+g})} & N=1 \\ \sum_{g=1}^{K-N} \sum_{S_{K,N+g}} \Big[\binom{N+g}{N+g-1} - 1\Big] \overline{P_d}^{(z_1,z_2,\dots,z_{N+g})} & K \geq N > 1 \end{cases} \tag{4.9}$$

where $S_{K,N+g}$ is the set including total possible combinations of $N+g$ members chosen from the set S_K, and $\overline{P_d}^{(z_1,z_2,...,z_{N+g})}$ represents the joint probability of any $N+g$ elements, regarded as $\{\gamma^{(z_1)}, \gamma^{(z_2)}, ..., \gamma^{(z_{N+g})}\}$, in S_K set and is also evaluated using (4.7).

4.2.3 i.n.d Rayleigh Fading Channels

Given that the SNR of the PU signal follows exponential distribution for all P-R and P-D links, for any i link ($1 \leqslant i \leqslant L$), the corresponding PDF and CDF are written as [49]

$$f_i(\gamma) = \frac{1}{\overline{\gamma_i}} e^{-\frac{\gamma}{\overline{\gamma_i}}} \tag{4.10}$$

$$F_i(\gamma) = 1 - e^{-\frac{\gamma}{\overline{\gamma_i}}} \tag{4.11}$$

where $\overline{\gamma_i}$ represents the average SNR of the ith link. Similar to the i.i.d. case, the destination first orders the R-D and P-D links in-terms of their SNRs to form the set $U = \{\gamma^{(1)}, \gamma^{(2)}, ..., \gamma^{(L)}\}$ in a descending manner. By combining (4.10) and (4.11), the PDF of the $\gamma^{(k)}$ ($1 \leqslant k \leqslant K$) in the set U is expressed as [64]

$$\begin{aligned} f^{(k)}(\gamma^{(k)}) &= \sum_{x_1=1}^{L} f_{x_1}(\gamma^{(k)}) \sum_{R_{L,k,x_1}} \left(\prod_{m=2}^{L-k+1} F_{x_m}(\gamma^{(k)}) \prod_{v=L-k+2}^{L} (1 - F_{x_v}(\gamma^{(k)})) \right) \\ &= \sum_{x_1=1}^{L} \frac{1}{\overline{\gamma_{x_1}}} e^{-\frac{\gamma}{\overline{\gamma_{x_1}}}} \sum_{R_{L,k,x_1}} \prod_{m=2}^{L-k+1} F_{x_m}(\gamma^{(k)}) \prod_{v=L-k+2}^{L} e^{-\frac{\gamma^{(k)}}{\overline{\gamma_{x_v}}}} \end{aligned} \tag{4.12}$$

where R_{L,k,x_1} is the set including total possible combinations of $L-k$ members chosen from the difference set $\{1, 2, ...L\} - \{x_1\}$. For instance, when $L = 4$, $k = 2$ and $x_1 = 1$, $R_{L,k,x_1} = \{(2,3), (2,4), (3,4)\}$. f_{x_1} is given by (4.10). Since all L links have a chance to be in the set U, $1 \leqslant x_1 \leqslant L$ and F_{x_m} and F_{x_v} are given by (4.11). It is to be noted that the term $\prod_{m=2}^{L-k+1} F_{x_m}(\gamma^{(k)})$ in (4.12) can be expressed as [64]

$$\prod_{m=2}^{L-k+1} F_{x_m}(\gamma^{(k)}) = \sum_{w=0}^{L-k} (-1)^w \sum_{2 \leq b_1 < b_2 < ... < b_w \leq L-k+1} \prod_{p=1}^{w} e^{-\frac{\gamma^{(k)}}{\overline{\gamma_{x_{b_p}}}}} \tag{4.13}$$

Therefore, the PDF of $f^{(k)}(\gamma^{(k)})$ in (4.12) is simplified as

$$f^{(k)}(\gamma^{(k)}) = \sum_{x_1=1}^{L} \frac{1}{\overline{\gamma_{x_1}}} \sum_{R_{L,k,x_1}} \sum_{w=0}^{L-k} (-1)^w \sum_{2\leq b_1<b_2<...<b_w\leq L-k+1} e^{-\delta_w \gamma^{(k)}} \tag{4.14}$$

with

$$\delta_w = \sum_{p=1}^{w} \frac{1}{\overline{\gamma_{x_{bp}}}} + \sum_{v=L-k+2}^{L} \frac{1}{\overline{\gamma_{x_v}}} + \frac{1}{\overline{\gamma_{x_1}}}. \tag{4.15}$$

The joint PDF of any N elements in the set S_K, regarded as $\{\gamma^{(z_1)}, \gamma^{(z_2)}, ..., \gamma^{(z_N)}\}$ $(1 \leqslant z_1 < z_2, .., < z_N \leqslant K; 1 < N \leqslant K)$ for $\gamma^{(z_1)} > ... > \gamma^{(z_N)}$, is given by [65]

$$\begin{aligned} f^{(z_1,z_2...,z_N)} = & \frac{1}{(z_1-1)!(z_2-z_1-1)!...(z_N-z_{N-1})!(L-z_N)!} \\ & \times \sum_{P} \Bigg[\Big(1 - F_{r_1}(\gamma^{(z_1)})\Big) ... \Big(1 - F_{r_{(z_1-1)}}(\gamma^{(z_1)})\Big) \\ & \times f_{r_{z_1}}(\gamma^{(z_1)}) \Big(F_{r_{(z_1+1)}}(\gamma^{(z_1)}) - F_{r_{(z_1+1)}}(\gamma^{(z_2)})\Big) ... \\ & \Big(F_{r_{(z_2-1)}}(\gamma^{(z_1)}) - F_{r_{(z_2-1)}}(\gamma^{(z_2)})\Big) f_{r_{z_2}}(\gamma^{(z_2)}) ... \\ & f_{r_{z_N}}(\gamma^{(z_N)}) F_{r_{(z_N+1)}}(\gamma^{(z_N)}) ... F_{r_L}(\gamma^{(z_N)}) \Bigg] \end{aligned} \tag{4.16}$$

where the set P includes all $L!$ permutations $(r_1, r_2, ..., r_L)$ of $(1, 2, ..., L)$. For example, when $L = 3$, $P = \Big\{(1,2,3),(1,3,2),(2,1,3),(2,3,1),(3,2,1),(3,1,2)\Big\}$ and $(r_1, r_2, ..., r_3)$ can be any element in P.

Now, the probability of detection of $\gamma^{(k)}$ in the set U can be obtained by averaging (3.15) over (4.14) while changing the variable $x = \sqrt{2y}$ and using [66, Eq.(30)] to yield

$$\begin{aligned} \overline{P_d}^{(k)} = & \sum_{x_1=1}^{L} \frac{1}{\overline{\gamma_{x_1}}} \sum_{R_{L,k,x_1}} \sum_{w=0}^{L-k} (-1)^w \sum_{2\leq b_1<b_2<...<b_w\leq L-k+1} \frac{1}{\delta_w} exp\Big(-\frac{\lambda}{2}\Big) \times \\ & \Bigg\{ \Big(\frac{\delta_w+1}{\delta_w}\Big)^{q-1} \Bigg[exp\Big(\frac{\lambda}{2\delta_w+2}\Big) - \sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2\delta_w+2}\Big)^t \Bigg] + \sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2}\Big)^t \Bigg\} \end{aligned} \tag{4.17}$$

Finally, the overall probability of detection using the joint PDF $f^{(z_1,z_2...,z_N)}$ can be obtained by averaging (3.15) over (4.16). The structure of the overall probability of detection over i.n.d channels is the same as (4.8) and (4.9) while replacing the probability of detection of $\gamma^{(k)}$ in the set U by (4.7) and the joint probability of detection of any n elements in the set S_K by the expression (3.15) averaged over (4.16).

4.3 Performance Results

In this section, we compare the proposed multi-selective scheme with some current schemes (SC [6], SLS [7] and general *N-out-of-K* rule [14]) via receiver operating characteristics (ROC) over i.i.d and i.n.d Rayleigh fading channels scenarios. Without loss of generality, for simulation convenient, we assume that the one-sided bandwidth W is 1000Hz, the observation time T is 0.005s, the time bandwidth product q is 5, the number of SUs $L = 6$, multi-selective cooperation scheme selects K=3 reporting links for cooperation where it adopts an OR rule for final decision on PU activity. For the homogenous (i.i.d) case, the average SNR $\overline{\gamma}$ is set to 5 dB while the average SNR $\overline{\gamma}$ in all links ranges from 3dB to 8dB for the heterogeneous (i.n.d) case. We first consider the case of error-free R-D links and then present results for the case of AWGN channel.

In Fig. 4.2, the ROC of the multi-selective cooperation scheme is compared to other combining schemes where it is shown that it outperforms all schemes. This advantage comes from the reason that the proposed scheme selects links with high SNRs where the final decision of the other schemes are based on all links. The same remarks can be drawn for the case of i.n.d Rayleigh fading channels as evident from Fig. 4.3.

To relax the error-free assumption on the R-D links, we consider the case where the links between the relays and destination suffer from AWGN. Since the R-D links are not error-free more, selection combining and the proposed multi-selective scheme consider each relay channel condition consisting of the P-R and R-D links. In this case the multi-selective cooperation requirement is modified to $SNR_{pr-rd} \geq SNR_{pd}$ while selection combining picks out the link with the largest SNR among SNR_{pr-rd} and SNR_{pd}. Without loss of generality, for simulation convenient, we assume that $L = 6$, $P_f = 0.3$, the average SNR ($\overline{\gamma}_{PR} = \overline{\gamma}_{PD} =$

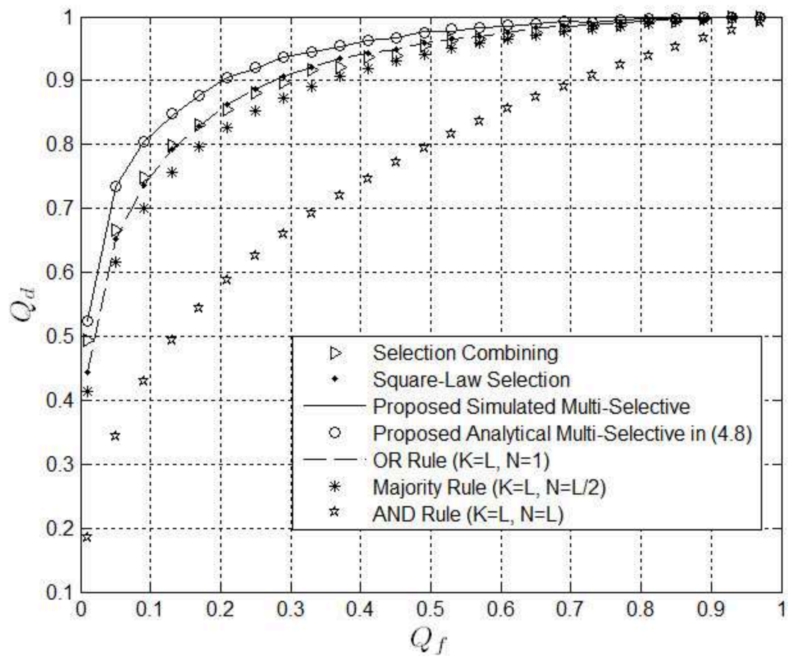

Figure 4.2: ROC curves for SC, SLS, general *N-out-of-K* rule and multi-selective over i.i.d Rayleigh fading channels, $\overline{\gamma} = 5dB$, $L = 6$, $K = 3$, $N = 1$.

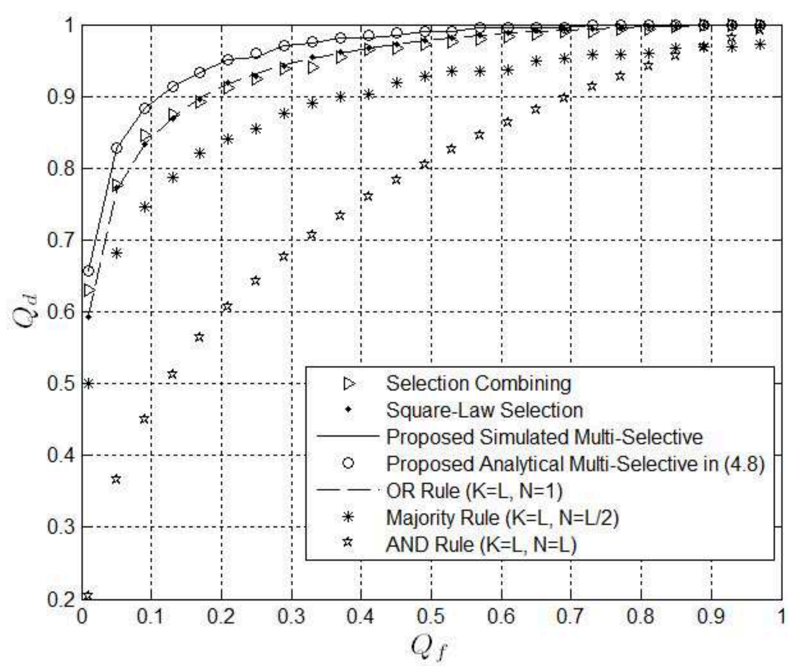

Figure 4.3: ROC curves for SC, SLS, general *N-out-of-K* rule and multi-selective over i.n.d Rayleigh fading channels, $L = 6$, $K = 3$, $N = 1$ and the $\overline{\gamma}$ in L links are arranging from 3dB to 8dB.

$5dB$) for the i.i.d scenario. These results are shown in Fig. 4.4 where the proposed scheme still offers the best performance compared to other detection schemes.

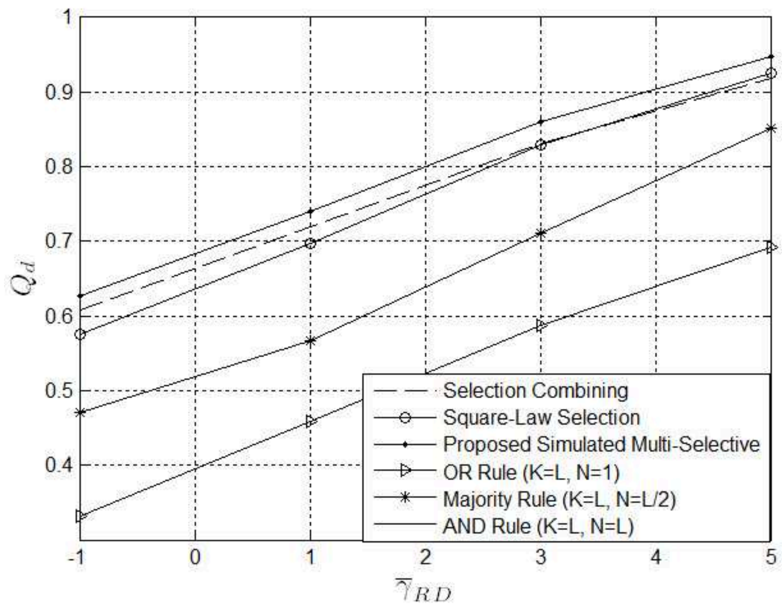

Figure 4.4: Multi-selective and current schemes (SC, general *N-out-of-K* rule, SLS) under the variation of $\overline{\gamma}_{RD}$, $\overline{\gamma}_{PR} = \overline{\gamma}_{PD} = 5dB$, $L = 6$, $P_f = 0.3$, $K = 3$, $N = 1$.

4.4 Optimization of Multi-Selective Scheme over i.i.d and i.n.d Channels

Since the proposed scheme selects K reporting links to form the final decision on the PU activity by using *N-out-of-K* rule, there exists optimal values for N and K that allow for optimum performance results. In this section, we consider such an investigation and find the optimal N and K.

When the threshold λ and N from the *N-out-of-K* rule are given, the performance of detection Q_d and false alarm Q_f increase as the number of selected links K goes high according to (4.1) and (4.8). Thus, the total probability of miss detection $Q_m = 1 - Q_d$ decreases as K goes high. In this case, a performance metric that can be used to assess the performance of the receiver is the total error rate $Q_f + Q_m$ proposed in [24]. In what follows, we use the total error rate as the performance metric to find the optimal K that achieves target error bound $Q_f + Q_m \leq \rho$ for the multi-selective scheme.

Given the detection threshold λ, according to (4.1) and (4.8), the number of selected links K directly affects the total error rate. However when K is fixed, the performance of the multi-selective scheme is dominated by the *N-out-of-K* rule chosen according to (4.8). Therefore, we first solve for the optimal N for a given K. Then we evaluate the optimal number of selected links K that achieves a target error bound $Q_f + Q_m \leq \rho$ for a given optimal N.

4.4.1 Decision Rule

We first examine the performance of the multi-selective cooperation scheme under different *N-out-of-K* rules, i.e., OR, majority, and AND rules. The results of this investigation are presented in Fig. 4 showing the total error rate $Q_f + Q_m$ versus threshold with different *N-out-of-K* rules varying from $N = 1$ to $N = 6$ when the multi-selective scheme selects $K = 6$ reporting links among $L = 10$ SU links. As Fig. 4.5 shows, when the detection threshold is small, i.e. $\lambda = 6$, the OR rule ($N = 1$) outperforms all other rules. Meanwhile, the AND rule ($N = 6$) offers the best performance when the threshold is large, i.e. $\lambda = 21$. Therefore, the optimal N in *N-out-of-K* rule, N_{opt}, is different under different thresholds λ when K is fixed. We express the total error rate using the function $H(N)$ as follows:

$$\begin{aligned} Q_f + Q_m &= Q_f + 1 - Q_d = 1 + H(N) \\ &= 1 + \sum_{j=N}^{K} \binom{K}{j} {P_f}^j (1 - P_f)^{K-j} - \\ &\sum_{S_{K,N}} \overline{P_d}^{(z_1, z_2, \ldots, z_N)} - P_{common}^N \qquad \text{when } N < K \end{aligned} \tag{4.18}$$

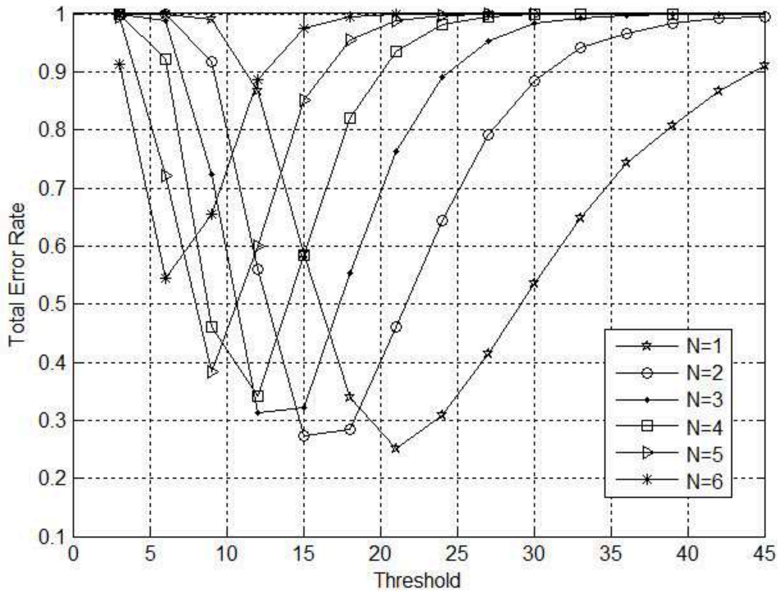

Figure 4.5: Total error rate of multi-selective selected K=6 cooperative nodes in Rayleigh channels: selected relays are N=1,2,3,4,5,6 of L=8, average SNR=5dB.

After some simplifications, the optimal N is reached when $\frac{\partial H(N)}{\partial N} = 0$.

$$\begin{aligned}\frac{\partial H(N)}{\partial N} &\approx H(N+1) - H(N)\\ &= \sum_{S_{K,N}} \overline{P_d}^{(z_1,z_2,\ldots,z_N)} + 2\sum_{g=1}^{K-N} \overline{P_d}^{(z_1,z_2,\ldots,z_{N+g})} - \binom{K}{N} {P_f}^N (1-P_f)^{K-N} +\\ &\sum_{g=2}^{K-N} \sum_{S_{K,N+g}} \left[N+g-1-(-1)^{g+1}\right] \overline{P_d}^{(z_1,z_2,\ldots,z_{N+g})} = 0\\ &\qquad \text{when } N = 1\end{aligned}$$

$$\begin{aligned}\frac{\partial H(N)}{\partial N} &\approx H(N+1) - H(N)\\ &= \sum_{S_{K,N}} \overline{P_d}^{(z_1,z_2,\ldots,z_N)} - \sum_{S_{K,N+1}} \binom{N+1}{N} \overline{P_d}^{(z_1,z_2,\ldots,z_{N+1})} -\\ &\binom{K}{N} {P_f}^N (1-P_f)^{K-N} = 0\\ &\qquad \text{when } K > N > 1\end{aligned} \tag{4.19}$$

Since the number of selected links K is fixed, $\overline{P_d}^{(z_1,z_2,\ldots,z_N)}$ varies with N. Now let us define a function $G(N)$ to express the polynomial in (4.19). Thus, N_{opt} is obtained when it satisfies the following function

$$G(N_{opt}) = \binom{K}{N_{opt}} {P_f}^{N_{opt}}(1-P_f)^{K-N_{opt}}. \tag{4.20}$$

According to (3.14),(3.15) and (4.7), $\overline{P_d}^{(z_1,z_2,\ldots,z_N)}$ and P_f decrease with the threshold λ (this was also proved in [6, Fig. 1]). Therefore, when the threshold is small enough, the right hand side of (4.20) goes high with N. From (4.8), since the left hand side of (4.20) decreases with N, $N_{opt} = 1$ when the threshold is small and $N_{opt} = K$ when the threshold is large.

4.4.2 Optimal Number of Selected Links (K)

In the multi-selective scheme, the local decisions of K selected links are used for final decision at the destination. Our objective here is to find the optimal $K_{opt}(1 \leq K_{opt} \leq L)$ that achieves a total error rate target bound, $Q_f + Q_m \leq \rho$ for a given detection threshold λ.

We first evaluate the corresponding optimal *N-out-of-K* rule for each K, N_K^{opt}, by using (4.20). Then we define a new function $T(.,.)$ in terms of the variable K as

$$T(K, N_K^{opt}) = Q_f + Q_m - \rho = 1 + Q_f - Q_d - \rho \tag{4.21}$$

where K is the number of selected links used for final decision. Since the false alarm Q_f and detection Q_d are varied with K, and N_K^{opt} is given by (4.20), the optimal K is the one that satisfies the following conditions

$$T(K_{opt}, N_{K_{opt}}^{opt}) \leq 0 \tag{4.22}$$

$$T(K_{opt}-1, N_{K_{opt}-1}^{opt}) > 0. \tag{4.23}$$

From (4.22) and (4.23), K_{opt} is the first crossing zero of the function $T(K, N_K^{opt})$ plotted against K. For example, consider $L = 20$ available links to the destination with average

SNR $\gamma = 5dB$ over all links, and a target error rate bound $Q_f + Q_m \leq 0.1$ with a given detection threshold $\lambda = 18$. Fig. 4.6 shows $Q_f(K,N) + Q_m(K,N)$ versus K applied with optimal *N-out-of-K* rule ($N = N_K^{opt}$). As the results in Fig. 4.6 show, $Q_f + Q_m \leq 0.1$ is achieved when $K_{opt} = 4$ under corresponding optimal rule $N_{K_{opt}}^{opt} = 2$ which is shown in Fig. 4.7.

Now, we explain the reason why N_{opt} increases as K increases. As shown in (4.21), $Q_m = 1 - Q_d$ decreases when K goes high while Q_f increases when K goes high under the conditions that the threshold λ, the average SNR γ, N and the total number of links to destination L are fixed. These phenomenons match well with the simulations in Figs. 4.8,4.9. However, the rate of Q_m decrease (Q_m versus K) and the rate of Q_f increase (Q_f versus K) are functions of N as evident from Figs. 4.8,4.9. For instance, when $N = 2$, we notice that the rate of Q_m decrease (Q_m versus K) is much slower than the rate of Q_f increase (Q_f versus K) as K goes high. Furthermore, we notice that the rate of Q_f increase (Q_f versus K) becomes flat as N increases which agrees well with the finding in [14]. Hence, to achieve the optimal performance on the total error, N is increased as K goes high to slow down the rate of Q_f increase (evident from Fig. 4.7). This in-turns results in lower total error rate as Fig. 4.6 shows.

As a final investigation, we consider the case of i.n.d Rayleigh fading channels. The optimization analysis is similar to the i.i.d case where the probability of detection is given by (4.17) for the i.n.d case. Let us consider the performance of the multi-selective scheme over i.n.d Rayleigh fading channels with $L = 14$ where the SNR of the different P-R links ranges from $2dB$ to $15dB$, and the target error rate $Q_f + Q_m \leq 0.02$ with a given threshold $\lambda = 18$. As Figs. 4.10, 4.11 show, the required total error rate is achieved when $K_{opt} = 2$ with a corresponding optimal rule $N_{K_{opt}}^{opt} = 2$.

4.5 Conclusions

Multi-selective cooperation not only improves SC performance but also saves bandwidth usage in sharing spectrum sensing data. After optimization analysis of total error rates, we

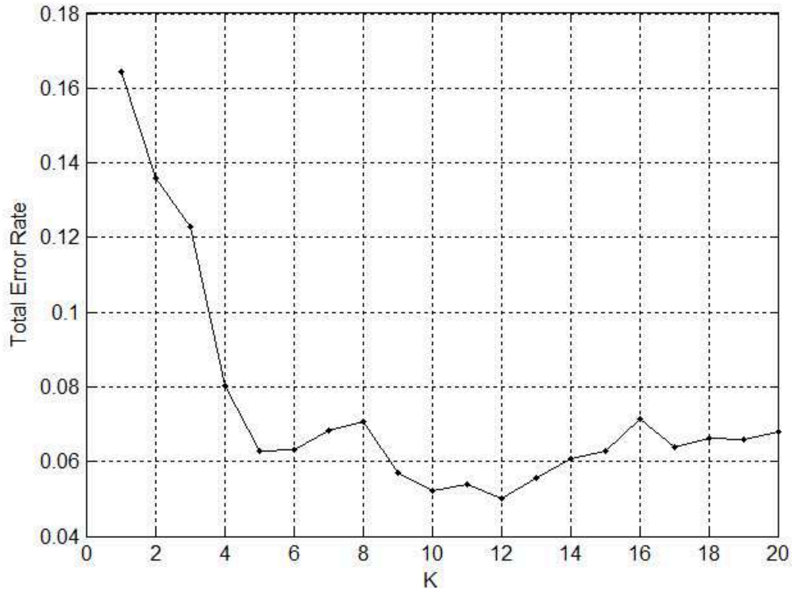

Figure 4.6: Total error rate of multi-selective energy detection versus number of cooperative selected nodes K in a network with $L = 20$ in Rayleigh fading with average $SNR = 5dB$, optimal voting rule applied for each K, detection threshold $\lambda = 18$.

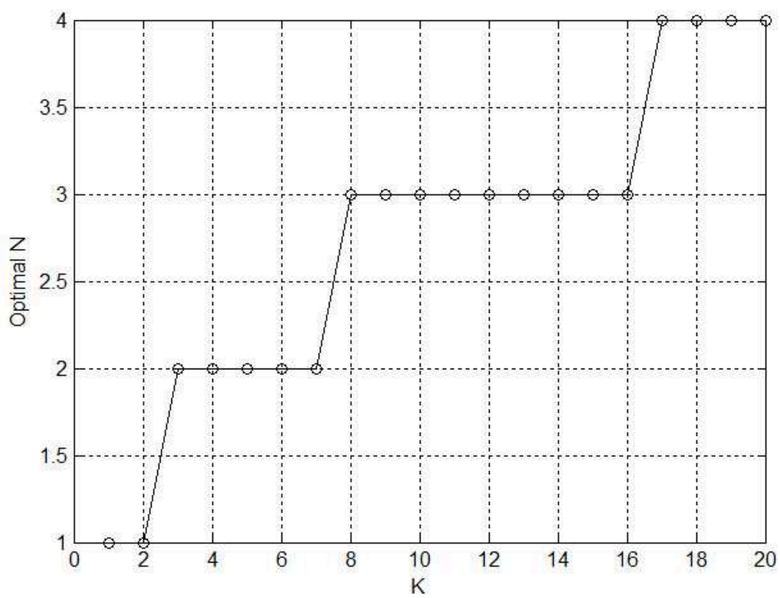

Figure 4.7: Corresponding optimal voting rule for each K, detection threshold $\lambda = 18$, $L = 20$ and average $SNR = 5dB$.

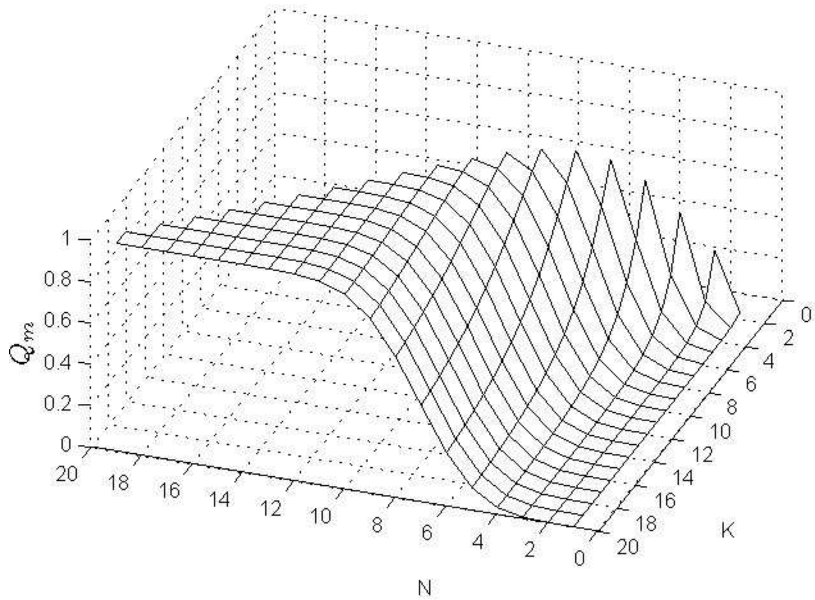

Figure 4.8: Total average probability of miss detection of multi-selective energy detection versus number of cooperative selected nodes K and N in *N-out-of-K* rule in a network with $L = 20$ in Rayleigh fading with average $SNR = 5dB$, detection threshold $\lambda = 18$.

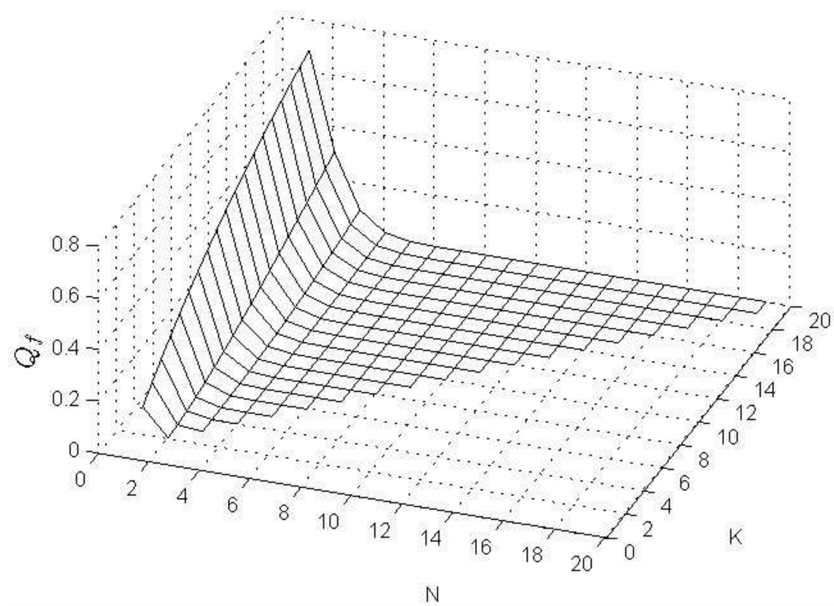

Figure 4.9: Total average probability of false alarm of multi-selective energy detection versus number of cooperative selected nodes K and N in *N-out-of-K* rule in a network with $L = 20$ in Rayleigh fading with average $SNR = 5dB$, detection threshold $\lambda = 18$.

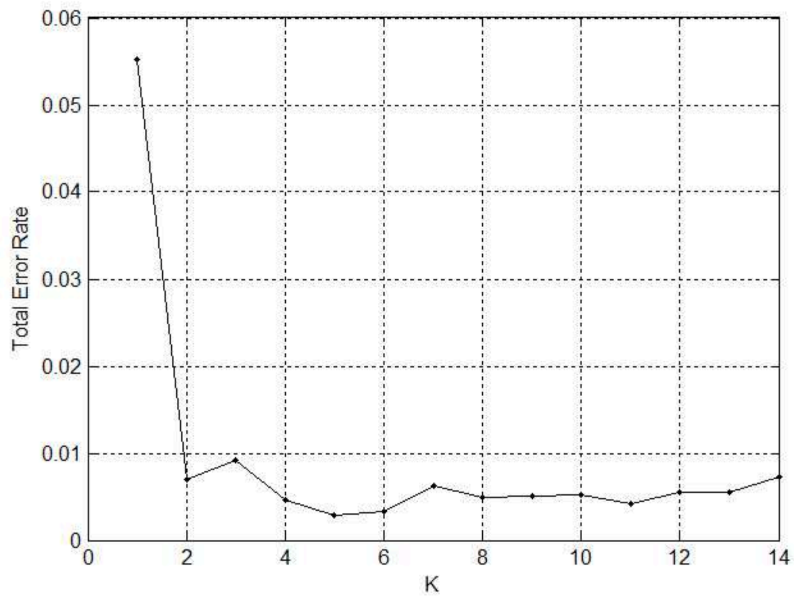

Figure 4.10: Total error rate of multi-selective energy detection versus number of cooperative selected nodes K in a network with $L = 14$ in Rayleigh fading with average SNR for all links arranged from $2dB$ to $15dB$ respectively, optimal voting rule is applied for each K and the detection threshold $\lambda = 18$.

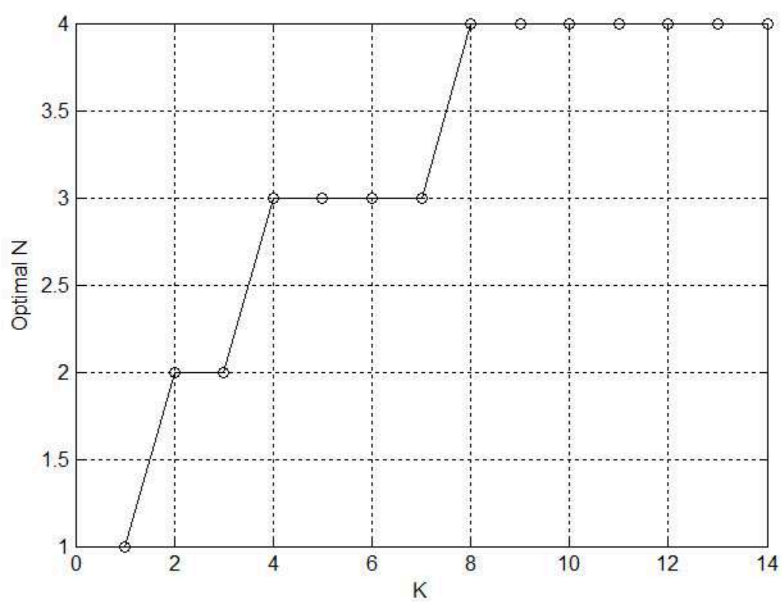

Figure 4.11: Corresponding optimal voting rule for each K, detection threshold $\lambda = 18$, $L = 14$ and with average SNR for each link from $2dB$ to $15dB$ respectively.

have noticed that optimal N in N-*out-of*-K rule is monotonous increase with threshold λ and found a method to approach optimal k, the number of selected SUs under total error rate requirement. Simulation has shown that multi-selective scheme offers much improvement in detection compared with SC over i.i.d Rayleigh fading channels and performs better than SLC and SLS do in i.n.d Rayleigh fading channels. However, multi-selective cooperation scheme requires complex optimization calculation to reach cognitive network's requirement, i.e. total error requirement. Thus, selective-cooperation scheme is proposed in the next chapter.

Chapter 5

Selective-Cooperation Scheme

Although multi-selective cooperation has much improved selection combining (SC) spectrum sensing performance, it still performs a little bit worse than square-law combining (SLC). Thus, this chapter proposes more efficient scheme, named selective-cooperation, which performs better than SLC and other schemes mentioned above over both i.i.d Rayleigh fading i.n.d Rayleigh fading. In this chapter, the probability of detection equation will be derived over both i.i.d Rayleigh fading channels and i.n.d Rayleigh fading channels. Later, the performance comparison between selective-cooperation scheme and other cooperative spectrum sensing schemes mentioned above will be analyzed and the conclusions will follow.

Firstly, we introduce selective-cooperation scheme's mechanism. We consider that the SU which is waiting for using spectrum, as destination, other SUs as cooperative relays; the number of links including P-R (from primary to relay) links and single P-D (from primary to destination) link is represented by L. Also, R-D (from relay to destination) links are assumed as free of error for deriving selective-cooperation detection expressions. Then we relax this assumption by considering more realistic P-D links that suffer from AWGN, where the destination and relays are in the vicinity of each other forming a cluster. Also, we assume the link is block-fading, that is the instantaneous SNRs remain constant for the duration of one observation time. Given this assumption, the destination accepts relays' collaboration only if the collaboration requirement $SNR_{pr} \geq SNR_{pd}$ is achieved, i.e. when the destination finds out that the relay's received signal is more reliable than destination's received signal. If all relays do not satisfy the requirement above, the destination will switch to noncooperation mode. Each relay sends its own 1-bit local decision representing primary signal status, and local SNR_{pr} to the destination. The destination accepts the relay local decision when its local SNR_{pr} is larger than SNR_{pd}. Then the destination combines the decisions by using OR rule since OR rule outperforms other rules in *N-out-of-K* [14]. Here, the concept of OR rule is that the destination confirms primary user is absent if single or more local decisions confirm(s) the absence of primary user.

In what follows, we introduce the advantages of selective-cooperation in-terms of the bandwidth usage, probability of detection, and false alarm.

5.1 Bandwidth Usage for Sharing the Spectrum Sensing Data

For SLS and SLC, relays send their decision statistic y_i to destination for sharing the spectrum sensing data while SC scheme requires relays send both local SNR_{pr} status information and y_i to destination. Thus, SC requires more bandwidth for sharing the spectrum sensing data compared with SLC and SLS. On the other hand, the selective-cooperation scheme requires relays to send local SNR_{pr} status information and 1-bit local decision to destination. In comparison with SLS and SLC, selective-cooperation requires nearly the same bandwidth as SLS and SLC do for sharing the spectrum sensing data.

5.2 Probability of False Alarm

Under selective-cooperation scheme, the relay satisfying the requirement, $SNR_{pr} \geq SNR_{pd}$, is selected where $\gamma = \frac{a^2 E_s}{N_{01}}$. Thus, the destination selects the relay with required a as (3.1) shows. However, the received signal under H_0 only includes noise irrespective of the destination relay selection. Hence the destination will switch to noncooperation model.

Thus, the average false alarm probability using selective-cooperation ($\overline{P}_f$) is equate to the (3.14).

5.3 Probability of Detection

In what follows, we will discuss and derive the probability of detection of selective-cooperation over both i.i.d and i.n.d Rayleigh fading channels.

5.3.1 i.i.d Rayleigh Fading Channels

We assume that the order statistics of L links' SNRs are arranged as a non-increasing set, $U = \{\gamma^{(1)}, \gamma^{(2)}, ..., \gamma^{(L)}\}$. Since the probability of $SNR_{pr} = SNR_{pd}$ is small, U is considered as strictly decreasing set in the following expression deduction. Since selective-cooperation scheme accepts relays' collaboration only if the collaboration requirement $SNR_{pr} \geq SNR_{pd}$ is achieved, we assume that P-D link's SNR is settled in $\gamma^{(h)}$ in the U set. That is the scheme will accept links from $\gamma^{(1)}$ to $\gamma^{(h)}$ for collaboration, represented by the set $S_h = \{\gamma^{(1)}, \gamma^{(2)}, ..., \gamma^{(h)}\}$.

We first present the general PDF of $\gamma^{(\tau)}$ ($1 \leq \tau \leq L$) in the U set. From the general PDF, the PDF of P-D link's SNR settled in $\gamma^{(h)}$ in the U set, the conditional PDF of $\gamma^{(j)}$ ($j < h$) in the S_h set, and the conditional joint PDF of the $\gamma^{(i)}$ and $\gamma^{(j)}$ ($i < j < h$) in the S_h set are derived.

Since the SNR follows i.i.d. Rayleigh fading channels in P-D, P-R links, the SNR's corresponding probability density function (PDF) of the SNR follows exponential distribution [6]. Thus, the general PDF of the $\gamma^{(\tau)}$ in the U set, $f^{(\tau)}(\gamma^{(\tau)})$, is given by [62]

$$f^{(\tau)}(\gamma^{(\tau)}) = \frac{L!}{(\tau-1)!(L-\tau)!} F^{L-\tau}(\gamma^{(\tau)})[1 - F(\gamma^{(\tau)})]^{\tau-1} f(\gamma^{(\tau)}) \tag{5.1}$$

where $F(\gamma^{(\tau)}) = 1 - e^{-\gamma^{(\tau)}/\overline{\gamma}}$ is the cumulative distribution function (CDF) of the SNR over Rayleigh fading channel, and $f(\gamma^{(\tau)})$ is the corresponding PDF [49].

Since the SNRs in all L links are i.i.d, any link has the same probability $(1/L)$ being settled in $\gamma^{(\tau)}$. Thus, we rewrite (5.1) as

$$\begin{aligned} f^{(\tau)} &= L\frac{(L-1)!}{(\tau-1)!(L-\tau)!}F^{L-\tau}(\gamma^{(\tau)})[1-F(\gamma^{(\tau)})]^{\tau-1}f(\gamma^{(\tau)}) \\ &= L\binom{L-1}{\tau-1}F^{L-\tau}(\gamma^{(\tau)})[1-F(\gamma^{(\tau)})]^{\tau-1}f(\gamma^{(\tau)}). \end{aligned} \tag{5.2}$$

From (5.2), we notice that the PDF of the P-D link's SNR settled in $\gamma^{(h)}$ when $\tau = h$ in the U set is derived as

$$f^{(h)}_{PD=h}(\gamma^{(h)}) = \binom{L-1}{h-1}F^{L-h}(\gamma^{(h)})[1-F(\gamma^{(h)})]^{h-1}f(\gamma^{(h)}) \tag{5.3}$$

Since the selective-cooperation scheme adopts OR rule in the S_h set for collaboration, the overall probability of detection of S_h is calculated as the sum of element's corresponding probability of detection in this set. Thus, to derive the PDF of $\gamma^{(j)}$ $(1 \leqslant j < h)$ in the S_h set under the condition that P-D link's SNR in $\gamma^{(h)}$. Since the P-D link's SNR is in $\gamma^{(h)}$ and other $L-1$ links have the same probability $(1/(L-1))$ to be settled in $\gamma^{(j)}$, we derive this PDF of $\gamma^{(j)}$ according to (5.1) as

$$f^{(j)}_{PD=h}(\gamma^{(j)}) = (L-1)\frac{(L-2)!}{(j-1)!(L-j-1)!}F^{L-j}(\gamma^{(j)})[1-F(\gamma^{(j)})]^{j-1}f(\gamma^{(j)}) \tag{5.4}$$

and hence

$$f^{(j)}_{PD=h}(\gamma^{(j)}) = \frac{(L-1)!}{(j-1)!(L-j-1)!}\sum_{i=0}^{L-j}\frac{(-1)^i}{j+i}\binom{L-j}{i}\frac{1}{\overline{\gamma}/(j+i)}e^{-\frac{\gamma^{(j)}}{\overline{\gamma}/(j+i)}}. \tag{5.5}$$

Therefore, the $f^{(h)}_{PD=h}$ corresponding average probability detection $\overline{P}^{(j)}_{d(PD=h)}$, is evaluated by averaging (3.15) over (5.5) yielding

$$
\begin{aligned}
\overline{P_{d(PD=h)}^{(j)}} &= \int f_{PD=h}^{(j)}(\gamma^{(j)}) Q_q(\sqrt{2\gamma^{(j)}}, \sqrt{\lambda}) d\gamma^{(j)} \\
&= \frac{(L-1)!}{(j-1)!(L-j-1)!} \sum_{i=0}^{L-j} \frac{(-1)^i}{j+i} \binom{L-j}{i} \overline{P_{dR}}\Big(\frac{\overline{\gamma}}{j+i}\Big)
\end{aligned} \tag{5.6}
$$

where $\overline{P_{dR}}\Big(\frac{\overline{\gamma}}{j+i}\Big)$ is from (3.20) by replacing $\overline{\gamma}$ with $\frac{\overline{\gamma}}{j+i}$.

Comparing (5.3) with (5.4), we notice that average probability detection $\overline{P_{d(PD=h)}^{(h)}}$ is similar to $\overline{P_{d(PD=h)}^{(j)}}$ by replacing $\frac{(L-1)!}{(j-1)!(L-j-1)!}$ with $\frac{(L-1)!}{(h-1)!(L-h)!}$,

$$
\begin{aligned}
\overline{P_{d(PD=h)}^{(h)}} &= \int f_{PD=h}^{(h)}(\gamma^{(h)}) Q_q(\sqrt{2\gamma^{(h)}}, \sqrt{\lambda}) d\gamma^{(h)} \\
&= \frac{(L-1)!}{(h-1)!(L-h)!} \sum_{i=0}^{L-h} \frac{(-1)^i}{h+i} \binom{L-h}{i} \overline{P_{dR}}\Big(\frac{\overline{\gamma}}{h+i}\Big).
\end{aligned} \tag{5.7}
$$

However, elements in S_h are dependent from each other, the overall probability of detection of S_h should minus all possible joint probability of detection in S_h. Thus, we need to derive the joint PDF in the S_h set under the condition that P-D link's SNR in $\gamma^{(h)}$. In this chapter, we derive the joint PDF of $\gamma^{(i)}$ and $\gamma^{(j)}$ $(i < j < h)$ in the S_h set under the condition that P-D link's SNR in $\gamma^{(h)}$. Since P-D link's SNR is in $\gamma^{(h)}$, one of the $L-1$ links has the probability $(1/(L-1))$ settled in $\gamma^{(j)}$ and other $L-2$ links have the same probability $(1/(L-2))$ to be settled in $\gamma^{(i)}$, this joint PDF is derived as

$$
\begin{aligned}
f_{PD=h}^{(i,j)}(\gamma^{(i)}, \gamma^{(j)}) = (L-1)&\binom{L-i-2}{j-i-1}(L-2)\binom{L-3}{i-1} \times \\
&F^{L-j}(\gamma^{(j)})[F(\gamma^{(i)}) - F(\gamma^{(j)})]^{j-i-1}[1-F(\gamma^{(i)})]^{i-1} f(\gamma^{(i)}) f(\gamma^{(j)}) \\
&= \frac{(L-1)!}{(i-1)!(j-i-1)!(L-j-1)!} \times \\
&F^{L-j}(\gamma^{(j)})[F(\gamma^{(i)}) - F(\gamma^{(j)})]^{j-i-1}[1-F(\gamma^{(i)})]^{i-1} f(\gamma^{(i)}) f(\gamma^{(j)}) \\
&for \qquad i < j \qquad and \qquad \gamma^{(i)} > \gamma^{(j)} \geqslant \gamma^{(h)}
\end{aligned} \tag{5.8}
$$

The average joint probability of $f^{(i,j)}_{PD=h}$ is evaluated by averaging (3.15) over (5.8) yielding

$$\begin{aligned}\overline{P}^{(i,j)}_{d(PD=h)} = \int_{\gamma_i}^{\infty}\int_{0}^{\gamma_j} & f^{(i,j)}_{PD=h}(\gamma^{(i)},\gamma^{(j)})\times \\ & Q_q\Big(\sqrt{2\gamma^{(i)}},\sqrt{\lambda}\Big)Q_q\Big(\sqrt{2\gamma^{(j)}},\sqrt{\lambda}\Big)d\gamma^{(j)}d\gamma^{(i)}.\end{aligned} \tag{5.9}$$

The joint probability of any two or more elements in the S_h set can be derived from (5.8) and (5.9).

Now, we start to evaluate the total probability of selective-cooperation over i.i.d Rayleigh fading channels. Let P_h represents the overall probability of detection in the S_h set. Since P-D link can be settled in any place in the U set, h is varied from 1 to L. Therefore, the total probability of detection of selective-cooperation is written as the sum of P_h $(h = 1, 2, 3, ..., L)$,

$$\overline{P}_d = \sum_{h=1}^{L} P_h. \tag{5.10}$$

In S_h set, we adopt OR rule for P_h calculation. In another words, signal is present when at least one of the reporting links from $\gamma^{(1)}$ to $\gamma^{(h)}$ having detected the primary signal. Since elements in S_h are not independent according to (5), P_h is expressed as

$$P_h = \begin{cases} \left(\sum_{i=1}^{h}\overline{P}^{(i)}_{d(PD=h)}\right) - P^{PD=h}_{common} & \text{if } h > 1 \\ \overline{P}^{(1)}_{d(PD=1)} & \text{if } h = 1 \end{cases} \tag{5.11}$$

where $\overline{P}^{(i)}_{d(PD=h)}$ is expressed by (5.6) when $i < h$ and is expressed by (5.7) when $i = h$; $P^{PD=h}_{common}$ represents the sum of joint probability of detection of elements in the S_h set. For instance, when $PD = h = 3$, $P^{PD=h}_{common}$ is expressed as $P^{PD=h}_{common} = \overline{P}^{(1,2)}_{d(PD=3)} + \overline{P}^{(1,3)}_{d(PD=3)} + \overline{P}^{(2,3)}_{d(PD=3)} - \overline{P}^{(1,2,3)}_{d(PD=3)}$, where $\overline{P}^{(i,j)}_{d(PD=h)}$, calculated by (12), represents the joint probability of SNRs in i_{th} and j_{th} ($\gamma^{(i)}$ and $\gamma^{(j)}$) in the S_h set under the condition that P-D link's SNR in $\gamma^{(h)}$. In general, $P^{PD=h}_{common}$ is derived as

$$P^{PD=h}_{common} = \sum_{g=2}^{h}\sum_{S_{h,g}}(-1)^g\overline{P}^{(z_1,z_2,...,z_g)}_{d(PD=h)} \tag{5.12}$$

where $\overline{P}_{d(PD=h)}^{(z_1,z_2,...,z_g)}$ represents the joint probability of $\gamma^{(z_1)}, \gamma^{(z_2)}, ..., \gamma^{(z_g)}$ $(1 \leq z_1 < z_2 < ... < z_g \leq h)$ in the S_h set under the condition that P-D link's SNR in h_{th} in the U set. $\overline{P}_{d(PD=h)}^{(z_1,z_2,...,z_g)}$ can be derived from (5.8).

5.3.2 i.n.d Rayleigh Fading Channels

All L links' SNRs are arranged in a decreasing order, denoted by $U = \{\gamma^{(1)}, \gamma^{(2)}, ..., \gamma^{(L)}\}$ for short. Still, we assume that P-D link's SNR is settled in $\gamma^{(h)}$ in the U set.

The SNR follows an exponential distribution in all the P-R and P-D links over Rayleigh fading channels. For any i link $(1 \leqslant i \leqslant L)$, the corresponding PDF and CDF are written as [6]

$$f_i(\gamma) = \frac{1}{\overline{\gamma}_i} e^{-\frac{\gamma}{\overline{\gamma}_i}} \tag{5.13}$$

$$F_i(\gamma) = 1 - e^{-\frac{\gamma}{\overline{\gamma}_i}} \tag{5.14}$$

In $U = \{\gamma^{(1)}, \gamma^{(2)}, ..., \gamma^{(L)}\}$, the PDF of $\gamma^{(\tau)}$, is obtained from [64], which is expressed as

$$f^{(\tau)}(\gamma^{(\tau)}) = \sum_{x_1=1}^{L} f_{x_1}(\gamma^{(\tau)}) \sum_{R_{L,\tau,x_1}} \left(\prod_{m=2}^{L-\tau+1} F_{x_m}(\gamma^{(\tau)}) \prod_{v=L-\tau+2}^{L} [1 - F_{x_v}(\gamma^{(\tau)})] \right) \tag{5.15}$$

where R_{L,τ,x_1} is the set including total possible combinations of $L-\tau$ members chosen from the difference set regarded as $\{1, 2, ...L\} - \{x_1\}$. For instance, when $L = 4$, $\tau = 2$ and $x_1 = 1$, $R_{L,\tau,x_1} = \big\{(2,3), (2,4), (3,4)\big\}$. f_{x_1} is given by (5.13). F_{x_m} and F_{x_v} are given by (5.14).

The general PDF of $\gamma^{(\tau)}$ over i.n.d channels is given above. We start to derive the PDF of $\gamma^{(h)}$ when $\tau = h$ in the U set over i.n.d Rayleigh fading channels from (5.15). Using (5.13) and (5.14) into (5.15), the PDF of $f^{(h)}(\gamma^{(h)})$ in (5.15) is further simplified as

$$f^{(h)}(\gamma^{(h)}) = \sum_{x_1=1}^{L} \frac{1}{\overline{\gamma}_{x_1}} \sum_{R_{L,h,x_1}} \sum_{w=0}^{L-h} (-1)^w \sum_{2 \leq n_1 < n_2 < ... < n_w \leq L-h+1} e^{-\mu_w \gamma^{(h)}} \tag{5.16}$$

with

$$\mu_w = \sum_{p=1}^{w} \frac{1}{\overline{\gamma_{x_{np}}}} + \sum_{v=L-h+2}^{L} \frac{1}{\overline{\gamma_{x_v}}} + \frac{1}{\overline{\gamma_{x_1}}}. \tag{5.17}$$

Assume $\overline{\gamma_1}$ i.e, $x_1 = 1$, as the average SNR $\overline{\gamma}$ of the P-D link. From $\sum_{x_1=1}^{L} f_{x_1}(\gamma^{(h)})$ in (5.15), we notice that each link's SNR has a chance to be arranged in $\gamma^{(h)}$ in the U set. Therefore, the PDF of P-D link's SNR settled in $\gamma^{(h)}$ in the U set is derived from (5.16) by replacing $\sum_{x_1=1}^{L} \frac{1}{\overline{\gamma_{x_1}}}$ with $\frac{1}{\overline{\gamma_1}}$,

$$\begin{aligned} f_{PD=h}^{(h)}(\gamma^{(h)}) &= f_1(\gamma^{(h)}) \sum_{R_{L,h,1}} \left(\prod_{m=2}^{L-h+1} F_{x_m}(\gamma^{(h)}) \prod_{v=L-h+2}^{L} [1 - F_{x_v}(\gamma^{(h)})] \right) \\ &= \frac{1}{\overline{\gamma_1}} \sum_{R_{L,h,1}} \sum_{w=0}^{L-h} \left((-1)^w \sum_{2 \le n_1 < n_2 < \ldots < n_w \le L-h+1} e^{-\mu_w^{'} \gamma^{(h)}} \right) \end{aligned} \tag{5.18}$$

with

$$\mu_w^{'} = \sum_{p=1}^{w} \frac{1}{\overline{\gamma_{x_{np}}}} + \sum_{v=L-h+2}^{L} \frac{1}{\overline{\gamma_{x_v}}} + \frac{1}{\overline{\gamma_1}}, \tag{5.19}$$

where $S_{L,h,1}$ is the set including total possible combinations of $L-h$ members chosen from the difference set $\{1, 2, \ldots L\} - \{1\}$.

On the other hand, each P-R link has a chance to be arranged in $\gamma^{(j)}$ $(j < h)$ under the condition that P-D link settled in $\gamma^{(h)}$. Thus, this PDF of $\gamma^{(j)}$ is written as

$$\begin{aligned} f_{PD=h}^{(j)}(\gamma^{(j)}) &= \sum_{x_1=2}^{L} f_{x_1}(\gamma^{(j)}) \sum_{R_{L,j,x_1,1}} \left(F_1(\gamma^{(j)}) \prod_{m=2}^{L-j} F_{x_m}(\gamma^{(j)}) \prod_{v=L-j+2}^{L} [1 - F_{x_v}(\gamma^{(j)})] \right) \\ &= \sum_{x_1=2}^{L} \frac{1}{\overline{\gamma_{x_1}}} \sum_{R_{L,j,x_1,1}} \left(\sum_{w=0}^{L-j-1} (-1)^w \times \right. \\ & \left. \left[\sum_{2 \le n_1 < n_2 < \ldots < n_w \le L-j} e^{-\mu_w^{''} \gamma^{(j)}} - \sum_{2 \le n_1 < n_2 < \ldots < n_w \le L-j} e^{-\mu_w^{'''} \gamma^{(j)}} \right] \right) \end{aligned} \tag{5.20}$$

with

$$\mu_w^{''} = \sum_{p=1}^{w} \frac{1}{\overline{\gamma_{x_{np}}}} + \sum_{v=L-j+2}^{L} \frac{1}{\overline{\gamma_{x_v}}} + \frac{1}{\overline{\gamma_{x_1}}}. \tag{5.21}$$

$$\mu_w^{'''} = \frac{1}{\gamma_1} + \sum_{p=1}^{L-j-1} \frac{1}{\gamma_{x_{np}}} + \sum_{v=L-j+2}^{L} \frac{1}{\gamma_{x_v}} + \frac{1}{\gamma_{x_1}}. \tag{5.22}$$

where $R_{L,j,x_1,1}$ is the set including total possible combinations of $L-j-1$ members chosen from the difference set $\{1,2,...L\} - \{1\} - \{x_1\}$ $(2 \leqslant x_1 \leqslant L)$.

The probability of detection of $f_{PD=h}^{(j)}$ is obtained by averaging (3.15) over (5.20) while making use of [66, Eq.(30)]

$$\begin{aligned}
\overline{P}_{d(PD=h)}^{(j)} = &\sum_{x_1=2}^{L} \frac{1}{\gamma_{x_1}} \sum_{R_{L,j,x_1,1}} \Bigg(\sum_{w=0}^{L-j-1} (-1)^w \Bigg(\sum_{2 \leq n_1 < n_2 < ... < n_w \leq L-j} \frac{1}{\mu_w^{''}} exp\Big(-\frac{\lambda}{2}\Big) \times \\
&\Bigg\{ \Big(\frac{\mu_w^{''}+1}{\mu_w^{''}} \Big)^{q-1} \Big[exp\Big(\frac{\lambda}{2\mu_w^{''}+2} \Big) - \sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2\mu_w^{''}+2} \Big)^t \Big] + \sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2} \Big)^t \Bigg\} - \\
&\sum_{2 \leq n_1 < n_2 < ... < n_w \leq L-j} \frac{1}{\mu_w^{'''}} exp\Big(-\frac{\lambda}{2}\Big) \Bigg\{ \Big(\frac{\mu_w^{'''}+1}{\mu_w^{'''}} \Big)^{q-1} \Big[exp\Big(\frac{\lambda}{2\mu_w^{'''}+2} \Big) - \\
&\sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2\mu_w^{'''}+2} \Big)^t \Big] + \sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2} \Big)^t \Bigg\} \Bigg) \Bigg)
\end{aligned} \tag{5.23}$$

For the P-D link, its corresponding probability of detection $\overline{P}_{d(PD=h)}^{(h)}(\gamma)$ is obtained by averaging (3.15) over (5.18) given as

$$\begin{aligned}
\overline{P}_{d(PD=h)}^{(h)} = &\frac{1}{\gamma_1} \sum_{R_{L,h,x_1}} \sum_{w=0}^{L-h} (-1)^w \sum_{2 \leq n_1 < n_2 < ... < n_w \leq L-h+1} \Bigg(\frac{1}{\mu_w^{'}} exp\Big(-\frac{\lambda}{2}\Big) \times \\
&\Bigg\{ \Big(\frac{\mu_w^{'}+1}{\mu_w^{'}} \Big)^{q-1} \Big[exp\Big(\frac{\lambda}{2\mu_w^{'}+2} \Big) - \sum_{t=0}^{q-2} \frac{1}{t!} \Big(\frac{\lambda}{2\mu_w^{'}+2} \Big)^t \Big] + \sum_{t=0}^{q-2} \frac{1}{t!} (\frac{\lambda}{2})^t \Bigg\} \Bigg).
\end{aligned} \tag{5.24}$$

Under the condition that P-D link' SNR in $\gamma^{(h)}$ $(i < j < h)$ in the S_h set, each P-R link's SNR gets an opportunity to be ordered in i_{th} or j_{th}. Therefore, this joint PDF of $\gamma^{(i)}$ and

$\gamma^{(j)}$ in the S_h set is evaluated from (5.16) and (5.20),

$$f^{(i,j)}_{PD=h}(\gamma^{(i)},\gamma^{(j)}) = \sum_{x_1=2}^{L}\sum_{\substack{x_2=2\\x_1\neq x_2}}^{L} f_{x_1}(\gamma^{(i)})f_{x_2}(\gamma^{(j)}) \sum_{R_{L,x_1,x_2,1}} \Bigg(F_1(\gamma^{(j)})\prod_{m=3}^{L-j+1} F_{x_m}(\gamma^{(j)})\times \prod_{v=L-j+2}^{L-i}[F_{x_v}(\gamma^{(i)})-F_{x_v}(\gamma^{(j)})]\prod_{c=L-i+1}^{L-1}[1-F_{x_c}(\gamma^{(i)})]\Bigg) \tag{5.25}$$

where $R_{L,x_1,x_2,1}$ is the set including total possible combinations of $L-j-1$ members chosen from the difference set $\{1,2,...,L\}-\{x_1\}-\{x_2\}-\{1\}$ $(x_1 \neq x_2)$.

The joint probability of detection of $f^{(i,j)}_{PD=h}(\gamma^{(i)},\gamma^{(j)})$ is given by averaging (3.15) over (5.25) yielding expression same as (5.9). Finally, the total probability of detection over i.n.d channels, P_d, is the combination of (5.10), (5.11) and (5.12) replacing $\overline{P_d}^{(i)}_{(PD=h)}$, $\overline{P_d}^{(h)}_{(PD=h)}$ and $f^{(i,j)}_{PD=h}$ by (5.23), (5.24) and (5.25).

The performance comparison between selective-cooperation, SC (selection combination) [6], SLS (Square-Law Selection) [7] and SLC (Square-Law Combining) [7] is analyzed in the next section.

5.4 Simulations Results

In this section, we compare selective-cooperation scheme with some current schemes mentioned in section I via receiver operating characteristic (ROC) curves over both i.i.d and i.n.d Rayleigh fading channels scenarios [6]. Besides, we also present the comparison between selective-cooperation scheme with some current schemes over i.i.d Rayleigh fading channels under the the condition that R-D link with AWGN at the end of this section.

Over i.i.d Rayleigh fading, without loss of generality, for simulation convenient, we assume that the P-R link and the P-D link under AWGN channel with Rayleigh fading, the one-sided bandwidth W is 1000Hz, the observation time T is 0.005s, the time bandwidth product q is 5, the number of links, including P-D and P-R, L is 6, the average SNR $\overline{\gamma}$ of the P-R link, $\overline{\gamma}_{PR}$, is 5dB and the average SNR $\overline{\gamma}$ of the P-D link, $\overline{\gamma}_{PD}$, is 5dB. In the following figures, $\overline{P_d}$,

P_f represent the probability of detection at the destination, the probability of false alarm at the destination, respectively.

We first show the performance of SLS, SC, SLC and selective-cooperation schemes. Fig. 5.1 describes ROC curves (P_d versus P_f) for SC, SLC, SLS and selective-cooperation schemes over i.i.d Rayleigh fading channels. For selective-cooperation scheme, the analytical results in (5.10) matches well with the simulations, confirming the accuracy of the analysis. Selective-cooperation performs much better than SLS, SLC, SC in low P_f (from 0.05 to 0.5). For SLC, it involves all relays in combination for destination final detection as its expression shows $y_{SLC} = \sum_{i=1}^{L} y_i$ [7]. Thus, SLC may involve some relays with small received signals y_i affected severely by the fading channel. The weak received signals consequently affect the destination final decision. On the other hand, selective-cooperation only involves relays with high instantaneous SNR. For further comparison, we compare selective-cooperation with SLS, SLC and SC under the variation of average SNR ($\overline{\gamma}_{PR}, \overline{\gamma}_{PD}$) and L, respectively.

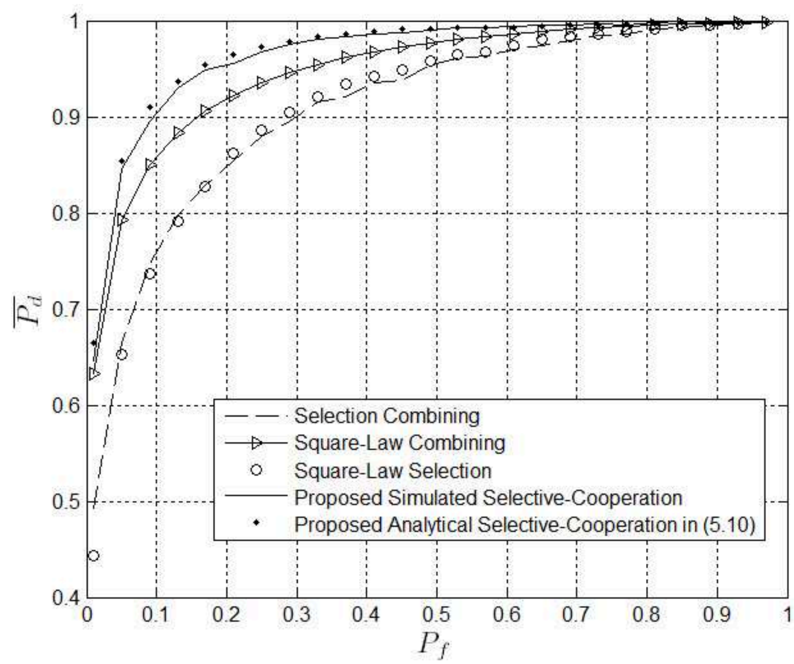

Figure 5.1: ROC curves for current schemes (SC [6], SLC [7], SLS [7]) and selective-cooperation schemes in Rayleigh fading channels,$\overline{\gamma}_{PR} = \overline{\gamma}_{PD} = 5dB$

We assume $L = 6$, $P_f = 0.1$ and vary the average SNR ($\overline{\gamma}_{PR}, \overline{\gamma}_{PD}$) in i.i.d channels from 1dB to 15dB. As Fig. 5.2 shows, selective-cooperation performance is much better than SLS and SC when the average SNR in the range of 1dB to 11dB. We also notice that SC outperforms SLS in the low average SNR (from 1dB to 5dB) and then performs slightly worse than SLS when the average SNR is larger than 5dB. This is because SC picks the relay with highest instantaneous SNR among P-R and P-D links, hence assuring the destination in good performance [66] while the performance of SLS depends mainly on relay's average SNR of the P-R links [59] resulting in the poor performance of destination. Meanwhile, selective-cooperation selects several relays with high instantaneous SNR among P-R links. As the average SNR increases, each relay's performance is improved.

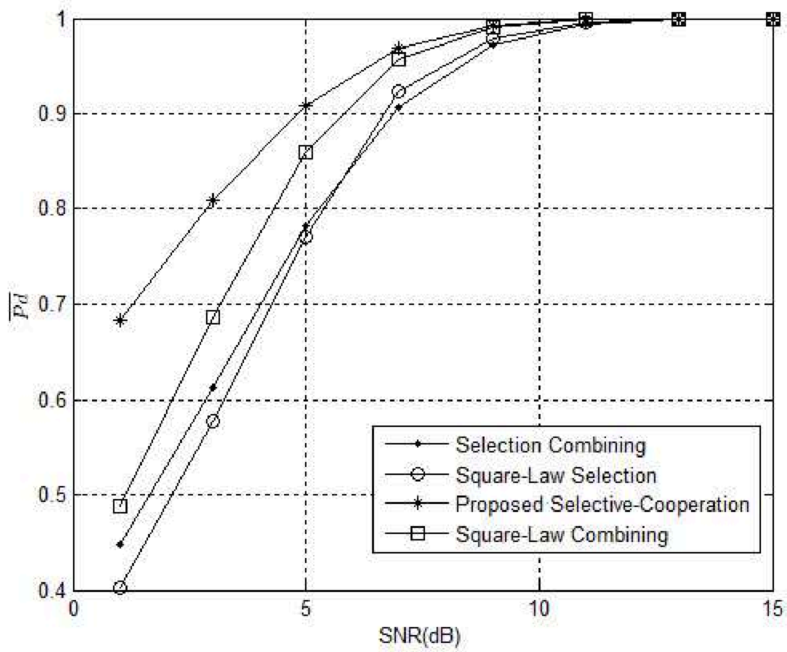

Figure 5.2: Selective-cooperation and current schemes (SC [6], SLC [7], SLS [7]) under the variation of $\overline{\gamma}_{PR}$ and $\overline{\gamma}_{PD}$ from 1dB to 15dB, $L = 6$, $P_f = 0.1$.

Then, we assume average SNR $\overline{\gamma}_{PR} = \overline{\gamma}_{PD} = 5dB$, $P_f = 0.1$ and vary L from 4 to 16. Our scheme always surpass SLS and SC as Fig. 5.3 shows.

Through comparisons, we notice that SC and SLS have their own advantages: 1) SC outperforms SLS when L and average SNR are small; 2) SLS gets its space diversity advantage when L or average SNR is large enough. For our proposed scheme, it offers both advantages mentioned above.

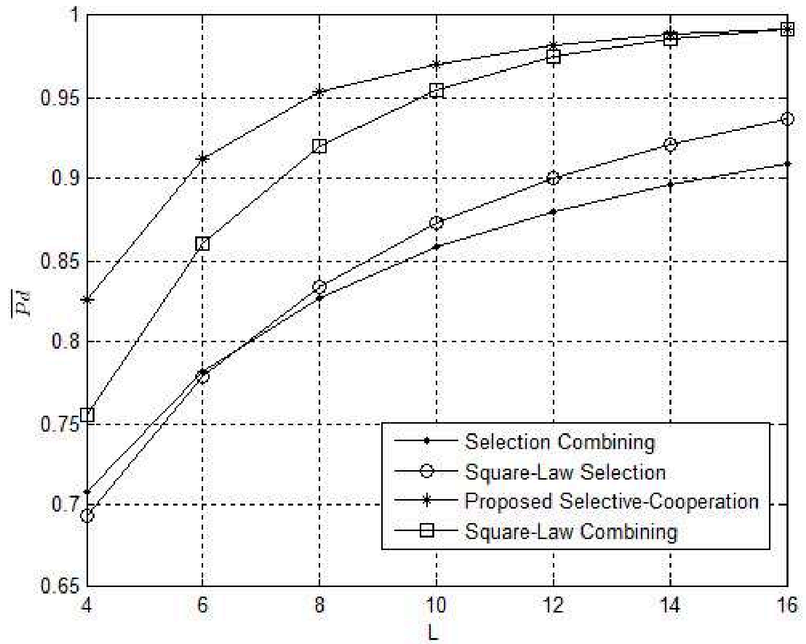

Figure 5.3: Selective-cooperation and current schemes (SC [6], SLC [7], SLS [7]) under the variation of L, $\overline{\gamma}_{PR} = \overline{\gamma}_{PD} = 5dB$, $P_f = 0.1$.

Now, we start to analyze schemes over i.n.d Rayleigh fading channels. Before further analysis, let us look at SLS, SLC, SC and selective-cooperation over i.n.d Rayleigh fading channels. We assume that $L = 6$, $\overline{\gamma}_{PD} = 2dB$, $\overline{\gamma}_{PR}$s from 3dB to 7dB. As shown in Fig. 5.4, the performance of selective-cooperation is better than other schemes since it always select relays with high instantaneous SNR for destination detection.

From selective-cooperation scheme mechanism, we know that instantaneous SNR in P-D link is a crucial parameter for relay selection. Thus, we focus on the analysis of each scheme performance under the variation of $\overline{\gamma}_{PD}$ and assume L and P_f are fixed. In Fig. 5.5 , selective cooperation probability of detection decreases when $\overline{\gamma}_{PR}$ and $\overline{\gamma}_{PD}$ are close, i.e. when $\overline{\gamma}_{PD} = 5dB$. When $\overline{\gamma}_{PD}$ is much larger than $\overline{\gamma}_{PR}$, selective cooperation performance goes well because it avoids collaboration from relays with low instantaneous SNR. Thus, selective cooperation always perform better in low SNR condition than other schemes under the variation of $\overline{\gamma}_{PD}$.

We have compared selective-cooperation scheme with some current schemes (SC, SLS and SLC) via receiver operating characteristic (ROC) curves over i.i.d and i.n.d Rayleigh fading

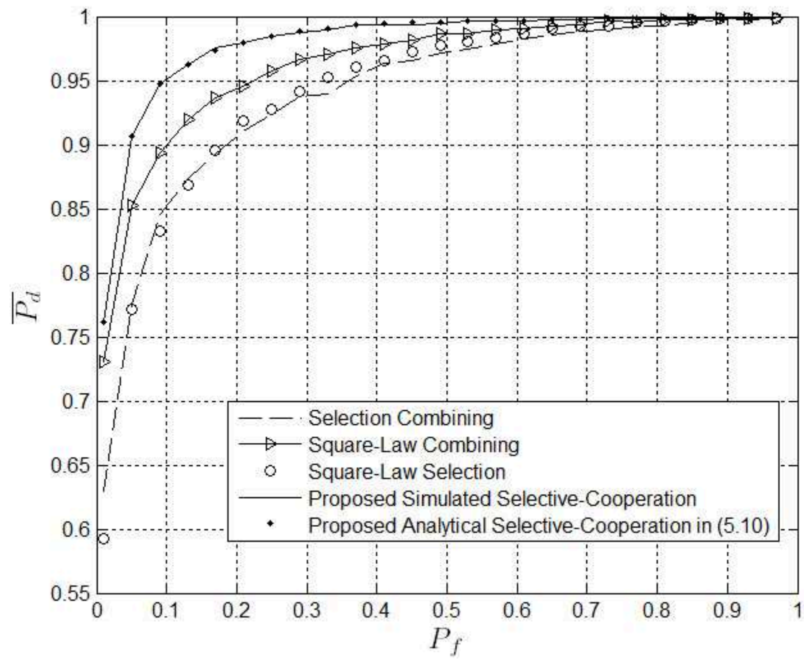

Figure 5.4: ROC curves for current schemes (SC [6], SLC [7], SLS [7]) and selective-cooperation schemes in Rayleigh fading channels,$\overline{\gamma}_{PD} = 2dB$, $L = 6$, $\overline{\gamma}_{PR}$s in the whole P-R links are arranged from 3dB to 7dB.

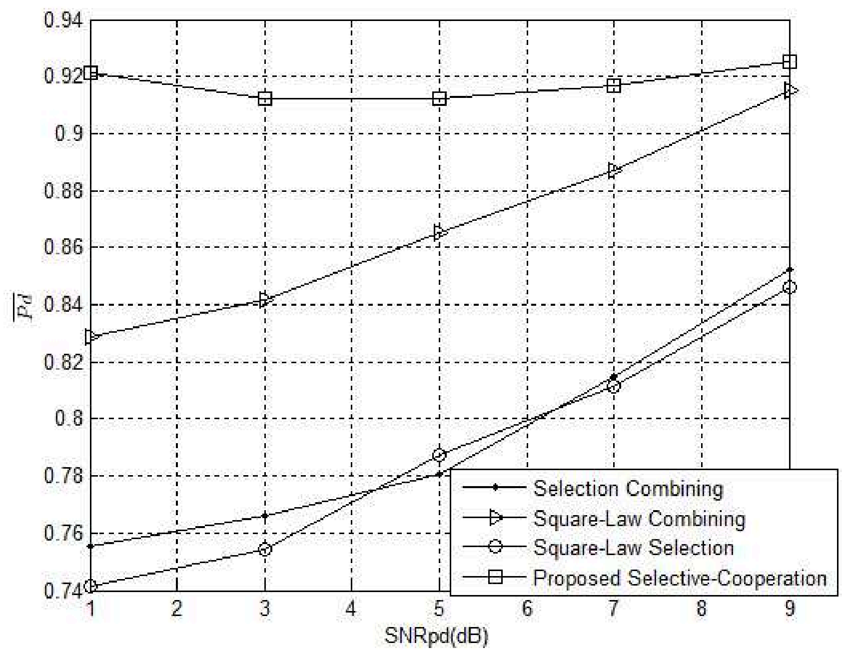

Figure 5.5: Performances of selective-cooperation and current schemes (SC [6], SLC [7], SLS [7]) under the variation of $\overline{\gamma}_{PD}$, $\overline{\gamma}_{PR} = 5dB$, $L = 6$, $P_f = 0.1$.

channels. Now, we start to consider a more realistic scenario: destination is surrounded by relays forming a cluster and each R-D link suffers from AWGN. Since R-D link is not ideal any more, SC and selective-cooperation should consider each relay's cascaded links represented by the P-R link and R-D links. Thus, selective-cooperation scheme's collaboration requirement changes to $SNR_{pr-rd} \geq SNR_{pd}$ while SC picking out the link with largest SNR among SNR_{pr-rd} and SNR_{pd}. Without loss of generality, for simulation convenient, we assume that $L = 6$, $P_f = 0.2$, the average SNR ($\overline{\gamma}_{PR} = \overline{\gamma}_{PD} = 5dB$) in i.i.d channels. As Fig. 5.6 shows, selective-cooperation still offers the best among other schemes.

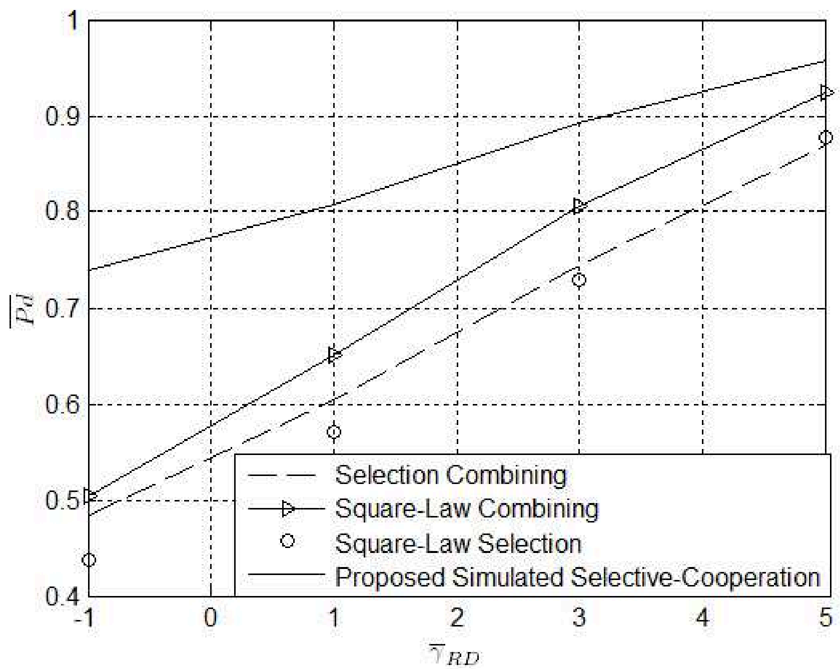

Figure 5.6: Selective-cooperation and current schemes (SC [6], SLC [7], SLS [7]) under the variation of $\overline{\gamma}_{RD}$, $\overline{\gamma}_{PR} = \overline{\gamma}_{PD} = 5dB$, $L = 6$, $P_f = 0.2$.

5.5 Conclusions

We proposed a selective-cooperation scheme to improve the performance of cooperative sensing using order-statistics over both i.i.d and i.n.d, Rayleigh fading channels. The probability of detection and false alarm of selective-cooperation are derived over both i.i.d and i.n.d Rayleigh fading channels. These expressions match well with the simulation results.

Our numerical results also reveal that selective-cooperation outperforms SC, SLS and SC in three dimensions: 1) our scheme has better performance when P-R links have low average SNR; 2) our scheme provides a significant improvement in the probability of detection while requiring few relays to join the destination detection; 3) The proposed scheme is bandwidth efficient for sharing the spectrum sensing data.

Chapter 6

Conclusions and Future Work

This thesis is contributed to the performance analysis of cooperative spectrum sensing schemes over both i.i.d and i.n.d Rayleigh fading channels. Two new schemes, multi-selective scheme and selective scheme, have been proposed to improve cooperative spectrum sensing performance and save bandwidth usage. This chapter summarizes of the main contributions introduced in this thesis and introduces future research directions.

6.1 Conclusions

In Chapter 3, we have introduced and simulated the performance of the energy detection technique over different fading channels. Next, the expressions of SC, SLC, SLS and *N-out-of-K* rule over i.n.d Rayleigh fading channels have been introduced. Through simulations, we notice that SC performs as well as SLS but worse than SLC. Also, OR rule from *N-out-of-K* performs as the same as SLS but saves much bandwidth compared with SLS.

In chapter 4, we proposed multi-selective scheme in order to maximize SC performance. Also, for saving bandwidth usage, we suggested our new scheme adopt *N-out-of-K* rule in final decision and send 1-bit local decision. The probability of detection and false alarm of multi-selective scheme are derived over both i.i.d and i.n.d Rayleigh fading channels. For optimization of multi-selective scheme performance, optimal *N-out-of-K* rule and optimal number of selected nodes k are derived under both i.i.d and i.n.d scenario. Through simulation and comparison, we notice that multi-selective scheme offers much improvement compared with SC, SLS with less bandwidth requirements.

In chapter 5, selective-cooperation scheme is proposed. The probability of detection and false alarm of selective scheme are derived over both i.i.d and i.n.d Rayleigh fading channels. Compared with SLC, the performance of our selective-cooperation is much better over i.i.d Rayleigh fading channels in different SNR conditions, and it needs less cooperative SUs to achieve required accuracy of spectrum sensing.

6.2 Future Work

In this section, we will present some possible future research directions.

In Chapter 4 and 5, both multi-selective and selective schemes adopt local decision instead of decision statistics (soft information) being by relays to the destination to save bandwidth. However, applying local decisions at relays will cost extra energy. It is of interest to compare the performance of the proposed schemes using data fusion concept with the one adopted here for decision fusion. This comparison should show the trade-off study of bandwidth and accuracy of detection.

In real cognitive network scenario, spectrum access management is a major challenge for SUs competing for the channel. Thus, another future work is to integrate the proposed combining schemes with spectrum access management and investigate the optimal performance of these schemes.

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