PERFORMANCE ANALYSIS OF ENERGY DETECTOR FOR AMPLIFY AND FORWARD RELAYING SYSTEM VIA NAKAGAMI CHANNEL IN COGNITIVE RADIO NETWORKS

CHANIDAPHAR SANGUANPUAK

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หัวข้อวิทยานิพนธ์	การวิเคราะห์สมรรถนะของการตรวจจับพลังงานสำหรับระบบรีเลย์ที่มีการขยายและส่งต่อบนช่องสัญญาณนาคากามิของเครือข่ายคอกนิทีฟ เรดิโอ
นักศึกษา	นางสาว ชนิดาภา สงวนพวก
รหัสประจำตัว	52611251
ปริญญา	วิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชา	วิศวกรรมโทรคมนาคม
พ.ศ.	2555
อาจารย์ที่ปรึกษาวิทยานิพนธ์	รศ.ดร.สุวิพล สิทธิชีวภาค

บทคัดย่อ

วิทยานิพนธ์นี้เป็นการศึกษา การรับรู้ของสเปกตรัมในระบบเทคโนโลยีคอกนิทีฟ เรดิโอ (CR) ซึ่งเป็นการประยุกต์ใช้ประโยชน์ ของเทคนิคการรับรู้ของสเปกตรัมที่คอกนิทีฟรีเลย์ แต่ละตัวร่วมมือกัน ในการตรวจจับสัญญาณ อันเป็นพื้นฐานของเครือข่ายคอกนิทีฟ เรดิโอ รีเลย์ที่ถูกกำหนดให้ส่งสัญญาณของผู้ใช้ลำดับแรกไปยังจุดควบคุมของระบบผู้ใช้ลำดับที่สอง การวิเคราะห์สมรรถนะของการตรวจจับพลังงาน โดยการใช้คอกนิทีฟรีเลย์ แบ่งเป็นสามระบบ ดังนี้

ระบบแรก แสดงถึง คอกนิทีฟรีเลย์ โดยใช้วิธีการ การตรวจจับพลังงานของผู้ใช้ลำดับแรก โดยการส่งผ่านคอกนิทีฟ รีเลย์ตัวเดียว ระบบที่สอง เป็นการแสดงถึง การเลือกคอกนิทีฟรีเลย์ที่ดีที่สุด เพื่อการรับรู้ของสเปกตรัม นอกจากนี้แสดงถึง การวิเคราะห์สมรรถนะของการตรวจจับพลังงานสำหรับการจางหายของช่องสัญญาณ นาคากามิ-เอ็ม ทั้งสองแบบ คือ independently and non-identically (i.n.i.d.) และ independently and identically (i.i.d.) โดยที่ การตรวจจับพลังงานถูกใช้ในจุดควบคุมในการรับรู้ที่เกิดขึ้น ความน่าจะเป็นของการตรวจจับสัญญาณที่ผิดพลาด และขอบเขตล่างของความน่าจะเป็นในการตรวจจับสัญญาณได้ถูกแสดงในเชิงทฤษฎี โดยปราศจากการสื่อสารระหว่าง ผู้ใช้ลำดับแรก และจุดควบคุมของระบบผู้ใช้ลำดับที่สอง ซึ่งแสดงโดยการใช้พื้นที่ใต้กราฟของเส้นกราฟ อาร์โอซี (AUC) และถูกกำหนดสำหรับคอกนิทีฟรีเลย์ เชิงเดี่ยว ความเป็นไปได้ของการ

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Thesis	Performance Analysis of Energy Detector for Relaying System via Nakagami Channel in Cognitive Radio Networks
Student	Miss Chanidaphar Sanguanpuak
Student ID.	52611251
Degree	Master of Engineering
Program	Telecommunications Engineering
Year	2012
Thesis Advisor	Assoc.Prof.Dr. Suvipol Sitthichivaphak

ABSTRACT

This thesis investigates aspects of cooperative spectrum sensing in cognitive radio (CR) technology. We exploit spectrum sensing technique for applications in single/multiple-relay based cognitive radio network. Relays are assigned in cognitive radio networks to transmit the primary user's signal to a fusion center. The performance analysis of energy detection is studied in cognitive relays where the energy detector is employed at the fusion center in three system models as follow.

Firstly, we exploit a single cognitive relay scenario with single antenna utilized for all nodes. Secondly, the best cognitive relay selection is studied with energy detection. Finally, multiple antennas employed at the cognitive relay is considered to explore the detection performance. In the first system model, the performance of energy detector is analyzed for both independent and non identically (i.n.i.d.) distributed, and independent and identically (i.i.d.) distributed Nakagami-*m* channels. False alarm and lower bound detection probabilities are expressed theoretically without direct communication between the primary user and the cognitive coordinator. Besides, closed form expressions of area under the receiver operating characteristic curves (AUC) are provided. In the second system model, the detection

probability of best cognitive relay selection is derived over i.i.d. Nakagami-*m* fading channel. The last system model, the cognitive relay employs multiple antennas for both the transmitter and the receiver sides. Probability of detection is provided for this scenario.

Therefore, our analytical results here including over several aforementioned cases and new additional ones. Finally, our analytical expressions are validated by Monte Carlo simulations with the help of Mathematica and MATLAB programs.

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Chanidaphar Sanguanpuak

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CHAPTER 1
INTRODUCTION

1.1 Rationale

Nowadays cognitive radio systems have been proposed as a possible solution to the spectrum management of future wireless networks. And the wireless communications have grown rapidly, which play a vital rule and become an important part of daily life.

Cognitive radio is a new concept aimed at vastly improving the way radio spectrum is utilized. One approach of cognitive radio is to permit the secondary usage of licensed spectrum through cognitive radios.

The wireless spectrum is one of the most cost-effective and reliable media to deliver broadband access to both urban and rural residential areas. As the wireless spectrum is a natural national resource, spectrum management is needed to mitigate spectrum pollution, maximize the utilization, and minimize the interference to other users. As a result, every wireless system (commercial or government operated) has been allocated a chunk of spectrum (licensed) by the regulatory agencies.

The licensed users (primary users) rarely utilize the assigned frequency bands most of the time, which means that the spectrum holes exist. Because of the spectrum holes has motivated the application for cognitive radio networks so the spectrum has no efficiency for the communications. The most important for avoiding interference to the licensed users is sensing accuracy. Such as ,unlicensed users (secondary users) first sense the activities of licensed users (primary users) if no licensed users activities are detected will access to the spectrum holes (whites spaces).Spectrum sensing is a key element in cognitive radio communications, as it enables the cognitive radio to adapt to its environment by detecting spectrum holes.

To enhance the detection probability, many signal detection techniques can be used in spectrum sensing. There are many techniques of spectrum sensing such as matched filter detection (Sahai et al., 2004), cyclostationary detection (Sutton et al., 2008), and energy detection (Urkowitz, 1967) and (Digham et al., 2007). Energy detection is the most popular method, among these spectrum sensing techniques. The signal power is measured by the energy detection.

An energy detector measures the energy of the received signal within the pre-defined bandwidth and time period. The measured energy is then compared with a threshold to determine the status of the transmitted signal. Since it does not require channel gains and other parameter estimation, the energy detector might enable certain wireless devices to become low-cost and low- complexity. However, the energy detector performs worse when there is background interference. A conventional analog energy detector (Urkowitz, 1967), consists of a pre-filter followed by a square-law device and a finite time integrator. The pre-filter limits the noise bandwidth and normalizes the noise variance.

Alternatively, a digital implementation of an energy detector is similar to the analog implementation except for the analog-to-digital converter which is implemented after the noise pre-filter. The output of the integrator, called test statistic, is proportional to the energy of the received signal.

When the receiver knows only noise power, the energy detector is an optimum non-coherent detector to detect an unknown signal when the signal is: (i) Gaussian; (ii) uncorrelated; and (iii) independent with the background noise (Tandra and Sahai, 2008). The energy detector is not optimal for correlated signals.

Spectrum sensing in cognitive radio may suffer from the notorious hidden terminal problem. When secondary user is close to the primary user, but there is a disturbance between the link (e.g. the link is blocked by a high building or a mountain), then the secondary user cannot detect signals from the primary transmitter and thus starts its transmission, which will interfere with the primary receiver who is nearby. Reliable spectrum sensing is not always guaranteed due to the multipath fading, shadowing and hidden terminal problem. Therefore, cooperative spectrum sensing technique has been introduced for quick and reliable detection. This research designs cognitive-relay network based on energy detection with much improved reliability using cooperative relay networks. Moreover, to determine the detection capability of an energy detector, proper and correct channel model, and a simple analytical framework are vital. Therefore, Nakagami fading channel which can characterize different channel conditions is considered. Based on these, the complicated mathematically resulting expressions do not facilitate rapidly performance evaluation of detection capability. Therefore, little attention was paid to investigating the performance of energy detectors in the past. Thus this research addresses this problem by using a marked line analytical framework.

In our work, when energy detection is utilized for cooperative spectrum sensing, the secondary users report to a fusion center their sensing results. The cognitive users behave as amplify-forward relays which are assumed to know statistics of CSI from the primary user. The amplified factor is tuned according to the statistics of CSI to maintain long term average power constraint. First case, we consider two hops with single cognitive relay, then extend to multiple cognitive relays with employing best cognitive relay selection. In the former works (Digham et al., 2007) and (Atapattu et al., 2010), the two hop and the best cognitive relay selection are not considered for Nakagami-m fading channel.

1.2 Contribution

In this thesis, it is deeper and broader extension of previous research in the open literature e.g. (Digham et al., 2007) and (Atapattu et al., 2010). In chapter 3, our work is for energy detection with employing cognitive relay over independently and non-identically distributed (i.n.i.d.) Nakagami-m fading, it differs from (Atapattu et al., 2010), which employs cognitive relay over Rayleigh fading channel. Futhermore, in (Atapattu et al., 2010), they provide the area under the ROC curve expressions without employing cognitive relay. In our work, the expressions of area under the ROC curves with using the cognitive relay over i.n.i.d. and i.i.d. Nakagami-m fading are expressed. In chapter 4, we consider the best cognitive relay selection scheme over i.i.d. Nakagami-m fading. None of the aforementioned works have been considered energy detection with employing selection scheme before. Moreover, we enable multiple-input multiple-output at the cognitive relay which is a new system model which none of available papers has done.

1.3 Objectives of Thesis

1. To study the performance measurement of two hop cognitive relaying in spectrum sensing over independently but not necessarily identically distributed (i.n.i.d.) Nakagami-m fading channel.

2. To study the performance measurement of two hop cognitive relaying in spectrum sensing over independently and identically distributed (i.i.d.) Nakagami-m fading channel.

3. To observe the detection measurement and area under receiver operating characteristic (AUC) curve in cognitive relaying system over both i.n.i.d. and i.i.d. Nakarami-m fading channel.

4. To study the performance measurement of the best cognitive relay selection over i.i.d. Nakagami-m fading channel.

5. To study the performance measurement of multiple antennas employed at the cognitive relay, the single antenna enables at the source and the fusion center over independently and identically (i.i.d.) Nakagami-m fading channel.

1.4 Scope and Limitations of Thesis

The scope of this work includes analytical performance analysis and computer simulation. Throughout the research, each outcome at each phase is verified via extensive Monte Carlo simulations (using MATLAB) and numerical methods (using MATHEMATICA). Only amplify and forward cognitive relay systems are considered. For spectrum sensing, energy detection is used at the fusion center. In chapter 3, we consider performance analysis of two hop cognitive relaying along with the verified results. The two hop cognitive relay system model is single antenna which employed for all nodes (the primary user, the cognitive relay and the fusion center). The lower bound energy detection expressions are derived in both i.n.i.d. and i.i.d. Nakagami-m fading environment. Area under the ROC curve (AUC) expressions are also evaluated. In chapter 4, the performance measurement for lower bound energy detection with employing best cognitive relay selection and with enabling multiple antennas (MIMO) at the cognitive relay are derived. For both cases, we employ single antenna at the primary user and at the fusion center. Independently and identically distributed (i.i.d.) Nakagami-m fading channels are considered for the two hops. The numerical results which validating between analytical and Monte Carlo simulation are provided. The conclusion for all of our works are drawn in chapter 5.

CHAPTER 2
BACKGROUND AND RELATED LITERATURE

2.1 Motivation and Background

With the increasing number of wireless users, scarcity of electromagnetic spectrum is obvious. Taking this into consideration, the Federal Communications Commission (FCC) published a report prepared by Spectrum Policy Task Force (SPTF) (Haykin, 2005). This report recommends certain rules and regulations for the efficient use of radio spectrum and the ways to improve the existing spectrum usage. In relation to the spectrum utilization this report illustrates that there is significant inefficient spectrum utilization than the actual spectrum scarcity due to the legacy system and the rules imposed by FCC. Most of the allotted channels are not in use most of the time; some are partially occupied while others are heavily used.

Most of the licensed radio-wave spectral bands are under-utilized in time and space domain (Mitola and Maguire, 1999; Haykin, 2005), resulting in unused white spaces in the time-frequency grid at any particular location. The spectrum utilization is mainly around certain parts of the spectrum whereas a considerable amount of the spectrum is unutilized as depicted in Fig. 2.1. As can be observed, spectrum utilization is more intense and competitive at frequencies below 3 GHz whereas the spectrum is under-utilized in the 3-6 GHz bands. The Federal Communications Commission (FCC) has also reported the temporal and geographic variations in spectrum utilization to range from 15% to 85%. On the other hand, fixed spectrum allocation policies do not allow for reusing of the rarely used spectrum allocated to licensed users by unlicensed users. This problem coupled with the rapidly increasing demand for wireless services and radio spectrum has led to spectrum scarcity for wireless applications.

This has necessitated a new communication standard that allows unlicensed (secondary) users to utilize the vacant bands which are allocated to licensed (primary) users. However, this opportunistic access should be in a manner that does not interrupt any primary process in the band. Therefore, the secondary users must be aware of the activity of the primary user in the target band. They should spot the spectrum holes and the idle state of the primary users in order to exploit the free bands and also promptly vacate the band as soon as the primary user becomes active. Cognitive radio, encompasses this awareness by dynamically interacting with the environment and altering the operating parameters with the mission of exploiting the unused spectrum without interfering with the primary users (Mitola and Maguire, 1999; Haykin, 2005). Showing support for the cognitive radio idea, the FCC allowed for usage of the unused television spectrum by unlicensed users wherever the spectrum is free. IEEE has also supported the cognitive radio paradigm by developing the IEEE 802.22 standard for wireless regional area network (WRAN) which works in unused TV channels.

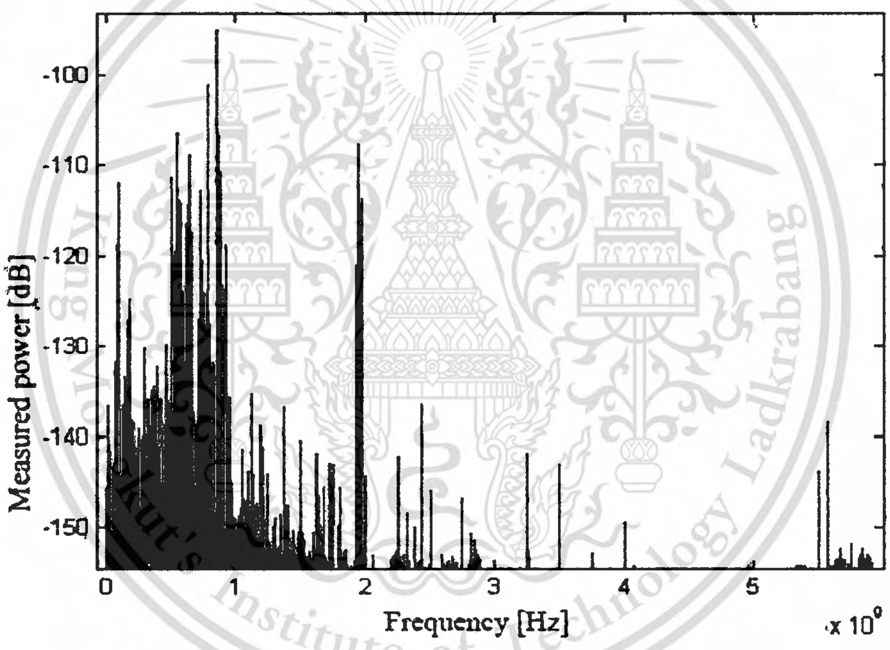

Figure 2.1 Spectrum utilization measurements.

2.2 Cognitive Radio Networks

The wireless spectrum is one of the most cost-effective and reliable media to deliver broadband access to both urban and rural residential areas. As the wireless spectrum is a natural national resource, spectrum management is needed to mitigate spectrum pollution, maximize the utilization, and minimize the interference to other users. As a result, every wireless system (commercial or government operated) has been allocated a chunk of spectrum (licensed) by the regulatory agencies.

As the demand for wireless communications has increased dramatically, the demand for radio spectrum has also increased. With the rising demand, new broadband communication technologies are required to utilize radio spectrum effectively. Some key novel technologies are as follows.

• The spectrum sharing among multiple systems using sophisticated and computationally complex technologies such as spread spectrum, narrowband transmissions with low-power, coded wideband signals, etc., improves the spectrum usage greatly (Schilling et al., 1991).

• Smart antenna systems can determine the destination location and direct the antenna radiation pattern accordingly to reduce interference caused by traditional omini-directional antennas (Alexiouand Haardt, 2004).

• Cooperative communications enable reliable transmission and larger data rate by achieving spatial diversity in a multi-user environment. Relaying technology facilitates the signal transmission between the source and the destination utilizing less power (Nosratinia et al., 2004).

• Ultra-wideband operates at very low power level such that it does not interfere with other traditional narrowband users in the same frequency band (Yang and Giannakis, 2004).

Despite the advanced technologies, because of spectrum scarcity, the FCC in the United States and regulatory bodies in other countries still face difficulties when new service providers request new frequency bands.

2.2.1 Spectrum Scarcity

There is only a little spectrum left not allocated in the usable range. Although, it seems that the usable radio frequencies are running out. An actual spectrum usage experiment conducted by the FCC shows that at any given time and location, much of the licensed spectrum is idle (between 80% and 90% of spectrum) because licensed users (termed primary users) rarely utilize all the assigned frequency bands at all time (Haykin, 2005). Such frequency bands not occupied by primary users at a certain time and location are called spectrum holes. Spectrum holes cause spectral inefficiency.

The FCC experiment suggests that this spectrum scarcity is caused by poor spectrum management rather than a true scarcity of usable frequencies. This fact has motivated cognitive radio technology, an emerging novel concept in wireless access.

The key features of a cognitive radio transceiver are radio environment awareness and spectrum intelligence. Intelligence can be achieved through learning the spectrum environment and adapting transmission parameters (Mitola andMaguire, 1999; Haykin, 2005).

2.2.2 Cognitive Radio Networks on Licensed Bands

In this case, for a secondary network with unlicensed users (termed secondary users or cognitive users), the secondary users are allowed to opportunistically access spectrum which has already been allocated to primary users. Because opportunistic access must not cause harmful interference to the operation of primary users, secondary users first detect the activities of primary users and get access to the spectrum only if primary activity is idle. Whenever the primary user becomes active, the secondary user must detect the presence of the primary user reliably and immediately vacate the channel. Subsequently, the secondary user must find another free channel for its continuing communication. In this scenario, primary users have high priority, while secondary users have low priority. Detecting the available spectrum, selecting the best available channel and sharing it without harmful interference to primary users are essential requirements (Akyildiz et al., 2006).

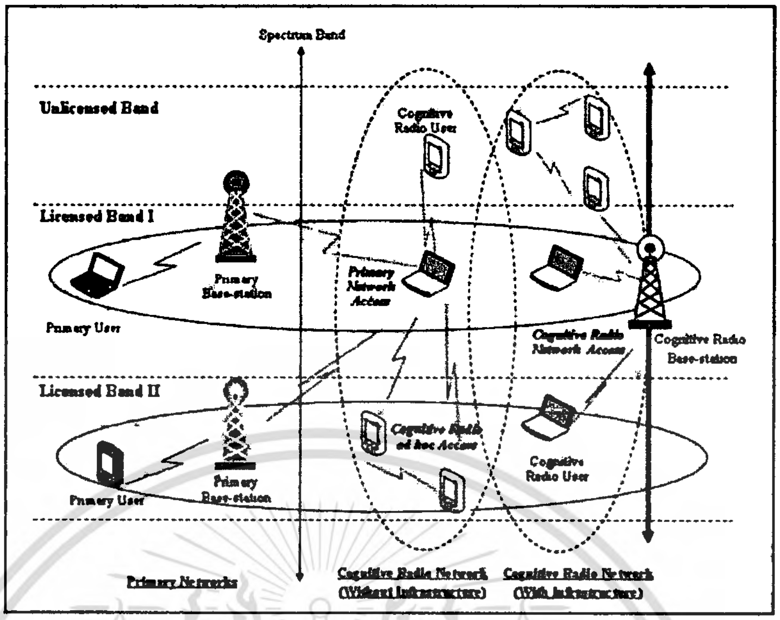

Figure 2.2 Cognitive radio architecture.

2.2.3 Dynamic Spectrum Access

Dynamic spectrum access (DSA) adopts a hierarchical access structure with primary users and secondary users. The basic idea of DSA is to open licensed spectrum to secondary users while limiting the interference perceived by primary users. This allows the secondary users to operate in the best available channel opportunistically. Therefore, DSA requires opportunistic spectrum sharing, which is implemented via two strategies (Zhao and Sadler, 2007):

(i) spectrum overlay does not necessarily impose severe constraints on the transmit power of secondary users, but rather on the opportunity that they may transmit. Consequently, a secondary user accesses a channel of a primary user only when the channel is not occupied; and

(ii) spectrum underlay imposes strict constraints on the transmit power of secondary users. Secondary users' transmit power at a certain portion of the spectrum is regarded as noise by the licensed users. In this case, both primary and secondary users may transmit simultaneously in the same frequency. Overall, a reliable spectrum sensing is essential in the overlay strategy, while is not required in the underlay strategy.

2.3 Cooperative communication

Traditional wireless networks have used direct point-to-point or point-to-multipoint (e.g., cellular) topologies. In contrast to conventional point-to-point communications, cooperative communications and networking allows different users or nodes in a wireless network to share resources and to create collaboration through distributed transmission/ processing, in which each users information is sent out not only by the user but also by the collaborating users (Nosratinia et al., 2004). Cooperative communications and networking is a new communication that promises significant capacity and multiplexing gain increase in wireless networks.

In recent times, the advantages of the multiple-input multiple-output (MIMO) system have been very much appreciated to an extent that, certain diversity techniques have become a very essential part of the wireless standards. Taking this into consideration, a new technique known as cooperative communication have been proposed for single antenna system to gain some of the benefits of the MIMO systems (Nosratinia et al., 2004). The basic idea behind cooperative communication is that a single antenna systems being active in a multiple-user environment could share their antenna in such a way that creates a virtual MIMO system.

It has been seen that the channels in a wireless environment suffer a great deal of fading, which leads to the exponential decay in the signal strength over the course of its transmission. Diversity could be achieved when independent copies of the signals are transmitted, and is very effective in combating the harmful effects of fading. In general, spatial diversity could be achieved by transmitting independent copies of the signal from different stations, hence allowing different faded versions of the signal at the receiver.

2.3.1 Relaying scheme

In cooperative communication, in order to improve the performance of the overall network, we focus on a wireless networks where an intermediate terminal called a “relay node” are used to increase the probability of detection or for the bit error rate improvement. In cooperative communication system, it is the duty of each wireless user to act as a transmitter as well as to act as a cooperative agent for the neighboring agents (Nosratinia et al., 2004), (Ganesan and Li, 2007b), (Ganesan and Li, 2007a). Cooperative communication is a technique of enabling different receivers in the multiple-user environment to share their antennas in a way to create a virtual MIMO system in order to achieve transmit diversity. A relay station in the network acting as a transceiver forwards the radio signals in the wireless network. Cooperative communication has been a main research topic for the spectrum bands that are above 2 GHz range, because at this frequency the radio signals are more affected by the environmental conditions and also by non-line-of-sight conditions. A solution to this problem would be to increase the density of the PUs (source), but as this is very expensive to deploy, researchers are motivated to use the relays to increase the density of the network access points. It has also been seen that the transmit power requirement of the relay transceiver is significantly less compared to the PU. The use of this multi-hop transmission through relays is shown in Fig. 2.3.

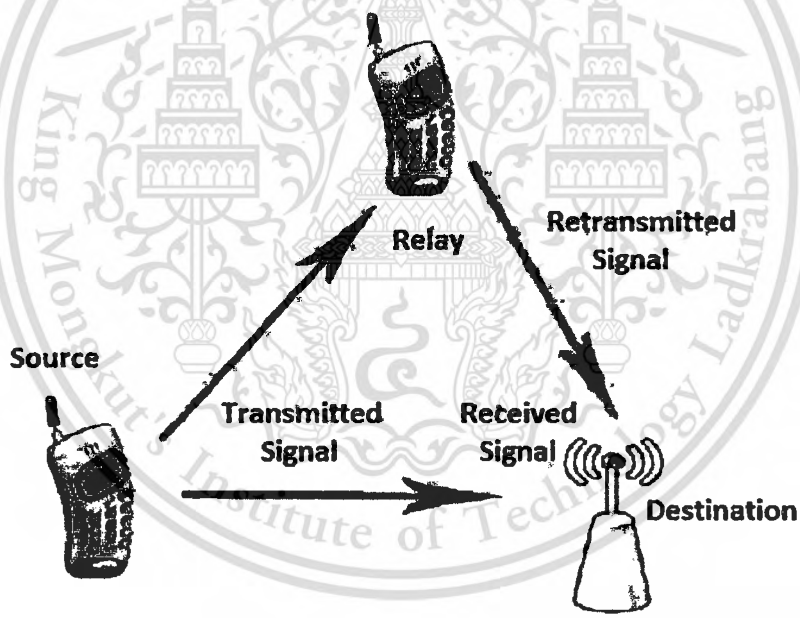

Figure 2.3 A two hop cooperative communication network.

Cooperative relaying protocols could be further subcategories on the basis of their forwarding scheme as: decode-forward (DF) and amplify-forward (AF) (Ganesan and Li, 2007b). In our system, we consider the amplify-forward (AF) protocol, which will be explained in chapter 3.

2.4 Principle of Spectrum Sensing

Cognitive radio is desired to monitor the radio spectrum continuously and to identify the network and primary user parameters such as carrier frequency, bandwidth and transmission power in order to maximize the spectrum utilization. One of the most important tasks is to identify the spectrum holes. This task is called spectrum sensing, which is required whenever there is an opportunity to access the radio spectrum. After available channels are detected successfully by spectrum sensing, a secondary transmitter and a secondary receiver can communicate over the available channel if the secondary transmitter does not interfere with the primary receivers and the secondary receiver is not affected by primary transmitters. Thus, the spectrum opportunity depends on both users Transmission power levels (Yucek and Arslan, 2009).

Cognitive radio decides on spectrum availability based on the received signal from the primary user. Primary user has two states, idle or busy. With the presence of the noise, the signal detection at the receiver can be viewed as the classical binary hypothesis testing problem in which Hypothesis 0 (H_0) and Hypothesis 1 (H_1) are the primary signal absence and the primary signal presence, respectively (Liang et al., 2008). Based on this, the received signal at time t can be given under the two hypotheses H_0 and H_1 as:

$$y(t)=\begin{cases} n(t) & : H_0 \\ hs(t)+w(t) & : H_1, \end{cases} \tag{1.1}$$

where $s(t)$ is the primary signal, h is the channel gain, and $w(t)$ is the AWGN with variance σ_w^2. Three fundamental performance metrics of spectrum sensing are as follows:

• False alarm probability (P_f): the probability of deciding the signal is present while H_0 is true, which leads to undetected spectrum holes. A large P_f results in poor efficiency.

• Missed-detection probability (P_m): the probability of deciding the signal is absent while H_1 is true, which means a wrong decision on the unavailable spectrum. A large P_m means poor reliability, which introduces unexpected interference to the primary user.

• Detection probability (P_d): the probability of deciding the signal is present when H_1 is true. And thus, P_d =1-P_m.

Both reliability and efficiency are expected from the spectrum sensing technique built into the cognitive radio, i.e., a higher P_d (or lower P_m) and lower P_f are preferred.

There are four major spectrum sensing techniques, referred to as energy detection, matched filter, cyclostationary feature detection, and eigenvalue detection. The last three are briefly described next, followed by a detailed description of energy detection.

2.4.1 Matched Filter

Matched filter is an optimal method of detecting an unknown signal. This detection of unknown signal is done by correlating (matching) it with a known signal or its template. Matched filter maximizes the signal-to-noise ratio (SNR) of received signal in the presence of the additive white Gaussian noise (AWGN) (Sahai et al., 2004). The transmitted signal from the PU in the presence of AWGN is passed through the matched filter in order to maximize the SNR which is also known as non-coherent detection. The matched filter correlates the unknown signal from the PU with an already known signal to detect the presence or absence of the PU's activity. This process is equivalent to convolving the PU's signal with its own delayed and time-reversed template of the signal. This whole procedure of detection through matched filter is clearly depicted in Fig.2.3 where H_1 and H_0 indicate the presence and absence of the PU's signal, respectively.

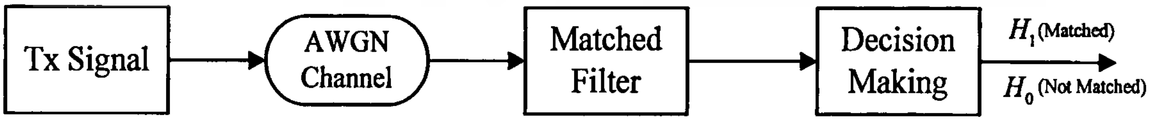

Figure 2.4 Matched filter detector.

2.4.2 Cyclostationary Feature Detection

If the signal from the licensed user possesses cyclic characteristics, then this signal could be easily detected at very low SNR with the aid of cyclostationary detection technique. The spectrum correlation function of AWGN is zero due to its stationarity. The stationary feature of AWGN makes cyclostationary detector more robust against the uncertainty in noise. Any kind of signals from PU's has some distinct spectrum correlation functions which differentiate it from AWGN. If the PU's signal is cyclostationary, by calculating the spectrum correlation function of the PU's signal at the cyclostationary detector, it is identified that the signal is present or not. If the output of the detector is greater than some threshold level λ, the primary signal is present otherwise it is absent (Gardner, 1988). A simple block diagram of a cyclostationary detector is shown in Fig. 2.5.

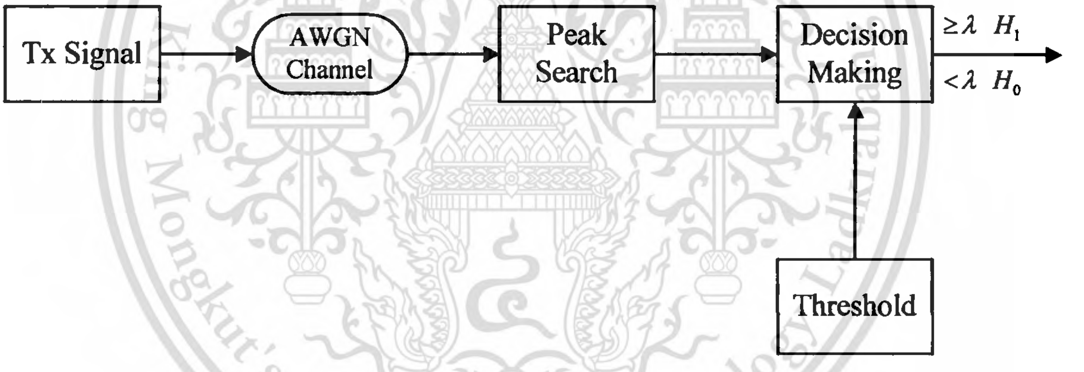

Figure 2.5 Cyclostationary detector.

2.4.3 Eigenvalue Detection

The eigenvalue-based detector uses the ratio between the maximum to the minimum eigenvalue of the covariance matrix of the received signal vector to detect the absence or the presence of the primary signal. The correlation of the primary signal samples is required for this method. If no correlation is found (e.g., primary signal appears as white noise), this method fails, which however is a very rare event. Although the eigenvalue-based detector does not need the knowledge of the noise power, its main drawbacks are the computational complexity required to compute the covariance matrix and the eigenvalue decomposition and the difficulty of an appropriate threshold selection (Juang et al., 2009).

2.4.4 Energy Detection

An energy detector measures the energy of the received signal within the pre-defined bandwidth and time period. The measured energy is then compared with a threshold to determine the status of the transmitted signal. Since it does not require channel gains and other parameter estimation, the energy detector might enable certain wireless devices to become low-cost and low-complexity. However, the energy detector performs worse when there is background interference. A conventional analog energy detector (Urkowitz, 1967), consists of a pre-filter followed by a square-law device and a finite time integrator. The pre-filter limits the noise bandwidth and normalizes the noise variance.

Alternatively, a digital implementation of an energy detector is similar to the analog implementation except for the analog-to-digital converter which is implemented after the noise pre-filter. The output of the integrator, called test statistic, is proportional to the energy of the received signal. The energy detector structure is shown in Fig. 2.5

When the receiver knows noise power only, the energy detector is an optimum non-coherent detector to detect an unknown signal when the signal is: (i) Gaussian; (ii) uncorrelated; and (iii) independent with the background noise (Tandra and Sahai, 2008). The energy detector is not optimal for correlated signals.

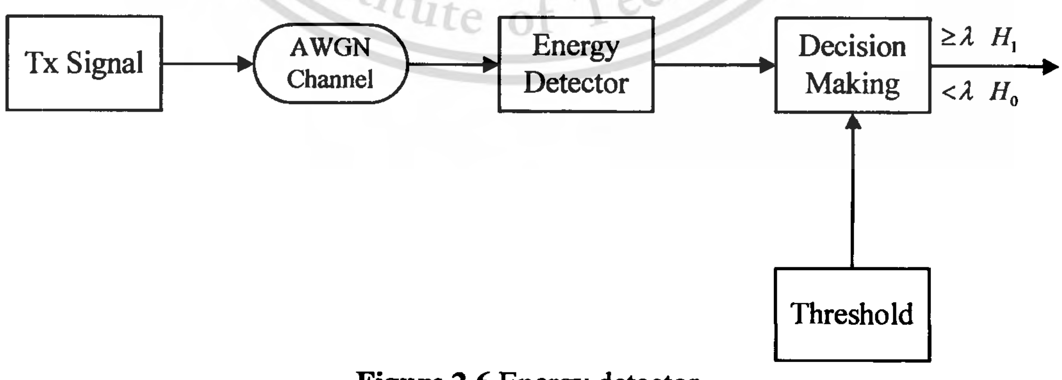

Figure 2.6 Energy detector.

When the receiver knows noise power only, the energy detector is an optimum non-coherent detector to detect an unknown signal when the signal is: (i) Gaussian; (ii) uncorrelated; and (iii) independent with the background noise (Tandra and Sahai, 2008). The energy detector is not optimal for correlated signals.

2.5 Cooperative Spectrum Sensing

The energy detector is generally operated in a low SNR region. Hence, if a signal from the primary transmitter is severely shadowed as well as faded, a secondary sensing node should experience difficulty in deciding whether the primary spectrum is unused or occupied by the primary system. A spatially faded primary signal can be effectively sensed by using multi-antenna. But it cannot be a solution to the secondary sensing node which is located in a deeply shadowed region from the primary transmitter, which can be overcome by cooperative sensing techniques. To address this issue, multiple cognitive relays can be designed to collaborate in spectrum sensing (Khaled and Wei, 2009). Recent work has shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels (Ganesan and Li, 2007a). In general, cooperative spectrum sensing can be performed as,

a. Every cognitive relay performs its own local spectrum sensing measurements independently and then makes a binary decision on whether the primary user is present or not.
b. All of the cognitive relays forward their decisions to a common receiver.
c. The common receiver fuses the cognitive relay decisions and makes a final decision to infer the absence or presence of the primary user

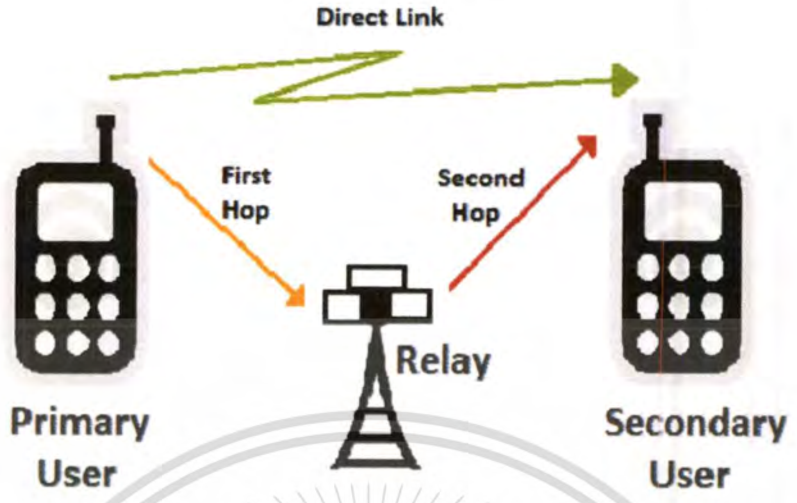

Figure 2.7 Cooperative spectrum sensing.

Fig 2.7 shows two-hop communication in wireless network in order to achieve cooperative diversity. A two hop digital relaying system is placed in between the primary user (PU) and the secondary user (SU) in order to induce end-to-end diversity gain. Cooperative spectrum sensing plays an important role in cognitive radios network in order to improve the detection probability of licensed spectrum.

1. Decision Fusion : This cooperative spectrum sensing scheme can be seen as a decode and forward protocol for cooperative network, where each cooperative partner makes a binary decision based on the local observation and then forwards one bit of the decision to the common receiver. At the common receiver, all 1-bit decisions are fused together according to an or logic.

2. Data Fusion: Instead of transmitting the 1-bit decision to the common receiver, each cognitive relay can just send its observation value directly to the common receiver. This approach can be seen as an amplify and forward (AF) protocol for cooperative networks (Khaled and Wei, 2009). This cooperation scheme is demonstrated in Fig. 2.8

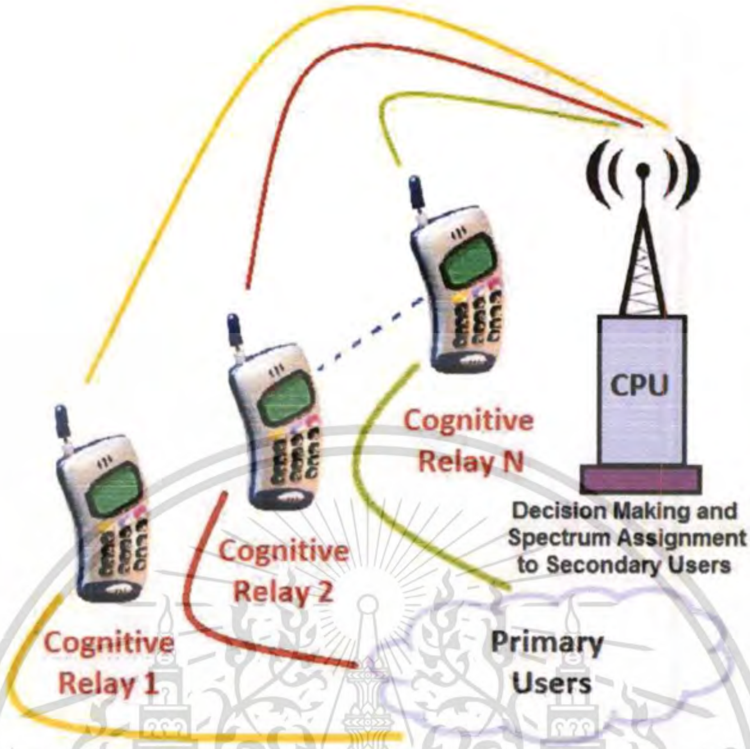

Figure 2.8 Cooperative spectrum sensing for data fusion scheme.

3. Sensing Diversity Gain: Cooperative spectrum sensing will go through two successive channels which are 1) sensing channel (from the primary user to cognitive relays) and 2) Reporting channel (from the cognitive relays to the fusion center). Sensing through one cognitive relay may fail to detect the signal of the primary user, there are still many chances for other cognitive relays to detect it. With the increase of the number of cooperative cognitive relays, the probability of missed detection for all the users will be small (Khaled and Wei, 2009). When one cognitive relay is far away from the primary user, the received signal may be too weak to be detected. By employing a cognitive relay that is located nearby the primary user as a relay, the signal of the primary user can be detected reliable by the far user.

2.6 Multiple Antennas with Spectrum Sensing

The relationship between the spectrum efficiency (the false alarm probability) and the sensing performance (the detection probability). The proportion between the false alarm probability and the detection probability can be adjusted via threshold control, it is not possible to simultaneously attain a low false alarm probability and a high detection probability, as long as the probabilistic characteristics of the received signal are fixed. In order to improve the sensing performance, the distance between two PDFs should be lengthened as Fig. 2.9.

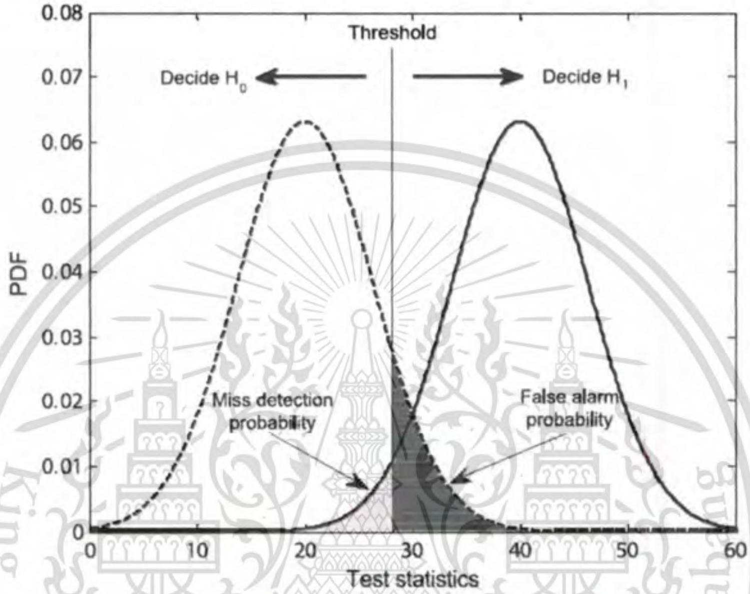

Figure 2.9 Binary hypothesis testing.

This can be achieved via two methods as follows 1) Intensifying the received SNR of the primary user measured at the secondary user or 2) Increasing the dimension or degree of freedom of the received signal space (Wang et al., 2010). The first method is very challenging within a practical situation, due to noise uncertainty, shadowing. These effects are neither predictable nor able to be compensated for. Increasing the degree-of-freedom of the received signal space is possible to be handled. The secondary user receives an increased number of observation samples, they are combined into an aggregated observation and the final decision can be made with more reliability. The sources for degree-of-freedom are mainly time and space. If the secondary user sums N samples of received energy within a sensing period, we obtain N degree-of-freedom in the time domain. The degree-of-freedom of the sensing signal space should be expanded into the spatial domain. If the secondary user is equipped with M antennas or M secondary users are engaged in cooperative sensing. There is an opportunity for exploiting M degree-of-freedom within the spatial domain. As a simple scenario, it is assumed that M nodes are located at spatially independent positions, so M nodes are located at spatially independent positions, so M degree-of-freedom is exploited during the energy detection process.

For a given degree-of-freedom obtained from M nodes of from M number of antennas and a sensing duration of N samples. Given the transmit signal $s(n)$. The energy detector is employed, which combines the measured energy during N and M. Assuming each node or each antenna and each sample is independent, the energy is combined with equal gain. The decision statistic T can be written as $T=\sum_{n=1}^{N}\sum_{m=1}^{M}|s(n)|^2$, (Wanget al., 2010).

With multiple-antenna or multi-node, it can be assumed that the channels for each antenna are independently faded. The different fading channels for multiple antennas, the maximal ratio combining or square law combining increases the spectrum sensing performance (Khaled and Wei, 2009). The secondary user utilizing energy detection cannot coherently receive the primary signal due to unavailability of the primary signal information, including the modulation technique, pilot signaling and etc. Hence, any schemes requiring the channel measurements cannot be practically implemented with the energy detector scheme.

2.7 Test Statistic

The output of the integrator is the test statistic which is given as $\Lambda=\sum_{n=1}^{N}|y(n)|^2$ where N is the number of signal samples which are collected during the sensing period T. The decision of the energy detector depends on the statistical properties of Λ. Deterministic signal is considered.

• Deterministic signal: The signal is assumed to have a fixed waveform. This model has been used in early stage of energy detection applications (Urkowitz, 1967; Digham et al., 2007).

2.8 Performance Measurements

The energy detection process is affected by path loss, large-scale fading and small-scale fading of the propagation channel. Therefore, detection performance has been discussed under such conditions (Urkowitz, 1967). As the energy detector is being used with new wireless technologies, the energy detection problem and its performance have been revisited recently (Digham et al., 2003, 2007; Herath and Rajatheva, 2008).Possible performance measurements are as follows.

2.8.1 Average Detection Probability

The probability of false alarm P_f can easily be calculated because it does not depend on the statistics of the wireless channel. In a fading/shadowing channel, it is essential to evaluate the average P_d, $\overline{P}_d$, over the channel SNR distribution $f_\gamma(\gamma)$. It can be evaluated by direct averaging of P_d over the respective SNR distribution as $\overline{P}_d = \int_0^\infty P_d f_\gamma(x)\,dx$. This is the traditional way of evaluating the performance of an energy detector (Kostylev, 2002; Digham et al., 2003, 2007; Herath and Rajatheva, 2008). The plot of $\overline{P}_d$ versus the average SNR for a given P_f is one way of representing the detection performance of an energy detector.

2.8.2 Receiver Operating Characteristic Curve

The receiver operating characteristic (ROC) curve is a popular performance measure. The (average) P_d versus the P_f traces out the ROC curve as the threshold varies from 0 to ∞. Each point on the ROC plot represents a (P_f, P_d) pair corresponding to a particular threshold. Since higher P_d with lower P_f is desirable, if the ROC curve moves to the upper left corner, the overall detection capability is higher.

2.8.3 Area under the ROC Curve

The Area Theorem has shown that the area under the ROC curve (AUC) is a measure of the detection capability. In (Atapattu et al., 2010), it has been proved that the area under the curve represents the probability that choosing the correct decision at the detector is more likely than choosing the incorrect decision. Thus, AUC is a compact measure of how detector performs in a binary hypothesis problem under possibly varying parameters. The AUC varies between 1, 2 and 1. If the detectors performance is no better than flipping a coin, then the AUC becomes 1, 2, and it increases to one as the detector performance improves.

CHAPTER 3

COOPERATIVE SPECTRUM SENSING USING SINGLE AMPLIFY-FORWARD RELAY

3.1 Introduction

Cognitive radio systems have been proposed as a possible solution to the spectrum management of future wireless networks. The licensed users (primary users) rarely utilize the assigned frequency bands most of the time, which means that spectrum holes exist. The spectrum inefficiency due to these spectrum holes has motivated the application of cognitive radio networks. One approach of cognitive radio is to permit secondary usage of licensed spectrum through cognitive radios (Haykin, 2005). For example, unlicensed users (secondary users) first sense the activities of licensed (primary users) and access the spectrum holes (white spaces) if no primary users activities are detected. Sensing accuracy is important for avoiding interference to the primary users. This detection task is quite challenging due to the requirement of reliable signal detection over multipath fading, shadowing and hidden node. Thus, cooperative spectrum sensing has been introduced to detect faster and more reliable (Ganesan and Li, 2007b), (Ganesan and Li, 2007a).

There are many techniques to sense the spectrum such as matched filter detection (coherent detection through maximization of the signal-to-noise ratio (SNR)) (Sahai et al., 2004), cyclostationary detection (Sutton et al., 2008), and energy detection (Urkowitz, 1967), (Digham et al., 2003), (Digham et al., 2007). Among these spectrum sensing techniques, energy detection is the most popular method, which measuring the received signal power. The performance of an energy detector has been studied recently in (Atapattu et al., 2011), (Atapattu et al., 2010). In our work, when energy detection is utilized for cooperative spectrum sensing, the secondary users report to a fusion center their sensing results.

Our work is a pionieer work which explores the energy detection with cognitive relays in Nakagami-m fading channels. Although some works rely on a Rayleigh fading channel, the Nakagami-m fading channel has received attention due to its great versatility, in the sense that it has greater flexibility and accuracy in matching various experimental data more general than Rayleigh distributions. Many works are explored in relaying network in Nakagami-m fading channel such as, Duong et al. (Duong et al., 2009), derive the closed form expressions for the symbol error probability and the outage probability of fixed decode and forward cooperative networks with relay selection over Nakagami-m fading channel. Karaginnidis et al. (Karagiannidis et al., 2005), present closed form lower bounds for the outage probability and the average bit-error probability of multihop transmission with non-regerative relays over Nakagami-m fading channels.

In this work, the cognitive users behave as amplify-forward relays which is called "cognitive relays". This research work, the cognitive relays are assumed to know statistics of CSI from the primary user. The amplified factor is tuned according to the statistics of CSI to maintain long term average power constraint. We consider two hops with single cognitive relay in this chapter. In earlier works (Digham et al., 2003), (Digham et al., 2007), the authors consider energy detection in Rayleigh and Nakagami-m fading channels without applying the relays. In recent works (Atapattu et al., 2011), and (Atapattu et al., 2010), consider cognitive relays with energy detection in Rayleigh fading channels. They provides the average detection probability expressions at the fusion center when two-hop cognitive relay channels are independent and identically distributed (i.i.d.). The residue theorem is used to derive the average detection probability. In this chapter, we present a pionier work which explores the energy detection in both independent and identically distributed (i.i.d.) along with independent and non-identically distributed (non i.i.d.) Nakagami-m fading channels for single cognitive relay.

The average detection probability and area under receiver operating characteristics (AUC) expressions are provided. The expressions are simple, and therefore they are very useful for rapid performance evaluations. Our analytical results are validated by semi Monte-Carlo simulation. Following the numerical and simulation results, it can be seen that the analytical expression of the average detection probability is tight with the exact simulation results. The performance of detection capability is characterized by plotting complementary receiver operating characteristics (complementary ROC) curves which is a plot of missed detection probability (P_m) versus false alarm probability (P_f). The expressions of average detection probability are simple because they include only one term infinite series summation.

The rest of this chapter is organized as follows. Section 2, introduces the system and channel model under the consideration. In Section 3, energy detection over AWGN is explained. In Section 4, area under ROC curve (AUC) is mentioned. In Section 5, performance analysis is introduced. Detection probability expressions in both i.i.d and i.n.i.d Nakagami-m fading channels are presented along with AUC closed form expressions. In Section 6, some numerical and simulation results are given. Section 7, gives a conclusion for this chapter. Next chapter, we introduce the energy detection with employing best cognitive relay selection case.

3.2 Channel Model

For simplicity, for two hop cognitive relay case, channel from the primary user (p) to the cognitive relay (r) and from the cognitive relay to the fusion center (d) denoted as h_{pr}, and h_{rd} respectively, are independent and non-identically Nakagami-m variables

Therefore, the received signal-to-noise ratio (SNR) γ_{pr} and γ_{rd} are gamma distribution with parameters $\left(m_1, \frac{\Omega_1}{m_1}\right)$ and $\left(m_2, \frac{\Omega_2}{m_2}\right)$, respectively. Their corresponding PDFs are given by (Simon and Alouini, 2005)

$$f_{\gamma_{pr}}(\gamma) = \frac{{m_1}^{m_1}}{{\Omega_1}^{m_1}\Gamma(m_1)}\gamma^{m_1-1}exp\left(\frac{-m_1\gamma}{\Omega_1}\right)$$

$$f_{\gamma_{rd}}(\gamma) = \frac{{m_2}^{m_2}}{{\Omega_2}^{m_2}\Gamma(m_2)}\gamma^{m_2-1}exp\left(\frac{-m_2\gamma}{\Omega_2}\right) , \tag{3.1}$$

Where m_1 and m_2 are parameters describing the fading severity of each hop with values $m_1, m_2 \geq \frac{1}{2}$; Ω_1 and Ω_2 are expectation of signal power $\left(\mathrm{E}\left[|h_{pr}|^2\right], \mathrm{E}\left[|h_{rd}|^2\right]\right)$ respectively.

For an independent and identically Nakagami-m fading channel in both hops. Assuming that both hops from the primary user (p) to the cognitive relay (r) and from the cognitive relay (r) to the fusion center (d) are identical Nakaagmi-m variables. Therefore, the received signal-to noise ratio (SNR) γ_{pr}, and γ_{rd}, are identical gamma distribution with parameters $\left(m, \frac{\Omega}{m}\right)$. The corresponding PDFs, $f_{\gamma_{pr}}(\gamma)$, $f_{\gamma_{rd}}(\gamma)$ are identical and given by (Simon and Alouini, 2005),

$$f_{\gamma_{pr}}(\gamma) = \frac{m^m}{\Omega^m \Gamma(m)} \gamma^{m-1} exp\left(\frac{-m\gamma}{\Omega}\right). \tag{3.2}$$

3.3 Energy Detection over AWGN Channel

At the energy detector, by following binary hypothesis testing, the received signal at time t can be written

$$y(t) = \begin{cases} n(t) & : H_0 \\ hx(t) + n(t) & : H_1, \end{cases} \tag{3.3}$$

Where *x(t)* is the transmitted signal with an average power E_s, *h(t)* is the channel gain from the transmitter and the receiver. *n(t)* is the AWGN with single sided power spectrum density N_0 at the receiver. Under hypothesis H_0 and H_1 means that the transmitted signal *x(t)* is absent and present, respectively.

The energy detector is constructed by first, passing the received signal through bandpass filter with bandwidth *W* and carrier frequency f_c. Thus, the noise variance will become N_0W. Each component (in-phase or quadrature-phase) of the received signal, a value of degree of freedom *(u)* can be *TW*. The values of T and W have to be defined to restrict *u* to be integer values. Second, to measure the energy of received signal *(Y)*, square the output signal from bandpass filter are integrated over time period *T*. The signal energy E acts as a test statistic to compare with a pre-specified threshold λ. If this test statistic $E > \lambda$, the hypothesis H_1 is chosen or the hypothesis H_0, otherwise.

Under H_1, E has a non-central chi-square distribution with u degree of freedom. Likewise, under H_0, E will be central chi-square distributed. An expression for the probability of detection

(P_d) and the probability of false alarm (P_f), are written as $P_r\,(E > \lambda|\,H_1)$ and $P_r\,(E > \lambda|\,H_0)$, respectively. Now, the probability density function (PDF) of y can be expressed as,

$$f_Y(y) = \begin{cases} \dfrac{1}{N_0^u 2^u \Gamma(u)} y^{u-1} e^{-\frac{y}{2N_0}} & : H_0 \\ \dfrac{1}{2N_0}\left(\dfrac{y}{2\gamma}\right)^{\frac{u-1}{2}} e^{-\frac{2\gamma+y}{2N_0}} I_{\frac{N}{2}-1}\left(\dfrac{\sqrt{2\gamma y}}{N_0}\right) & : H_1\,, \end{cases} \tag{3.4}$$

where $\Gamma(.)$ is the gamma function eq.(8.31.3) in (Gradshteyn and Ryzhik, 2000), $I_v(.)$ is the vth-order modified Bessel function of the first kind and γ denotes the signal to noise ratio (SNR).

Thus, the cumulative distribution function expressions of P_f and P_d are given (Digham et al., 2003), (Digham et al., 2007),

$$P_f(\lambda) = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)} \tag{3.5}$$

$$P_d = Q_u(\sqrt{2\gamma}, \sqrt{\lambda})\,, \tag{3.6}$$

Where E_s is transmitted power from the primary user, γ is an instantaneous SNR of the target signal. The instantaneous SNR is given by $\gamma = E_s|h|^2 / N_0$, where $Q_u(.,.)$ is the *uth* order generalized Marcum-Q function, $\Gamma(.)$ is the gamma function, $\Gamma(.,.)$ is the upper incomplete gamma function.

3.4 Area under ROC Curve (AUC)

Although the ROC curves (P_d versus P_f) characterize the performance of an energy detector. The area under the curve represents the probability that choosing correct decision at the detector is more likely than choosing the incorrect decision. The closed form expressions of area under ROC curve for energy detection was introduced in

(Atapattu et al., 2010). As mentioned, the AUC is a measure of the detection capability at the energy detector. For two energy detectors, to compare the performance with using ROC curves sometimes is difficult, since the curves may cross. According to detection and false alarm probabilities which vary from value 0 to value 1, the AUC values vary from 0.5 to 1. The AUC of instantaneous SNR (γ) with sample u is given in (Atapattu et al., 2010),

$$\begin{aligned} A(\gamma) &= \int_0^1 P_d(\gamma,\lambda)dP_f(\lambda) \\ &= \frac{1}{2^{u-1}\Gamma(u)}\int_0^\infty t^{2u-1}e^{\frac{-t^2}{2}}Q_u(\sqrt{2\gamma},t)dt \\ &= 1-\sum_{k=0}^{u-1}\frac{\gamma^k e^{\frac{-\lambda}{2}}}{2^k k!}+\sum_{k=1-u}^{u-1}\frac{\Gamma(u+k)}{2^{u+k}\Gamma(u)}e^{-\gamma}\mathbb{F}(u,k,\gamma), \end{aligned} \tag{3.7}$$

Where $\mathbb{F}={}_1\tilde{F}_1(u+k;1+k;\frac{\gamma}{2})$ which ${}_1\tilde{F}_1(.;\,.;\,.)$ is the regularized confluent hypergeometric function of the confluent hypergeometric function ${}_1F_1(.;.;.)$. The corresponding regularized hypergeometric function is defined in (Wolfram,2009)

$$\begin{aligned} {}_p\tilde{F}_q(a_1,\dots,a_p;b_1,\dots b_q;z) &= \frac{{}_pF_q(a_1,\dots,a_p;b_1,\dots b_q;z)}{\Gamma(b_1)\dots\Gamma(b_q)} \\ &= \sum_{k=0}^{\infty}\frac{\Pi_{j=1}^{p}(a_j)_k z^k}{k!\,\Pi_{j=1}^{q}\Gamma(k+b_j)} \end{aligned} \tag{3.8}$$

This AUC $A(\gamma)$ is obtained as unfaded AUC. We will consider AUC under cooperative cognitive relay also.

3.5 Two hop cognitive relay for energy detection

Without any estimation and complexity at the secondary users, the cognitive relay simply amplify the received signal from the primary users and then forward to the fusion center. We consider single cognitive relay based spectrum sensing in Fig. 3.1., Each node (primary user, cognitive relay, and fusion center) has only one antenna which can be used for both transmission and reception. There is no direct link from the primary user to the fusion center.

3.5.1 Two-hop Cognitive Relay Cooperative Scheme

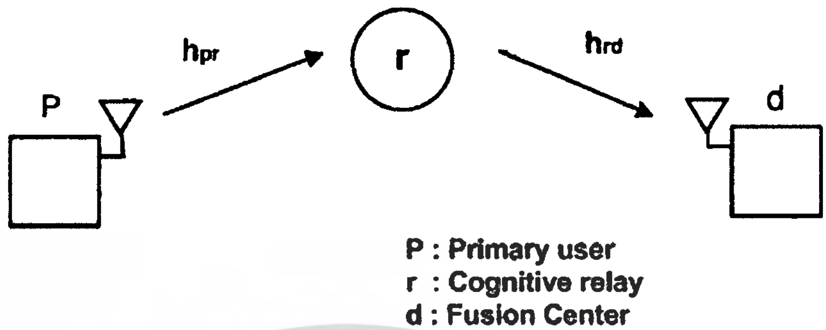

Figure 3.1 Energy detection with employing single cognitive relay.

When a primary user starts using the band, a cognitive relay receive transmitted signal from the primary user. Therefore, in the first phase, the cognitive relay listens to the primary user signal. Then, the cognitive relay simply amplifies and retransmits the amplified version of the received signals to the fusion center in the second phase. Energy detector is equipped at the fusion center, the received signal energy is then compared with a pre-define threshold λ .

3.5.2 Single Cognitive Relay with Spectrum Sensing

Firstly, we consider a single cognitive relay. In this case, we have three nodes which contain a primary user, a cognitive relay and a fusion center. The primary user transmits signal to the cognitive relay without direct transmission to the fusion center. The cognitive relay continuously receives and amplifies the received signal from the primary user. Further, during detection process, we assume that both the channels from primary user to the cognitive relay and from the cognitive relay to the fusion center are time invariant. At particular time t, the received signal by the cognitive relay denoted as $y_{pr}(t)$, written as

$$y_{pr}(t) = \theta h_{pr} x(t) + n_r(t) , \tag{3.9}$$

where θ indicates the primary signal which is equals to 1 at the presence of primary transmitted signal or equal to 0 otherwise, $x(t)$ is the transmitted signal from the primary user with power E_p, h_{pr} is slow flat fading channel gain between primary and secondary relay, $n_r(t)$ is the AWGN at the cognitive relay with variance $N_{0,r}$. At the fusion center then, the received signal denoted $y_{rd}(t)$ is given by,

$$y_{rd}(t) = Gh_{rd}y_{pr}(t) + n_d(t) \tag{3.10}$$

$$= \theta hx(t) + n(t), \tag{3.11}$$

where G is the amplification gain at the cognitive relay, h_{rd} is the flat fading channel gain between the cognitive relay and the fusion center. n_d is the AWGN at the fusion center. Therefore, $h = Gh_{pr}h_{rd}$ and $n(t) = Gh_{rd}n_r(t) + n_d(t)$ can be assumed as channel gain and effective noise from the primary user to the fusion center, respectively.

1) At the amplified forward cognitive relay, first, the received signal power from the primary user is normalized and then is amplified by cognitive relay power consumed E_r. Thus, the amplification factor G is given as,

$$G = \sqrt{\frac{E_r}{N_{0,r} + E_s\mathrm{E}[|H_{pr}|^2]}}.$$

2) At the fusion center, the received SNR can be written by,

$$\gamma = \frac{(\gamma_{pr}\gamma_{rd})}{(\gamma_{pr} + \gamma_{rd})}, \tag{3.12}$$

where $\gamma_{pr} = \frac{|h_{pr}|^2}{N_0}$ and $\gamma_{rd} = \frac{|h_{rd}|^2}{N_0}$. γ_{pr} and γ_{rd} are the average SNRs of the channels from the primary user to the cognitive relay and from the cognitive relay to the fusion center, respectively.

The lower bound of overall end-to-end SNR can be approximated by (Anghel and Kaveh, 2004).

$$\gamma^{\min} = 0.5\min(\gamma_{pr}, \gamma_{rd}). \tag{3.13}$$

The energy detector is employed at the fusion center thus; the received signal will be filtered by an ideal bandpass filter. This bandpass filter normalizes noise variance and limits the expectation of noise power. The output of filter is then squared and integrated over the time T to obtain the decision statistic.

3.5.3 Detection Analysis of Single Cognitive Relay

In preceding this part, we use a new alternative series representation of generalized Marcum-Q function which is derived eq.(18) in (Annamalai et al., 2009) for any real order $M \geq 0.5$ as

$$Q_M(\alpha,B)=e^{\frac{-\alpha^2}{2}}\sum_{k=0}^{\infty}\frac{1}{k!}\left(\frac{\alpha^2}{2}\right)^k\frac{\Gamma(M+k,\beta^2/2)}{\Gamma(M+k)} \tag{3.14}$$

Firstly, we consider an independent and identically distribution (i.i.d) Nakagami-m fading channel for both hops (from the primary user (p) to the cognitive relay (r) and from the cognitive relay (r) to the fusion center (d)). For identically case, the fading parameter m_1 and m_2 are assumed to be equal which denoted as m. The average power Ω_1 and Ω_2 are assumed to be similar and denoted as. The average detection probability in this case ($\overline{P}_d$) can now be evaluated by averaging eq.(3.14) over the PDF of lower bounded end-to-end SNR ($f_{\gamma_{iid}^{\min}}(\gamma)$),

$$\overline{P}_d = \int_0^{\infty} Q_u(\sqrt{2\gamma},\sqrt{\lambda})f_{\gamma_{i.i.d.}^{\min}}(\gamma)d\gamma \tag{3.15}$$

$$= \sum_{k=0}^{\infty}\sum_{n=0}^{u+k+1} A\int_0^{\infty} e^{-\left(1+\frac{2m}{\Omega}\right)\gamma}\gamma^{k+m+p-1}d\gamma \tag{3.16}$$

$$= \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\sum_{p=0}^{m-1} A\frac{\left(\frac{2m}{\Omega}\right)}{(m)p!}\int_0^{\infty} e^{-\left(1+\frac{4m}{\Omega}\right)\gamma}\gamma^{k+m+p-1}d\gamma, \tag{3.17}$$

where $A=\frac{e^{\frac{-\lambda}{2}}\left(\frac{\lambda}{2}\right)^{n}2^{1+m}\left(\frac{m}{\Omega}\right)^{m}}{k!n!}$. For integer values of m, the incomplete gamma function can be written based on eq.(8.352.4) in (Gradshteyn and Ryzhik, 2000). Besides, with the help of eq.(3.351.1) in (Gradshteyn and Ryzhik, 2000), $\int_0^\infty x^{v}e^{-\mu x}dx=v!\mu^{-v-1}$, where $\mathrm{Re}(\mu)>0$, and $v=k+m+p-1$ and $\mu=1+\frac{4m}{\Omega}$. The average detection probability is derived as,

$$\overline{P}_d = \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\sum_{p=0}^{m-1}\frac{2^{\alpha}e^{\frac{-\lambda}{2}}\left(\frac{\lambda}{2}\right)^{n}\left(\frac{m}{\Omega}\right)^{m+p}(m)_{k+p}}{k!p!n!\left(\frac{4m}{\Omega}+1\right)^{k+m+p}}, \tag{3.18}$$

where $\alpha=1+m+p$ and $(n)_t$ is a Pochammer symbol as $(n)_t=\frac{\Gamma(n+t)}{\Gamma(n)}$ (Gradshteyn and Ryzhik, 2000). Secondly, an independent and non-identically (non i.i.d.) Nakagami-m for both hops are considered. The average detection probability in this case $(\overline{P}_d)$ can now be evaluated by averaging eq. (3.14) over the PDF of lower bounded end-to-end channel SNR $(f_{\gamma_{\min}}(\gamma))$ given by,

$$\begin{aligned}\overline{P}_d &= \int_0^\infty Q_u(\sqrt{2\gamma},\sqrt{\lambda})f_{\gamma_{\min}}(\gamma)d\gamma \\ &= \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\frac{e^{-\frac{\lambda}{2}}\left(\frac{\lambda}{2}\right)^{n}2^{m_2}\left(\frac{m_2}{\Omega_2}\right)^{m_2}}{k!n!\Gamma(m_1)\Gamma(m_2)}\int_0^\infty e^{-\left(1+\frac{2m_2}{\Omega_2}\right)\gamma}\gamma^{k-1+m_2}\Gamma\left(m_1,\frac{2m_1\gamma}{\Omega_1}\right)d\gamma \\ &+ \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\frac{e^{-\frac{\lambda}{2}}\left(\frac{\lambda}{2}\right)^{n}2^{m_1}\left(\frac{m_1}{\Omega_1}\right)^{m_1}}{k!n!\Gamma(m_1)\Gamma(m_2)}\int_0^\infty e^{-\left(1+\frac{2m_1}{\Omega_1}\right)\gamma}\gamma^{k-1+m_1}\Gamma\left(m_2,\frac{2m_2\gamma}{\Omega_2}\right)d\gamma\end{aligned} \tag{3.19}$$

For integer values of m, the incomplete gamma function can be written based on eq.(8.352.4) (Gradshteyn and Ryzhik, 2000), $\Gamma(x,a)=\Gamma(x)e^{-a}\sum_{p=0}^{x-1}\frac{a^{p}}{p!}$. Besides, with the help of eq.(3.351.1) (Gradshteyn and Ryzhik, 2000), $\int_0^\infty x^v e^{-\mu x}dx = v!\mu^{-v-1}$ for $\mathrm{Re}(\mu) > 0$. Where, $v = k + m_2 + p - 1$ and $v = k + m_1 + s - 1$ in the first and second term, respectively. And $\mu = 1 + \frac{2m_1}{\Omega_1} + \frac{2m_2}{\Omega_2}$ in the first and second term similarly. The average detection probability is derived as,

$$\begin{aligned} \overline{P}_d &= \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\sum_{n=0}^{m_1-1}\frac{e^{-\frac{\lambda}{2}}\left(\frac{\lambda}{2}\right)^n 2^{m_2+p}\left(\frac{m_1}{\Omega_1}\right)^p\left(\frac{m_2}{\Omega_2}\right)^{m_2}(m_2)_{k+p}}{k!n!p!\left(1+\frac{2m_1}{\Omega_1}+\frac{2m_2}{\Omega_2}\right)^{m_2+k+p}} \\ &+ \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\sum_{s=0}^{m_2-1}\frac{e^{-\frac{\lambda}{2}}\left(\frac{\lambda}{2}\right)^n 2^{m_1+p}\left(\frac{m_2}{\Omega_2}\right)^s\left(\frac{m_1}{\Omega_1}\right)^{m_1}(m_1)_{k+s}}{k!n!s!\left(1+\frac{2m_1}{\Omega_1}+\frac{2m_2}{\Omega_2}\right)^{m_1+k+s}} \end{aligned} \tag{3.20}$$

where $(n)_t$ is a Pochammer symbol as $(n)_t = \frac{\Gamma(n+t)}{\Gamma(n)}$ (Gradshteyn and Ryzhik, 2000).

To obtain an average AUC expression, we will derive average AUC expressions for i.i.d Nakagami-m fading channel. The average AUC can be evaluated by averaging eq. (3.7) over the SNR distribution $(f_{\gamma_{i.i.d.}^{\min}}(\gamma))$.

$$\begin{aligned} \overline{A}_{\gamma^{\min}} &= \int_0^\infty A(\gamma) f_{\gamma_{i.i.d.}^{\min}}(\gamma)d\gamma \\ &= \frac{2^m\left(\frac{m}{\Omega}\right)^m}{\Gamma(m)\Gamma(m)}\int_0^\infty e^{-\frac{2m\gamma}{\Omega_2}}\gamma^{m-1}\Gamma\left(m,\frac{2m\gamma}{\Omega}\right)d\gamma \\ &- \sum_{k=0}^{u-1}\frac{e^{-\frac{\lambda}{2}}2^m\left(\frac{m}{\Omega}\right)^m}{2^k k!}\int_0^\infty \gamma^{k-1+m}e^{-\frac{2m\gamma}{\Omega}}\Gamma\left(m,\frac{2m\gamma}{\Omega}\right)d\gamma \\ &+ \sum_{1-u}^{u-1}\frac{\Gamma(u+k)\left(\frac{m}{\Omega}\right)^m}{2^{u+k-m}\Gamma(u)\Gamma(m)\Gamma(m)}\int_0^\infty e^{-\left(1+\frac{2m}{\Omega}\right)\gamma}\gamma^{1+m}\mathbb{F}(u,k,\gamma)\Gamma\left(m,\frac{2m\gamma}{\Omega}\right)d\gamma \end{aligned} \tag{3.21}$$

Next, we will derive the expressions of an average AUC for non i.i.d Nakagami-m fading channel over single cognitive relay case. The average AUC $(\overline{A}_{\gamma^{\min}})$ can be evaluated through averaging eq.(3.7) by the SNR distribution $(f_{\gamma^{\min}}(\gamma))$ given in (A.4).

$$
\begin{aligned}
\overline{A_{\gamma^{\min}}} &= \int_0^\infty A(\gamma) f_{\gamma^{\min}}(\gamma)\, d\gamma \\
&= \frac{2^{m_2}\left(\frac{m_2}{\Omega_2}\right)^{m_2}}{\Gamma(m_1)\Gamma(m_2)} \int_0^\infty e^{-\frac{2m_2\gamma}{\Omega_2}} \gamma^{m_2-1} \Gamma\left(m_1, \frac{2m_1\gamma}{\Omega_1}\right) d\gamma \\
&+ \frac{2^{m_1}\left(\frac{m_1}{\Omega_1}\right)^{m_1}}{\Gamma(m_1)\Gamma(m_2)} \int_0^\infty e^{-\frac{2m_1\gamma}{\Omega_1}} \gamma^{m_1-1} \Gamma\left(m_2, \frac{2m_2\gamma}{\Omega_2}\right) d\gamma \\
&- \sum_{k=0}^{u-1} \frac{e^{-\frac{\lambda}{2}} 2^{m_2}\left(\frac{m_2}{\Omega_2}\right)^{m_2}}{2^k k!} \int_0^\infty \gamma^{k-1+m_2} e^{-\frac{2m_2\gamma}{\Omega_2}} \Gamma\left(m_1, \frac{2m_1\gamma}{\Omega_1}\right) d\gamma \\
&- \sum_{k=0}^{u-1} \frac{e^{-\frac{\lambda}{2}} 2^{m_1}\left(\frac{m_1}{\Omega_1}\right)^{m_1}}{2^k k!} \int_0^\infty \gamma^{k-1+m_1} e^{-\frac{2m_1\gamma}{\Omega_1}} \Gamma\left(m_2, \frac{2m_2\gamma}{\Omega_2}\right) d\gamma \\
&+ \sum_{1-u}^{u-1} \frac{\Gamma(u+k)\left(\frac{m_2}{\Omega_2}\right)^{m_2}}{2^{u+k-m_2}\Gamma(u)\Gamma(m_1)\Gamma(m_2)} \int_0^\infty e^{-\left(1+\frac{2m_2}{\Omega_2}\right)\gamma} \gamma^{-1+m_2} \mathbb{F}(u,k,\gamma) \Gamma\left(m_1, \frac{2m_1\gamma}{\Omega_1}\right) d\gamma \\
&+ \sum_{1-u}^{u-1} \frac{\Gamma(u+k)\left(\frac{m_1}{\Omega_1}\right)^{m_1}}{2^{u+k-m_1}\Gamma(u)\Gamma(m_1)\Gamma(m_2)} \int_0^\infty e^{-\left(1+\frac{2m_1}{\Omega_1}\right)\gamma} \gamma^{-1+m_1} \mathbb{F}(u,k,\gamma) \Gamma\left(m_2, \frac{2m_2\gamma}{\Omega_2}\right) d\gamma
\end{aligned}
\tag{3.22}
$$

First, we expand the incomplete gamma function for integer values of m by using eq. (8.352.4) (Gradshteyn and Ryzhik, 2000). The incomplete gamma function can be written as, $\Gamma(x,a) = \Gamma(x)e^{-a}\sum_{p=0}^{x-1}\frac{a^p}{p!}$. Besides, with the help of eq.(3.351.1) (Gradshteyn and Ryzhik, 2000), $\int_0^\infty x^v e^{-\mu x} dx = v!\mu^{-v-1}$ for $\mathrm{Re}(\mu) > 0$. Where,

$v=m_2+p-1$, $v=m_1+s-1$, $v=m_2+k+p-1$ and $v=m_1+k+s-1$ in the first, second, third, and forth terms, respectively. And $\mu=\frac{2m_1}{\Omega_1}+\frac{2m_2}{\Omega_2}$ in the first, second, third, and fourth terms similarly. Now to solve the fifth and the sixth terms, we have to define one additional term $J_2(a,p,d,c)$. From eq. (3.7), we can define this term as

$$J_2(a,p,d,c) \;=\; \int_0^{\infty} x^{a-1}e^{-px}\,{}_1\tilde{F}_1(b;d;cx)dx \tag{3.23}$$

with parameters a, p, d, c, where $\mathrm{Re}[a]>0$ and $\mathrm{Re}[p]>0$. Using the definition of the regularized hypergeometric function ${}_p\tilde{F}_q$ in eq.(3.8), $J_2(a,p,b,d,c)$ can be solved as (Atapattu et al., 2010)

$$J_2(a,p,b,d,c) \;=\; p^{-a}\Gamma(a)\,{}_2\tilde{F}_1(a;b;d;\frac{c}{p}) \tag{3.24}$$

The fifth and the sixth terms we expand the incomplete gamma function as, $\Gamma(x,a) \;=\; \Gamma(x)e^{-a}\sum_{p=0}^{x-1}\frac{a^p}{p!}$ and use the integration in eq.(3.23). Therefore, a close form expression of $\overline{A}_{\gamma^{\min}}$ can be written as follow, where ${}_2\tilde{F}_1(.;.;.;.)$ is the regularized confluent hypergeometric function of the confluent hypergeometric function ${}_2F_1(.;.;.;.)$.

$$\overline{A}_{\gamma^{\min}} \;=\; I_1+I_2+I_3 \tag{3.25}$$

Where

$$I_1 \;=\; \sum_{p=0}^{m_1-1}\frac{\left(\frac{m_2}{\Omega_2}\right)^{m_2}\left(\frac{m_1}{\Omega_1}\right)^{p}(m_2)_p}{p!\left(\frac{m_1}{\Omega_1}+\frac{m_2}{\Omega_2}\right)^{m_2+p}}+\sum_{s=0}^{m_2-1}\frac{\left(\frac{m_1}{\Omega_1}\right)^{m_1}\left(\frac{m_2}{\Omega_2}\right)^{s}(m_1)_s}{p!\left(\frac{m_1}{\Omega_1}+\frac{m_2}{\Omega_2}\right)^{m_1+s}}$$

$$I_2 = -\sum_{k=0}^{u-1}\sum_{p=0}^{m_1-1}\frac{\left(\frac{m_1}{\Omega_1}\right)^p\left(\frac{m_2}{\Omega_2}\right)^{m_2}(m_2)_{k+p}}{2^k k!p!\left(\frac{m_1}{\Omega_1}+\frac{m_2}{\Omega_2}\right)^{k+m_2+p}}-\sum_{k=0}^{u-1}\sum_{s=0}^{m_2-1}\frac{\left(\frac{m_2}{\Omega_2}\right)^p\left(\frac{m_1}{\Omega_1}\right)^{m_1}(m_1)_{k+n}}{2^k k!s!\left(\frac{m_1}{\Omega_1}+\frac{m_2}{\Omega_2}\right)^{k+m_1+s}}$$

$$I_3 = \sum_{k=1-u}^{u-1}\sum_{p=0}^{m_1-1}\frac{\left(\frac{m_2}{\Omega_2}\right)^{m_2}\left(\frac{m_1}{\Omega_1}\right)^p(u)_k(m_1)_p L(m_1,m_2)}{2^{u+k-m_2}p!\left(\frac{2m_1}{\Omega_1}+\frac{2m_2}{\Omega_2}+1\right)^{m_2+p}}$$
$$+\sum_{k=1-u}^{u-1}\sum_{s=0}^{m_2-1}\frac{\left(\frac{m_1}{\Omega_1}\right)^{m_1}\left(\frac{m_2}{\Omega_2}\right)^s(u)_k(m_1)_s L(m_1,m_2)}{2^{u+k-m_1}s!\left(\frac{2m_1}{\Omega_1}+\frac{2m_2}{\Omega_2}+1\right)^{m_1+s}}$$

The constant $L(m_1,m_2)$ is written as ${}_2\tilde{F}_1\left[u+k;m_1+n;k+1;\frac{1}{\left(\frac{2m_1}{\Omega_1}+\frac{2m_2}{\Omega_2}+1\right)}\right]$

which is in the form of the regularized confluent hypergeometric function.

3.6 Numerical Analysis and Simulation Results

We calculate an average P_d for eq. (3.18) by using Mathematica software. To illustrate the number of terms required in evaluating the infinite series form expressions. The minimum number of terms required to obtain an accuracy of P_d for single cognitive relay is shown in the Table 3.1. For the area under the ROC curve (AUC), there is no infinite series term.

Table 3.1 Number of Terms Required to Obtain A Five Figure Accuracy k in eq.(3.18)

u	1	5	5	5	5
P_f	0.01	0.01	0.01	0.0001	0.0001
m	1	2	4	2	4
Ω (dB)	5	5	5	5	5
k	11	10	11	10	10
Ω (dB)	10	10	10	10	10
k	24	24	25	24	25

To validate the analysis, the complementary receiver operating characteristics (complementary ROC) curves are shown. The value of u is set to be 5. The simulation and analytical results are shown. The analytical results are validated with Monte Carlo simulation. The simulation results, we use Matlab program and for the theoretical results Mathematica software is used.

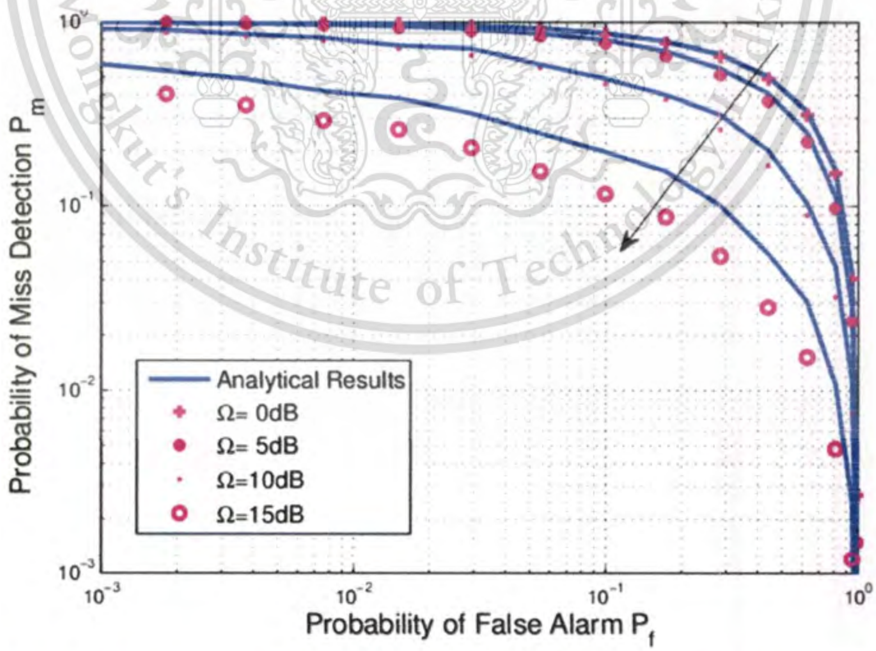

Figure 3.2 Energy detection with employing single cognitive relay with m=2 for i.i.d. Nakagami-m fading channels for different average SNR (Ω) values.

Fig. 3.2 shows the complementary ROC curves for single cognitive relay over i.i.d. Nakagami-m fading channel for two hops parameterized over different average SNR (Ω) values. It is clearly seen that the curves obtained from analytical results (solid lines) lie tightly match to the exact simulation curves (marked lines) for low Ω values. The analytical results are plotted from the lower bound detection probability in eq.(3.18). We set m to be 2 and the values of Ω are set to be 0, 5, 10 and 15 dB equally for both first and second hops. The complementary ROC curves which are P_m or $1-P_d$ versus P_f are generated. We can see that the complementary ROC curves decrease when Ω values increase. It means that the missed-detection probability improves when Ω values increase. The lower bound detection probability equation is tight with the simulation results for low Ω values which are 0 and 5 dB.

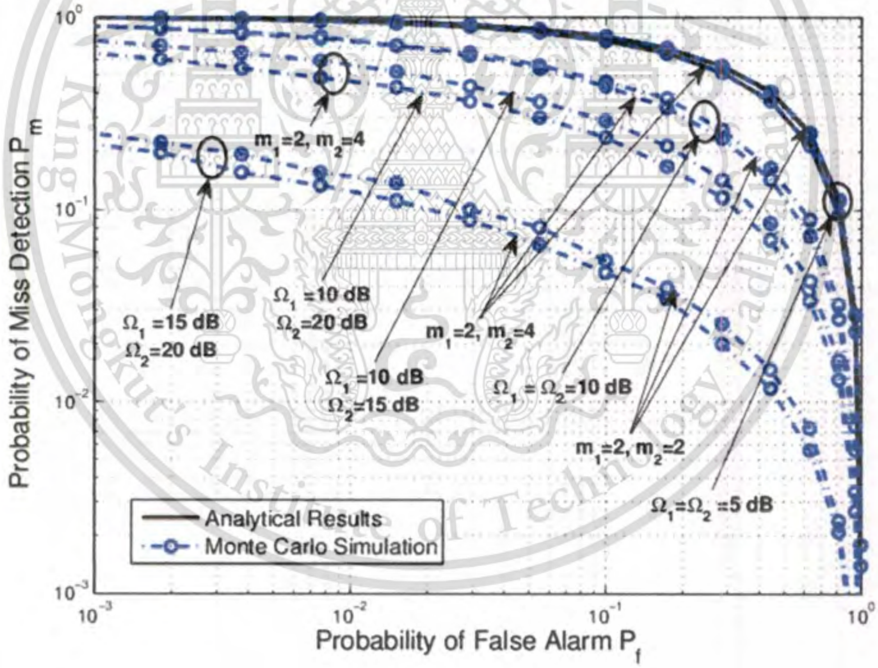

Figure 3.3 Energy detection with employing single cognitive relay with the degree of freedom u=5 over non-i.i.d Nakagami-m fading channels with different fading parameters m_1 and m_2 along with various average SNR Ω_1 and Ω_2 values.

Fig. 3.3 shows the complementary ROC curves for single cognitive relay over non-i.i.d. Nakagami-m fading channel for two hops parameterized over different fading parameters m_1 and m_2 as well as different average SNR Ω_1 and Ω_2 values. It can be observed that the curves obtained from analytical results (solid lines) lie tightly match to the exact simulation curves (marked and dotted lines) for $\Omega_1 = \Omega_2 = 5$ dB.The analytical results are plotted from the lower bound detection probability for dual hop non-i.i.d Nakagami-m channels in eq.(3.20). We plot both analytical expression in eq.(3.20) and Monte Carlo simulation for $\Omega_1 = \Omega_2 = 5$ dB. For high Ω values, only the simulation results are shown. We set the degree of freedom u=5 with varying $\Omega_1 = 5$, 10 and 15 dB, $\Omega_2 = 5$, 10, 15 and 20 dB. For the fading parameters m_1 and m_2, they are assumed to be 2 and 4, respectively. The complementary ROC curves which are P_m or $1 - P_d$ versus P_f are generated. We can see that the complementary ROC curves enhances when m_2 increases. For example, at the same average SNR $\Omega_1 = 15$dB, $\Omega_2 = 20$ dB, when $m_1 = 2$, $m_2 = 4$ the complementary ROC is lower than when $m_1 = 2$, $m_2 = 2$. Moreover, at the same fading parameters $m_1 = 2$, $m_2 = 4$, the complementary ROC improves when Ω_2 increases from 15 to 20 dB with $\Omega_1 = 10$dB. It means that the missed-detection probability becomes lower with increasing Ω_2 values.

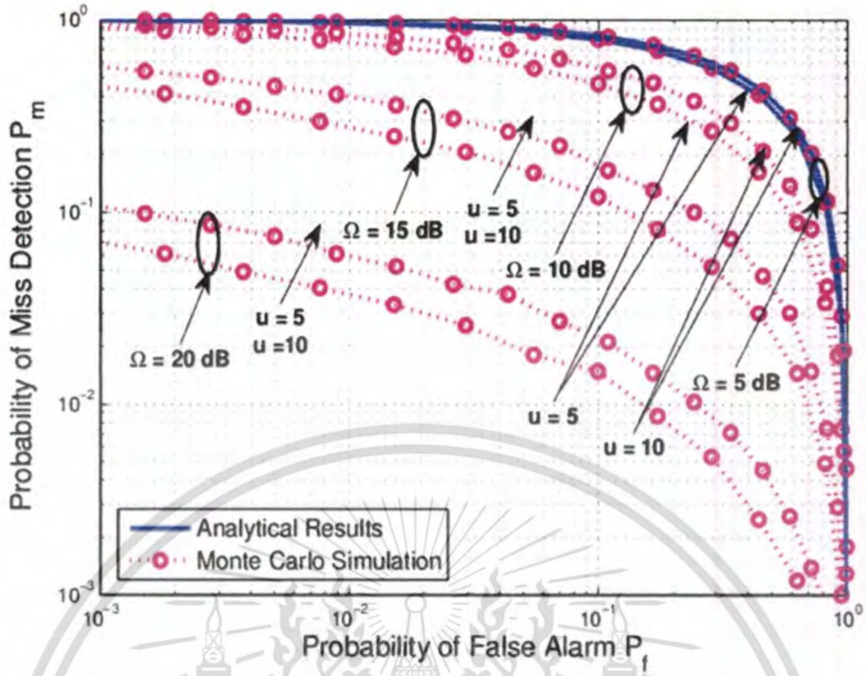

Figure 3.4 Energy detection with employing single cognitive relay parameterized over different degree of freedom u and various average SNR Ω over i.i.d. Nakagami-m fading channels with fading parameters $m_1 = m_2$=2.

Fig. 3.4 shows the complementary ROC curves for single cognitive relay over i.i.d. Nakagami-m fading channel for two hops parameterized over different degree of freedom u and various average SNR Ω. The analytical results are shown as solid and the exact simulation curves are plotted as marked and dotted lines. The analytical results are plotted from the lower bound detection probability equation in eq.(3.18). In this Fig. we plot both analytical expression in eq.(3.18) and Monte Carlo simulation for Ω=5dB. For high Ω values, only the simulation results are shown. According to our analytical results are perfectly match with the Monte Carlo simulation for low average SNR (Ω) such as Ω=0 and 5dB. We set m to be 2, the values of Ω are set to be 5, 10, 15 and 20 dB, and the values of degree of freedom u are set to be 5 and 10. The complementary ROC curves which are P_m or $1-P_d$ versus P_f are generated. We can see that the complementary ROC curves decrease with decreasing of the degree of freedom u. It means that the missed-detection probability improves when u decreases.

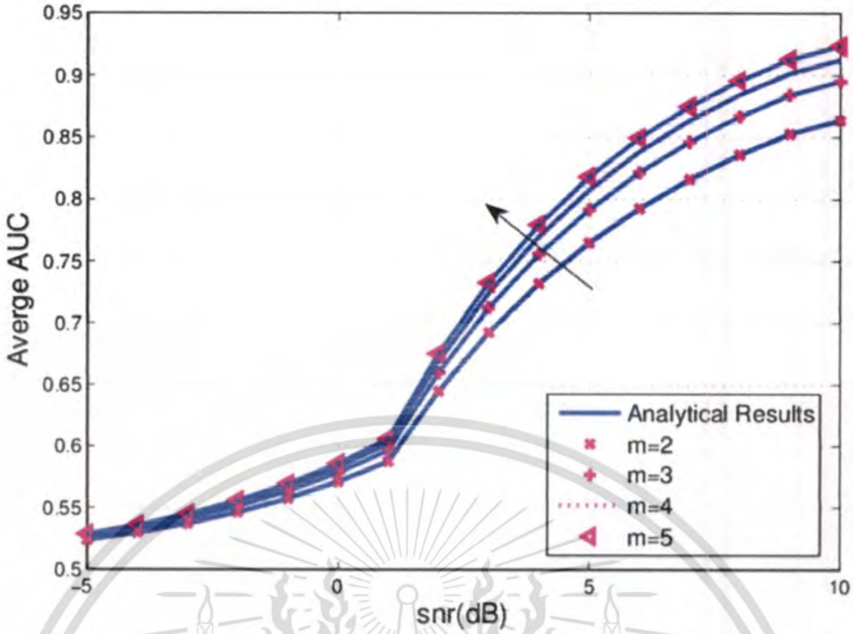

Figure 3.5 Numerical results and Monte Carlo simulation of average AUC for single cognitive relay i.i.d. Nakagami-m fading channels with varying fading parameters m.

Fig. 3.5., it is clearly seen that the curves obtained from analytical results (solid lines) lie quite match to the exact simulation curves (marked line) from SNR region (−5, 10) dB. The analytical results are plotted from the equation of lower bound AUC expression in equation eq. (3.25) by assuming $m_1 = m_2$. We set $m_1 = m_2 = 2$ and the SNR region are set from (−5, 10) dB. The degree of freedom (u) is set to be 5. We can see that the fading parameter m effect the AUC curve. The AUC curves increase when the parameter m increases. The AUC equation is tight with the simulation results for SNR region from (−5, 10) dB.

3.7 Conclusion

In this chapter, we have derived the lower bounded detection probability expressions of single cognitive relay over independently and identically (i.i.d.) and non i.i.d. Nakagami-m fading channels. Besides the equations of area under the ROC curve (AUC) for both i.i.d. and non i.i.d. are provided. In our system model, each node (the primary user, the cognitive relay and the fusion center) is equipped with single antenna.

The amplify-and-forward cognitive relay is used to retransmit the amplified signal to the fusion center.

The average detection probability is evaluated by averaging an alternative series representation of generalized Marcum-Q function over the PDF of end-to-end SNR at the fusion center. And then, we evaluate the area under the ROC (AUC) by averaging a faded AUC in eq.(3.7) over the PDF of end-to-end SNR at the fusion center. For the average detection expressions, we can see the expressions in eq.(3.18) and eq.(3.20) are simple and easily converged with one infinite series summation. In order to verify our expressions, an accuracy of detection probability for five digits accuracy is shown in the Table 3.1. The analytical expressions are evaluated by using Mathematica sofware package. The simulation results are computed by Monte Carlo using Matlab program. The analytical results are plotted by solid lines and the Monte Carlo simulation is shown as marked lines. Our bounded expressions are tightly match with the Monte Carlo simulation for low SNR values.

The complementary ROC curves for i.i.d. two-hop Nakagami-m fading channels is shown in Fig. 3.2., we can see that when SNR values (Ω) increase, missed detection probability (P_m) decreases. It means that detection probability (P_d) improves with respect to higher SNR values. For non-i.i.d. dual hop Nakagami-m fading channels in Fig. 3.3., the missed detection probability P_m improve with an increasing of fading parameters m_1, m_2 as well as higher average SNR (Ω) values. When we plot by varying the degree of freedom values (u) for i.i.d. two hop Nakagami-m channels in Fig. 3.4, we can see that missed detection probability decreases when decreasing the degree of freedom values (u). The performance of detection in AUC curves with changing the fading parameters m over i.i.d. Nakagami-m channels in Fig. 3.5, we can see that the AUC curves are higher due to increasing the fading parameters m. The numerical results are provided to show a good agreement between analytical and simulated curves, as such, validating the accuracy of our analytical approach.

CHAPTER 4

COOPERATIVE SPECTRUM SENSING EMPLOYING BEST COGNITIVE RELAY SELECTION

4.1 Introduction

Cooperative diversity techniques (Nosratinia et al., 2004) and (Duong et al., 2009) have been recently proposed to mitigate the signal fading caused by the multipath propagation. In the cooperative diversity network, the source transmits the signal to the destination not only through the direct link but also through indirect links by using cooperating relays. The performance of cooperative-communication systems is analyzed for various system and channel models, such as Rayleigh and Nakagami-m fading channels, (Ikki and Ahmed, 2007) and (Duong et al., 2009). There are two well -known cooperative protocols: amplify-and-forward (AF) and decode-and- forward (DF). The AF and DF protocols improve the system performance, while losing bandwidth efficiency since the relays must use orthogonal channels in order to avoid interfering with the source node and with each other as well (Ikki and Ahmed, 2007).

The problem of the inefficient use of the channel resources can be eliminated with the use of the best-relay selection scheme. (Ikki and Ahmed, 2007) proposed the best-relay scheme in Rayleigh fading channels, the source-relay and relay-destination channels are assumed to be independently and identically distributed. The relay with the highest SNR at the destination is selected for the source signal retransmission. Moreover, for the AF protocol, performance of the best-relay selection and the best-relay selection with direct link transmission schemes have been compared and reported in (Ikki and Ahmed, 20008).

The best relay selection, however, might be unavailable in practice due to the load balancing and scheduling issues. In this case the decision may be made to use the second best relay or more generally the Nth best relay. Consequently, (Ikki and Ahmed, 2010), investigated the Nth best-relay scheme over Rayleigh fading channels. Nevertheless, the source-relay and relay-destination channels are assumed independent and identically distributed.

In wireless network communication, when the channel resources are efficiently utilized, the way to improve spectrum efficiency and link reliability is to employ multiple antennas at both ends of a wireless link, called multiple-input multiple-output (MIMO) technology. More recently, applying MIMO techniques to the relay networks (Yijia and Thompson, 2007), has come under consideration. For multiple antennas or MIMO relay channels where every terminal in the network can be deployed with multiple antennas, studies are mainly concentrated on spatial multiplexing systems, capacity and symbol error rate. In our work, we also apply multiple input multiple output (MIMO), where multiple antennas are employed at the relay.

In this chapter, we present a pioneer work which explores cooperative relay schemes with energy detection in independently and identically (i.i.d.) Nakagami- m fading channels. Two cooperative scenarios are considered which the best cognitive relays are and multiple antennas applied at the cognitive relay. The first case, best cognitive relay selection scheme is considered and energy detector is employed at a fusion center. All nodes (a primary user, multiple cognitive relays, and a fusion center) are configured with single antenna. In the second case, we employ single antenna with both the primary user and the fusion center. The maximal ratio combining (MRC) is applied in multiple-input multiple-output (MIMO) at the cognitive relay. The energy detector is constructed at the fusion center. We consider amplify and forward (AF) cognitive relaying as a practical implementation. Under these two system models, we derive detection probability based on energy detector enabled at the fusion center. The performance of detection capability is characterized by plotting complementary receiver operating characteristics (complementary ROC) curves which is a plot of missed detection probability (P_m) versus false-alarm probability (P_f). We validate our analytical results with Monte Carlo simulations with the help of Mathematica and MATLAB programs.

The rest of this chapter is organized as follows. Section 4.2, introduces the system model and analysis of detection probability for the best cognitive relay selection. The energy detector is employed the fusion center over i.i.d. Nakagami-*m* fading channels.

Section 4.3, the cooperative scheme with using multiple-input multiple-output at the cognitive relay is configured over i.i.d. Nakagami-*m* fading channels. At the fusion center, the energy detector is constructed. The analysis of detection probability is also shown in Section 4.3. In Section 4.4, some numerical and simulation results are given. Section 4.5, gives a conclusion for this chapter.

4.2 Cooperative spectrum sensing

We consider cognitive relays based spectrum sensing in Fig. 4.1. N cognitive relays (namely, r_1, r_2, . . . , r_N) are considered in the cognitive radio sensing system. Each node (primary user, cognitive relay, and fusion center) is restricted to have only one antenna in this study. We assume that there is no direct link from the primary user to the fusion center. In the first phase when a primary user starts using the band, cognitive relays receive signal from the primary user. In the second phase, the cognitive relays forward the amplified version of the received signals to the fusion center. Assume that each *ith* cognitive relay does not have instantaneous channel state information (CSI) from the primary user p, but assumed to know its own average channel power $\mathrm{E}\left[\left|h_{pr_i}\right|\right]^2$ and the fusion center assumed to know all average channel power which are $\mathrm{E}\left[\left|h_{pr_i}\right|\right]^2$ and $\mathrm{E}\left[\left|h_{r_id}\right|\right]^2$, respectively.

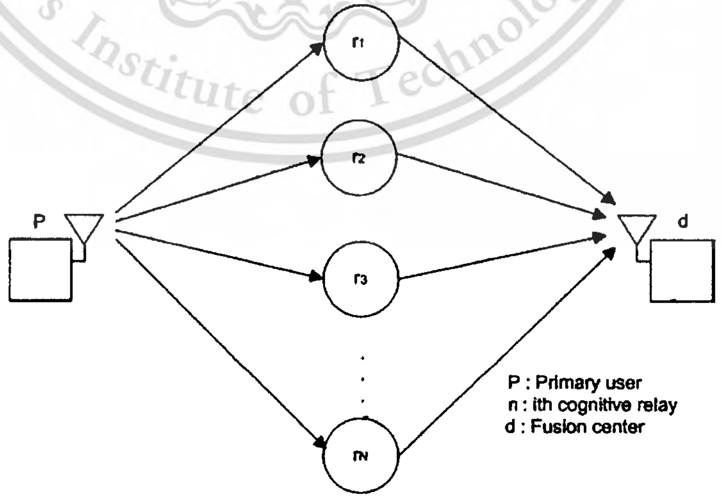

Figure 4.1 Cooperative spectrum sensing with employing cognitive relays.

Each communication channel between cognitive relays and fusion center occurs in orthogonal channels. Energy detector is equipped at the fusion center, the received signal energy is then compared with a pre-define threshold λ.

4.2.1 Analysis of Best Cognitive Relay Selection for Spectrum Sensing

In this case, we consider best cognitive relay selection scheme. The fusion center knows all average channel power of both two hops. Then, the cognitive relay whose path has the maximum SNR statistic is selected, the detection probability (P_d) is derived. The average energy detection in this case can be evaluated through averaging eq.(3.14) by the PDF of $\gamma_{\max}\left(f_{\gamma_{\max}}(\gamma)\right)$ which is given an appendix,

$$\overline{P}_d = \int_0^\infty Q_u\left(\sqrt{2\gamma},\sqrt{\lambda}\right) f_{\gamma_{\max}}(\gamma)\, d\gamma \tag{4.1}$$

$$= \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1} C\int_0^\infty e^{-\beta\gamma}\gamma^{k+p_{sum}}\left[\frac{p_{sum}}{\gamma}-\frac{2mq}{\Omega}\right]d\gamma, \tag{4.2}$$

where $C=\dfrac{e^{-\frac{\lambda}{2}}\left(\frac{\lambda}{2}\right)^n L(N,m)}{k!n!}$ and $\beta=\dfrac{2m}{\Omega}+1$.With the help of eq.(3.381.4) (Gradshteyn and Ryzhik, 2000) $\int_0^\infty x^{v-1}e^{-\mu x}dx=\dfrac{\Gamma(v)}{\mu^v}$, where $\mathrm{Re}(\mu)>0$. and $\mu=\dfrac{2m}{\Omega}+1$, $v=k+p_{sum}$ in the first term and $v=k+p_{sum}+1$ in the second term. The average detection probability is written by

$$\overline{P}_d = \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\frac{e^{-\frac{\lambda}{2}}\left(\frac{\lambda}{2}\right)^n}{k!n!}\frac{L(N,m)\Gamma(k+p_{sum})}{\left(1+\frac{2mq}{\Omega}\right)^{k+p_{sum}}} \times\left(p_{sum}-\frac{\left(\frac{2mq}{\Omega}\right)(k+p_{sum})}{\left(1+\frac{2mq}{\Omega}\right)}\right). \tag{4.3}$$

4.3 Spectrum Sensing with Employing Multiple Antennas at the Cognitive Relay

This section, we assume that a primary user and a fusion center enable single antenna similarly to the first scenario in chapter 3. The primary and the fusion center are employed with single antenna. The cognitive relay is enabled with L number of antennas and there is no direct link from the primary user to the fusion center. Our system model is shown in Fig.4.2.

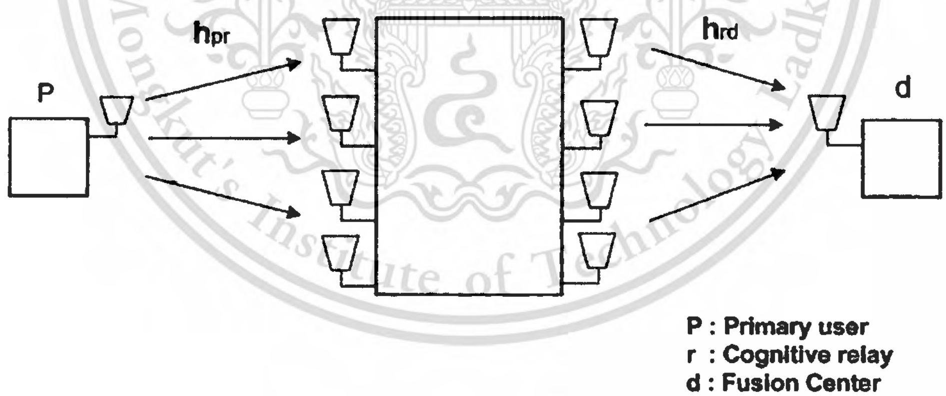

Figure 4.2 Energy detection with employing multiple antennas at the cognitive relay, single antenna at the primary user and the fusion center.

In the first phase, the primary user transmits signal to the cognitive relay which can be expressed as,

$$y_{pr} = \theta h_{pr} x + n_r , \tag{4.4}$$

where y_{pr} is the $L \times 1$ received signal vector at the cognitive relay, h_{pr} is a random channel vector $L \times 1$, n_r is an AWGN noise vector $L \times 1$ with independent components. In the second phase, the cognitive relay combines the received signal from each antenna by using maximal ratio combining (MRC) and amplifies signal with the variable gain G in (Atapattu et al., 2011) then, forward to the fusion center. The received signal at the fusion center denoted as, y_{rd} which is given by

$$y_{rd} = \theta G h_{pr} h_{rd} x + G h_{rd} n_r + n_d , \tag{4.5}$$

where y_{rd} is the $1 \times L$ received signal vector at the fusion center. h_{rd} is the random channel vector $1 \times L$. n_d is an AWGN noise vector $1 \times L$ with independent components. At the fusion center, the received SNR can be written by,

$$\gamma_D = \frac{\gamma_{pr}\gamma_{rd}}{\gamma_{pr} + \gamma_{rd}}, \tag{4.6}$$

where $\gamma_{pr} = \frac{|h_{pr}|^2}{N_0}$ and $\gamma_{rd} = \frac{|h_{rd}|^2}{N_0}$. γ_{pr} and γ_{rd} are the instantaneous SNRs of channels from the primary user to the cognitive relay and from the cognitive relay to the fusion center, respectively.

The lower bound of overall end-to-end SNR is similar to chapter 3, which is (Anghel and Kaveh, 2004).

$$\gamma_D = 0.5 \min\left(\gamma_{pr}, \gamma_{rd}\right). \tag{4.7}$$

The average detection probability in this case $\left(\overline{P}_{d,1}\right)$ can now be evaluated by averaging eq. (3.14) over the PDF of lower bounded end-to-end SNR $\left(f_{\gamma_D}(\gamma)\right)$,

$$\overline{P}_{d,1} = \int_0^\infty Q_u\left(\sqrt{2\gamma},\sqrt{\lambda}\right) f_{\gamma_D}(\gamma)\,d\gamma \tag{4.8}$$

$$= \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1} K\int_0^\infty e^{-\left(1+\frac{2m}{\Omega}\right)\gamma}\gamma^{k-1+Lm}\frac{\Gamma\left(Lm,\frac{2m\gamma}{\Omega}\right)}{\Gamma(Lm)^2}d\gamma, \tag{4.9}$$

where $K=\dfrac{e^{\frac{-\lambda}{2}}\left(\frac{\lambda}{2}\right)^n 2^{1+Lm}\left(\frac{m}{\Omega}\right)^{Lm}}{k!m!}$. For integer values of m, the incomplete gamma function can be written based on eq.(8.352.4) in (Gradshteyn and Ryzhik, 2000). Besides, with the help of eq. (3.351.1) in (Gradshteyn and Ryzhik, 2000), $\int_0^\infty x^v e^{-\mu x}dx = v!\mu^{-v-1}$, where $\mathrm{Re}(\mu)>0$, and $v=k+m+p-1$ and $\mu=1+\dfrac{4m}{\Omega}$. The average detection probability is derived as, Finally, the average detection probability $\left(\overline{P}_{d,1}\right)$ is expressed as,

$$\overline{P}_{d,1} = \sum_{k=0}^{\infty}\sum_{n=0}^{u+k-1}\sum_{p=0}^{Lm-1}\frac{2^a e^{\frac{-\lambda}{2}}\left(\frac{\lambda}{2}\right)^n\left(\frac{m}{\Omega}\right)^{Lm+p}(Lm)_{k+p}}{k!p!n!\left(\frac{4m}{\Omega}+1\right)^{k+Lm+p}}, \tag{4.10}$$

where $a=1+L_m+p$ and $(n)_t$ is a Pochammer symbol as $(n)_t=\dfrac{\Gamma(n+t)}{\Gamma(n)}$ (Gradshteyn and Ryzhik, 2000).

4.4 Analytical and Simulation Results

We calculate an average P_d for eq. (4.3), and eq.(4.10) by using Mathematica software. To illustrate the number of terms required in evaluating the infinite series form expressions. The minimum number of terms required to obtain an accuracy of P_d for single cognitive relay, the best cognitive relay selection, and multiple antennas employed at the cognitive relay are shown in the Table 4.1, and 4.2, respectively.

Table 4.1 Number of Terms Required to obtain A Five Figure Accuracy k in (4.3)

u	1	5	5	5	5
P_f	0.01	0.01	0.01	0.0001	0.0001
m	1	2	2	2	2
N	3	3	6	3	6

Ω (dB)	5	5	5	5	5
k	11	12	13	12	13

Ω (dB)	10	10	10	10	10
k	25	25	26	25	26

Table 4.2 Number of Terms Required to obtain A Five Figure Accuracy k in (4.10)

u	1	5	5	5	5
P_f	0.01	0.01	0.01	0.0001	0.0001
m	1	2	2	2	2
L	2	3	4	2	3

Ω (dB)	0	0	0	0	0
k	14	14	15	14	15

Ω (dB)	5	5	5	5	5
k	20	20	22	21	22

To validate the analytical expressions, the complementary receiver operating characteristics (complementary ROC) curves which are P_m or $1-P_d$ versus P_f are shown. The value of the degree of freedom u is set to be 5. The simulation and theoretical results are shown. For the Monte Carlo simulation, we use Matlab program and for the theoretical results Mathematica software package is used. Our analytical results are validated for low average SNR (Ω) values.

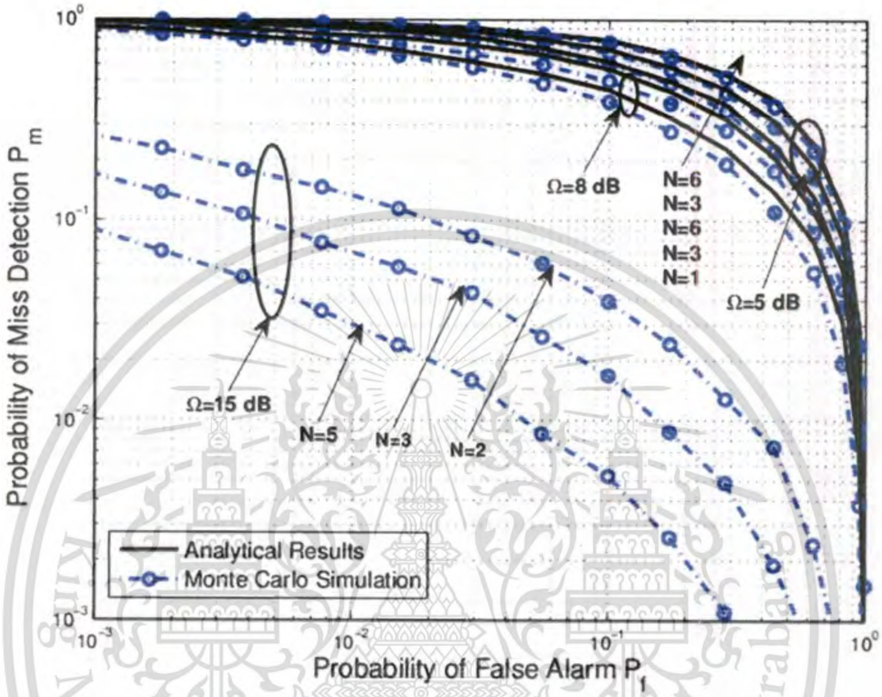

Figure 4.3 The best cognitive relay selection scheme over dual hop i.i.d. Nakagami-m fading channels for different number of available cognitive relay (N) and various average SNR (Ω) with fading parameter m=2, degree of freedom u=5.

Fig. 4.3, the best cognitive relay selection for two-hop i.i.d. Nakagami-m channels in eq.(4.3) is plotted. It shows the complementary ROC curves for the best cognitive relay selection over i.i.d. Nakagami-m channel parameterized over different number of available cognitive relays (N) .We set the fading parameter m equals to 2, the average SNR Ω values are set to be 5, 8 and 15 dB. The best cognitive relay is selected from 3 and 6 available cognitive relays for Ω=5 and 8 dB. Moreover, for Ω=15 dB, the number of available cognitive relays are changed from N=2 to 3 and 5. At Ω=15 dB, only the Monte Carlo simulation results are plotted. Our theoretical expression is shown to validate for low Ω values. The complementary ROC curves are plotted by increasing the number of cognitive relays. It is clearly seen that when number of available cognitive relays increases, the missed-detection probability decreases. Especially for high Ω value (Ω= 15 dB), the complementary ROC improves a lot with higher number of available cognitive relays.

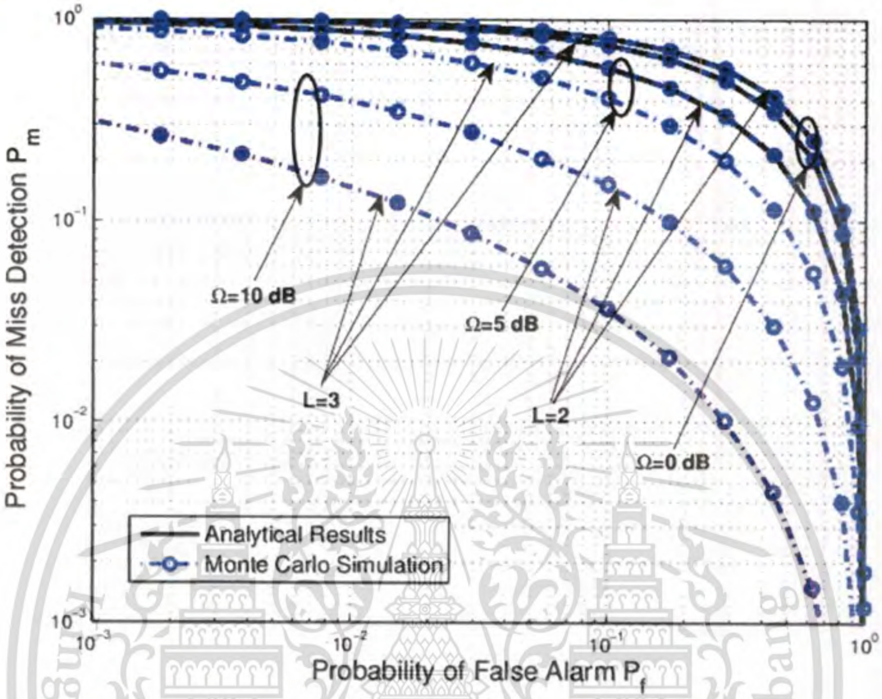

Figure 4.4 Complementary ROC curves of cooperative cognitive scheme for single cognitive relay with employing MIMO over i.i.d. Nakagami-m fading channels for different number of antennas L and various average SNR (Ω) with fading parameter m=2, degree of freedom u=5.

Fig. 4.4 shows the complementary ROC curves for single cognitive relay with employing multiple antennas (MIMO) at the cognitive relay over i.i.d. Nakagami-m fading channels parameterized with different average SNR (Ω) and various number of antennas (L). The analytical results are plotted from the lower bound detection probability eq. (4.10). We assume the fading parameter m to be 2 and the values of Ω are set to be 0, 5 and 10 dB. The complementary ROC curves, which are P_m or $1-P_d$ versus P_f are generated to verify the performance of detection. We can see that the complementary ROC curves decrease when number of antennas (L) increases. Besides, it can be observed clearly that for high Ω value which equals to 10 dB in this Fig. the complementary improves a lot when increasing number of antennas L. As we expect, the detection capability improves when the number of antennas increases especially for high Ω values.

4.5 Conclusion

In this chapter, we have derived the lower bounded detection probability expressions of single cognitive relay and the best cognitive relay selection for cognitive radio networks over i.i.d. Nakagami-m fading channels. In the first case, we assume each node (the primary user, the cognitive relay and the fusion center) is enabled with single antenna. Then, for the second case, we suppose the primary user and the fusion center are equipped with single antenna and the cognitive relay is employed with multiple antennas. For the second case, the cognitive relay receiver the maximal ratio combining (MRC) is used to combine the received signal from each antenna. The amplify-and-forward cognitive relay is used to retransmit the amplified signal to the fusion center for both cases. The average detection probability is evaluated by averaging an alternative series representation of generalized Marcum-Q function over the PDF of end-to-end SNR at the fusion center. The average detection expressions are simple and easily converged with one infinite series summation for both cases. In order to verify our expressions, an accuracy of detection probabilities for five digits accuracy are shown in the table. The analytical results are plotted by solid lines and Monte Carlo simulation is shown as marked lines. As expected, we can see that the detection capability improves when increasing number of available cognitive relays for the best cognitive relay selection case. Besides, for multiple antennas employed at the cognitive case in Fig. 4.4., we can observe that the detection capability improves along with increasing number of antennas. The numerical results are provided to show a good agreement between analytical and simulated curves for low Ω values, as such, validating the accuracy of our analytical approach.

CHAPTER 5
CONCLUSIONS

5.1 Summary of Conclusions

Recently, cognitive radios (CRs) have been introduced as a potential solution to this problem (Mitola and Maguire, 1999; Haykin, 2005). In a widely studied form of CR technology sometimes known as opportunistic or dynamic spectrum access, the secondary users, are allowed to opportunistically utilize a frequency band allocated to primary users, when it is not being used. The CR network has to be able to detect the presence of the primary networks signals, so as to avoid interfering with it. Therefore, spectrum sensing plays a crucial role in the successful deployment of CRs.

In chapter 2, we describe background and related literature for cognitive radio networks, the cooperative diversity communication is also mentioned. Besides, the cooperative spectrum sensing and sensing techniques are conceptually described. In chapter 3, we study cooperative spectrum sensing with energy detection. Energy detector is performed at the fusion center to detect the primary user's signal. We consider single cognitive relay with single antenna employed for all nodes in this chapter. The detection probability is derived by integrating an alternative form of Marqum-Q function over end-to-end signal to noise ratio (SNR). Besides, closed form expressions of area under the ROC are provided. The dual-hop cognitive relay is studied over independent and non-identically distributed (i.n.i.d), and independent and identically distributed (i.i.d) Nakagami-m channels. The fading parameter m is assumed to be integer values. The performance of detection capability is shown by plotting complementary receiver operating characteristics (complementary ROC) curves which is a plot of missed detection probability (P_m) versus false-alarm probability (P_f). Area under the ROC curves, are plotted versus SNR (dB).

In chapter 4, we study two scenarios which are 1) the best cognitive relay selection and 2) multiple antennas employed at the cognitive relay over i.i.d. Nakagami-m fading channels. In the first case, a primary user, multiple cognitive relays, and a fusion center are enabled with single antenna. The link with highest end-to-end SNR is selected among multiple-relay nodes. In the second case, we employ single antenna with both the primary user and the fusion center, multiple antennas at the cognitive relay.

The maximal ratio combining (MRC) is applied in multiple-input multiple-output (MIMO) at the cognitive relay. We consider amplify and forward (AF) cognitive relaying as a practical implementation. The performance of detection capability is characterized by plotting complementary receiver operating characteristics (complementary ROC) curves which is a plot of missed detection probability (P_m) versus false-alarm probability (P_f). We validate our analytical results with Monte Carlo simulations by Mathematica and MATLAB programs.

5.2 Future Work

This thesis presents spectrum sensing technique with using energy detection. Cooperative spectrum sensing scheme is studied with energy detection technique. We assume the transmitted signal to be deterministic signal. All channel statistics are known at the fusion center. We employ the cognitive relay for amplify the transmitted signal from the primary user and retransmit the amplified version to the fusion center. Energy detector is constructed at the fusion center. We consider three system scenarios which are 1) single cognitive relay, 2) the best cognitive relay selection and 3) multiple antennas employed at the cognitive relay. For all these three system models, the primary user, and the fusion center are equipped with single antenna. The possible for future work, some extension can be done for this work 1) the correlation between multiple antennas at the cognitive relay can be considered. 2) Multiple antennas employed at the fusion center and using square law combining to combine the received signal. 3) Random signal transmitted instead of deterministic signal. 4) Multiple cognitive relays without selection scheme use to retransmit signal to the fusion center.

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APPENDICES

APPENDIX A

A. Derivation of Probability Density Function of $\gamma_{iid}^{\min}$

A.1 The Cumulative Distribution Function (CDF) of $\gamma_{iid}^{\min}$

The cumulative distribution function (CDF) of $\gamma_{iid}^{\min}$ is applied from (Waqar et al., 2009). In can be written as, $\gamma_{i.i.d.}^{\min} = 0.5\min\left(\gamma_{pr_i}, \gamma_{r_i d}\right)$

$$
\begin{aligned}
F_{\gamma_{iid}^{\min}}(\gamma) &= 1 - P_r\left(0.5\gamma_{pr_i} > \gamma, 0.5\gamma_{r_i d} > \gamma\right) \\
&= 1 - \frac{\Gamma\left(m, \frac{m}{\Omega}2\gamma\right)^2}{\Gamma(m)^2}.
\end{aligned}
\tag{A.1}
$$

Probability density function (PDF) of $\gamma_{iid}^{\min}$ by the first order derivative of $F_{\gamma_{iid}^{\min}}(\gamma)$ using incomplete gamma expansion eq. (8.352.4) (Gradshteyn and Ryzhik, 2000). Thus, the PDF is given by

$$
f_{\gamma_{iid}^{\min}}(\gamma) = \frac{\left(\frac{m}{\Omega}\right)^m 2^{1+m}\gamma^{m-1}e^{\frac{-2m\gamma}{\Omega}}\Gamma\left(m, \frac{2m\gamma}{\Omega}\right)}{\Gamma(m)^2}.
\tag{A.2}
$$

A.2 Probability Density Function of $\gamma^{\min}$

The cumulative distribution function (CDF) of $\gamma^{\min} = 0.5\min\left(\gamma_{pr}, \gamma_{rd}\right)$ is given by

$$F_{\gamma^{\min}}(\gamma) = 1 - P_r\left(0.5_{\gamma_{pr}} > \gamma, 0.5_{\gamma_{rd}} > \gamma\right)$$
$$= 1 - \frac{\Gamma\left(m_1, \frac{m_1}{\Omega_1}2\gamma\right)}{\Gamma(m_1)} \frac{\Gamma\left(m_2, \frac{m_2}{\Omega_2}2\gamma\right)}{\Gamma(m_2)^2}, \tag{A.3}$$

where $F_{\gamma_{pr}}(\gamma)$ and $F_{\gamma_{rd}}(\gamma)$ are the CDFs of signal-to-noise-ratio (SNR) of γ_{pr} and γ_{rd}, respectively. $F_{\gamma_{pr},\gamma_{rd}}(\gamma,\gamma)$ is the joint CDF of γ_{pr} and γ_{rd}.

A.3 Probability Density Function (PDF) of $\gamma^{\min}$

By taking the first order derivative of

$$f_{\gamma^{\min}}(\gamma) = \frac{2^{m_2}\left(\frac{m_1}{\Omega_1}\right)^{m_2} \gamma^{m_2-1} e^{-\frac{2m_2\gamma}{\Omega_2}} \Gamma\left(m_1, \frac{2m_1\gamma}{\Omega_1}\right)}{\Gamma(m_1)\Gamma(m_2)} + \frac{2^{m_1}\left(\frac{m_1}{\Omega_1}\right)^{m_1} \gamma^{m_1-1} e^{-\frac{2m_1\gamma}{\Omega_1}} \Gamma\left(m_2, \frac{2m_2\gamma}{\Omega_2}\right)}{\Gamma(m_1)\Gamma(m_2)}. \tag{A.4}$$

APPENDIX B

B. Derivation of Probability Density Function of $\gamma_{\max}$

B.1 The Cumulative Distribution Function (CDF) of $\gamma_{\max}$

Firstly, let $\gamma_{\max} = \max\left\{\gamma_1^{\min},...,\gamma_N^{\min}\right\}$ and $\gamma_1^{\min},...,\gamma_N^{\min}$ are i.i.d random variables with gamma distribution. The cumulative distribution function (CDF) of $\gamma_{\max}$ $\left(F_{\gamma_{\max}}(\gamma)\right)$ is applied from (Waqar et al., 2009). The CDF can be written as $F_{\gamma_{\max}}(\gamma) = \Pi_{i=1}^{N} F_{\gamma_i^{\min}}(\gamma)$,

$$F_{\gamma_{\max}}(\gamma) = \left(1 - \frac{\Gamma\left(m, \frac{m}{\Omega} 2\gamma\right)^2}{\Gamma(m)^2}\right)^N . \tag{B.1}$$

Applying the incomplete gamma and binomial expansions to (B.1) yields,

$$F_{\gamma_{\max}}(\gamma) = \sum_{q=0}^{N} \binom{N}{q} (-1)^q e^{-\left(\frac{2mq\gamma}{\Omega}\right)} \left[\sum_{p=0}^{m-1} \frac{\left(\frac{2m\gamma}{\Omega}\right)^p}{p!}\right]^{2q} . \tag{B.2}$$

We proceed to expand the power sum in (B.2) according to

$$\left[\sum_{a=0}^{M} \frac{x^a}{a!}\right]^b = \sum_{a_1=0}^{M} \sum_{a_2=0}^{M} \cdots \sum_{a_b=0}^{M} \frac{x^{\sum_{c=1}^{b} a_c}}{\Pi_{c=1}^{q} p_c!}. \tag{B.3}$$

Then, we denote $P_{sum} = \sum_{c=1}^{2q} p_c$ and $L(N,m)$ as

$$L(N,m) = \sum_{q=0}^{N}\binom{N}{q}(-1)^q\left[\sum_{p_1=0}^{m-1}\sum_{p_2=0}^{m-1}\cdots\sum_{p_{2q}=0}^{m-1}\frac{\left(\frac{2m}{\Omega}\right)^{p_{sum}}}{\Pi_{c=1}^{q}p_c!}\right]. \qquad \text{(B.4)}$$

Thus, $F_{\gamma_{\max}}(\gamma)$ is

$$F_{\gamma_{\max}}(\gamma) = L(N,m)e^{-\left(\frac{2mq\gamma}{\Omega}\right)}\gamma^{p_{sum}}. \qquad \text{(B.5)}$$

B.1.1 The Cumulative Distribution Function (CDF) of $\gamma_{\max}$

To obtain the PDF of $\gamma_{\max}\left(f_{\gamma_{\max}}(\gamma)\right)$, we take the first order derivative of $F_{\gamma_{\max}}(\gamma)$. Thus, $f_{\gamma_{\max}}(\gamma)$ is given as,

$$f_{\gamma_{\max}}(\gamma) = L(N,m)e^{-\left(\frac{2mq\gamma}{\Omega}\right)}\gamma^{p_{sum}}\left[\frac{p_{sum}}{\gamma}-\left(\frac{2mq}{\Omega}\right)\right]. \qquad \text{(B.6)}$$

APPENDIX C

C. Derivation of Probability Density Function of γ_D

C.1 Probability Density Function of γ_D

Firstly, we obtain the probability density function (PDF) of γ_{pr} and γ_{rd} which can be expressed as (Hongjian et al., 2011),

$$f_{\gamma_{pr}}(\gamma) = \frac{m^{Lm}\gamma^{Lm-1}e^{-\frac{m\gamma}{\Omega}}}{\Omega^{Lm}\gamma(Lm)}. \tag{C.1}$$

According to independently and identically distributed (i.i.d.) Nakagami-m fading channels for the two hops, the PDF of γ_{rd} is similarly to γ_{pr}. Then, the cumulative distribution function (CDF) of γ_D is written by,

$$\begin{aligned} F_{\gamma_D}(\gamma) &= 1-\Pr\left(0.5\gamma_{pr}>\gamma, 0.5\gamma_{rd}>\gamma\right) \\ &= 1-\frac{\Gamma\left(Lm,\frac{2m\gamma}{\Omega}\right)^2}{\Gamma(Lm)^2}. \end{aligned} \tag{C.2}$$

C.2 Probability Density Function (PDF) of γ_D

The PDF of γ_D is obtained from the first order derivative of $F_{\gamma_D}(\gamma)$ with using incomplete gamma expansion in eq. (8.352.4) (Gradshteyn and Ryzhik, 2000). Thus, the probability density function (PDF) of γ_D is given by,

$$f_{\gamma_D}(\gamma) = \frac{2^{1+Lm}\left(\frac{m}{\Omega}\right)^{Lm}\gamma^{Lm-1}e^{\frac{-2m\gamma}{\Omega}}\Gamma\left(Lm,\frac{2m\gamma}{\Omega}\right)}{\Gamma(Lm)^2}. \tag{C.3}$$

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Cooperative spectrum sensing using an amplify-forward cognitive relay

Chanidaphar Sanguanpuak, Suvipol Sitthichivaphak*
Department of Telecommunication Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL), Bangkok, Thailar

***Abstract*—In this paper, we explore cooperative spectrum sensing technique for cognitive radio network. An amplify and forward relay are assigned in cognitive radio networks to amplify and transmit the primary user's signal to a cognitive coordinator. This work is focused on the detection of primary user in single relay case. The performance of energy detector is analyzed for independent and non-identical (i.n.i.d) nakagami-m fading channels. Primary user transmits signal through single cognitive relay without direct link between the primary user and the fusion center. An upperbound of detection probability and area under ROC curve are provided. Our numerical results are validated with simulation results by using matlab and mathematica softwares.**

I. Introduction

Cognitive radio systems have been proposed as a possible solution to the spectrum management of future wireless networks. The licensed users (primary users) rarely utilize the assigned frequency bands most of the time, which means that spectrum holes exist. The spectrum inefficiency due to these spectrum holes has motivated the application of cognitive radio networks. One approach of cognitive radio is to permit secondary usage of licensed spectrum through cognitive radios [1]. For example, unlicensed users (secondary users) first sense the activities of licensed (primary users) and access the spectrum holes (white spaces) if no primary users activities are detected. Sensing accuracy is important for avoiding interference to the primary users. This detection task is quite challenging due to the requirement of reliable signal detection over multipath fading, shadowing and hidden node. Thus, cooperative spectrum sensing has been introduced to detect faster and more reliable [2], [3].

There are many techniques to sense the spectrum such as matched filter detection (coherent detection through maximization of the signal-to-noise ratio (SNR)) [4], cyclostationary detection [5], and energy detection [6], [7], [8]. Among these spectrum sensing techniques, energy detection is the most popular method, which measuring the received signal power. The performance of an energy detector has been studied recently in [9], [10]. In our work, when energy detection is utilized for cooperative spectrum sensing, the secondary users report to a fusion center their sensing results.

In our work, the cognitive users behave as amplify-forward relays which is called "cognitive relays". This research work, the cognitive relays are assumed to know statistics of CSI fron the primary user. The amplified factor is tuned according to the statistics of CSI to maintain long term average power constraint. First case, we consider two hop with single cognitive relay, then extend to multihop with multiple cognitive relays. In the former works [7], [8],[9],and [10], the two hop and multihop cognitive relays are not considered for Nakagami-m channel. At the fusion center, for the multihop cognitive relays case, energy detection will utilize longer time to detect transmitted signal from the primary user. But from the results, detection performance of this multihop case is better.

The rest of this papers is organized as follows. Section 2 introduces the system and channel model under the consideration. In section 3, energy detection over AWGN is explained. In section 4, area under ROC curve (AUC) is mentioned. In section 5, performance analysis is introduced. Detection probability and AUC closed form expressions are presented. In section 6, some numerical and simultaion results are given. Section 7, gives conclusions for the paper.

II. Channel Model

For simplicity, for two hop cognitive relay case, channel from the primary user (p) to the cognitive relay (r) and from the cognitive relay to the fusion center(d) denoted as h_{pr}, and h_{rd} respectively, are independent and non-identical Nakagami-m variables

Therefore, the received signal-to-noise ratio (SNR) γ_{pr}, γ_{rd} and γ_{rd}, are gamma distribution with parameters $(m_1, \frac{\Omega_1}{m_1})$ and $(m_2, \frac{\Omega_2}{m_2})$, respectively. Their corresponding pdfs are given by [11]

$$\begin{aligned} f_{\gamma_{pr}}(\gamma) &= \frac{{m_1}^{m_1}}{\Omega_1^{m_1}\Gamma(m_1)}\gamma^{m_1-1}exp(\frac{-m_1\gamma}{\Omega_1}) \\ f_{\gamma_{rd}}(\gamma) &= \frac{{m_2}^{m_2}}{\Omega_2^{m_2}\Gamma(m_2)}\gamma^{m_2-1}exp(\frac{-m_2\gamma}{\Omega_2}) \end{aligned} \quad (1)$$

where m_1 and m_2 are parameters describing the fading severity of each hop with values $m_1, m_2 \geq \frac{1}{2}$; Ω_1 and Ω_2 are expectation of signal power ($\mathbb{E}[|h_{pr}|^2]$, $\mathbb{E}[|h_{rd}|^2]$) respectively .

III. Energy detector over AWGN channel

At the energy detector, by following binary hypothesis testing, the received signal at time t can be written

$$y(t) = \begin{cases} n(t) & : H_0 \\ hx(t) + n(t) & : H_1 \end{cases} \quad (2)$$

where $x(t)$ is the transmitted signal with an average power E_s, $h(t)$ is the channel gain from the transmitter and the receiver. $n(t)$ is the AWGN with single sided power spectrum density N_0 at the receiver. Under hypothesis H_0 and H_1 means that the transmitted signal $x(t)$ is absent and present, respectively.

The energy detector in [6],[7],[8] is constructed by first, passing the received signal through bandpass filter with bandwidth W and carrier frequency f_c. Thus, the noise variance will become N_0W. In [7], each component (in-phase or quadrature-phase) of the received signal, a value of degree of freedom (u) can be TW. The value of T and W have to be defined to restrict u to be interger values. Second, to measure the energy of received signal (E), square the output signal from bandpass filter and integrate over time period T. The signal energy E acts as a test statistic to compare with a pre-specified threshold λ. If this test statistic $E > \lambda$, the hypothesis H_1 is chosen or the hypothesis H_0, otherwise.

Under H_1, E has a noncentral chi-square distribution with u degree of freedom. Likewise, under H_0, E will be central chi-square distributed. An expression for the probability of detection (P_d) and the probability of false alarm (P_f), are written as $Pr(E > \lambda|H_1)$ and $Pr(E > \lambda|H_0)$, respectively. Thus, the cumulative distribution function expressions of P_f and P_d are $P_f(\lambda) = \frac{\Gamma(u,\frac{\lambda}{2})}{\Gamma(u)}$ and $P_d = Q_u(\sqrt{2\gamma}, \sqrt{\lambda})$, respectively [7], [8]. Where E_s is transmittted power from the primary user, γ is as instantaneous SNR of the target signal. The instantaneous SNR is given by $\gamma = E_s|h|^2/N_0$, where $Q_u(.,.)$ is the uth order generalized Marcum-Q function, $\Gamma(.)$ is the gamma function, $\Gamma(.,.)$ is the upper incomplete gamma function.

IV. Area under ROC curve (AUC)

Although the ROC curves (P_d versus P_f) characterize the performance of an energy detector. The area under the curve represents the probability that choosing correct decision at the detector is more likely than choosing the incorrect decision. The closed form expressions of area under ROC curve for energy detection was introduced in [10]. As mentioned, the AUC is a measure of the detection capability at the energy detector. For two energy detectors, to compare the performance with using ROC curves sometimes is difficult, since the curves may cross. According to detection and false alarm probabilities which vary from value 0 to value 1, the AUC values vary from 0.5 to 1. The AUC of instanstaneous snr (γ) with sample u is given in [10],

$$\begin{aligned} A(\gamma) &= \int_0^1 P_d(\gamma,\lambda)dP_f(\lambda) \\ &= \frac{1}{2^{u-1}\Gamma(u)}\int_0^\infty t^{2u-1}e^{\frac{-t^2}{2}}Q_u(\sqrt{2\gamma},t)dt \\ &= 1-\sum_{k=0}^{u-1}\frac{\gamma^k e^{\frac{-\lambda}{2}}}{2^k k!}+\sum_{k=1-u}^{u-1}\frac{\Gamma(u+k)}{2^{u+k}\Gamma(u)}e^{-\gamma}\mathbb{F}(u,k,\gamma) \end{aligned} \tag{3}$$

where $\mathbb{F} = {}_1\tilde{F}_1\left(u+k; 1+k; \frac{\gamma}{2}\right)$ which ${}_1\tilde{F}_1(.;.;.)$ is the regularized confluent hypergeometric function of the confluent hypergeometric function ${}_1F_1(.;.;.)$. This AUC $A(\gamma)$ is obtained as unfaded AUC.

V. Single cognitive relay

Without any estimation and complexity at the secondary users, the cognitive relay simply amplify the received signal from the primary users and then forward to the fusion center.

A. Cooperative Scheme

We consider single cognitive relay based spectrum sensing. Each node (primary user, cognitive relay, and fusion center) has only one antenna which can be used for both transmission and reception. The is no direct link from the primary user to the fusion center.

When a primary user starts using the band, a cognitive relay receive transmitted signal from the primary user. Therefore, in the first phase, the cognitive relay listens to the primary user signal. Then, the cognitive relay simply amplify and retransmit the amplified version of the received signals to the fusion center in the second phase. Energy detector is equipped at the fusion center, the received signal energy is then compared with a pre-define threshold λ.

B. Single cognitive relay spectrum sensing

Firstly, we consider a single cognitive relay. In this case, we have three nodes which contain a primary user, a cognitive relay and a fusion center. The primary user transmits signal to the cognitive relay without direct transmission to the fusion center. The cognitive relay continously receives and amplifies the received signal from the primary user. Further, during detection process, we assume that both the channels from primary user to the cognitive relay and from the cognitive relay to the fusion center are time invariant. At particular time t, the received signal by the cognitive relay denoted as $y_{pr}(t)$, written as $y_{pr}(t) = \theta h_{pr}x(t) + n_r(t)$ where θ indicates the primary signal which is equals to 1 at the presence of primary transmitted signal or equal to 0 otherwise, $x(t)$ is the transmitted signal from the primary user with power E_p, h_{pr} is slow flat fading channel gain between primary and secondary relay, $n_r(t)$ is the AWGN at the cognitive relay with variance $N_{0,r}$. At the fusion center then, the received signal denoted $y_{rd}(t)$ is given by $y_{rd}(t) = Gh_{rd}y_{pr}(t) + n_d(t) = \theta hx(t) + n(t)$ where G is the amplification gain at the cognitive relay, h_{rd} is the flat fading channel gain between the cognitive relay and the fusion center. n_d is the AWGN at the fusion center. Therefore, $h = Gh_{pr}h_{rd}$ and $n(t) = Gh_{rd}n_r(t) + n_d(t)$ can be assumed as channel gain and effective noise from the primary user to the fusion center, respectively.

1) At the amplified forward cognitive relay, first, the received signal power from the primary user is normalized and then is amplified by cognitive relay power consumed E_r. Thus, the amplification factor G is given as, $G = \sqrt{\frac{E_r}{N_{0,r}+E_s\mathbb{E}[|H_{pr}|^2]}}$. This amplication factor G can be written as $G^2 = E_r/(CN_{0,r})$ where the constant C equals to $1 + E_s\mathbb{E}[|H_{pr}|^2]/N_{0,r}$.

2) At the fusion center, the received SNR can be written as, $\gamma = (\gamma_{pr}\gamma_{rd})/(C + \gamma_{rd})$ with $\gamma_{pr} = \frac{\mathbb{E}[|h_{pr}|]^2}{N_0}$ and $\gamma_{rd} = \frac{\mathbb{E}[|h_{rd}|]^2}{N_0}$. Where, γ_{pr} and γ_{rd} are the average SNRs of the channels from the primary user to the cognitive relay and from the cognitive relay to the fusion center, respectively. The upper bound of overall end-to-end snr can be approximated by $\gamma^{min} = min(\gamma_{pr}, \gamma_{rd})$ [12]. The energy detector is employed at the fusion center thus, the received signal will be filtered by an ideal bandpass filter. This bandpass filter normalizes noise variance and limits the expectation of noise power. The output of filter is then squared and integrated over the time T to obtain the decision statistic.

C. Detection Analysis of single cognitive relay

In preceding this part, we use a new alternative series representation of generalized Marcum-Q function which is derived in [13, eq.(18)] for any real order $M \geq 0.5$ as

$$Q_M(\alpha, \beta) = e^{\frac{-\alpha^2}{2}} \sum_{k=0}^{\infty} \frac{1}{k!} (\frac{\alpha^2}{2})^k \frac{\Gamma(M+k, \beta^2/2)}{\Gamma(M+k)} \quad (4)$$

The average detection probability in this case ($\bar{P}_d$) can now be evaluated by averaging (4) over the PDF of upper bounded end-to-end channel SNR ($f_{\gamma^{min}}(\gamma)$) which is given by

$$\begin{aligned}
\bar{P}_d &= \int_0^\infty Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) f_{\gamma^{min}}(\gamma) d\gamma \\
&= \Bigg(\int_0^\infty e^{-\gamma - \frac{m_1\gamma}{\Omega_1}} \sum_{k=0}^{\infty} \frac{\gamma^{k+m_1-1}}{k!} \frac{\Gamma(u+k, \frac{\lambda}{2})}{\Gamma(u+k)} \\
&\times \frac{\left(\frac{m_1}{\Omega_1}\right)^{m_1} \Gamma\left(m_2, \frac{m_2\gamma}{\Omega_2}\right)}{\Gamma(m_1)\Gamma(m_2)} d\gamma \Bigg) \\
&+ \Bigg(\int_0^\infty e^{-\gamma - \frac{-m_2\gamma}{\Omega_2}} \sum_{k=0}^{\infty} \frac{\gamma^{k+m_2-1}}{k!} \frac{\Gamma(u+k, \frac{\lambda}{2})}{\Gamma(u+k)} \\
&\times \frac{\left(\frac{m_2}{\Omega_2}\right)^{m_2} \Gamma\left(m_1, \frac{m_1\gamma}{\Omega_1}\right)}{\Gamma(m_1)\Gamma(m_2)} d\gamma \Bigg) \quad (5)
\end{aligned}$$

After some manipulations and with incomplete gamma expansion $\Gamma(a,x) = (a-1)! e^{-x} \sum_{k=0}^{a-1} \frac{x^k}{k!}$. The closed form solution of the average detection probability in this case,

$$\begin{aligned}
\bar{P}_d = &\sum_{k=0}^{\infty} \sum_{n=0}^{u+k-1} \sum_{p=0}^{m_2-1} \frac{(\frac{m_1}{\Omega_1})^{m_1}}{\Gamma(m_1)} \frac{e^{\frac{-\lambda}{2}} \left(\frac{\lambda}{2}\right)^n \left(\frac{m_2}{\Omega_2}\right)^p \Gamma(k+m_1+p)}{n!k!p! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2} + 1\right)^{k+m_1+p}} \\
+ &\sum_{k=0}^{\infty} \sum_{n=0}^{u+k-1} \sum_{q=0}^{m_1-1} \frac{(\frac{m_2}{\Omega_2})^{m_2}}{\Gamma(m_2)} \frac{e^{\frac{-\lambda}{2}} \left(\frac{\lambda}{2}\right)^n \left(\frac{m_1}{\Omega_1}\right)^q \Gamma(k+m_2+q)}{n!k!q! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2} + 1\right)^{k+m_1+q}} \quad (6)
\end{aligned}$$

The average AUC ($\bar{A}_{\gamma^{min}}$) over single cognitive relay can be evaluated through averaging (3) by the SNR distribution ($f_{\gamma^{min}}(\gamma)$) given in (10).

$$\bar{A}_{\gamma^{min}} = \int_0^\infty A(\gamma) f_{\gamma^{min}}(\gamma) d\gamma \quad (7)$$

Closed form expression of $\bar{A}_{\gamma^{min}}$ can be written as follow, where ${}_2\tilde{F}_1(.;.;.;.)$ is the regularized confluent hypergeometric function of the confluent hypergeometric function ${}_2F_1(.;.;.;.)$.

$$\bar{A}_{\gamma^{min}} = I_1 + I_2 + I_3 \quad (8)$$

where

$$I_1 = \sum_{n=0}^{m_2-1} \frac{\left(\frac{m_1}{\Omega_1}\right)^{m_1} \left(\frac{m_2}{\Omega_2}\right)^n (m_1)_n}{n! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2}\right)^{m_1+n}} + \sum_{p=0}^{m_1-1} \frac{\left(\frac{m_2}{\Omega_2}\right)^{m_2} \left(\frac{m_1}{\Omega_1}\right)^p (m_2)_p}{p! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2}\right)^{m_2+p}}$$

$$\begin{aligned}
I_2 = &- \sum_{k=0}^{u-1} \sum_{n=0}^{m_2-1} \frac{\left(\frac{m_2}{\Omega_2}\right)^n \left(\frac{m_1}{\Omega_1}\right)^{m_1} (m_1)_{k+n}}{2^k k! n! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2} + \frac{1}{2}\right)^{k+m_1+n}} \\
&- \sum_{k=0}^{u-1} \sum_{p=0}^{m_1-1} \frac{\left(\frac{m_1}{\Omega_1}\right)^p \left(\frac{m_2}{\Omega_2}\right)^{m_2} (m_2)_{k+n}}{2^k k! p! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2} + \frac{1}{2}\right)^{k+m_2+p}}
\end{aligned}$$

$$\begin{aligned}
I_3 = &\sum_{k=1-u}^{u-1} \sum_{n=0}^{m_2-1} \frac{\left(\frac{m_1}{\Omega_1}\right)^{m_1} \left(\frac{m_2}{\Omega_2}\right)^n (u)_k (m_1)_n \mathbb{L}(m_1, m_2)}{2^{u+k} n! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2} + 1\right)^{m_1+n}} \\
+ &\sum_{k=1-u}^{u-1} \sum_{p=0}^{m_1-1} \frac{\left(\frac{m_2}{\Omega_2}\right)^{m_2} \left(\frac{m_1}{\Omega_1}\right)^p (u)_k (m_1)_p \mathbb{L}(m_1, m_2)}{2^{u+k} p! \left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2} + 1\right)^{m_2+p}}
\end{aligned}$$

The constant $\mathbb{L}(m_1, m_2)$ is written as ${}_2\tilde{F}_1\Big[u+k; m_1+n; k+1; \frac{1}{2\left(\frac{m_1}{\Omega_1} + \frac{m_2}{\Omega_2} + 1\right)}\Big]$ which is in the form of the regularized confluent hypergeometric function.

VI. Numerical Results

This section presents numerical and simulation results for the proposed energy detection in dual-hop AF cognitive relaying. In the figures, the numerical results are represented by curves, while the simulation results are given by discrete marks. It is obvious that the numerical results match with their simulation counterparts, which confirms the accuracy of the analysis in section 3. In computing the average detection probability and AUC, we substitute infinity to be 15. The detection threshold (λ) is considered to be 9.21034. We vary fading parameters m, and average SNR Ω, to observe the results.We consider the performance of energy detection probability, and average area under ROC curve (AUC). The theoretical and simulation results are presented.

Figure 1, shows the numerical and simulation results regarding how the detection probability P_d changes with the false alarm probability (P_f). We can see that when the false alarm probability increases the detection probability (P_d) also increases with higher value. Thus, the amplify cognitive relay helps to improve detection probability. When fading parameter (m) and average SNR (Ω) are higher, detection performances are also increases.

Figure 2, shows the area under ROC curve (AUC). In this case we assume parameters $m_1 = m_2$ and $\Omega_1 = \Omega_2$. We plot AUC curve against the snr (Ω). It can be seen that when

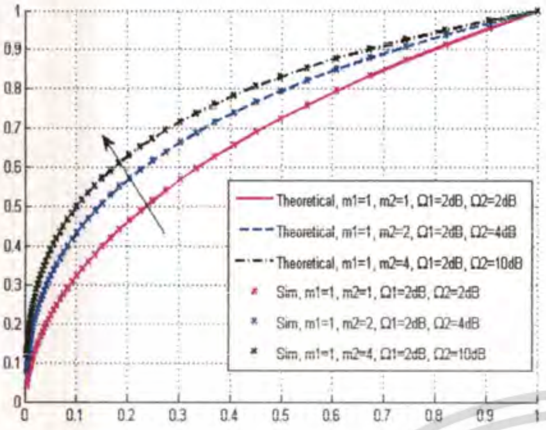

Fig. 1. Simulation and numerical results ROC for single cognitive relay over non i.i.d Nakagami-m fading

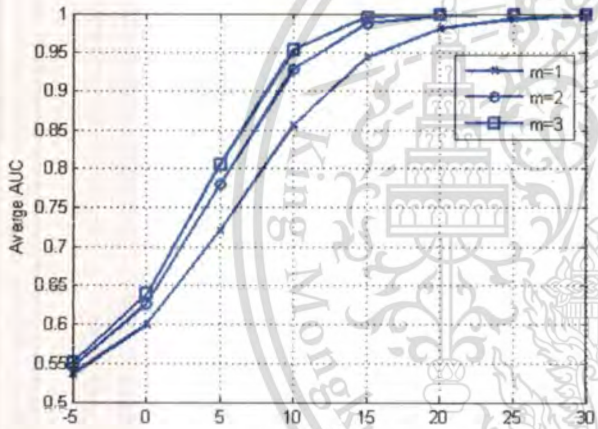

Fig. 2. Numerical results average AUC for single cognitive relay over non i.i.d Nakagami-m fading

the fading parameters m increase, the AUC curves are also increase.

VII. Conclusion

We analyze the performance of primary user energy detection with cognitive relay system in Nakagami-m fading channels. The cognitive relay (CR) transmits an amplified signal. We consider the energy detection probability (P_d) variation with the false alarm probability (P_f). The upperbound of overall received instaneaous SNR from the the primary user is utilized to find the detection probability. As seen from the numerical results, the detection probability (P_d) increase with higher fading parameters and SNR (m_1, m_2 and Ω_1, Ω_2.). The AUC curves increase with higher fading parameter m_1, m_2.

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Appendix

A. Single cognitive relay PDF and CDF

1) Probability density function an moment generating function of γ_i^{min}: The cumulative distribution function (cdf) of $\gamma^{min} = min(\gamma_{pr}, \gamma_{rd})$ is given by

$$F_{\gamma^{min}}(\gamma) = 1 - \frac{\Gamma\left(m_1, \frac{m_1}{\Omega_1}\gamma\right)}{\Gamma(m_1)} \frac{\Gamma\left(m_2, \frac{m_2}{\Omega_2}\gamma\right)}{\Gamma(m_2)} \tag{9}$$

where $F_{\gamma_{pr}}(\gamma)$ and $F_{\gamma_{rd}}(\gamma)$ are the cdf of signal-to-noise-ratio (snr) γ_{pr} and γ_{rd} respectively, $F_{\gamma_{pr},\gamma_{rd}}(\gamma,\gamma)$ is the joint cdf of γ_{pr} and γ_{rd}.

Probability density function (pdf) of γ^{min} by the first order derivative of $F_{\gamma^{min}}(\gamma)$ using incomplete gamma expansion in [14, eq.(8.352.7)], $\Gamma(a,x) = (a-1)!e^{-x}\sum_{k=0}^{a-1}\frac{x^k}{k!}$. Thus, the pdf is given by

$$f_{\gamma^{min}}(\gamma) = \frac{\left(\frac{m_1}{\Omega_1}\right)^{m_1}\gamma^{m_1-1}e^{-\frac{m_1\gamma}{\Omega_1}}\Gamma\left(m_2, \frac{m_2\gamma}{\Omega_2}\right)}{\Gamma(m_1)\Gamma(m_2)} + \frac{\left(\frac{m_2}{\Omega_2}\right)^{m_2}\gamma^{m_2-1}e^{-\frac{m_2\gamma}{\Omega_2}}\Gamma\left(m_1, \frac{m_1\gamma}{\Omega_1}\right)}{\Gamma(m_1)\Gamma(m_2)} \tag{10}$$

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Author Biography

Author: Miss Chanidaphar Sanguanpuak

Address: 69, Ramkamhaeng Road, Huamark, Bangkapi, Bangkok, Thailand

Bachelor Degree: Bachelor Degree in Telecommunications Engineering

Institution: King Mongkut's Institute of Technology Ladkrabang

High School: Triamudom Suksa School

Secondary School: Bodindecha (Sing Singhaseni) School

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1. C. Sanguanpuak, S. Sitthichivaphak, "Cooperative Spectrum Sensing Using an Amplify-Forward Cognitive Relay", Proceedings of the 1st International Symposium on Technology for Sustainability (ISTS 2011), KMITL, Bangkok, Thailand, pp.329-332, Jan 2012.
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