Performance Analysis of Cognitive Radio Network over SIMO System

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To Our Parents

আমাদের আহ্মু আব্বুকে
ABSTRACT

As resources are limited, radio spectrum becomes congested due to the growth of wireless applications. However, measurements address the fact that most of the licensed spectrums experience low utilization even in intensively teeming areas. In the exertion to improve the utilization of the limited spectrum resources, cognitive radio networks have emerged as a powerful technique to resolve this problem.

There are two types of user in cognitive radio networks (CRNs) named as primary user (PU) and secondary user (SU). Therein, the CRN enables the SU to utilize the unused licensed frequency of the PU if it possibly finds the vacant spectrum or white space (known as opportunistic spectrum access). Alternatively, SU can transmit simultaneously with the PU provided that transmission power of SU does not cause any harmful interference to the PU (known as spectrum sharing systems).

In this thesis work, we study fundamental knowledge of the CRNs and focus on the performance analysis of the single input multiple output (SIMO) system for spectrum sharing approach. We assume that a secondary transmitter (SU-Tx) has full channel state information (CSI). The SU-Tx can adjust its transmit power not to cause harmful interference to the PU and obtain an optimal transmit rate. In particular, we derive the closed-form expressions for the cumulative distribution function (CDF), outage probability and an analytical expression for symbol error probability (SEP).

Keywords: Cognitive Radio, Outage Probability, Symbol Error Probability, Single Input Multiple Output, Selection Combining, Spectrum Sharing System.
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Iqbal Hasan Haider & MD. Fazla Rabby
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<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ACMA</td>
<td>Australian communication and media authority</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive white Gaussian noise</td>
</tr>
<tr>
<td>CRN</td>
<td>Cognitive radio network</td>
</tr>
<tr>
<td>CSI</td>
<td>Channel state information</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative distribution function</td>
</tr>
<tr>
<td>CR</td>
<td>Cognitive radio</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code division multiple access</td>
</tr>
<tr>
<td>DSA</td>
<td>Dynamic spectrum access</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier transform</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal communication commission</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>4G</td>
<td>Fourth generation</td>
</tr>
<tr>
<td>3G</td>
<td>Third generation</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple input multiple output</td>
</tr>
<tr>
<td>MISO</td>
<td>Multiple input single output</td>
</tr>
<tr>
<td>M-PSK</td>
<td>Multiple phase shift keying</td>
</tr>
<tr>
<td>MRC</td>
<td>Maximal ratio combining</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal frequency division multiple access</td>
</tr>
<tr>
<td>PU</td>
<td>Primary user</td>
</tr>
<tr>
<td>PU-Rx</td>
<td>Primary receiver</td>
</tr>
<tr>
<td>PSD</td>
<td>Power spectral density</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability density function</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal digital assistant</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of service</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received signal strength indicator</td>
</tr>
<tr>
<td>RADAR</td>
<td>Radio detection and ranging communication</td>
</tr>
<tr>
<td>SU</td>
<td>Secondary user</td>
</tr>
<tr>
<td>SU-Tx</td>
<td>Secondary transmitter</td>
</tr>
<tr>
<td>SU-Rx</td>
<td>Secondary receiver</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single input multiple output</td>
</tr>
<tr>
<td>SISO</td>
<td>Single input single output</td>
</tr>
<tr>
<td>SEP</td>
<td>Symbol error probability</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single carrier-frequency division multiple access</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SCF</td>
<td>Spectral correlation function</td>
</tr>
<tr>
<td>SC</td>
<td>Selection combining</td>
</tr>
<tr>
<td>SIMO-MAC</td>
<td>Single input multiple output multiple access channel</td>
</tr>
<tr>
<td>WiFi</td>
<td>Wireless fidelity</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless local area network</td>
</tr>
</tbody>
</table>
CHAPTER 1

1. INTRODUCTION

1.1 Introduction

The radio frequency spectrum band has become very inadequate in certain bands due to dramatically increased demand in wireless devices, mobiles, smart phones, etc. As a consequence, the demand for high data rates, bandwidth and spectrum utilization has increased day by day. In most countries, the government regulates the use of a frequency spectrum band by issuing exclusive licenses and allocating a frequency band to the systems restricted by a geographical area. This allocated spectrum keeping out from the unauthorized users or at least regulating other systems with respect to these allocated bands. The recent spectrum occupancy measurement and studies have shown, however, that a large number of these allocated spectrums are rarely or seldom operationally occupied by licensed users or so-called primary user (PU). The assigned band to the PU may be absolutely free or idle at the particular time or geographical area [1-4]. Since the massive demand for spectrum keeps growing, it is important to diverse means by which these unutilized or idle spectrums could be effectively utilized by a wireless system of any suitable type.

Dynamic Spectrum Access (DSA) is a potential technology for this purpose. The overall spectrum utilization can be increased by the DSA to licensed spectrum in an opportunistic manner, only under consideration of no or limited interference to the primary users. The effective usage of spectrum white spaces or spectrum holes by the SU must be able to intelligently and autonomously adapt their transmission characteristics to suit the conditions under which must operate at any time. Such solutions can be found in cognitive radio network (CRN). The CRN is expected to be able to identify few things such as white space for unlicensed users or the secondary user (SU), the CRNs dynamically select the route to a specific destination based on some particular criteria and accordingly adapt different parameters like power, frequency, channel coding, modulation technique etc. in order not to disturb the ongoing PUs communications. Cognitive radio (CR) users select the best available route or channel, afterwards, synchronized access to this channel with other CR users and free this occupied channel whenever the PU reclames or continues the simultaneous transmission with the other PU [1].
1.2 Thesis Objectives

In this thesis, we will present background knowledge about CRNs. Subsequently, we consider a single input multiple output (SIMO) system model for spectrum sharing approach. On this basis, a closed-form expression for the outage probability and an analytical expression for symbol error probability (SEP) will be derived. Moreover, we will evaluate the performance of the outage probability and SEP with respect to peak interference power-to-noise ratio for the considered system model. Finally, we will analyse the results from the graph that is obtained from the numerical data.

1.3 Thesis Outline

Chapter 2: This chapter provides general background knowledge of cognitive radio networks. It also covers brief information about categorization of CRNs, spectrum sensing and spectrum sharing.

Chapter 3: In this chapter, a survey of previous studies about CRNs is discussed. In addition, system and channel model for our problem is introduced.

Chapter 4: In this chapter, a detail derivation for the cumulative distribution function (CDF) of signal-to-noise ratio (SNR) for the considered CRN is provided. Utilizing this result, a closed-form expression for the outage probability and an analytical expression for symbol error probability are obtained. The numerical results are also discussed in this chapter.

Chapter 5: In this chapter, the conclusions and recommendation for future research are presented.
CHAPTER 2

2. BACKGROUND

2.1 Why Cognitive Radio

In the last few years, communication systems have a revolutionary rising in wireless applications and consumers. The demand for inexpensive but high-speed data services such as wireless Internet access with rich multi-media services create consumer’s massive demand of radio spectrum. To meet the consumers growing demand, most of the frequency has already been allocated, and the bandwidth has become very expensive. Therefore, the radio spectrum has become precious and limited resource in the wireless communication systems.

At present, radio communication is moving towards the fourth generation (4G). This 4G systems expected to substitute the existing third generation (3G) communication and provide secure and complete voice, data and streamed multi-media applications.

Table 2.1: Comparison between 3G and 4G systems [2].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>3G</th>
<th>4G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency bands</td>
<td>1.8 - 2.5 GHz</td>
<td>2 - 8 GHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>Up to 2 Mbps (384 kbps deployed)</td>
<td>Up to 100 Mbps</td>
</tr>
<tr>
<td>Technologies</td>
<td>CDMA</td>
<td>OFDMA (uplink) and SCFDMA(downlink)</td>
</tr>
<tr>
<td>Network architecture</td>
<td>Wide area cell based</td>
<td>Integration of WLAN and wide area</td>
</tr>
<tr>
<td>Radio interfaces</td>
<td>Fixed radio interfaces</td>
<td>Adaptive radio interfaces</td>
</tr>
</tbody>
</table>

Table 2.1 shows a basic comparison between 3G and 4G communication systems. The table portrayed that the expected frequency band and data rate in 4G are much higher than the 3G system [2, 18]. Providing the required frequency bands and data rate to the 4G communication system has become challenging because of adopted usual spectrum allocation methods.

The applications of wireless communication are directly related to the usage and management of the radio spectrum. To meet the upcoming demand for one trillion
wireless devices by 2020 and also facing the challenges for further development of radio communication, we need new radio spectrum allocation. A summary of wireless communication applications is presented in Table 2.2 [2]. However, in practice, most of the spectra are already allocated and the bandwidth becomes more expensive.

Table 2.2: Accommodated applications in different frequency bands [2]

<table>
<thead>
<tr>
<th>Frequency Bands</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-30 Hz</td>
<td>Submarine Communications</td>
</tr>
<tr>
<td>30-300 Hz</td>
<td>AC Power Grids</td>
</tr>
<tr>
<td>300-3000 Hz</td>
<td>Mine Communications</td>
</tr>
<tr>
<td>3-30 kHz</td>
<td>Ultra sound Applications</td>
</tr>
<tr>
<td>30-300 kHz</td>
<td>AM Radio</td>
</tr>
<tr>
<td>300-3000 kHz</td>
<td>Aviation</td>
</tr>
<tr>
<td>3-30 MHz</td>
<td>Short Wave Radio</td>
</tr>
<tr>
<td>30-300 MHz</td>
<td>FM Radio, Television Broadcast</td>
</tr>
<tr>
<td>300-3000 MHz</td>
<td>Television Broadcast</td>
</tr>
<tr>
<td>3-30 GHz</td>
<td>Wireless Networking, Satellite Commun.</td>
</tr>
<tr>
<td>30-300 GHz</td>
<td>Satellite Communication and Advance W.</td>
</tr>
</tbody>
</table>

It is really hard for regulatory bodies to find the spectrum for new wireless applications where the demand for radio spectrum is expected to grow even more in the upcoming years. As a solution of this problem, the concept of cognitive radio technology has been proposed [3].

### 2.2 About Cognitive Radio

The reasons of the spectrum shortage are not only the growing demand but also traditional spectrum allocation methods. In conventional or existing radio spectrum methods, radio spectrums were divided into different channels and licensed by the
different providers such as telecommunication, Internet corporations, etc. This licensing is managed by government regulatory bodies like FCC (Federal Communication Commission) in United States, ACMA in Australia (Australian Communication and Media Authority). In addition, these regulatory bodies are responsible to prohibit the unlicensed applications and consumers using this licensed band. Unfortunately, research shows that most of the licensed spectrum remains unutilized. For instance, in [1], a snapshot of spectrum occupancy by the licensed users is shown. The spectrum usage is focused on certain portion of the spectrum while a significant amount (94 %) of the spectrum remains unutilized.

Fig. 2.1 shows another scenario of spectrum used in Australia. This is measured by the Victoria University in Melbourne, Australia. This figure shows that most of the frequency bands remain unused (in blue colour) at the time of observation [18].

![Spectrum Utilization](image)

**Fig. 2.1:** Utilization of radio spectrum in Melbourne, Australia [18].

Hence, the scarcity of the radio spectrum has been found artificial because practical measurements have shown that spectrum remains unutilized most of the times [18]. Therefore, researchers try to utilize the unutilized radio spectra, licensed to primary users under temporal opportunities. To mitigate this unused radio spectrum and fulfil the massive demand of the radio spectrum, a new technology has been proposed first by Mitola, called CRN.
According to Mitola [3]:

“The term cognitive radio identifies the point at which wireless personal digital assistants (PDAs) and the related network are sufficiently computationally intelligent about radio resources and related computer to computer communications to:

(a) Detect user communication needs as a function of use context and (b) to provide radio resources and wireless services most appropriate to those needs.”

Later, Haykin in [4] described cognitive radio as:

“Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), usage the methodology of understanding to learn from the environment, adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit power, carrier frequency and modulation strategy) in real-time, with two primary objectives in mind: highly reliable communication whenever and wherever needed; efficient utilization of the radio spectrum.”

Another popular definition given by FCC [20] is as follows:

“Cognitive radio that can change its transmitter parameter (i.e., transmit power) based on interaction with the environment in which it operates.”

So all of the above definitions focus on three major criteria of cognitive radio as follows:

- Sensing of an unutilized spectrum band efficiently.
- Allowing the cognitive users to use these bands efficiently.
- Confirming no or limited interference to the licensed users.

Research on cognitive radio attracted significant attention both the academia and industry [1]-[9]. This is observed by the increasing number of publications, IEEE conferences, journals etc.
2.3 Categorization of Cognitive Radio

CRNs can be classified based on different parameters such as interference, spectrum in use and spectrum in access. This classification can be shown more specifically in Fig. 2.2.

![Diagram of Cognitive Radio categorization]

Fig. 2.2: Classification of Cognitive Radio [1, 2, 3, 27].

Depending on interference, cognitive radio can be classified as:

(a) Overlay approach [24]: The basic idea of overlay approach is based on the spectrum hole detection. If a spectrum hole is detected, the cognitive user can use it to transmit. In this approach, cognitive users can transmit their information causing no interference, so it is known as an interference-free approach. In overlay system, secondary transmitter can pursue two interesting strategies: selfish approach and selfless approach. In selfish approach, the secondary transmitter uses all the available power to send its own information to the secondary receiver. So, this approach violates the CRNs principles of protecting the PUs. It provides a theoretical upper bound on the maximum output achievable by the SUs. On the other hand, in selfless approach, secondary transmitter allocates a part of its power to assist the PUs transmission to the primary receiver. The remaining power is used to transmit the SUs information.
Not interfering with the primary transmission is known as an advantage of this approach. At the same time, the secondary users are required to sense the spectrum before transmission and this is the main disadvantage of this approach.

(b) Underlay approach [24]: Wideband system is implemented by the underlay or interference tolerant approach. Through frequency spreading or power allocation technique, the SUs use the radio spectrum at the same time with the PUs. To ensure a perfect tolerable interference to the PU, the SUs must transmit with low power to operate below the noise floor of the PUs.

This approach provides flexibility of transmission at any time and does not need to be synchronized with the primary user’s band, known as an advantage of the underlay approach. On the other hand, the disadvantage of this approach is the interference power constraint which allows only short-range communications.

Depending on the utilization of spectrum band, cognitive radio can be divided in some approaches as follows:

(a) Ideal cognitive radio [3]: The ideal cognitive radio knows all radio operating parameters and can take fully informed decision on how to make the best use of an unutilized radio spectrum.

(b) Spectrum sensing cognitive radio: It is a special case of the ideal cognitive radio. In this case, before the transmission, the primary spectrum bands are observed by the cognitive users.

The cognitive radio can be divided into the following categories based on the available spectrum band:

(a) Licensed band cognitive radio [27]: The cognitive radio system uses the spectrum band which is assigned to the licensed users is called licensed band cognitive radio system.

(b) Unlicensed band cognitive radio: When the cognitive radio is only allowed to use the unlicensed part of the spectrum band, this is called unlicensed band cognitive
radio such as cordless phones, remote controls, video cameras and Wi-Fi based wireless LANs. The disadvantage to use unlicensed bands is the possibility of interference. This interference can be mitigated to a great degree by a spread-spectrum technology, sophisticated radio modulation schemes, channel-selection algorithms etc. 

2.4 Spectrum Sensing

In general, the spectrum sensing technique is used to obtain necessary observation about its surrounding radio environment such as the presence or absence of the PUs in the spectrum bands and appearance of spectrum holes [1]. Cognitive radio can identify the spectrum band if it is occupied by the PUs or not through spectrum sensing. If the spectrum band is not occupied, then the SUs can use this unused spectrum band as long as the PU does not reclaim its own spectrum. In this process, cognitive radio can detect and follow the PUs activity. As such, no unwanted interference occurs due to the SUs transmission. To meet various quality of service (QoS) requirements, cognitive radio enables the SUs to choose the best frequency bands according to time varying channel characteristics after sensing. Finally, cognitive radio adapts the radio environment to re-configure and transmit to an available spectrum band. To do so, cognitive radio changes its transmit power, carrier frequency and modulation scheme to match with an available spectrum band. In other words, spectrum sensing ensures the efficient utilization of the spectrum. There are many techniques in spectrum sensing to recognize spectrum holes in the spectrum band.

2.5 Spectrum Sensing Techniques

Transmitter detection is the most important task of spectrum sensing. Some methods of spectrum sensing are given as follows [17]:

1. Energy Detection
2. Cyclostationary Method
3. Matched Filter Detection
4. Wavelet Detection

In the next section, we present a brief of spectrum sensing techniques. Further information and techniques can be found in [1, 17].
2.5.1 Energy Detection

The energy detection method is used to detect any unknown zero-mean constellation signals [17]. In this approach, the received signal strength indicator (RSSI) or radio frequency energy in the channel are measured to determine whether the channel is occupied or not. Energy detector measures the energy of available radio spectrum and compares it with a given threshold. Radio spectrum seems like available for further use if the measured energy falls below a predefined threshold level. Radio spectrum is marked as occupied when the measured energy level is greater than a predefined threshold. The energy detection is considered as a simple technique because it does not require prior knowledge of the primary user signal. In particular, it does not care about transmission parameters such as modulation technique used for transmission, phase or any other parameter of the signals. Mathematically, the energy detection is considered as a method based on binary decision, which can be formulated as [1, 17]:

\[ x(t) = n(t), \quad H_0 \] \hspace{1cm} (2.1)

\[ x(t) = s(t) + n(t), \quad H_1 \] \hspace{1cm} (2.2)

where, \( s(t) \) is the received signal and \( n(t) \) is the additive white Gaussian noise (AWGN). \( H_0 \) is the null hypothesis which shows that no primary users are present in the certain spectrum band. On the other hand, \( H_1 \) is the hypothesis of the existence of primary users in the spectrum. The energy detection implementation for spectrum sensing is shown in Fig. 2.3.

![Diagram of energy detection method](image)

Fig. 2.3: Energy detection method [17].

In Fig. 2.4, the received signal \( x(t) \) is sampled in a time window then it is passed through a Fast Fourier Transform (FFT) device to get spectrum \( X(f) \) in frequency
After windowing the peak of the spectrum $X(f)$, we get peak spectrum $Y(f)$. The signal energy is then collected in the frequency domain as follows:

$$\begin{align*}
H_1, \text{if } \sum |Y(f)|^2 \geq \lambda \\
H_0, \text{otherwise}
\end{align*}$$

The magnitude of $Y(f)$ is compared with a threshold level $\lambda$. Finally, the binary decision $H_0$ or $H_1$ is made. Although energy detection method can be implemented without any prior knowledge of PU signal, it still has some drawbacks. The first problem is that it can only detect the signal of the PU if the detected energy is above a threshold. Another challenging issue is that the energy detection approach cannot distinguish between other SUs sharing the same channel and the PU. It is not reliable in low SNR regimes as well.

### 2.5.2 Cyclostationary Method

Cyclostationary process is the technique to detect the PUs receiving the data within the communication area of the CRNs at low signal-to-noise ratio (SNR) regimes. In this process, the PUs signal acts as a periodic signal where the mean and autocorrelation have periodicity. Cyclostationary process is also known as a statistical process. This process repeats itself cyclically or periodically. Mathematically, we can represent the cyclostationary detection process as [1, Eq.(2.4)]:

$$Rx(\tau) = E[x(t + \tau)x^*(t - \tau)e^{-j2\alpha \pi t}]$$

where $Rx(\tau)$ denotes the autocorrelation of the observed signal $x(t)$, $\tau$ is the periodicity and $^*$ is the complex conjugation. $E[\cdot]$ is the expectation of the outcome and $\alpha$ represents the cyclic frequency. In Fig. 2.4, by employing discrete Fourier transformation (DFT) over the resulting correlation, we get the desired result $X(f)$ in the frequency domain. The peak in the acquired data gives the information about spectrum occupancy. After autocorrelation of $X(f)$, we obtain spectral correlation function (SCF), $S(f,\alpha)$, also called cyclic spectrum, which is a two-dimensional function in terms of frequency and cyclic frequency $\alpha$. Finally, detection is
completed by searching for the unique cyclic frequency corresponding to the peak in the SCF plane.

![Diagram](image)

**Fig. 2.4:** Cyclostationary detection method [17].

Cyclostationary detector can differentiate noise from the PUs’ signal and has better detection robustness in low SNR regime. This process requires prior information of a periodic signal and is only be used if the signal processing cyclostationary properties are known.

### 2.5.3 Matched Filtering

Matched filtering is an optimal detection method [1, 17]. It requires the prior information about the PUs signal such as operating frequency, bandwidth, modulation order and type, pulse shape, packet format, etc. Matched filtering can correlate the already known primary signal with received signal from the available radio resource to detect the presence of the PUs and maximize the SNR in the presence of AWGN. The match filter detection method is commonly used in radio detection and ranging (RADAR). The main advantages of matched filter are that it takes short time to maximize the SNR; it has a low probability of missed detection and false alarm in a certain detection performance level. Moreover, matched filter needs fewer received signal samples. On the other hand, the use of matched filter detection is very limited as its implementation complexity and power consumption is too high, because the matched filter requires receivers for all types of signals. Furthermore, if wrong prior information of the PUs is used for matched filtering, the detection performance will be degraded a lot.
2.5.4 Wavelet Detection Method

Wavelet detection method offers an advantage over all other detection methods to detect wideband signals in terms of simplicity and flexibility. It can be used for dynamic access. To find the spectrum hole from the available spectrum band, the entire spectrum band is divided as the sequence of the frequency sub-band. Each sub-band has smooth power characteristics but changes suddenly on the edge of the next sub-band within the sub-bands.

We can find the spectrum hole by using wavelet detection method at a given instance of time with finding the singularities to attain the results. The following Fig. 2.5 [17] shows the wavelet detection implementation for spectrum sensing.

![Wavelet Detection Method Diagram](image)

Fig. 2.5: Wavelet detection method [17].

In Fig. 2.5, the observed signal $x(t)$ can be obtained in frequency domain $X(f)$ after passing through the FFT block. By employing wavelet transformation of the power spectral density (PSD) of observed signal $x(t)$, the singularities of the PSD $S(f)$ can be located and thus the vacant frequency band can be found. The most challenging issue of implementing wavelet approach in practice is the high sampling rates for characterizing the large bandwidth.

2.6 Spectrum Management and Handoff

Cognitive radio analyses the available spectrum bands when more than one spectrum hole is detected in a desired frequency band [1]. Spectrum analysis finds the different activity of the spectrum bands to ensure the effective use of the spectrum according to QoS requirements. The QoS of the spectrum band depends on some parameters
such as interference, holding time, path loss, wireless link error and link layer delay. When the spectrum analysis job is done, a suitable spectrum band should be selected among the available multiple bands. Due to coexistence with PU network and diverse QoS requirements, there are some challenging issues for spectrum management such as how to integrate all parameters of the spectrum for spectrum decision, interference avoidance, QoS awareness, seamless communication, spectrum decision over heterogeneous spectrum bands [25].

When the PUs appear and reclaim their assigned channels or current channel condition becomes worse, the SUs need to stop their transmission and find another available channel to continue their transmission. This kind of handoff in cognitive radio is known as spectrum handoff. The SUs experience longer packet delay meanwhile the secondary transmission is suspended during spectrum handoff. To overcome this longer packet delay, a certain number of channels should be reserved for potential spectrum handoff. Then, the SUs can pick one channel whenever they need to switch to another frequency. Since, the PUs may not reclaim their licensed band very frequently; the throughput may be unnecessarily low if the SUs reserve too much bandwidth for spectrum handoff. Therefore, there are trade-offs in optimizing the channel reservation. The blocking probability can be minimized by optimizing the number of channels reserved for spectrum handoff. Hence, the secondary user’s throughput is maximized by optimizing the channel reservation. Several techniques are proposed to optimize the handoff latency such as location-assisted handover algorithm, a joint spectrum handoff scheduling and routing protocol in multi-hop multi-radio cognitive networks. Spectrum handoff also depends on channel capacity which is measured by the noise and interference levels, path loss, channel error rate and holding time.

2.7 Spectrum Sharing Techniques

In order to utilize the spectrum resources efficiently, the SUs should be able to address some issues such as how to co-exist with the PUs and the other SUs, when and how to use spectrum band, and which spectrum band they should sense and access. Thus, we will review existing spectrum allocation and sharing schemes in this section that answer these questions.
Based on different criteria, the classifications of spectrum sharing are as follows [1], [17]:

1. Spectrum band used by SUs: open versus hierarchical spectrum sharing.
2. Spectrum access technique: overlay versus underlay spectrum sharing.
3. Based on network architecture: centralized versus distributed spectrum sharing.

2.7.1 Spectrum Bands used by Secondary Users: Open versus Hierarchical Spectrum Sharing

Spectrum sharing among the SUs who access the unlicensed spectrum band is called open spectrum sharing [1, 17]. There is no user’s classification in the open sharing system. In open sharing, every user has the same rights to use this spectrum as no users have spectrum licensed. One example is the unlicensed industrial, medical, scientific band.

In the hierarchical model, licensed spectrum is shared by the PUs and the SUs. It is also known as licensed spectrum sharing. In cognitive radio network, secondary user has cognitive attributes while PU is not equipped with cognitive ability. The PU has the highest priority in using the own spectrum. Thus, the PU does not need to perform dynamic/opportunistic spectrum access. If the PU reclams its spectrum band, the SUs have to adjust their operating frequency, transmit power and bandwidth to ensure no interruption to the PUs.

2.7.2 Spectrum Access Technique: Overlay versus Underlay Spectrum Sharing

In spectrum underlay [1, 17], the SUs co-exist with the PUs and transmit data simultaneously with the PUs. To avoid interference, the SU always operates with transmit power below the interference temperature limit of the PUs, and the SU utilizes a wide range of the spectrum by adopt spread spectrum techniques. However, due to transmission power constraints, the SU achieves a short range of communication. Spectrum underlay does not require the SUs to detect and exploit the spectrum white space.
In the spectrum overlay, the SUs only transmit if the PU does not transmit in the licensed spectrum. Unlike spectrum underlay; the SUs simultaneously transmit their information with the PUs. The SUs will only use the licensed spectrum when the PUs are not transmitting. Hence, there is no interference temperature limit imposed on the SUs transmission. In order to avoid harmful interference to the PUs, the SUs need to sense the PUs spectrum and detect the spectrum holes. Fig. 2.6 illustrates the overlay and underlay approaches.

Besides, to improve further spectrum efficiency, underlay and overlay approach can be employed simultaneously.
2.7.3 Based on Network Architecture: Centralized versus Distributed Spectrum Sharing

In centralized spectrum sharing [16, 17], there exists a central entity which collects the spectrum measurements from all the SUs in the system. This central entity controls and coordinates the spectrum allocation and access of the SUs. The primary goal of the centralized entity is to increase performance of wireless networks by intelligently distributing segments of the available radio frequency spectrum. Thus, the centralized spectrum sharing avoids overcrowding, minimizes the interference as well as adjusts the client’s wireless channel usage through central entity.

Because of the high cost of constructing an infrastructure or ad-hoc nature of the network, when there is no infrastructure or central controller present such as emergency or military use. Then this kind of spectrum sharing belongs to distributed spectrum sharing. In distributed spectrum sharing, each user makes use of the available spectrum based on its local observation of the spectrum.

2.7.4 Spectrum Allocation Behaviour: Cooperative versus Non-Cooperative Spectrum Sharing.

This classification is according to access behaviour [1, 16, 17]. In cooperative spectrum sharing, all SUs work towards a common goal. In this case, they may belong to the same operator or service provider. In order to maximize their social welfare, they will coordinate their allocation and access. The effect of their communication with each other is considered such that any harmful interference can be avoided as effectively as possible. This technique is also called coordinated sharing or cooperative sharing as it ensures coordination among the SUs to reduce the possible interference. The most centralized spectrum allocation can be considered as cooperative. Unlike cooperative spectrum sharing, non-cooperative spectrum sharing describes a selfish behaviour of the SUs where they are not always belong to the same service provider, such as those who access the open spectrum band. Moreover, the SUs do not coordinate with each other but rather allocate the available channels to them based on their local observation of the spectrum. Furthermore, different users have different goals, and the only aim of them to maximize their own benefit by using spectrum resources. As they have no longer cooperation to achieve the same goals, this kind of spectrum sharing is called non-cooperative spectrum sharing.
CHAPTER 3

3. SYSTEM MODEL AND PERFORMANCE ANALYSIS

Recently, to improve the system capacity and spectrum utilization for underlay cognitive radio, antenna diversity techniques used in conventional networks has been considered as powerful technique. It has attained huge interest in the research community [5]-[16]. Specifically in [5, 6], spectrum underlay has been investigated for single input multiple output multiple access channel (SIMO-MAC) considering the interference constraints for the PUs and peak power constraints for the SUs. Some problems have been solved such as a multi-constraint optimization problem, the sum-rate maximize problem and the signal-to-interference ratios balance problem. Considering single PU and SU, a fundamental limit of operation of MIMO CRN has been studied in [7]. An achievable rate region has been derived. In [8], a MIMO CRN has been explored for given average interference power constraints. Moreover, the effects of the number of PUs and SUs on the average uplink capacity are represented. A closed-form expression for the outage probability and complementary cumulative distribution have been presented by considering a cognitive relay assisted SIMO network scenarios through Rayleigh fading channel in [10]. In [12], the parallel communication between MISO and a single input single output (SISO) of the CRN has been proposed. The outage probabilities of the SU for different cooperative feedback/feedback forward algorithm have been investigated. In [14], a SIMO CRN has been investigated wherein the SU-Tx is subject to peak interference power constraint of the PU as well as joint average interference power constraint. The optimal power allocation policy and beam forming weights of the SU have been derived for outage capacity under the most versatile Nakagami-m fading channel. In [15], an efficient algorithm has been proposed to achieve a high sum rate capacity of MIMO broadcast channels in CRN. Besides, the sum rate capacity with average interference power constraints, transmit power constraints are derived and multi-constraints optimization problem has been solved. In [16], a pre-coding scheme has been proposed in order to minimize interference to PU and maximize sum capacity of MIMO CRN. The ergodic capacity and outage capacity for antenna selection based-scheme and power allocation scheme of MIMO CRN has been
calculated in [13]. The closed-form expression for outage probabilities has been derived. However, all studies above have not investigated the impact of change of channel mean powers among the users and number of antennas at the primary receiver (PU-Rx) and secondary receiver (SU-Rx) on the system performance. Therefore, in our thesis, we investigate the impact of mean channel powers and the number of antennas on the performance of SIMO cognitive radio networks. In particular, we assume that the secondary transmitter (SU-Tx) is equipped with a single antenna while the SU-Rx and PU-Rx are equipped with multiple antennas. The selection combining is used to process the received signal at the destination. Furthermore, we assume that all channels experience Rayleigh fading and the transmit power of the SU-Tx is restricted by peak interference power constraint. The CDF of the SNR is derived. Moreover, a closed-form expression for the outage probability and an analytical expression for the SEP are obtained. These formulas are used to evaluate the impact of number antennas and channel mean power gains among users on the system performance. Finally, Monte-Carlo simulation is provided to validate the correctness of analytical results.

3.1 System and Channel Model

Let us consider a spectrum sharing system as shown in Fig. 3.1. Therein, the SU-Tx communicates with the SU-Rx over Rayleigh fading channel. Here, the SU-Tx is equipped with a single antenna while the SU-Rx is equipped with N antennas and the PU-Rx is equipped with M antennas. It is noted that the SU-Tx can transmit simultaneously with PU as long as its interference caused to the PU-Rx does not jump over a predefined threshold. The SU-Rx uses selection combiner to process the signal. The channel gains from SU-Tx to SU-Rx and SU-Tx to PU-Rx are denoted by $h_j$ and $g_i$, $j = 1,\ldots, N$ and $i = 1,\ldots, M$, respectively.
Fig. 3.1: System model of the considered spectrum sharing system.

Receiver diversity is a well-known technique for improving the performance of wireless communication in a fading channel [19]. The main advantage of receiver diversity is that it reduces the fluctuations due to fading. The fact behind diversity combining is that independent signal paths have low probability of experiencing deep fades simultaneously. Thus, the idea behind diversity is to send the same signal over independent fading paths. These paths are combined in such a way that the fading of the resulting signal is reduced. In our thesis, we use the selection combining (SC) technique. In SC [19], the combiner selects the branch with highest SNR as a combiner output. With selection combining, the path output of the combiner has an SNR equal to the maximum SNR of all branches. The SC technique is used for synchronization in our spectrum sharing system, the SNR in each branch can be denoted as

$$
\gamma_j = \frac{h_j P_s}{N_0 B}, \quad j = 1, \ldots, N
$$

(3.1)

where $P_s$ is the transmit power of the SU-Tx, $N_0$ is noise power spectral density and $B$ is the system bandwidth.
The SNR at the SU-Rx can be expressed as

\[ \gamma_{sc} = \max_j (\gamma_j), j = 1, ..., N \]  \hspace{1cm} (3.2)

In order not to cause harmful interference to the PU-Rx, the transmit power \( P_s \) of the SU-Tx should be adjusted to satisfy the following condition.

\[ g_i P_s \leq Q, i = 1, ..., M \]  \hspace{1cm} (3.3)

where \( Q \) is peak interference power constraint. Substituting the value of \( P_s \) into (3.1), we get

\[ \gamma_j = \frac{h_i Q}{\max_i (g_i) N_0 B} \]  \hspace{1cm} (3.4)

Let us define \( g = \max_i (g_i) \), then (3.4) can be write as

\[ \gamma_j = \frac{h_i Q}{g N_0 B} \]  \hspace{1cm} (3.5)

Replacing (3.5) into (3.2), we have

\[ \gamma_{sc} = \max_j \left\{ \frac{h_i Q}{g N_0 B} \right\} \]  \hspace{1cm} (3.6)

By assuming that SU-Tx has full channel state information (CSI), transmission power control of SU-Tx is optimal, \( g_i \) and \( h_j \) are Rayleigh fading channel coefficients with mean channel powers \( \frac{1}{\lambda_{sp}} \) and \( \frac{1}{\lambda_{sd}} \) respectively. Here, \( g_i \) as well as \( h_j \) are exponentially distributed random variables.
So, the PDF and CDF of $g_i$ can be defined as

$$f_{g_i}(x) = \lambda_{sp} e^{\lambda_{sp} x}, \ F_{g_i}(x) = 1 - e^{-\lambda_{sp} x} \quad (3.7)$$

Similarly, the PDF and CDF of $h_j$ are given by

$$f_{h_j}(y) = \lambda_{sd} e^{\lambda_{sd} y}, \ F_{h_j}(y) = 1 - e^{-\lambda_{sd} y} \quad (3.8)$$

Since $Q$, $B$ and $N_0$ are constants in (3.5), let us derive the CDF of $X = \max_j \left\{ \frac{h_j}{g} \right\}$ as follows:

$$F_X(x) = P_r\left\{ X = \max_j \left\{ \frac{h_j}{g} \right\} \leq x \right\}$$

$$= \int_0^\infty P_r\left\{ \max_j \left\{ \frac{h_j}{g} \right\} \leq x \left| g = y \right\} f_g(y) \ dy$$

$$= \int_0^\infty P_r\left\{ \max_j \left\{ h_j \right\} \leq xy \right\} f_g(y) \ dy$$

$$= \int_0^\infty \prod_{j=1}^N P_r\left\{ h_j \leq xy \right\} f_g(y) \ dy \quad (3.9)$$

where $N$ is the number of antennas at the SU-Rx. Using (3.8) in (3.9), the term $P_r\left\{ h_j \leq xy \right\}$ can be expressed as $P_r\left\{ h_j \leq xy \right\} = F_{h_j}(xy) = 1 - e^{-\lambda_{sd} xy}$. Substituting this expression into (3.9), we can rewrite (3.9) as

$$F_X(x) = \int_0^\infty \prod_{j=1}^N \left( 1 - e^{\lambda_{sd} xy} \right) f_g(y) \ dy \quad (3.10)$$
On the other hand, the CDF of $g$ is formulated as

$$F_g(y) = P_r \{ \max \{ g_i \} \leq y \}$$

$$= \prod_{i=1}^{M} P_r \{ g_i \leq y \} = \prod_{i=1}^{M} (1 - e^{-\lambda_{sp} y}) = (1 - e^{-\lambda_{sp} y})^M$$  \hspace{1cm} (3.11)

where $M$ is the number of antennas at the PU-Rx.

By differentiating (3.11) with respect to $y$, the PDF of $g$ is given by

$$f_g(y) = \frac{d}{dy} \{ F_g(y) \} = M\lambda_{sp} e^{-\lambda_{sp} y} (1 - e^{-\lambda_{sp} y})^{M-1}$$  \hspace{1cm} (3.12)

Substituting (3.12) into (3.10), we have

$$F_X(x) = \int_{0}^{\infty} (1 - e^{\lambda_{sd} x y})^{N} M\lambda_{sp} e^{-\lambda_{sp} y} (1 - e^{-\lambda_{sp} y})^{M-1} \, dy$$  \hspace{1cm} (3.13)

By using the binomial expansion in (3.13), we obtain

$$F_X(x) = \int_{0}^{\infty} \sum_{n=0}^{\infty} \sum_{m=0}^{M-1} \left( \begin{array}{c} N \\ n \end{array} \right) (-1)^n M \lambda_{sp} e^{-\lambda_{sp} y} \sum_{m=0}^{M-1} \left( \begin{array}{c} M-1 \\ m \end{array} \right) (-1)^m e^{-\lambda_{sp} y m} \, dy$$

$$= \int_{0}^{\infty} \sum_{n=0}^{N} \left( \begin{array}{c} N \\ n \end{array} \right) (-1)^n M \lambda_{sp} e^{-\lambda_{sp} y} \sum_{m=0}^{M-1} \left( \begin{array}{c} M-1 \\ m \end{array} \right) (-1)^m e^{-\lambda_{sp} y m} \, dy$$

$$= \sum_{n=0}^{N} \sum_{m=0}^{M-1} \left( \begin{array}{c} N \\ n \end{array} \right) \left( \begin{array}{c} M-1 \\ m \end{array} \right) (-1)^{n+m} M \lambda_{sp} \int_{0}^{\infty} e^{-\lambda_{sd} x y n} e^{-\lambda_{sp} y} e^{-\lambda_{sp} y m} \, dy$$
\[
\begin{align*}
\sum_{n=0}^{N} \sum_{m=0}^{M-1} \binom{N}{n} \binom{M-1}{m} (-1)^{n+m} M \lambda_{sp} \int_{0}^{\infty} e^{-y(\lambda_{sd} xn + \lambda_{sp}(m+1))} \, dy
\end{align*}
\]

(3.14)

By using exponential integral formula \((\int_{0}^{\infty} e^{ax} = \left[ \frac{1}{a} e^{ax} \right]_{0}^{\infty} )\) in (3.14), the final CDF of \(X\) can be derived as

\[
F_X(x) = \sum_{n=0}^{N} \sum_{m=0}^{M-1} \binom{N}{n} \binom{M-1}{m} (-1)^{n+m} \frac{M \lambda_{sp}}{\lambda_{sd} xn + \lambda_{sp}(m+1)}
\]

(3.15)

As a consequence, we can expressed the CDF of \(\gamma_{sc}\) as

\[
F_{\gamma_{sc}}(\gamma) = P_r\{\gamma_{sc} \leq \gamma\} = P_r\left\{X \leq \frac{Q}{N_0 B} \leq \gamma\right\} = P_r\left\{X \leq \gamma \frac{N_0 B}{Q}\right\}
\]

\[
F_{\gamma_{sc}}(\gamma) = F_X\left(\gamma \frac{N_0 B}{Q}\right)
\]

\[
= \sum_{n=0}^{N} \sum_{m=0}^{M-1} \binom{N}{n} \binom{M-1}{m} (-1)^{n+m} \frac{M \lambda_{sp}}{\lambda_{sd} n \frac{\gamma N_0 B}{Q} + \lambda_{sp}(m+1)}
\]

(3.16)

### 3.2 Outage Probability

In CRN, the outage probability can be defined as the probability that the instantaneous capacity is less than a predefined threshold. Outage probability is an important performance measurement metric for a wireless system. Therefore, the outage probability is a good measurement of the transmission opportunity in the interference tolerant cognitive radio system. It can be defined as

\[
P_{out} = P_r\{C_{sc} \leq r_0\} = Pr\{Blog_{2}(1 + \gamma_{sc}) \leq r_0\}
\]

\[
= Pr\{\gamma_{sc} \leq 2^{r_0} - 1\} = F_{\gamma_{sc}}\left(2^{r_0} - 1\right)
\]

(3.17)

where \(r_0\) is outage threshold.
3.3 Symbol Error Probability

The symbol error probability is the error which is associated with the received symbol. We derived an approximate expression of SEP for selection combining. In particular, the SEP for \(M\)-ary phase-shift keying signals (\(M\)-ary PSK) can be expressed as [26]:

\[
P_e = \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^\infty F_{\gamma_{sc}}(t) \frac{e^{-bt}}{\sqrt{t}} \, dt
\]

(3.18)

where \(a\) and \(b\) are modulation specific constants. For \(M\)-ary PSK, \(a = 2\) and \(b = \sin^2 \left( \frac{\pi}{M_{\text{PSK}}} \right)\).

By substituting (3.16) into (3.18), we can rewrite (3.18) as

\[
P_e = \frac{a\sqrt{b}}{2\sqrt{\pi}} \sum_{n=0}^N \sum_{m=0}^{M-1} \binom{N}{n} \binom{M-1}{m} (-1)^{n+m} M\lambda_{sp} I
\]

(3.19)

where \(I\) is defined as

\[
I = \int_0^\infty \frac{e^{-bt}}{\sqrt{t} \{\lambda_{sd} + \frac{t N_0 B}{Q} n + \lambda_{sp} (m + 1)\}} \, dt
\]

(3.20)

If \(n = 0\), then (3.20) can be expressed as

\[
I = \frac{1}{\lambda_{sp} (m + 1)} \int_0^\infty \frac{e^{-bt}}{\sqrt{t}} \, dt = \frac{\sqrt{\pi}}{\lambda_{sp} (m + 1) \sqrt{b}}
\]

(3.21)
If $n > 0$, then (3.20) can be derived as

$$
I = \frac{e^{\frac{b\lambda_{sp}(m+1)}{\lambda_{sd}n}}}{\pi \text{Erfc} \left[ \frac{b\lambda_{sp}(m+1)}{\lambda_{sd}n} \right]} \sqrt{\frac{\lambda_{sd}n}{\lambda_{sd}n\lambda_{sp}(m+1)}}
$$  \hspace{1cm} (3.22)

where \( \text{Erfc}[\cdot] \) is complementary error function, commonly denoted \( \text{Erfc}(z) \), defined as

$$
\text{Erfc}(z) = 1 - \text{Erf}(z) = \frac{2}{\sqrt{\pi}} \int_{z}^{\infty} e^{-t^2} \, dt
$$  \hspace{1cm} (3.23)
CHAPTER 4

4. NUMERICAL RESULTS

Numerical results are provided in this chapter in order to illustrate applicable prospect of our analysis. In this section, we show Monte-Carlo simulations and compare them with our analysis. The considered parameters are peak interference power-to-noise ratio, \( Q/N_0 \) (dB) from -6 dB to 12 dB, bandwidth is normalized, 8-PSK and outage threshold \( r_o = 1.5 \). To achieve acceptable accuracy, 50000 loops in Matlab simulation have been considered.

4.1 Outage Probability versus Peak Interference Power-to-Noise Ratio

This section presents the outage probability for the CRN with Rayleigh distributed channels. Fig. 4.1 to Fig. 4.4 plot the outage probability versus peak interference power-to-noise ratio, \( Q/N_0 \). We display the exact outage probability curves given by (3.17). For all figures below, lines indicate analytical results and markers indicate simulation results. The performance of the outage probability with parameters \( \lambda_{sp} = \lambda_{sd} = 1 \) and \( (M = N = 1, \ldots, 4) \) are presented in Fig. 4.1 and Table 4.1.

From Fig. 4.1 and Table 4.1, we see that the outage probability \( P_{out} \) decreases as \( Q/N_0 \) increases with simultaneous increases of the number of antennas. In particular, the outage probability decreases especially in the higher regimes of the peak interference power-to-noise ratio, \( Q/N_0 \geq 2 \) dB.

<table>
<thead>
<tr>
<th>( Q/N_0 ) (dB)</th>
<th>( P_{out} ) (anal) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
<th>( P_{out} ) (sim) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
<th>( P_{out} ) (anal) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
<th>( P_{out} ) (sim) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
<th>( P_{out} ) (anal) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
<th>( P_{out} ) (sim) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
<th>( P_{out} ) (anal) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
<th>( P_{out} ) (sim) ( \lambda_{sp}=1 ) ( \lambda_{sd}=1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
<td>0.8054</td>
<td>0.8048</td>
<td>0.8941</td>
<td>0.8993</td>
<td>0.9348</td>
<td>0.9340</td>
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<td>0.3517</td>
<td>0.3522</td>
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<td>0.3216</td>
<td>0.3023</td>
<td>0.2999</td>
</tr>
<tr>
<td>12</td>
<td>0.0615</td>
<td>0.0625</td>
<td>0.0123</td>
<td>0.0126</td>
<td>0.0031</td>
<td>0.0031</td>
<td>0.00087</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

Table 4.1: Analytical and simulated data for Fig. 4.1.
Fig. 4.1: Impact of peak interference power-to-noise ratio $Q/N_0$ on outage probability $P_{\text{out}}$ for different number of antennas $M = N = 1, \ldots, 4$ and $\lambda_{sp} = \lambda_{sd} = 1$.

It is due to the fact that since $Q/N_0$ increases the PU-Rx can tolerate more interference, i.e., the SU-Tx can transmit with higher power. As a result, the capacity increases and outage probability decreases.

Conversely, Fig. 4.2 and Table 4.2 show the outage probability for the selected parameters ($M = N = 1, \ldots, 4$) and ($\lambda_{sp} = 2, \lambda_{sd} = 1$). In this case, there is a significant improvement of outage probability as $\lambda_{sp}$ increases. The lower outage probability is the indication of better performance. It means that the SU-Tx can transmit with higher power without making harmful interference to the PU-Rx. Therefore, transmission rate increases, and the outage probability decreases as $\lambda_{sp}$ increases.

From the Tables 4.1 and 4.2, we can see that the outage probability reduces from 0.2999 to 0.0864 at $Q/N_0 = 2$ dB with $M = N = 4$. In addition, Fig. 4.2 also shows that for the value of $Q/N_0 \geq 0$ dB, the outage probability decreases as the number of the antennas increases. For the performance shown in Fig. 4.3 and Fig. 4.4, we have set the value of $\lambda_{sp}$ and $\lambda_{sd}$ equal to 1. In addition, in Fig. 4.3, we vary the number of
antennas of the SU-Rx in the range $N = 1, \ldots, 4$ and fix the antennas of the PU-Rx $M = 2$.

Table 4.2: Analytical and simulated data for Fig. 4.2.

<table>
<thead>
<tr>
<th>$Q/N_0$ (dB)</th>
<th>$P_{\text{out}}$ (anal)</th>
<th>$P_{\text{out}}$ (sim)</th>
<th>$P_{\text{out}}$ (anal)</th>
<th>$P_{\text{out}}$ (sim)</th>
<th>$P_{\text{out}}$ (anal)</th>
<th>$P_{\text{out}}$ (sim)</th>
<th>$P_{\text{out}}$ (anal)</th>
<th>$P_{\text{out}}$ (sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
<td>0.6742</td>
<td>0.6733</td>
<td>0.7431</td>
<td>0.7439</td>
<td>0.7846</td>
<td>0.7848</td>
<td>0.8133</td>
<td>0.8115</td>
</tr>
<tr>
<td>2</td>
<td>0.2469</td>
<td>0.2449</td>
<td>0.1608</td>
<td>0.1607</td>
<td>0.1155</td>
<td>0.1195</td>
<td>0.0876</td>
<td>0.0864</td>
</tr>
<tr>
<td>12</td>
<td>0.0317</td>
<td>0.0317</td>
<td>0.0034</td>
<td>0.0030</td>
<td>0.0004</td>
<td>0.0006</td>
<td>0.00007</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Fig. 4.2: Impact of peak interference power-to-noise ratio $Q/N_0$ on outage probability $P_{\text{out}}$ for different number of antennas $M = N = 1, \ldots, 4$ and $\lambda_{sp} = 2, \lambda_{sd} = 1$.
Table 4.3: Analytical and simulated data for Fig. 4.3.

<table>
<thead>
<tr>
<th>$Q/N_0$ (dB)</th>
<th>$P_{out}$ (anal)</th>
<th>$P_{out}$ (sim)</th>
<th>$P_{out}$ (anal)</th>
<th>$P_{out}$ (sim)</th>
<th>$P_{out}$ (anal)</th>
<th>$P_{out}$ (sim)</th>
<th>$P_{out}$ (anal)</th>
<th>$P_{out}$ (sim)</th>
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<tbody>
<tr>
<td>-6</td>
<td>0.9366</td>
<td>0.9372</td>
<td>0.8941</td>
<td>0.8936</td>
<td>0.8624</td>
<td>0.8640</td>
<td>0.8370</td>
<td>0.8361</td>
</tr>
<tr>
<td>2</td>
<td>0.5452</td>
<td>0.5448</td>
<td>0.3517</td>
<td>0.3509</td>
<td>0.2496</td>
<td>0.2492</td>
<td>0.1883</td>
<td>0.1909</td>
</tr>
<tr>
<td>12</td>
<td>0.0913</td>
<td>0.0916</td>
<td>0.0123</td>
<td>0.0119</td>
<td>0.0021</td>
<td>0.0019</td>
<td>0.00046</td>
<td>0.00048</td>
</tr>
</tbody>
</table>

Fig. 4.3: Impact of peak interference power-to-noise ratio $Q/N_0$ on outage probability $P_{out}$ for different number of antennas $M = 2, N = 1, \ldots, 4$ and $\lambda_{sp} = \lambda_{sd} = 1$. 
Table 4.4: Analytical and simulated data for Fig. 4.4.

<table>
<thead>
<tr>
<th>Q/N₀ (dB)</th>
<th>P_{out} (anal)</th>
<th>P_{out} (sim)</th>
<th>P_{out} (anal)</th>
<th>P_{out} (sim)</th>
<th>P_{out} (anal)</th>
<th>P_{out} (sim)</th>
<th>P_{out} (anal)</th>
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<tbody>
<tr>
<td>-6</td>
<td>0.7186</td>
<td>0.7188</td>
<td>0.8941</td>
<td>0.8936</td>
<td>0.9523</td>
<td>0.9517</td>
<td>0.9756</td>
<td>0.9774</td>
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<td>0.2248</td>
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<td>0.3517</td>
<td>0.3509</td>
<td>0.4354</td>
<td>0.4343</td>
<td>0.4957</td>
<td>0.4974</td>
</tr>
<tr>
<td>12</td>
<td>0.0071</td>
<td>0.0071</td>
<td>0.0123</td>
<td>0.0119</td>
<td>0.0164</td>
<td>0.0158</td>
<td>0.0199</td>
<td>0.0196</td>
</tr>
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</table>

Fig. 4.4: Impact of peak interference power-to-noise ratio Q/N₀ on outage probability P_{out} for different number of antennas M = 1,...,4, N = 2 and λ_{sp} = λ_{sd} = 1.
Besides, in Fig. 4.4, we change the number of antennas of the PU-Rx in the range $M = 1, \ldots, 4$ and fix the antennas of the SU-Rx $N = 2$.

It can be observed from Fig. 4.3, the outage probability decreases with the increase in the number of antenna at SU-Rx. Furthermore, the outage probability also decreases with the increase of $Q/N_0$. On the other hand, in Fig. 4.4, by increasing the number of antennas at the PU-Rx, the outage probability increases. If we look at the Tables 4.3 and 4.4, it shows the outage probability increases from 0.1909 (for $M=2$, $N=4$) to 0.4974 (for $M=4$, $N=2$) at $Q/N_0 = 2$ dB. The motivation is that when the number of antennas at the PU-Rx increases, then the SU-Tx must be subject to more constraint i.e., the SU-Tx power must decrease. Accordingly, the capacity or transmission rate decreases and the outage probability increases.

### 4.2 Symbol Error Probability versus Peak Interference Power-to-Noise Ratio

Fig. 4.5 to Fig. 4.8 illustrate the SEP with respect to peak interference power-to-noise ratio, $Q/N_0$. In this part, (3.19) is used to show the exact SEP curves. For all figures below, lines indicate analytical results and markers show simulation results.

In Fig. 4.5, the performance of the SEP with the parameters ($\lambda_{sp} = \lambda_{sd} = 1$) and ($M = N = 1, \ldots, 4$) are exhibited. In this case, the results indicate that the SEP decreases with the increases of $Q/N_0$ and the increase of the number of antennas. The SEP decreases especially for higher regimes of $Q/N_0$, starting from 4 dB. For lower regimes of $Q/N_0$, there is no significant change in SEP.

Table 4.5: Analytical and simulated data for Fig. 4.5.

<table>
<thead>
<tr>
<th>$Q/N_0$ (dB)</th>
<th>SEP (anal) $\lambda_{sp}=1\lambda_{sd}=1$ M=1 N=1</th>
<th>SEP (sim) $\lambda_{sp}=1\lambda_{sd}=1$ M=1 N=1</th>
<th>SEP (anal) $\lambda_{sp}=1\lambda_{sd}=1$ M=2 N=2</th>
<th>SEP (sim) $\lambda_{sp}=1\lambda_{sd}=1$ M=2 N=2</th>
<th>SEP (anal) $\lambda_{sp}=1\lambda_{sd}=1$ M=3 N=3</th>
<th>SEP (sim) $\lambda_{sp}=1\lambda_{sd}=1$ M=3 N=3</th>
<th>SEP (anal) $\lambda_{sp}=1\lambda_{sd}=1$ M=4 N=4</th>
<th>SEP (sim) $\lambda_{sp}=1\lambda_{sd}=1$ M=4 N=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
<td>0.7227</td>
<td>0.7242</td>
<td>0.7545</td>
<td>0.7521</td>
<td>0.7648</td>
<td>0.7652</td>
<td>0.7696</td>
<td>0.7697</td>
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<tr>
<td>2</td>
<td>0.4661</td>
<td>0.4665</td>
<td>0.4733</td>
<td>0.4721</td>
<td>0.4778</td>
<td>0.4781</td>
<td>0.4807</td>
<td>0.4881</td>
</tr>
<tr>
<td>12</td>
<td>0.1418</td>
<td>0.1405</td>
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<td>0.0966</td>
<td>0.0799</td>
<td>0.0797</td>
<td>0.0710</td>
<td>0.0711</td>
</tr>
</tbody>
</table>
Fig. 4.5: Impact of peak interference power-to-noise ratio Q/N₀ on symbol error probability for different number of antennas M = N = 1,...,4 and λ_sp = λ_sd = 1.

Table 4.6: Analytical and simulated data for Fig. 4.6.

<table>
<thead>
<tr>
<th>Q/N₀ (dB)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
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<tbody>
<tr>
<td></td>
<td>A_p=2</td>
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<td>A_p=2</td>
<td>A_p=2</td>
<td>A_p=2</td>
<td>A_p=2</td>
<td>A_p=2</td>
<td>A_p=2</td>
<td>A_p=2</td>
</tr>
<tr>
<td>M=1</td>
<td>N=1</td>
<td>M=1</td>
<td>M=2</td>
<td>M=2</td>
<td>M=3</td>
<td>M=3</td>
<td>M=3</td>
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<td>-6</td>
<td>0.6371</td>
<td>0.6357</td>
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<td>0.6646</td>
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<td>0.6822</td>
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</tr>
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<td>0.3572</td>
<td>0.3425</td>
<td>0.3420</td>
<td>0.3387</td>
<td>0.3395</td>
<td>0.3371</td>
<td>0.3359</td>
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</tr>
<tr>
<td>12</td>
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<td>0.0433</td>
<td>0.0434</td>
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<td>0.0296</td>
<td>0.0232</td>
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</table>
Fig. 4.6: Impact of peak interference power-to-noise ratio $Q/N_0$ on symbol error probability for different number of antennas $M = N = 1, \ldots, 4$ and $\lambda_{sp} = 2, \lambda_{sd} = 1$.

With the increase of $Q/N_0$, the SEP decreases, which means, the PU-Rx can tolerate more interference. Hence, the SU-Tx can transmit with higher power. Accordingly, the capacity of the system increase as well as the symbol error rate decreases.

Fig. 4.6 and Table 4.6 illustrate the SEP when $\lambda_{sp} = 2, \lambda_{sd} = 1$ and $M = N = 1, \ldots, 4$.

Fig. 4.6 depicts a significant improvement in the symbol error probability. This observation can be interpreted as, with the increases of $\lambda_{sp}$, the SEP significantly improves. Since $\lambda_{sp}$ increases, the mean channel power gain between the SU-Tx and the PU-Rx decreases. Consequently, the symbol error rate decreases especially in the higher regimes of $Q/N_0$ (i.e., $Q/N_0 \geq 2$ dB). If we investigate the statistical data from Table 4.5 and Table 4.6, then we observed that a substantial improvement of SEP from 0.0711 (for $\lambda_{sp} = 1, M = N = 4$) to 0.0230 (for $\lambda_{sp} = 2, M = N = 4$) at $Q/N_0 = 12$ dB.

In Fig. 4.7 and Fig. 4.8, let us consider that $\lambda_{sp}$ and $\lambda_{sd}$ are the same (i.e., $\lambda_{sp} = \lambda_{sd} = 1$). In Fig. 4.7, we change the number of antennas of the SU-Rx in the range $N = 1, \ldots, 4$ but fix the antennas of the PU-Rx $M = 2$. 

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Table 4.7: Analytical and simulated data for Fig. 4.7.

<table>
<thead>
<tr>
<th>Q/N₀ (dB)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
<td>0.8083</td>
<td>0.8079</td>
<td>0.7545</td>
<td>0.7555</td>
<td>0.7253</td>
<td>0.7254</td>
<td>0.7059</td>
<td>0.7059</td>
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<td></td>
</tr>
<tr>
<td>2</td>
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<td>0.4219</td>
<td>0.4219</td>
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<td>0.3906</td>
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</tr>
<tr>
<td>12</td>
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<td>0.1997</td>
<td>0.0968</td>
<td>0.0968</td>
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<td>0.0615</td>
<td>0.0453</td>
<td>0.0448</td>
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<td></td>
</tr>
</tbody>
</table>

Fig. 4.7: Impact of peak interference power-to-noise ratio Q/N₀ on symbol error probability for different number of antennas M = 2, N = 1,…,4 and λ_sp = λ_sd = 1.

In contrast in Fig. 4.8, we vary the number of antennas of the PU-Rx in the range M = 1,…,4 and fix the antennas of the SU-Rx N = 2. From both figures, we observe that the SEP is significantly improved in Fig. 4.7 than Fig. 4.8. Because the number of
antennas at the PU-Rx increases, it means that SU-Tx must be subject to more constraints. Thus, the SU-Tx power must be decreased in order not to cause harmful interference to the PU-Rx.

Table 4.8: Analytical and simulated data for Fig. 4.8.

<table>
<thead>
<tr>
<th>Q/N₀ (dB)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
<th>SEP (anal)</th>
<th>SEP (sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
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<td>0.6525</td>
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<td></td>
</tr>
<tr>
<td>2</td>
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<td>0.1206</td>
<td>0.1198</td>
<td>0.1383</td>
<td>0.1400</td>
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<td></td>
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</tbody>
</table>

Fig. 4.8: Impact of peak interference power-to-noise ratio Q/N₀ on symbol error probability for different number of antennas M = 1,…,4, N = 2 and λ_sp = λ_sd = 1.
Therefore, we get the expected result from Fig. 4.7 where the SEP improves from 0.1400 (for $M=4$, $N=2$) to 0.0448 (for $M=2$, $N=4$) at $Q/N_0 = 12$ dB. Besides, the opposite result is shown in Fig. 4.8, where $Q/N_0$ increases, the SEP increases with the increase of the number of antennas.

In conclusion, we can summarize from all of the above observations that when the peak interference power-to-noise ratio increases, the SU-Tx can transmit with higher power. As a result, as the outage probability and SEP decrease, the capacity or transmission rate increases. When the number of antennas increases at the PU-Rx, the system performance will decline. Conversely, when the antenna increases at the SU-Rx, the system performance will increase. Therefore, the SEP and outage probability decreases with the increase of the number of antennas at the SU-Rx. Moreover, if the mean channel power gain between the SU-Tx and PU-Rx increases, the SU-Tx cannot transmit with higher power. Therefore, the system performance will decrease as well. It can clearly be seen from above figures that simulation curves match well with analytical results.
CHAPTER 5

5. CONCLUSIONS AND FUTURE WORKS

Cognitive radio is a promising concept in radio communications which has the promising solution to overcome radio spectrum insufficiency and serve the massive demand on the radio spectrum. However, to achieve that, cognitive radio has to meet the challenge of acquiring vacant spectrum bands or partially utilized spectrum bands with limited or no interference to the primary user. In order to face these challenges, spectrum sharing is considered as a key technology. In this thesis, we have analysed the performances of the outage probability and the SEP for spectrum sharing approach. In particular, we have assumed that transmission channels undergo Rayleigh fading, the SU possess perfect CSIs and selection combining technique is used to process the received signal. Closed-form expression for the outage probability and an analytical expression for SEP are obtained. Further, the performance analysis curves for the outage probability versus $Q/N_0$ and the SEP versus $Q/N_0$ have been investigated. In addition, the impacts of the number of antennas at the PU-Rx as well as SU-Rx have been analysed. In particular, it has been shown that an increasing number of antennas at the SU-Rx significantly decreased the outage probability and SEP in the higher regimes of $Q/N_0$. Accordingly, a system performance improvement is observed. In contrast, an increasing number of antennas at the PU-Rx increased the outage probability and SEP in the range $Q/N_0 = -6$ dB to 12 dB. As a result, system performance degradation is observed. Finally, Monte-Carlo simulation has been provided to verify our theoretical results. In future, the developed analytical framework for SIMO system in spectrum sharing approach may be applied to efficiently examine system performance. For instance, Nakagami-m fading channel and maximal ratio combining (MRC) technique may be used. Furthermore, an increasing number of SUs or PUs and other higher order modulation techniques may also be applied.
REFERENCES


