Cooperative Spectrum Sharing with Two-way Relaying

by

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Submitted
in partial fulfillment of the requirements for the degree of
Master of Technology in Electronics & Communication Engineering

to

Indraprastha Institute of Information Technology Delhi
June, 2016

Keywords: Cooperative spectrum sharing, Cognitive radio, Quality of service, Adaptive, Bit Error Rate Selection Combining, Two-way Relaying.

Certificate

This is to certify that the thesis titled "**Cooperative Spectrum Sharing with Two-way Relaying**" submitted by **Saloni Mittal** for the partial fulfilment of the requirements for the degree of *Master of Technology* in *Electronics and Communication & Engineering* is a record of the bonafide work carried out by her under my guidance and supervision at Indraprastha Institute of Information Technology, Delhi.

The results enclosed in the thesis have not been submitted in any other university or institute for the reward of any other degree.

Dr. Vivek Ashok Bohara
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Abstract

Modern wireless communication seeks more capacity and higher data rates as the cellular technology evolves from one generation to next generation standards (for instance 3G to 4G, and from 4G to presumably 5G). As a consequence researchers and technologists are looking for solutions that can provide very high data rates and better coverage to the end user not withstanding the problems of channel fading, interference and spectrum scarcity etc. To cater the above, many new paradigms like cooperative relaying, cognitive radio, adaptive techniques and two-way relaying has been proposed in literature from time to time.

Cooperative communication can be realized as a relay network, in which the relay simply forwards the source information to the destination by a different path to provide spatial diversity thus improving the performance of a communication system. Along with this to have efficient spectrum utilization, cognitive radio has been proposed where different wireless systems operate on the same spectrum but with different priorities. The system with higher priority is termed as the primary system and the one with lower priority is termed as the secondary system. Cognitive radios work with a constraint that the secondary spectrum access should not adversely affect the performance of primary. Recently, in order to get the benefits of both cooperation and cognition, techniques such as cooperative spectrum sharing (CSS) have been considered by. In the CCS framework, the secondary system acts as a relay and helps the primary to have spatial diversity in exchange for OSA.

In the proposed work, a Bit Error Rate based Selection Combining (BER-SC) protocol for adaptive cooperative cognitive radios (CCR) is proposed, where the secondary system utilizes adaptive mode of transmission (with M-QAM where M = 4, 16 or 64 depending on the received channel feedback) to help the primary system to achieve the desired quality of service (QoS) in exchange for opportunistic spectrum access (OSA). BER-SC is employed to retrieve the primary signal, and at SR interference cancellation is used to retrieve the secondary signal.

Moreover, a two-way CSS protocol under Nakagami-m fading has been proposed to improve the spectrum efficiency. The primary system which has higher priority seeks the assistance of low priority secondary system to improve its QoS in-exchange for allowing the secondary system to access its spectrum.

Apart from above, we have also proposed a novel approach to solve the problems of spectrum efficiency where we have used AF relaying secondary node for two-way communication between the primary transceivers. As the decoding at the secondary node is not taking place due to amplify and forward (AF) approach being used at the secondary transmitter (ST), reducing the complexity of the system.

Acknowledgments

I express my sincere gratitude to my thesis supervisor Dr. Vivek Ashok Bohara for his valuable guidance and inspiration throughout my thesis work. The unwavering faith shown by him in my abilities is extremely valuable for me. It is a great honour for me to work with such a personality who has always appreciated my work, helped me to overcome the difficulties I faced and provided me guidance whenever I needed. I appreciate the way he prompted me to think beyond the obvious and the way he helped me at each and every step of my work. He has always been an inspiration for me. I am extremely fortunate to work with Dr. Vivek A. Bohara. I sincerely thank him from the bottom of my heart for the support, patience and the faith he has always shown in me. I would also like to thank Dr. Pankaj Jalote and all my professors at IIIT-Delhi for providing such a wonderful work environment.

I would also like to thank my best friends: Sakshi, Prince, Dhee, Pandit and Preet who made my stay at IIIT Delhi immensely memorable and enjoyable. I would always remain indebted to these fellows for the way they celebrated my success, rejoiced my happiness and backed me in the times of difficulty. I would always cherish the moments I have spent with them in IIIT-Delhi. I would also like to show my gratitude and sincere thanks to each and every individual who has directly or indirectly helped me ever in the completion of my work.

Last, but not the least, Id like to express my hearty gratitude towards my parents and my family who were always there to support me and encourage me to reach the zenith of success. All good or great things that I have done till now in my personal and professional life is because of the moral support and faith of my family in me. I am blessed to have the parents who were always there to help and encourage me in every endeavor of mine.

Saloni Mittal

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List of abbrevation

AF	amplify and forward
AWGN	additive white Gaussian noise
BPSK	binary phase shift keying
BER	bit error rate
BER-SC	bit error rate based selection combining
CCR	cooperative cognitive radios
CR	cognitive radio
CSI	channel state information
CSS	cooperative spectrum sharing
DF	decode and forward
EGC	equal gain combining
LOS	line-of-sight
MRC	maximum ratio combining
OSA	opportunistic spectrum access
PER	packet error rate
PN	primary network
PT	primary transmitter
PR	primary receiver
PU	primary user
QAM	quadrature amplitude modulation
QoS	quality of service
R_{pt}	primary user's target rate
R_{st}	secondary user's target rate
SC	selection combining
SD	secondary destination
SER	symbol error rate
SR	secondary receiver
SS	secondary source
ST	secondary transmitter
SU	secondary user
x_p	primary signal
x_s	secondary signal

Chapter 1

Introduction

1.1 Motivation and objective

"Our nations Frequency Spectrum Management, including licensing and the needs of all wireless users is governed by 1970s regulations which hinder the growth of wireless technology. Thus, we need to ensure that the spectrum is available for the entrepreneurs and innovators by modifying the approaches of spectrum utilization."

In this era, as the wireless and multimedia applications are increasing, there is an unappeasable demand for more radio spectrum. But recent studies have revealed that most of the spectrum (3kHz to 300GHz) is no longer available for wireless systems due to the allocation of the spectrum under licensed band [1]. Further, it is surveyed that most of the licensed spectrum is either not utilized or under-utilized [1, 2]. As a result of this inherent inefficiency of current spectrum allocation policies, as well as the scarcity of radio spectrum, researchers over the years have proposed alternative spectrum access techniques to improve the spectral efficiency and capacity in radio communication, giving birth to the notion of "cognitive radios" (CR) [3,4]. Conceptually, in CR, a cognitive user (unlicensed user) is allowed to coexist with the primary user in the licensed band, without degrading the performance of the primary user.

Recently, cooperative spectrum sharing (CSS) [5–11], which incorporates cooperative relaying [12] and cognitive radio [13], has been proposed as an effective way to further improve the performance of the primary users as it helps to solve two fundamentals problem of wireless communication, i.e. limited coverage and spectrum scarcity. In CSS protocol [14], primary and secondary systems coexist in the same frequency band albeit with different priorities. The primary system which has higher priority seeks the assistance of low priority secondary system to improve its quality of service (QoS) in-exchange for allowing the secondary system to access its spectrum. In the CSS architecture, the primary and secondary system consists of the transmitter-receiver pair known as the primary transmitter (PT) - primary receiver (PR) and secondary transmitter (ST) - secondary receiver (SR) respectively.

In a conventional CSS protocol [15] if the primary system is not able to achieve its target rate,

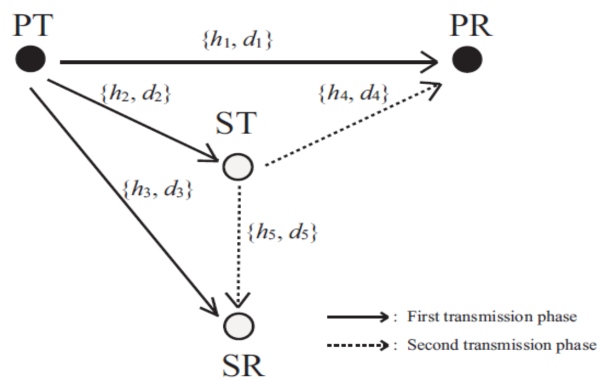

Figure 1.1: Conventional Scheme

it seeks cooperation. The secondary system, which disguises itself as a relay, helps the primary system to achieve its target rate in exchange for opportunistic spectrum access (OSA) [16], by adopting the following two phase transmission protocol as shown in Fig. 1.1. In transmission phase I, the primary transmitter (PT) broadcasts its data to the primary receiver (PR), which is also overheard by the secondary transmitter (ST) and secondary receiver (SR). In transmission phase II, the secondary system transmits the primary and secondary signal with α and 1-α amount of its available power respectively. The secondary system works with a constraint that the spectrum access by secondary should not affect the performance of the primary system. At PR, maximal ratio combining (MRC) is applied to get the desired data out of the data received in phase I and II, considering the secondary data as noise. At SR, the interference cancellation is applied in phase II, after successful decoding of primary signal in phase I, to obtain the secondary data. CSS protocols have also been recently proposed for next generations (beyond 4G and 5G), ad-hoc and cellular networks [17], [18].

Although conventional CSS scheme helps the primary user (PU) to improve its quality of service (QoS) with the help of the secondary user (SU) in exchange of OSA but there are many unresolved issues in a conventional scheme which are mentioned below:

- The time duration of each phase is independent of the channel conditions and thus we have equally divided time blocks for each phase.
- This scheme is limited by interference at the PR due to ST's data which deteriorates the performance of the primary system.
- Moreover, the performance of SU depends on the successful decoding of PT's data by SR in the first transmission phase (if the decode-and-forward scheme is used for the relaying of data in the second phase).
- Consequently, there is no diversity gain for secondary user.
- Further, there is an unavoidable loss in the spectral efficiency in the conventional CSS scheme due to the pre-log factor half.

These above mentioned issues, motivated us to dig deeper into the CSS protocols and to propose some new protocols which can resolve the above mentioned issues. The objective of this thesis is:

- To develop a new CSS protocol where the time duration of each phase is based on the channel conditions and thus to make the secondary transmission adaptive to improve the performance of both the systems.
- To improve the spectral efficiency by introducing two-way relaying [19] in CSS protocols.
- Comparing the proposed work with conventional schemes to show the huge improvement in the performance.
- Providing both simulated and analytically proved results to validate the proposed work.

1.2 Contribution

We have proposed a Bit Error Rate based Selection Combining (BER-SC) protocol for adaptive cooperative cognitive radios which helps in achieving higher performance gains for both primary and secondary system by using adaptive mode of transmission at ST and BER-SC at PR.

- Saloni Mittal, Vivek Ashok Bohara and Naveen Gupta, "A BER Based Selection Combining Protocol for Adaptive Cooperative Cognitive Radios" accepted as a poster in *EuCNC, European Conference on Networks and Communications 2016.*

- Saloni Mittal, Vivek Ashok Bohara and Naveen Gupta, "A BER Based Selection Combining Protocol for Adaptive Cooperative Cognitive Radios" submitted to *PHYCOM, Physical Communication journal 2016.*

We have proposed a two-way cooperative spectrum sharing (CSS) protocol under Nakagami-m fading which helps in increasing the spectrum efficiency as well as provides diversity gain.

- Saloni Mittal and Vivek Ashok Bohara, "Outage analysis of two-way cooperative spectrum sharing protocol under Nakagami-m fading", accepted in *ICACCI, International Conference on Advances in Computing, Communications and Informatics 2016.*

We have proposed a cooperative spectrum sharing protocol for cognitive Two-way AF relaying systems which helps in improving the spectral efficiency and reducing the outage probability of primary and secondary user.

- Saloni Mittal, Vivek Ashok Bohara, Naveen Gupta and Anubha Gupta, "A Cooperative Spectrum Sharing Protocol for Cognitive Two-way AF Relaying Systems", submitted to *Global SIP, IEEE Global Conference on Signal and Information Processing, 2016.*

1.3 Terminologies

1.3.1 Diversity and combining techniques

In wireless communication systems, the presence of fading channels between the transmitter and receiver can lead to signal attenuation and thus incorrect decoding at the receiver. Thus to have a better reception various diversity and combining techniques come into the picture.

Diversity

Space correlation, time correlation, and frequency correlation are the three important features of fading channels which lead to the notation called diversity. Conceptually, in the diversity schemes, two or more inputs are received at the receiver such that the fading phenomena among these inputs are uncorrelated. The decoding probability of the signal at the receiver improves because if, at a point, one radio path undergoes deep fade, another radio path independent (or at least highly uncorrelated) may have a strong signal at that input. For example, suppose p is the probability of a deep fade in one channel, then the probability for some N channels is p^N. Following are the three main diversity schemes given as,

- **Spatial Diversity**: By increasing the antenna spaces, the spatial diversity can be achieved. In the case of spatial diversity, different diversity branches are spatially distributed. This different spatial distribution leads to different characteristics of the channel.
- **Temporal Diversity**: In this case, the time the selective property of the channel is the base for the uncorrelation of various diversity branches.
- **Spectral Diversity**: The branches are uncorrelated on the basis of frequency selective property of channel in case of spectral diversity.

Combining

With the help of diversity, multiple replicas of the same signal are received at the receiver. To combine these multiple uncorrelated signals at the receiver various combining techniques are available which are summarized as below:

- **Selection Combining (SC)**: In this case, the strongest signal (with maximum SNR) is selected out of all the uncorrelated signals received at the receiver as shown in Fig. 1.2(a).
- **Maximum Ratio Combining (MRC)**: Various uncorrelated branches are weighted for maximum SNR in MRC as shown in Fig. 1.2(b).
- **Equal Gain Combining (EGC)**: In EGC, coherent combining of all the uncorrelated branches at the receiver is done with equal gain as shown in Fig. 1.2(c).

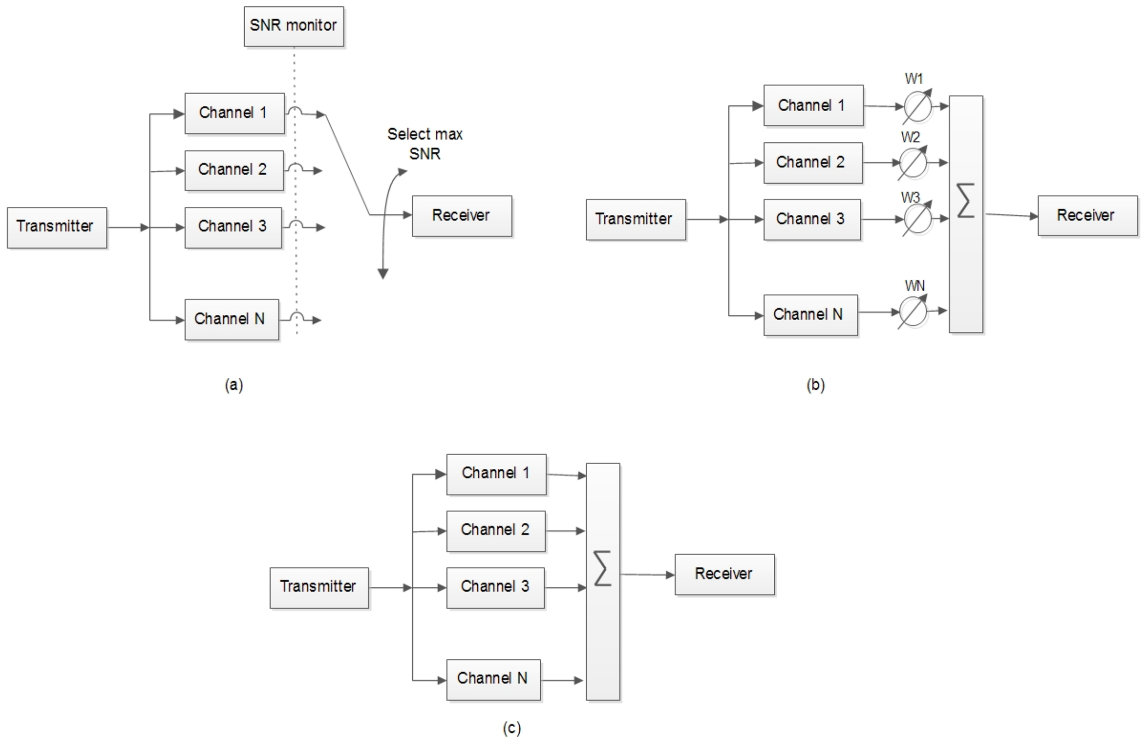

Figure 1.2: a) Selection Combining b) Maximum Ratio Combining c) Equal Gain Combining

1.3.2 Spectrum sharing schemes

Depending on the knowledge that is needed to coexist with the primary user, cognitive radio approaches fall into three classes given as:

- **Spectrum interweave/Interference avoidance**: In this spectral coexistence approach [15], [20], secondary user (SU) can occupy the spectrum rooms that has been left vacant by non cognitive user or primary user (PU). In order to facilitate the coexistence of both primary and secondary users within the same network in an opportunistic transmission mode, spectrum opportunities should be actively identified and monitored to detect as "spectrum holes" or "white spaces". It maintains the orthogonality between the primary and secondary signals in time and / or frequency and hence prevents interference between primary and secondary user.

- **Interference control/Underlay schemes**: In this scheme cognitive and non cognitive transmissions are allowed simultaneously in the primary user's frequency band as long as the interference level at the primary user side remains acceptable. Simultaneous exceeding in the predefined tolerable interference threshold may degrade dramatically the primary signal [21, 22].

- **Interference mitigation/Overlay schemes**: Besides the above mentioned two schemes, here also both PU and SU are allowed to transmit simultaneously in licensed band but in this scheme secondary's transmitter has non-causal information of the PU's message.

Thus, the interference at the primary user's receiver due to secondary transmission can be mitigated with the help of the non-causal information of the PU [23, 24].

1.3.3 Fading channels

Below mentioned fading channels are considered in this thesis,

- **Rayleigh fading**: In the case of absence of the direct ray component, rayleigh fading is used to simulate the rapidly varying amplitude fluctuations. Thus, it is used to model the effects of non line-of-sight (LOS) channels but it is apt only for the signals propagating over small distances, as they are unable to gauge properly the large scale propagation effects like shadowing due to large buildings or obstruction which are common in mobile communication [25]. Because of no LOS component, it is often classified as the worst case fading type. When the receiver travels a distance of a few wavelengths, this small scale distribution simulates the effects of rapid amplitude fluctuations using a one ray model. This single ray is scattered near the receiver which results in multiple rays arriving at the receiver from all directions. The received signals are added in and out of phase which leads to amplitude fluctuations varying at a rate dependent on the speed of the receiver. These amplitude variations are described with the help of the statistical model known as Rayleigh probability distribution function. Moreover, if there is a dominant LOS component then, Rayleigh fading is **Ricean fading**.

- **Nakagami fading**: A significant amount of work has been done in Rayleigh faded environment [26], however, this fading is used for the modeling of the effects of non line-of-sight channels for the signals propagating over small distances (which is generally not the case in mobile communication [25]. Thus to gauge the proper effects of multipath fading in urban scenario Nakagami-m distribution proves to be more helpful than the Rayleigh distribution [25]. Moreover, various fading channel conditions can be obtained by changing the shape parameter (m) of Nakagami-m distribution. For example, if m=1 Nakagami fading converges into Rayleigh fading and for m=0.5 into one-sided Gaussian fading [27].

1.3.4 Relay

Relay node helps to forward the source information to the destination via a different path and thus helps to achieve diversity. As already discussed above, the ST node has relaying functionality that's why it is able to relay the data of the primary user. Relays can be classified into the following mentioned categories depending on how the relay forwards the source information to the destination [28]:

- **Amplify and forward (AF) relay**: In AF, the received signal from the source node is amplified and forwarded by the relay to the destination [29]. Thus, the complexity of this AF relay is very less, helping in the easy implementation of the same. But this relaying generally suffers from the problem of noise enhancement and error propagation as no error correction facility is provided by the relay node.

- **Decode and forward (DF) relay**: In DF relaying, source broadcasts information that is decoded by destination and relay. The relay re-encodes the data and broadcasts this data to the destination [30]. Thus due to the regeneration of the source's information at the relay node, the error propagation from the source-relay node is minimized to the destination. But this also leads to the increase in complexity of the relay node.

1.3.5 Two-way Relaying Protocols

The spectral efficiency of the traditional one-way relaying is constrained due to the half duplex relaying. This loss in spectral efficiency can be mitigated with the help of two-way relaying where the two source nodes are allowed to communicate bi-directionally. Thus, improving the spectral efficiency in comparison to one-way relaying. Based on the time slots required to complete the bi-directional communication, two categories of protocols are classified as below [31]:

- **Time Division Broadcast (TDBC)**: In TDBC, a single round of information exchange is completed in three time slots. In the first two slots, the two sources will transmit their signal to the relay node respectively. In the third time slot, the relay node will broadcast the mixed signal to the two destinations. This can achieve a reliable transmission by exploiting the extra direct path link and thus, improving the performance.

- **Multiple Access Broadcast (MABC)**: In MABC, two time slots are required for a complete round of communication between the two sources. In the first time slot, the two sources will transmit their signal simultaneously to the relay node. In the second time slot, the relay will transmit the combined signal to the two destinations nodes. As this scheme needs fewer time slots for the communication thus, it is spectrally more efficient.

1.4 Outline

The remaining thesis is organized as below:

Chapter 2 deals with Proposed scheme 1 where, the performance of Bit Error Rate based Selection Combining (BER-SC) protocol for adaptive cooperative cognitive radios (CCR) is presented. This combined data (received at ST from phase I and secondary data), is adaptively modulated by M-QAM where M = 4, 16 or 64 depending on the received channel feedback, and relayed to PR and SR. At PR, BER-SC is employed to retrieve the primary signal, and at SR interference cancellation is used to retrieve the secondary signal. The analytical expressions are derived for the BER and the outage probability. The obtained results demonstrate that higher performance gains can be obtained for both primary and secondary system by using adaptive mode of transmission at ST and BER-SC at PR.

Chapter 3 deals with proposed scheme 2. Here the performance of a two-way cooperative spectrum sharing (CSS) protocol under Nakagami-m fading is illustrated. Closed form expressions for the outage probability of primary and secondary systems are derived by varying the shape parameter (m) and spread control parameter (Ω) of Nakagami-m fading channels. Moreover, comparisons between the simulation and theoretical results are also presented in this chapter.

Chapter 4 deals with proposed scheme 3 in which, we investigates the performance of a cooperative spectrum sharing protocol for cognitive Two-way AF relaying systems. Our analysis shows that two-way relaying helps in improving the spectral efficiency and reducing the outage probability of primary and secondary user. The theoretical and simulation results are provided to validate the analytically obtained expressions.

Chapter 5 This chapter concludes the thesis and suggests the possible directions for future work.

Chapter 2

A BER Based Selection Combining Protocol for Adaptive Cooperative Cognitive Radios

2.1 Introduction

In this chapter, a BER based selection combining protocol for adaptive cooperative cognitive radios is presented along with the mathematical models for the outage analysis of the primary and secondary systems. The BER-SC analysis has also been discussed. The proposed scheme intends to increase the overall throughput of both primary and secondary system by utilizing the adaptive modulation at ST (making it adaptable to different channel conditions). In this framework, the unlicensed (i.e. secondary) system utilizes an adaptive mode of transmission to help the licensed (i.e. primary) system to achieve the desired quality of service (QoS) in exchange for opportunistic spectrum access (OSA).

In the past, various studies have depicted the importance of CCR protocols. In [32], the benefits of CCR have been shown by deriving outage performance of the primary and secondary system. In phase I, PT broadcasts its data, which is received by ST, SR, and PR. In phase II, ST allocates a fraction of its available power to transmit primary data and the remaining power is used for transmission of secondary data. At PR, Maximal Ratio Combining (MRC) is applied to combine the signals received in two phases, wherein, secondary data is considered as an interference. At SR, interference cancellation is employed to retrieve the secondary data. In [33], the work of [32] has been extended to the scenario where ST is equipped with multiple antennas. By exploiting the receive diversity at ST, significant performance improvement has been shown for the primary and secondary system. The results in [32] and [33] were obtained by assuming a non-adaptive cooperative relaying protocol wherein ST employs the same modulation scheme as PT. Furthermore, the results were limited to outage probability and no bit error rate (BER) constraint was applied at PR.

For further advancements, adaptive modulation techniques will be a potential candidate to achieve higher capacity and data rate requirements anticipated in 5G standard. It helps to improve the average throughput and reduce the average BER of the system against the fluctuating channel conditions. In adaptive modulation, one can achieve high data rate by modulating the carrier by larger constellation size (M), if channel conditions are favorable. However, for an inferior channel, M can be reduced to maintain desired error performance. Authors in [34] proposed a protocol for cooperative communication where the spectral efficiency is improved for DF relaying through the employment of adaptive modulation. Further, in this paper, spectral efficiency was suggested as criteria to switch dynamically between the direct transmission and DF relaying. Although adaptive modulation has been considered extensively in cooperative relaying protocols, however, to the best of our knowledge, its impact on CCR has not been investigated.

In this chapter, we propose a CCR protocol which utilizes adaptive modulation at ST to increase overall throughput of both primary and secondary system by making it adaptable to different channel conditions. The proposed technique will also be extremely attractive for next generation 5G standards since it achieves efficient spectral utilization along with higher performance gains for two different wireless systems. Similar to conventional CCR protocol, in the proposed protocol the total transmission is divided into two phases. In phase I, PT broadcasts its signal to PR which is also overheard by ST and SR. At ST, the primary signal is regenerated and linearly combined with the secondary signal by assigning fractions α and $(1-\alpha)$ of the available power to the primary and secondary signals respectively. This combined data is modulated adaptively with M-QAM where M = 4, 16 or 64 depending on the received channel state information (CSI). In phase II, ST broadcasts the combined signal with higher modulation as compare to PT to provide high diversity and throughput gain to PR without violating the target BER constraint of the primary system. At PR, BER-SC scheme [35] is used to select the better signal received in the two time slots. The conventional MRC and SC can not be used because of the different constellation sizes, and different error resilient capabilities of the different modulation schemes respectively [36]. At PR, with the help of BER-SC, the branch which has the minimum BER is decoded. The BER of each branch can be calculated *apriori* with the help of received SNR and the modulation size being used[1].

2.2 Model Description with Performance Analysis

2.2.1 System Model

Fig. 2.1 shows the system model where the links PT→PR, PT→ST, PT→SR, ST→PR, and ST→SR are assumed to be Rayleigh flat fading with channel coefficients h_1, h_2, h_3, h_4, h_5 respectively. Here $h_i \sim \mathcal{CN}\left(0, d_i^{-v}\right)$ where i=1,2,3,4,5 and v is the path loss component and d_i is the distance between the respective transmitters and receivers. Each of the links can be characterized by the set of parameters $\{h_i, d_i\}$ as shown in Fig. 2.1, and we also denote $\gamma_i = \left|h_i^2\right|$. x_p and

[1] Due to control signal transmission PR will be aware of the modulation scheme employed at ST.

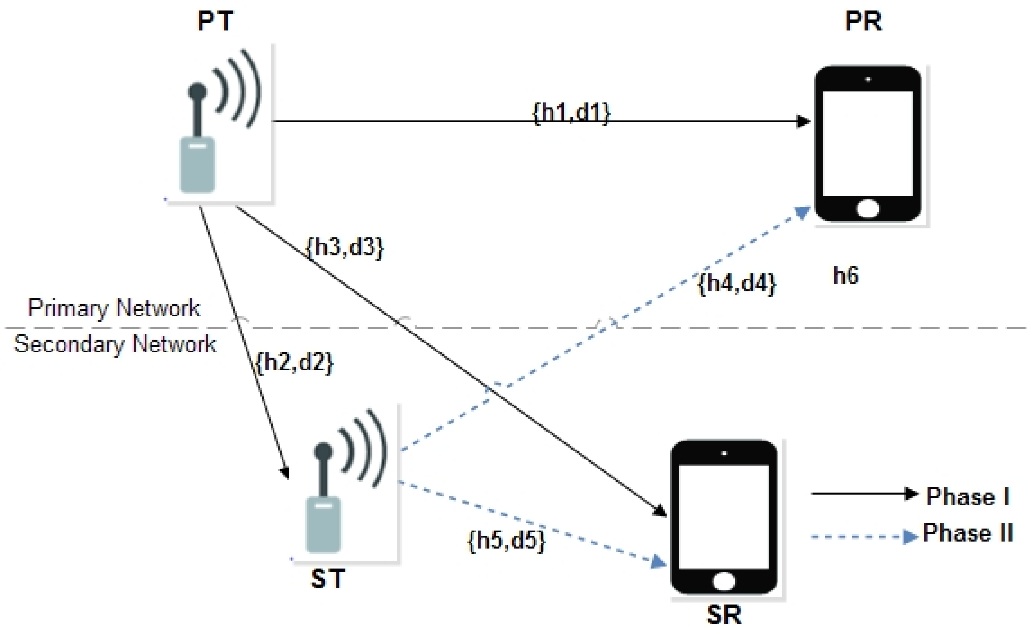

Figure 2.1: System Configuration

x_s are the primary and secondary signals respectively, with zero mean and $E\left\{x_p^* x_p\right\} = 1$ and $E\left\{x_s^* x_s\right\} = 1$, where $*$ denotes the complex conjugate operation. P_p and P_s are the primary and secondary transmit powers respectively. Let us assume that B_1 and B_2 are the number of symbols transmitted in the phase I and phase II from PT and ST respectively. If we denote symbol duration by T_s, thus the total time (T) required for the two phase transmission will be,

$$T = B_1 T_s + B_2 T_s. \tag{2.1}$$

Hence the fraction of total time required for the transmission in each phase will be,

$$I_1 = \frac{B_1 T_s}{T} \text{ and } I_2 = \frac{B_2 T_s}{T} \tag{2.2}$$

where I_1 and I_2 are the transmission intervals for the first and second phase respectively as shown in Fig. 2.2. If B denotes the total number of bits sent from PT to PR and, k_{PT} and k_{ST} is the number of bits per symbol in the phase I and phase II respectively, then, based on the modulation scheme employed at PT and ST, the transmission interval can be given as,

$$\begin{aligned} I_1 &= \frac{B_1}{B_1 + B_2} = \frac{B/k_{PT}}{B/k_{PT} + B/k_{ST}} = \frac{k_{ST}}{k_{PT} + k_{ST}} \\ I_2 &= \frac{B_2}{B_1 + B_2} = \frac{B/k_{ST}}{B/k_{PT} + B/k_{ST}} = \frac{k_{PT}}{k_{PT} + k_{ST}} \end{aligned} \tag{2.3}$$

Further, since ST is a cognitive system, k_{ST} is adaptive, which depends on the channel feedback, whereas k_{PT} is non-adaptive and is decided in advance by PT. This implies that if higher modulation scheme is used at ST then the time required for the transmission of same data in

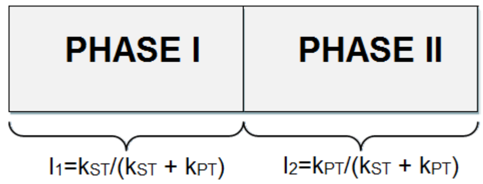

Figure 2.2: Transmission Intervals

second phase will be less and thus the overall transmission delay is reduced.

2.2.2 Outage Probability of Primary System

In phase I, the signal received by PR, ST and SR is given by,

$$y_{j1}(n) = \sqrt{P_p} h_j x_p(n) + n_{j1}(n), \quad n = 1, 2, ..., B_1. \tag{2.4}$$

where j=1,2,3 for reception at PR, ST and SR respectively. The achievable rate between PT and ST is given as,

$$R_2 = I_1 k_{PT} \log_2 \left(1 + \frac{P_p \gamma_2}{\sigma^2}\right). \tag{2.5}$$

The signal x_p is decoded at ST and linearly combined with x_s for the transmission in second phase. The signal Z_s is given by:

$$Z_s = \sqrt{\alpha P_s} x_p + \sqrt{(1-\alpha) P_s} x_s. \tag{2.6}$$

In phase II, ST broadcasts Z_s signal which is received by the PR and SR. The signal received by PR is,

$$y_{12}(w) = h_4 Z_s(w) + n_{12}(w), \quad w = 1, 2, 3, ..., B_2. \tag{2.7}$$

Rate between PT and PR (successful decoding at ST) is,

$$R_{BER}^{SC} = \begin{cases} I_2 k_{ST} \log_2 \left(1 + \frac{P_s \alpha \gamma_4}{P_s (1-\alpha) \gamma_4 + \sigma^2}\right) & BER_{ST} < BER_{PT} \\ I_1 k_{PT} \log_2 \left(1 + \frac{P_p \gamma_1}{\sigma^2}\right) & \text{otherwise.} \end{cases} \tag{2.8}$$

where BER_{ST} denotes the BER between ST-PR link and BER_{PT} denotes the BER between PT-PR link. The transmission rate between PT and PR with unsuccessful decoding at ST in phase I i.e. ST remains silent in phase II is,

$$R_1 = k_{PT} \log_2 \left(1 + \frac{P_p \gamma_1}{\sigma^2}\right). \tag{2.9}$$

Outage at primary system occurs when system fails to achieve the target transmission rate (R_{pt}). There are two such cases: In first case, outage occurs if ST is unable to decode the primary signal in phase I and along with this, the link between PT-PR also fails to achieve R_{pt}, or in second case, outage occur if ST successfully decodes x_p but still overall rate achieved at PR is less than R_{pt}. Therefore, the expression for outage probability at primary system is given as,

$$\begin{aligned} P_{out}^{p} &= P_r\left\{R_2 > R_{pt}\right\} P_r\left\{R_{BER}^{SC} < R_{pt}\right\} + P_r\left\{R_2 < R_{pt}\right\} P_r\left\{I_1 R_1 < R_{pt}\right\} \\ &= 1 - P_r\left\{R_2 > R_{pt}\right\} P_r\left\{R_{BER}^{SC} > R_{pt}\right\} - P_r\left\{R_2 < R_{pt}\right\} P_r\left\{I_1 R_1 > R_{pt}\right\}, \end{aligned} \tag{2.10}$$

where,

$$P_r\left\{\frac{k_{ST}}{k_{PT}+k_{ST}} R_1 > R_{pt}\right\} \Rightarrow P_r\left\{\gamma_1 > \frac{\sigma^2 \rho_1}{P_p}\right\} \Rightarrow \exp\left(-d_1^v \frac{\sigma^2 \rho_1}{P_p}\right), \tag{2.11}$$

where, $\rho_1 = 2^{\frac{(k_{PT}+k_{ST})}{k_{ST}k_{PT}} R_{pt}} - 1$.

$$P_r\left\{R_2 > R_{pt}\right\} \Rightarrow P_r\left\{\gamma_2 > \frac{\sigma^2 \rho_1}{P_p}\right\} \Rightarrow \exp\left(-d_2^v \frac{\sigma^2 \rho_1}{P_p}\right), \tag{2.12}$$

For $BER_{ST} > BER_{PT}$,

$$P_r\left\{R_{BER}^{SC} < R_{pt}\right\} \Rightarrow P_r\left\{\gamma_1 < \frac{\sigma^2 \rho_1}{P_p}\right\} \Rightarrow 1 - \exp\left(-d_1^v \frac{\sigma^2 \rho_1}{P_p}\right), \tag{2.13}$$

For $BER_{ST} < BER_{PT}$,

$$\begin{aligned} P_r\left\{R_{BER}^{SC} < R_{pt}\right\} &\Rightarrow P_r\left\{\gamma_4 < \frac{\sigma^2 \rho_1}{P_s\left(\alpha - (1-\alpha)\rho_1\right)}\right\} \\ &\Rightarrow \begin{cases} 1 - \exp\left(-d_4^v \frac{\sigma^2 \rho_1}{P_s(\alpha-(1-\alpha)\rho_1)}\right) & \alpha > \frac{\rho_1}{\rho_1+1} \\ 1 & \text{otherwise.} \end{cases} \end{aligned} \tag{2.14}$$

The outage probability for the primary system is,

$$P_{out}^{p} = \begin{cases} P_{out}^{'} & BER_{ST} \geq BER_{PT} \\ P_{out}^{1} & \alpha > \frac{\rho_1}{\rho_1+1}; BER_{ST} < BER_{PT} \\ P_{out}^{2} & \text{otherwise}; BER_{ST} < BER_{PT} \end{cases} \tag{2.15}$$

where,

$$P_{out}^{'} = 1 - \exp\left(-d_1^v \frac{\sigma^2 \rho_1}{P_p}\right), \tag{2.16}$$

and

$$\begin{aligned} P_{out}^{1} =& 1 - \exp\left(-\sigma^2\left(\frac{d_2^v \rho_1}{P_p} + \frac{d_4^v \rho_1}{P_s\left(\alpha - (1-\alpha)\rho_1\right)}\right)\right) \\ &+ \exp\left(-\frac{\sigma^2}{P_p}\left(d_2^v + d_1^v\right)\rho_1\right) - \exp\left(-d_1^v \frac{\sigma^2}{P_p}\rho_1\right), \end{aligned} \tag{2.17}$$

and

$$P_{out}^{2} = 1 + \exp\left(-\frac{\sigma^2}{P_p}\left(d_2^v + d_1^v\right)\rho_1\right) - \exp\left(-d_1^v \frac{\sigma^2}{P_p}\rho_1\right). \tag{2.18}$$

2.2.3 Outage Probability of Secondary System

In this section the outage probability of secondary system is evaluated. The signal received at SR in transmission phase I is given by,

$$y_{31}(n) = \sqrt{P_p} h_3 x_p(n) + n_{31}(n), \quad n = 1, 2, ..., B_1 \tag{2.19}$$

Rate between PT and SR:

$$R_3 = I_1 k_{PT} \log_2 \left(1 + \frac{P_p \gamma_3}{\sigma^2}\right). \tag{2.20}$$

In phase II, ST transmits the primary and secondary data with α and $1-\alpha$ amount of available power to PR and SR respectively, thus the signal received at SR is given as,

$$\begin{aligned} y_{32}(w) &= h_5 y_{22}(w) + n_{32}(w), \quad w = 1, 2, ..., B_2 \\ &= \sqrt{\alpha P_s} h_5 x_p(w) + \sqrt{(1-\alpha) P_s} h_5 x_s(w) + n_{32}(w), w = 1, 2, ..., B_2 \end{aligned} \tag{2.21}$$

At SR, interference cancellation is employed which cancels the primary signal component, x_p and then the secondary signal is retrieved. For this cancellation the signal received in the phase I, from primary is decoded and then converted to same constellation size, as that of the signal received from ST. Rate between ST and SR:

$$R_5 = I_2 k_{ST} \log_2 \left(1 + \frac{P_s (1-\alpha) \gamma_5}{\sigma^2}\right). \tag{2.22}$$

Outage probability of a secondary system is the probability by which secondary receiver fails to decode secondary signal with the target rate i.e. R_{st}. If in phase I, links between PT-ST and PT-SR fails in decoding x_p, interference cancellation at SR in phase II is not possible and hence outage will be declared for secondary system. The outage probability for secondary system can be given as [32],

$$P_{out}^s = 1 - P_r\{R_2 > R_{pt}\} P_r\{R_3 > R_{pt}\} P_r\{R_5 > R_{st}\}, \tag{2.23}$$

where,

$$P_r\{R_3 > R_{pt}\} \Rightarrow P_r\left\{\gamma_3 > \frac{\sigma^2 \rho_1}{P_p}\right\} \Rightarrow \exp\left(-d_3^v \frac{\sigma^2 \rho_1}{P_p}\right), \tag{2.24}$$

$$P_r\{R_5 > R_{st}\} \Rightarrow P_r\left\{\gamma_5 > \frac{\sigma^2 \rho_3}{P_s(1-\alpha)}\right\} \Rightarrow \exp\left(-d_5^v \frac{\sigma^2 \rho_3}{P_s(1-\alpha)}\right), \tag{2.25}$$

where $\rho_3 = 2^{\frac{(k_{PT}+k_{ST})}{k_{ST}k_{PT}} R_{st}} - 1$.

The expression for the outage probability of the secondary system will be,

$$P_{out}^s = 1 - \exp\left(-\sigma^2 \left(\frac{(d_2^v + d_3^v)\rho_1}{P_p} + \frac{d_5^v \rho_3}{P_s(1-\alpha)}\right)\right). \tag{2.26}$$

2.2.4 BER-SC Analysis

In this section we analyse the BER performance of primary system for BER-SC. From this analysis the value of *constellation size (M)* required at ST is calculated depending on the distance between PT-ST (d_2) and the minimum BER criteria. Specifically, from this analysis we can obtain the value of M which satisfies the given BER constraint at PR.
Since M-QAM is used for digital modulation, thus the BER can be defined as [37],

$$BER_{Mi} \approx k_{Mi} Q\left(\sqrt{2S_{Mi}^2 \gamma_i}\right), \tag{2.27}$$

$$k_{Mi} = \begin{cases} 1 & M_i = 2 \\ 2\left(\frac{1-\frac{1}{\sqrt{M_i}}}{\log_2 \sqrt{M_i}}\right) & M_i \geq 4, \end{cases} \tag{2.28}$$

$$S_{Mi} = \begin{cases} 1 & M_i = 2 \\ \sqrt{\frac{3}{2(M_i-1)}} & M_i \geq 4. \end{cases} \tag{2.29}$$

The average BER at PR with DF relaying for the proposed scheme is given as [35],

$$BER_{combPR} = PER_{PT-ST} BER_{PT-PR} + \left(1 - PER_{PT-ST}\right) BER_{BER-SC}. \tag{2.30}$$

where, PER_{PT-ST} is the average packet error rate between the PT-ST link. BER_{PT-PR} denotes the average BER of PT-PR (direct) link. BER_{BER-SC} is the average BER at PR after the selection combining. Average BER for M-QAM Rayleigh fading channel is given as [35],

$$\begin{aligned} BER_{ij} &\approx \int_0^\infty k_{Mi} Q\left(\sqrt{2S_{Mi}^2 \gamma_{ij}}\right) \frac{1}{\overline{\gamma}_{ij}} exp\left(-\frac{1}{\overline{\gamma}_{ij}} \gamma_{ij}\right) \\ &= \frac{1}{2} k_{Mi} \left(1 - \sqrt{\frac{S_{Mi}^2 \overline{\gamma}_{ij}}{1 + S_{Mi}^2 \overline{\gamma}_{ij}}}\right), \end{aligned} \tag{2.31}$$

where $\overline{\gamma}_{ij} = E\left[\gamma_{ij}\right]$.

$$\begin{aligned} BER_{PT-PR} &\approx \int_0^\infty k_{M_{PT}} Q\left(\sqrt{2S_{M_{PT}}^2 \gamma_1}\right) \frac{1}{\overline{\gamma}_1} exp\left(-\frac{1}{\overline{\gamma}_1} \gamma_1\right) \\ &= \frac{1}{2} k_{M_{PT}} \left(1 - \sqrt{\frac{S_{M_{PT}}^2 d_1^{-v} \tau}{1 + S_{M_{PT}}^2 d_1^{-v} \tau}}\right), \end{aligned} \tag{2.32}$$

where $\tau = \frac{P_p}{\sigma^2} = \frac{P_s}{\sigma^2}$. If all the symbols transmitted from PT are independent then the packet error rate can be calculated as,

$$\begin{aligned} PER_{PT-ST} &= 1 - (1 - SER_{PT-ST})^{\frac{B}{\log_2 M_{PT}}} \\ &= 1 - \left(1 - \frac{1}{2} k_{M_{PT}} \log_2 (M_{PT}) (1 - \varphi)\right)^{\frac{B}{\log_2 M_{PT}}}, \end{aligned} \tag{2.33}$$

where $\varphi = \sqrt{\frac{S_{M_{PT}}^2 d_2^{-v} \tau}{1 + S_{M_{PT}}^2 d_2^{-v} \tau}}$ and $SER \approx BER \log_2 (M_{PT})$. M_{PT} is the constellation size of the symbols transmitted at PT, $k_{M_{PT}}$ is the number of bits per symbol. Here binary phase shift keying (BPSK) modulation is considered at PT.
The average value of BER_{BER-SC} can be calculated as [35],

$$\begin{aligned} BER_{BER-SC} \approx \frac{1}{2} k_{M_{PT}} \left(1 - \sqrt{\frac{S_{M_{PT}}^2 d_1^{-v} \tau}{1 + S_{M_{PT}}^2 d_1^{-v} \tau}}\right) + \frac{1}{2} k_{M_{ST}} \left(1 - \sqrt{\frac{S_{M_{ST}}^2 d_4^{-v} \tau}{1 + S_{M_{ST}}^2 d_4^{-v} \tau}}\right) \\ - \left(\frac{1}{2} \frac{k_{M_{PT}} S_{M_{ST}}^2 d_4^{-v} + k_{M_{ST}} S_{M_{PT}}^2 d_1^{-v}}{S_{M_{ST}}^2 d_4^{-v} + S_{M_{PT}}^2 d_1^{-v}}\right) \left(1 - \sqrt{\frac{\lambda}{1 + \lambda}}\right), \end{aligned} \tag{2.34}$$

where,$\lambda = \frac{S_{M_{ST}}^2 d_4^{-v} S_{M_{PT}}^2 d_1^{-v} \tau}{S_{M_{ST}}^2 d_4^{-v} + S_{M_{PT}}^2 d_1^{-v}}$ and M_{ST} is the constellation size of the symbols transmitted at ST and $k_{M_{ST}}$ is the number of bits per symbol. After substituting (2.32), (2.33), (2.34) in (2.30) the total BER is given as,

$$\begin{aligned} BER_{combPR} \approx & \left(1 - \left(1 - \log_2 (M_{PT}) \Phi_{M_{PT}} \left(d_2^{-v} \tau\right)\right)^{\frac{N}{\log_2 M_{PT}}}\right) \Phi_{M_{PT}} \left(d_1^{-v} \tau\right) \\ & + \left(1 - \log_2 (M_{PT}) \Phi_{M_{PT}} \left(d_2^{-v} \tau\right)\right)^{\frac{N}{\log_2 M_{PT}}} \times \Bigg[\Phi_{M_{PT}} \left(d_1^{-v} \tau\right) + \Phi_{M_{ST}} \left(d_4^{-v} \tau\right) \\ & - \frac{1}{2} \frac{k_{M_{PT}} S_{M_{ST}}^2 d_4^{-v} + k_{M_{ST}} S_{M_{PT}}^2 d_1^{-v}}{S_{M_{ST}}^2 d_4^{-v} + S_{M_{PT}}^2 d_1^{-v}} \left(1 - \sqrt{\frac{\lambda}{1 + \lambda}}\right)\Bigg], \end{aligned}$$

where,

$$\Phi_M \left(d^{-v}\right) = \frac{1}{2} k_m \left(1 - \sqrt{\frac{S_M^2 d^{-v} \tau}{1 + S_M^2 d^{-v} \tau}}\right). \tag{2.35}$$

Eq. (37) can be simplified for high τ. The asymptotic BER expression is [35],

$$BER_{combPR} \overset{\tau \to \infty}{\approx} \frac{1}{(Z_{BER-SC} \times \tau)^2}, \tag{2.36}$$

where,

$$Z_{BER-SC} = 4 S_{M_{PT}}^2 S_{M_{ST}}^2 \sqrt{d_1^{-v} d_4^{-v}} \left(k_{M_{PT}}^2 S_{M_{ST}}^4 \eta^{-1} + 3 S_{M_{PT}}^2 S_{M_{ST}}^2 \left(k_{M_{PT}} + S_{M_{ST}}\right)\right)^{-\frac{1}{2}}, \tag{2.37}$$

and,

$$\eta = \frac{\log_2 M_{PT}}{B} \left(\frac{d_2^{-v}}{d_4^{-v}} \right). \tag{2.38}$$

2.3 Simulation Results and Discussion

In this section, we show the simulation results for BER and outage probability with respect to d_2 and the power allocation factor (α) respectively. PT, PR, ST, SR nodes are assumed to be collinear [32]. The distance between PT and PR is assumed to be 100m i.e. PT is situated at (0,0) and PR at (100,0) as shown in Fig. 2.3. SR is situated in between PT and PR at (75,0). ST is moving towards PR. The primary and secondary power is assumed to be 0dBm and the path loss exponent is chosen as 3. The noise variance at PR and SR is assumed to be -80dBm. The target rate, R_{pt} and R_{st} is equal to 1. For ease of analysis the modulation scheme at PT is assumed to be BPSK thus $k_{PT} = 1$.

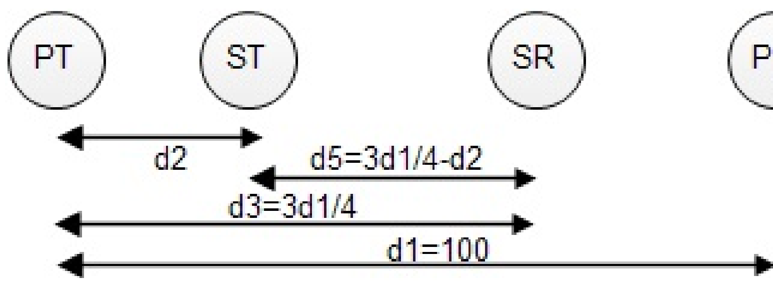

Figure 2.3: Distance between Nodes

Fig. 2.4 shows the BER plot for the primary system with the proposed analysis with respect to d_2 for different values of M at ST. As the distance between PT-ST increases, the distance between ST-PR decreases. From Fig. 2.4, we can observe that BER decreases initially with the increase in d_2 (for low value), as for low d_2 successful decoding of primary signal at ST is quite high, consequently, PER_{PT-ST} is very less. Thus, the main contribution in BER is because of BER_{BER-SC} which decreases with the increase in distance between PT-ST. However after a particular distance, BER increases as the main contribution in BER is because of the PER_{PT-ST} which increases with the distance between PT-ST. Another aspect of BER for different values of M can also be observed from Fig. 2.4. BER increases for M=4, 16 or 64 due to the fact that for fixed bandwidth and power, BER increases with increase in M.

Fig. 2.5 shows the outage probability of the primary system with respect to α for various M and d_2. For each M, the distance corresponding to the lowest BER is selected from Fig. 2.4. For instance, when $M = 4$, $d_2 = 25m$ is selected. It is quite obvious from Fig. 2.5 that the outage probability decreases with higher d_2 and M. Also, at higher M, the data transmission rates are enhanced. For a particular d_2 and M, as α increases, more and more power is allocated to primary signal thus the outage for primary decreases with α.

Fig. 2.6 shows the outage performance of the primary system with the varying distance between

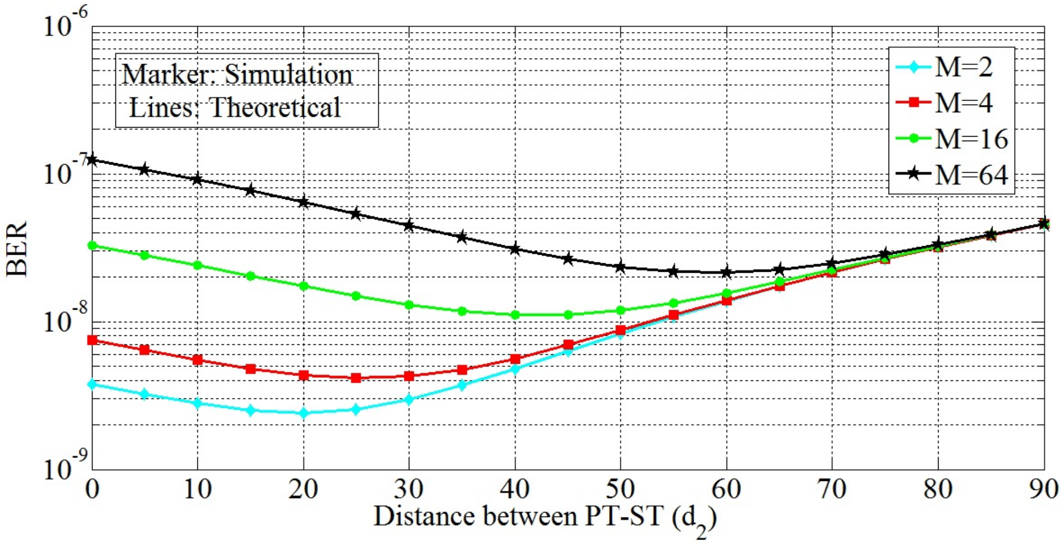

Figure 2.4: BER Performance of Primary System

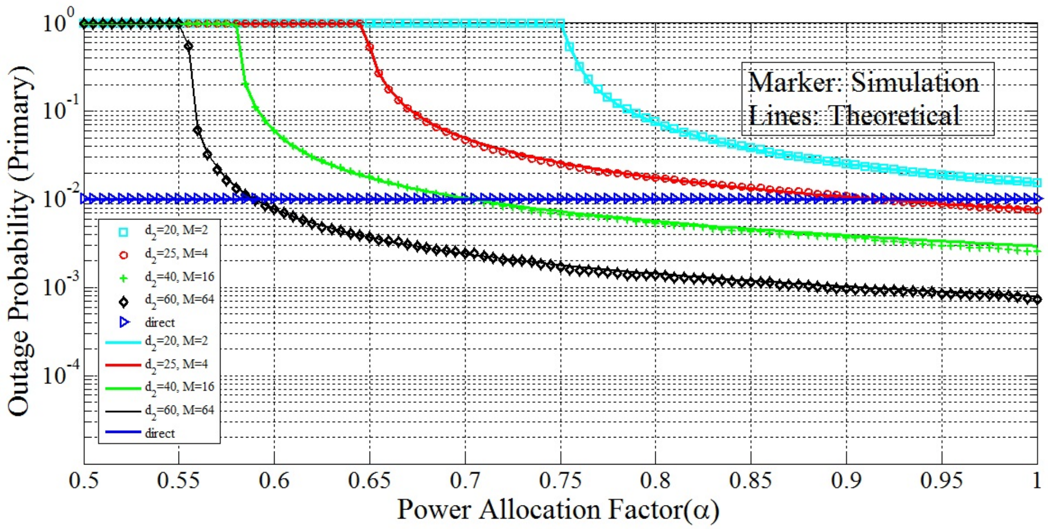

Figure 2.5: Outage Probability of Primary System v/s Power Allocation Factor (α)

PT-ST. The minimum BER constraint is chosen which is satisfied for different values of M at different distances as shown in Fig. 2.4. The plot shows that the outage probability decreases with increasing d_2. This is happening because of the decrease in ST-PR distance. Further, the outage performance is also improving with the higher value of M. This suggests that the data rate is increased along with the improvement in the outage performance.

Fig. 2.7 shows the BER of secondary with respect to d_2. As the SR is located at (75,0) and ST is moving along the x-axis, thus as d_2 increases, the distance between ST-SR decreases and thus, the BER also decreases. Further with increasing constellation size (M), the BER is increasing.

Fig. 2.8 shows the outage performance of the secondary system with respect to α for different values of M and d_2. For a fixed BER, the value of M at a particular distance is observed and the outage for the corresponding d_2 and M values is plotted. As α is increasing less power is

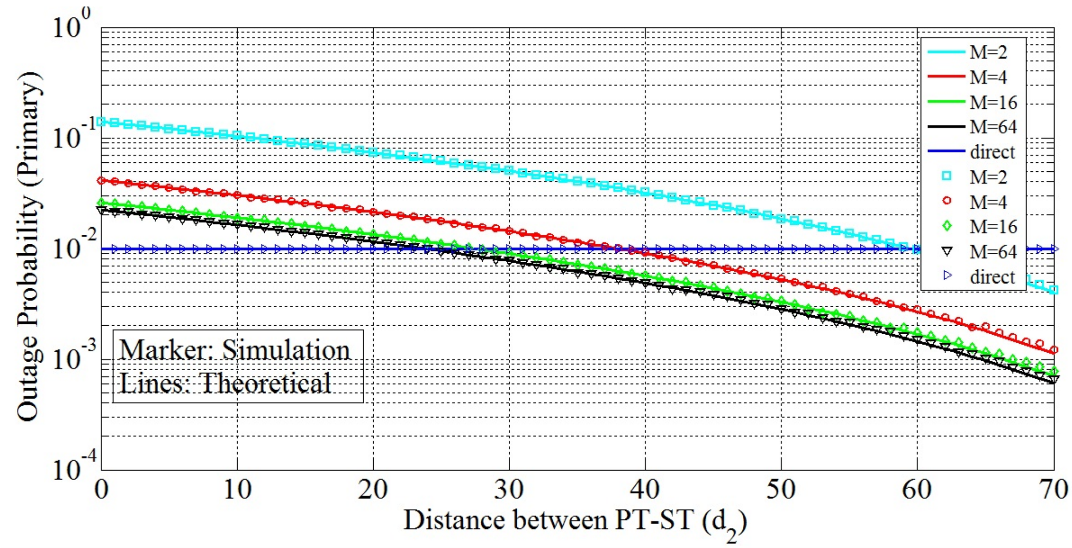

Figure 2.6: Outage Probability of Primary System v/s Distance between PT-ST (d_2)

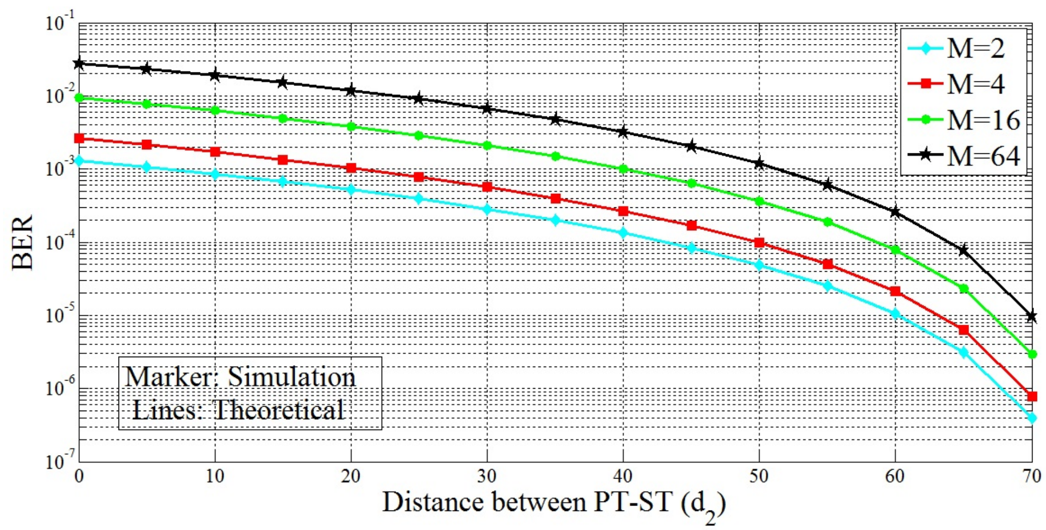

Figure 2.7: BER Performance of Secondary System

allocated for the transmission of secondary data thus the outage probability is increasing with α. There is an improvement in the data rates as the data is transmitted using higher modulation schemes. From Fig. 2.8, it can also be inferred that outage performance of the secondary system improves at higher M.

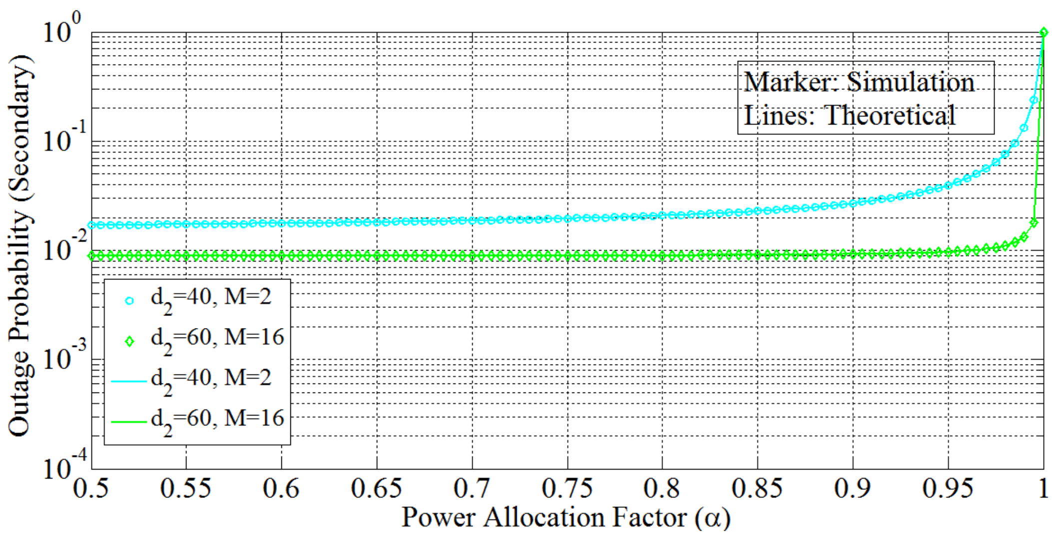

Figure 2.8: Outage Probability of Secondary System v/s Power Allocation Factor (α)

Chapter 3

Outage analysis of two-way cooperative spectrum sharing protocol under Nakagami-m fading

3.1 Introduction

In this chapter, we illustrate the performance of a two-way cooperative spectrum sharing (CSS) protocol under Nakagami-m fading. Conventional cooperative relaying protocols are usually restricted to "one-way" relaying wherein a relay node helps to forward the source information to the destination via a different path thus providing the benefits of spatial diversity [12], [38]. However, one way relaying suffers from an unavoidable loss of spectral efficiency due to increase in transmission time and reduction in capacity (the prelog factor one-half).

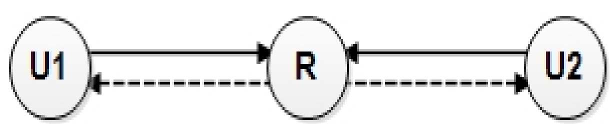

Figure 3.1: Two-way Relaying

The loss due to spectral efficiency in one-way relaying can be mitigated by using two-way relaying [39], [40] where two users are allowed to communicate bi-directionally with the help of a half-duplex relay node. As shown in Fig. 3.1, in two-way relaying the traffic flow of the two users U_1 and U_2 from the opposite directions, is decoded, combined or compressed at the relay node R depending on the relaying strategy used at the relay [17]. The information is then broadcasted to U_1 and U_2, where interference cancellations techniques are applied and respective information is retrieved.

Significant amount of work has been done over these protocols in Rayleigh faded environment [26], however, to the best of our knowledge very few literature are available that analyses the performance of these protocols over Nakagami-m fading channels. The Rayleigh fading is however used to model the effects of non line-of-sight channels but it is apt for the signals propagating over small distances,as they are unable to gauge properly the large scale propagation effects like shadowing due to large buildings or obstruction which are common in mobile communication [25]. Thus to gauge the proper effects of multipath fading in urban scenario Nakagami-m distribution proves to be more helpful than the Rayleigh distribution [25].

In [25], authors derived the outage behaviour of CSS protocol under Nakagami-m fading. In the developed framework secondary transmitter acts as a one-way relay to forward the information from PT to PR. In [26], the authors proposed a one-way relaying protocol where AF relaying is used to transmit the linearly combined primary and secondary signal with λ and $1-\lambda$ transmit powers respectively. Depending on λ the critical region for secondary is calculated and outage performances for primary and secondary systems are evaluated. In [41], the two phase two-way relaying protocol for AF and DF transmission is proposed. Further, depending on the decoding probability of primary data at secondary node outage performance of the proposed protocol was evaluated. In [42], the outage performance of an underlay cognitive system with DF and AF relaying schemes has been proposed. Secondary relays have been employed to transmit the secondary data. Along with that in order to keep the "interference temperature" at the primary receiver within a prescribed limit, the power of the secondary source and secondary relay are constrained to be within a given threshold.

It is quite obvious from above discussion, most of the proposed protocol for CSS are restricted to one-way relaying, which leads to spectral inefficiency. We believe that by incorporating two-way relaying in CSS protocols, significant performance gains can be obtained in limited spectrum environment. Motivated by above, in this chapter we propose a three phase two-way relaying CSS protocol which has a half duplex secondary relay node to increase overall throughput of both primary and secondary system. The system model for the proposed framework has been shown in Fig. 3.2. We assume that a primary network (PN) consists of two primary users, PU_1 and PU_2 . When the channel conditions are favorable there is continuous exchange of information between PU_1 and PU_2, and desired QoS is maintained, however, when the channel conditions deteriorate (in deep fades, blockage etc.), direct communication may not be possible and PN will seek assistance of a relay (i.e secondary node) to sustain the desired QoS [43]. A secondary system which disguises itself as a relay, helps PU_1 and PU_2 to communicate with each other at the desired rate in exchange for OSA[1]. Once a secondary system is confirmed as a relay, spectrum access for the secondary system is obtained by adopting the following three phase transmission protocol. In phase I, PU_1 broadcasts its data to PU_2 which is also overheard by the secondary source (SS) and secondary destination (SD). In phase II, PU_2 broadcasts its data to PU_1 which is also overheard by SS and SD. In phase III, SS decodes the data of primary transmissions and linearly combines the primary users data with its own data by assigning α and $(1-\alpha)$ fractions of the available power respectively. This combined data is broadcasted by SS to PU_1, PU_2 and SD. At PU_1 interference cancellation is employed to retrieve the data of PU_2 with the secondary data as noise. Similarly, the data of PU_1 is retrieved at PU_2. At SD,

[1]Interested readers may refer to [38] for further details on the control protocol.

secondary data is retrieved by cancelling the primary data obtained in first two phases.

The advantages of the proposed scheme are summarized as follows:

- The proposed scheme is spectrally more efficient as compared to conventional CSS schemes, as two users can communicate in the same physical channel, thus the achieved sum rate is greater than the one achieved in a single user environment.
- The proposed scheme also ensures spectrum access for the secondary system as long as it can help the primary network to sustain its QoS.
- The spatial diversity is inherent in the proposed scheme as the information from the source to destination is transmitted through two independent paths.
- The proposed scheme is mutually beneficial for both primary and secondary system, as primary gets desired QoS whereas secondary gets OSA.

3.2 System model with protocol description

3.2.1 System Model

Fig. 3.2 shows the system model where the links $PU_1 \rightarrow PU_2$, $PU_1 \rightarrow SS$, $PU_1 \rightarrow SD$, $SS \rightarrow SD$, $SS \rightarrow PU_2$, and $SD \rightarrow PU_2$ are assumed to follow Nakagami-m fading with channel coefficients $h_1, h_2, h_3, h_4, h_5, h_6$ respectively. For ease of analysis all the nodes are assumed to be half duplex. We have also denoted $\gamma_i = |h_i^2|$, where γ_i is a gamma distributed random variable.

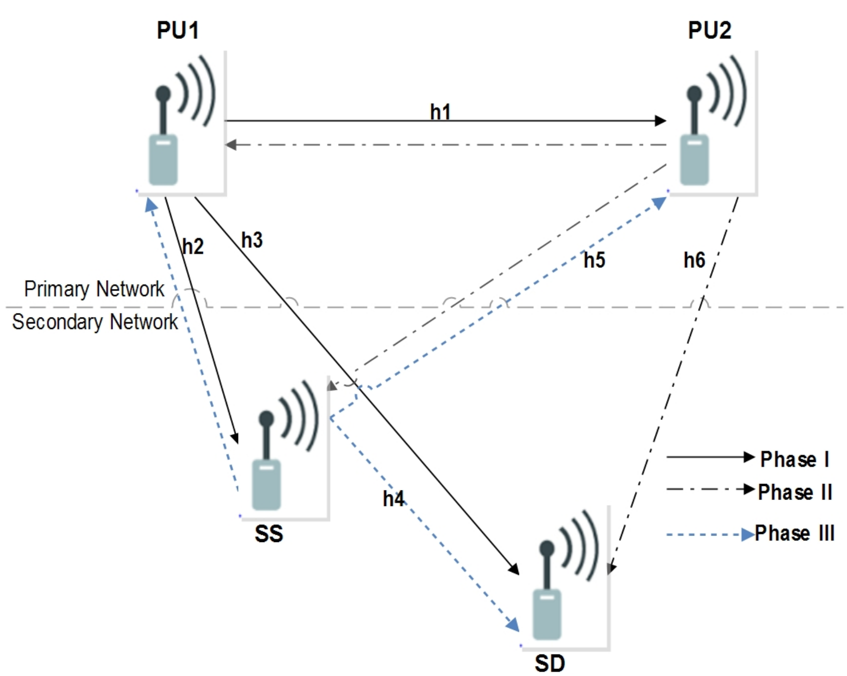

Figure 3.2: System Configuration

The Probability Density Function (PDF) of a Nakagami-m distributed random variable h is given by,

$$f_h(h) = \frac{2m^m}{\Gamma(m)\,\Omega^m} h^{2m-1} \exp\left(-\frac{m}{\Omega}h^2\right)$$

where $\Omega = E[h^2]$, m is the Nakagami fading parameter, and $\Gamma(.)$ is the Gamma function. We assume $\Omega_i = d_i^{-v}$ where i=1,2,3,4,5,6, v is the path loss component and d_i is the normalised distance between the respective transmitters and receivers. This normalisation is done with respect to distance between PU_1 and PU_2 i.e. $d_1 = 1$. For $m = 1$ the fading is Rayleigh and for $0.5 \leq m < 1$ the fading is more severe than Rayleigh fading.

Let x_{p_1}, x_{p_2} and x_s denote the signals for PU_1, PU_2 and secondary system respectively, with zero mean and $E\left\{x_{p_1}^* x_{p_1}\right\} = 1$, $E\left\{x_{p_2}^* x_{p_2}\right\} = 1$ and $E\left\{x_s^* x_s\right\} = 1$. $*$ denotes the complex conjugate operation. P_{p_1}, P_{p_2} and P_s are the transmit power for PU_1, PU_2 and secondary system respectively. R_{pt} and R_{st} denotes the required target rates for the primary and secondary system respectively[2]. The additive white Gaussian noise (AWGN) is denoted as $n_{ij} \sim \mathcal{CN}\left(0, \sigma^2\right)$ where $i\epsilon\left\{1,2,3\right\}$ and $j\epsilon\left\{1,2,3,4,5,6\right\}$ represents the transmission phases and the respective channel links with identical variance of σ^2 respectively.

3.3 Analysis on Outage probability

In this section outage probability for the primary and secondary system is calculated. Outage probability is about the throughput or capacity of data that can be transmitted through the channel. The target rate considered for the primary and secondary system is denoted by R_{pt} and R_{st} respectively.

3.3.1 For Primary System

Let x_{p_1} is the signal transmitted by PU_1 in phase I. Denoting the signals received by PU_2, SS and SD in phase I as y_{11}, y_{21} and y_{31} respectively, we have

$$y_{j1} = \sqrt{P_{p_1}} h_j x_{p_1} + n_{1j},$$

where j=1,2,3. In phase II, the signal received by PU_1, SS and SD is given by[3],

$$y_{k2} = \sqrt{P_{p_2}} h_k x_{p_2} + n_{2k},$$

where k=1,5,6 for reception at PU_1, SS and SD respectively. The signals thus received at ST are decoded for x_{p_1} and x_{p_2} respectively in the two phases. Rate between PU_1 and SS,

$$R_{SS} = \frac{1}{3}\log_2\left(1 + \frac{P_{p1}\gamma_2}{\sigma^2}\right), \tag{3.1}$$

[2] Without loss of generality, we assume that PU1 and PU2 desire the same target rate.

[3] Due to channel reciprocity we assume that the channels between $PU_1 - PU_2$, $PU_1 - SS$, $PU_1 - SD$, $SS - PU_2$, $SD - PU_2$, $SS - SD$ and vice versa are same.

where $\frac{1}{3}$ accounts the fact that the whole transmission is divided into three phases. The signals x_{p_1} and x_{p_2} are decoded at SS and linearly combined with x_s for the transmission in phase III. The combined signal Z_s is given by:

$$Z_s = \sqrt{\alpha P_s}\left(x_{p1} + x_{p2}\right) + \sqrt{(1-\alpha)P_s}x_s.$$

In phase III, SS broadcasts Z_s signal which is received by PU_1, PU_2 and SD. The signal received by PU_2 is,

$$\begin{aligned} y_{13} &= h_5 Z_s + n_{31} \\ &= \sqrt{\alpha P_s} h_5 x_{p_1} + \sqrt{\alpha P_s} h_5 x_{p_2} + \sqrt{(1-\alpha)P_s} h_5 x_s + n_{31}. \end{aligned}$$

At PU_2 interference cancellation is employed, which cancels x_{p_2} component and retrieves the data of PU_1 with the secondary data as noise. The signals in phase I and phase III, y_{11} and y_{13} are then combined at PU_2 using MRC. The achieved rate between SS and PU_2 is thus given by,

$$R_5^{MRC} = \frac{1}{3}\log_2\left(1 + \frac{P_{p1}\gamma_1}{\sigma^2} + \frac{P_s \alpha \gamma_5}{P_s\left(1-\alpha\right)\gamma_5 + \sigma^2}\right). \tag{3.2}$$

On the other hand if SS is not able to decode x_{p_1} and x_{p_2} in phase I and phase II respectively, then SS will not transmit any data in phase III. However, PU_2 may still be able to receive x_{p_1} through the direct link between PU_1 and PU_2 with the rate given below as,

$$R_d = \log_2\left(1 + \frac{P_{p_1}\gamma_1}{\sigma^2}\right). \tag{3.3}$$

The outage probability for PU_1 can be given as,

$$\begin{aligned} P_{out}^P &= P_r\left\{R_{SS} > R_{pt}\right\} P_r\left\{R_5^{MRC} < R_{pt}\right\} + P_r\left\{R_{SS} < R_{pt}\right\} P_r\left\{\frac{1}{3}R_d < R_{pt}\right\} \\ &= 1 - P_r\left\{R_{SS} > R_{PT}\right\} P_r\left\{R_5^{MRC} > R_{PT}\right\} - P_r\left\{R_{SS} < R_{PT}\right\} P_r\left\{\frac{1}{3}R_d > R_{PT}\right\}. \end{aligned} \tag{3.4}$$

where,

$$P_r\left\{\frac{1}{3}R_d > R_{pt}\right\} = 1 - \frac{1}{\Gamma\left(m\right)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_1 P_{p_1}}\right), \tag{3.5}$$

where $\rho_1 = 2^{3R_{PT}} - 1$, $\Gamma(.)$ is the Gamma function and $\gamma(.,.)$ is the incomplete Gamma function.

$$P_r\left\{R_{SS} < R_{pt}\right\} = \frac{1}{\Gamma\left(m\right)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_2 P_{p_1}}\right), \tag{3.6}$$

$$P_r\left\{R_{SS} > R_{pt}\right\} = 1 - \frac{1}{\Gamma\left(m\right)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_2 P_{p_1}}\right), \tag{3.7}$$

$$P_r\left\{R_5^{MRC} > R_{pt}\right\} = \begin{cases} 1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2}{\Omega_1 P_{p_1}}\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)\right) & 0 \le \alpha < \hat{\alpha} \\ 1 & \hat{\alpha} \le \alpha < 1. \end{cases} \tag{3.8}$$

Assuming $P_s >> \sigma^2$ in (3.2) and $\hat{\alpha} = \frac{\rho_1}{1+\rho_1}$. Substituting (3.5), (3.6), (3.7) and (3.8) in (3.4), we get the outage probability for primary transmission given as[4],

$$P_{out}^P = \begin{cases} P_{out}^1 & 0 \le \alpha < \hat{\alpha} \\ P_{out}^2 & \hat{\alpha} \le \alpha < 1. \end{cases} \tag{3.9}$$

$$\begin{aligned} P_{out}^1 = 1 &- \left[1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_2 P_{p_1}}\right)\right]\left[1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2}{\Omega_1 P_{p_1}}\left(\rho_1 - \frac{\alpha}{1-\alpha}\right)\right)\right] \\ &- \left[\frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_2 P_{p_1}}\right)\right]\left[1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_1 P_{p_1}}\right)\right] \end{aligned}$$

and

$$P_{out}^2 = 1 - \left[1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_2 P_{p_1}}\right)\right] - \left[\frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_2 P_{p_1}}\right)\right]\left[1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_1 P_{p_1}}\right)\right]$$

3.3.2 For Secondary System

In this section the outage probability of secondary system is evaluated. The signal received at SD in transmission phase I is given by,

$$y_{31} = \sqrt{P_{p_1}}h_3 x_{p_1} + n_{13}.$$

The rate at SD for the direct transmission from PU_1 is given by,

$$R_3 = \frac{1}{3}\log_2\left(1 + \frac{P_{p_1}\gamma_3}{\sigma^2}\right). \tag{3.10}$$

The signal received at SD in phase II is,

$$y_{32} = \sqrt{P_{p_2}}h_6 x_{p_2} + n_{23}.$$

The rate at SD for the transmission from PU_2 is,

$$R_6 = \frac{1}{3}\log_2\left(1 + \frac{P_{p_2}\gamma_6}{\sigma^2}\right). \tag{3.11}$$

The rate at SS for the transmission from PU_2 is,

$$R_5 = \frac{1}{3}\log_2\left(1 + \frac{P_{p_2}\gamma_5}{\sigma^2}\right). \tag{3.12}$$

[4]Due to channel reciprocity, the results for the transmission between PU_2 to PU_1 will be same as those obtained in (3.9).

In transmission phase III, the signal Z_s transmitted by SS is received by SD which is given as,

$$\begin{aligned} y_{33} &= h_4 Z_s + n_{33} \\ &= \sqrt{\alpha P_s} h_4 x_{p_1} + \sqrt{\alpha P_s} h_4 x_{p_2} + \sqrt{(1-\alpha) P_s} h_4 x_s + n_{33}. \end{aligned}$$

The rate between SS and SD, assuming the successful decoding of x_{p_1} and x_{p_2} at SS and SD is given by[5],

$$R_4 = \frac{1}{3}\log_2\left(1 + \frac{(1-\alpha) P_s \gamma_4}{\sigma^2}\right). \tag{3.13}$$

For ease of analysis it is assumed that x_{p_1} and x_{p_2} are successfully decoded at SD. Thus the outage at secondary can occur in one of the four possible cases: if x_{p_1} and x_{p_2} are not decoded successfully at SS, if x_{p_1} and x_{p_2} are successfully decoded at SS but the combined signal transmitted from SS is not successfully decoded at SD or if any of the two signals x_{p_1} and x_{p_2} is not decoded successfully at SS and the resulting signal transmission from SS is not decoded at SD. Taking into account the above cases, the outage probability for the secondary system can be given as,

$$\begin{aligned} P_{out}^{S} =& P_r\{R_3 > R_{pt}\} P_r\{R_6 > R_{pt}\} \big[P_r\{R_{SS} < R_{pt}\} P_r\{R_5 < R_{pt}\} + P_r\{R_{SS} > R_{pt}\} \\ & P_r\{R_5 > R_{pt}\} P_r\{R_4 < R_{st}\} + P_r\{R_{SS} > R_{pt}\} P_r\{R_5 < R_{pt}\} P_r\{R_4 < R_{st}\} + \\ & P_r\{R_{SS} < R_{pt}\} P_r\{R_5 > R_{pt}\} P_r\{R_4 < R_{st}\}\big]. \end{aligned} \tag{3.14}$$

where,

$$P_r\{R_5 < R_{PT}\} = \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_5 P_{p_2}}\right), \tag{3.15}$$

$$P_r\{R_5 > R_{PT}\} = 1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_5 P_{p_2}}\right), \tag{3.16}$$

$$P_r\{R_3 > R_{PT}\} = 1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_3 P_{p_1}}\right), \tag{3.17}$$

$$P_r\{R_6 > R_{PT}\} = 1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_1}{\Omega_6 P_{p_2}}\right), \tag{3.18}$$

$$P_r\{R_4 < R_{ST}\} = \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\sigma^2\rho_2}{\Omega_4 (1-\alpha) P_s}\right), \tag{3.19}$$

[5] At SD, interference cancellation is employed which cancels the primary signal component, x_{p_1} and x_{p_2} and then the secondary signal is retrieved.

where $\rho_2 = 2^{3R_{ST}} - 1$. Putting (3.6), (3.7), (3.15), (3.16), (3.17), (3.18) and (3.19) in (3.14) the outage performance of the secondary system is as given in (3.20),

$$P_{out}^{S} = \varphi \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_2 P_{p_1}}\right) \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_5 P_{p_2}}\right) + \varphi \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_2}{\Omega_4 (1-\alpha) P_s}\right) \Bigg[\Bigg(1 - \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_2 P_{p_1}}\right)\Bigg) \left(1 - \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_5 P_{p_2}}\right)\right) + \left(1 - \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_2 P_{p_1}}\right)\right) \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_5 P_{p_2}}\right) + \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_2 P_{p_1}}\right) \left(1 - \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_5 P_{p_2}}\right)\right) \Bigg] \tag{3.20}$$

where $\varphi = \left[1 - \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_3 P_{p_1}}\right)\right] \left[1 - \frac{1}{\Gamma(m)} \gamma\left(m, \frac{m\sigma^2 \rho_1}{\Omega_6 P_{p_2}}\right)\right]$.

3.4 Simulation Results and Discussion

In this section we present the simulation results for the proposed two-way relaying CSS protocol. The graphs for the outage probability of the primary user and secondary user with respect to the power allocation factor (α) and shape parameter (m) are plotted. PU_1, PU_2, SS, SD nodes are assumed to be collinear [32], [33]. The distance between PU_1 and PU_2 is normalised i.e. $d_1 = 1$. PU_1 is situated at (0,0) and PU_2 at (1,0). The distance between PU_1 and SS is assumed to be d_2 and all other distances between various nodes are expressed in terms of d_2. The distance between PU_1 to SD, SS to SD is $d_3 = d_4 = d_2/2$, SS to PU_2 is $1-d_2$ and SD to PU_2 is $1-d_2/2$ as shown in Fig. 3.3. The path loss exponent is chosen to be 4. We have taken $\frac{P_{p1}}{\sigma^2} = \frac{P_{p2}}{\sigma^2} = 20\ dB$ and $\frac{P_s}{\sigma^2} = 30\ dB$. The target rate, R_{pt} and R_{st} is equal to 1.

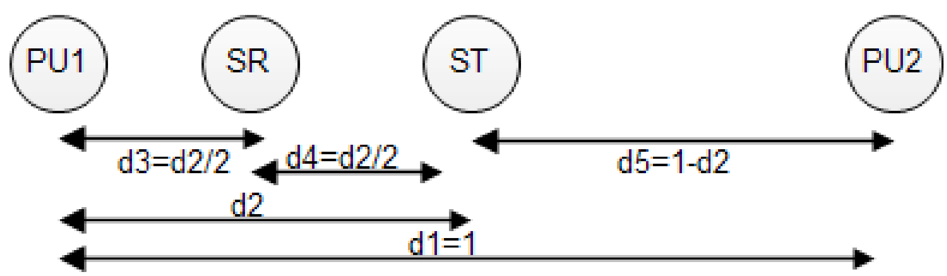

Figure 3.3: Distance between Nodes

Fig. 3.4 depicts the outage performance of the primary system with respect to the power allocation factor (α) for different values of d_2. The graph is plotted for m=0.7. The figure shows that with an increase in α, the outage probability decreases. This can be explained as follows. As α increases, more and more power of SS is allocated for the relaying of primary's signal and less power is allocated for the transmission of secondary's signal (which acts as an interference for the primary signal reception). Thus, the outage probability of the primary transmission decreases with increasing α.

However an outage probability floor appears after a particular value of α. This happens because as α tends to 1, the contribution of $Pr\left\{R_5^{MRC} < R_{pt}\right\}$ is almost negligible and the successful decoding at SS becomes the limiting factor i.e. $P_{out}^{P} = P_r\left\{R_{SS} < R_{pt}\right\} P_r\left\{\frac{1}{3}R_d < R_{pt}\right\}$. Thus increasing alpha has no effect in the outage probability of the primary system. Also as d_2 increases the decoding at SS becomes more difficult and thus, as the distance increases the outage probability floor becomes higher.

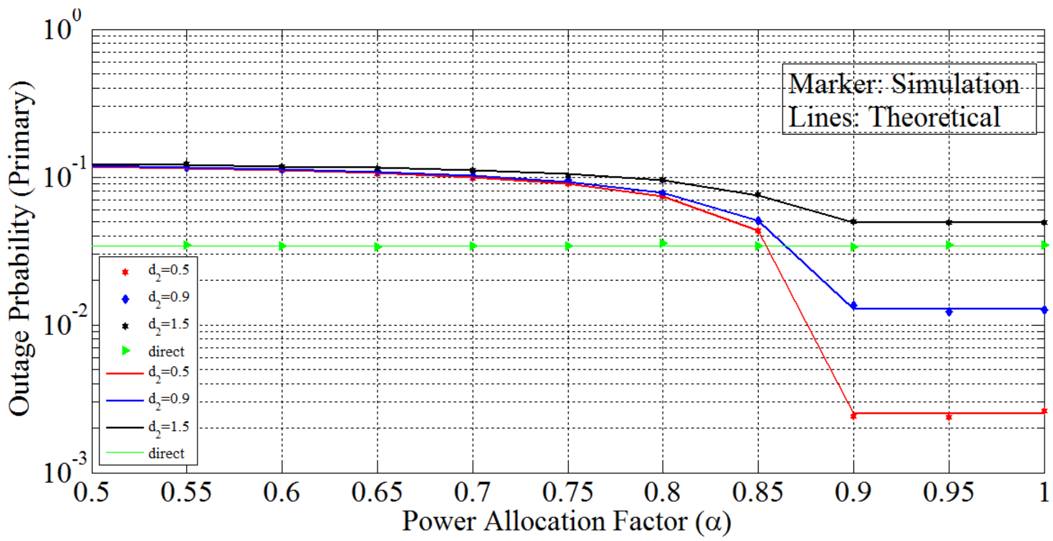

Figure 3.4: Outage Performance of Primary System

Fig. 3.5 shows the outage probability of the secondary system with respect to α for various d_2. It is quite obvious from the figure that as α increases, the outage probability also increases. This can be justified as the α increases more power is allocated for the primary's signal transmission and less power is allocated for the relaying of secondary's signal leading to an increase in the outage probability of secondary system. Further as d_2 increases, the distance between SS and SD (i.e. $d_2/2$) also increases. This increase in the distance between SS and SD results in the degradation of the signal quality thus leading to poorer outage performance.

Fig. 3.6 depicts the outage performance of the primary and secondary system with respect to the fading coefficient, m. As the value of m increases the outage probability of both the primary and secondary system decreases. This is due to the fact that with increasing m, the impact of fading decreases, hence the outage performance improves. For m=1, the outage performance of Nakagami-m fading reduces to the Rayleigh fading.

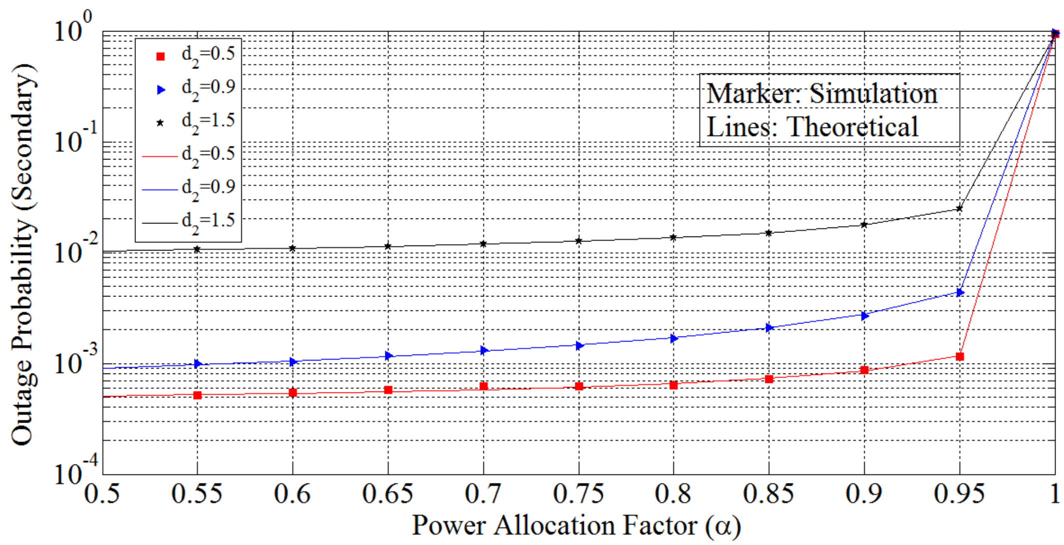

Figure 3.5: Outage Performance of Secondary System

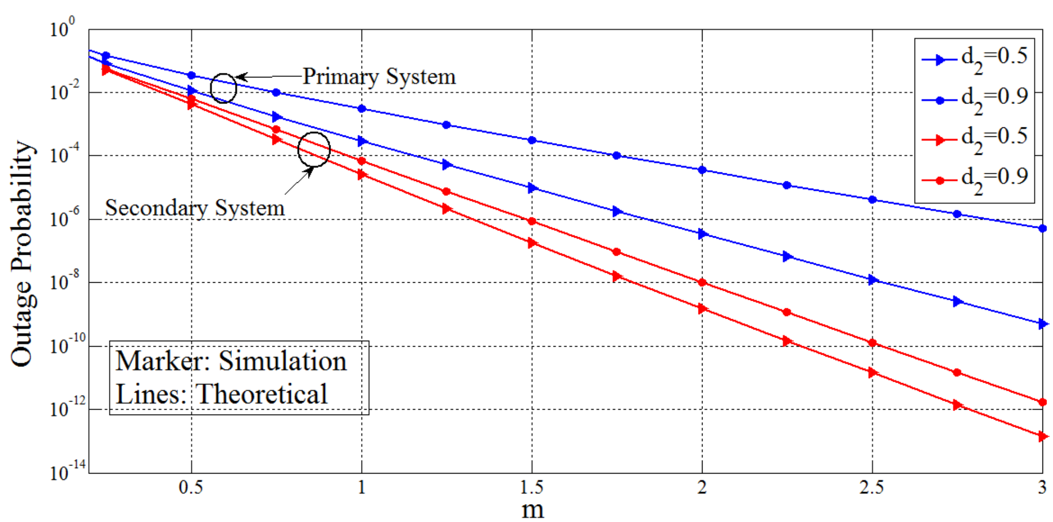

Figure 3.6: Outage Performance of Primary and Secondary System w.r.t. Fading Parameter m

Chapter 4

A Cooperative Spectrum Sharing Protocol for Cognitive Two-way AF Relaying Systems

4.1 Introduction

This chapter investigates the performance of a cooperative spectrum sharing protocol for cognitive Two-way AF relaying systems. In the proposed framework, two primary users (PUs), PU_1 and PU_2 coexist with a secondary user (SU) in the same frequency band albeit with different priorities. Primary users by virtue of having a license to operate over the frequency band have higher priority whereas secondary user has lower priority. When bi-directional communication between PU_1 and PU_2 is not possible due to link failure or deteriorating channel conditions, PUs seek the assistance of the secondary user. SU by acting as a Two-way AF relay helps in forwarding the information from PU_1 to PU_2 and vice-versa, in exchange, it is allowed to access the PU's spectrum. Our analysis shows that two-way relaying helps in improving the spectral efficiency and reducing the outage probability of primary and secondary user.

Due to the full processing requirement at the relay, the complexity of DF relaying is significantly higher than the AF relaying. In addition, DF relaying also requires sophisticated media access control layer, and it does not offer significant performance improvement if source to relay link is weak. Hence, AF relaying has been preferred on most of the recent work on cooperative relaying. For instance in [26], a cooperative AF relaying protocol is discussed wherein secondary transmits the linearly combined primary and secondary information with λ and $1-\lambda$ of the available transmit powers respectively with the help of AF relaying. Closed form expressions for the BER of both primary and secondary are derived. However, one way relaying in CSS inherently suffers from the unavoidable loss of spectral efficiency (pre-log half factor). Thus, this spectral efficiency loss due to one-way relaying can be compensated by adopting two-way relaying protocols [17, 40]. Two-way relaying has been studied extensively in non-cognitive systems, however, for cognitive scenario, its impact is yet to be investigated.

Motivated by above in this chapter, we propose a two phase two-way AF relaying protocol for CSS where the SU acts as a half-duplex relay helping the PUs to improve the overall throughput in exchange for opportunistic spectrum access (OSA). In our proposed protocol, two PUs are trying to communicate bi-directionally in the deteriorating channel conditions[1]. The total transmission is divided into two phases. In Phase I, PU_1 and PU_2 broadcasts their data to ST and SR. In phase II, ST amplifies and forwards the data of PU_1 and PU_2 along with its own data by assigning fractions α and $(1-\alpha)$ of the available power to the primary and secondary data respectively. The interference cancellation techniques are employed at PU_1, PU_2 and SR to retrieve the data of PU_2, PU_1 and ST respectively. The expressions for outage probability of primary and secondary users with varying distances between PU_1, ST, PU_2 and SR is derived.

4.2 System Model with Mathematical Analysis

Fig. 4.1 shows the system model where the links $PU_1 \rightarrow PU_2$, $PU_1 \rightarrow$ ST, $PU_1 \rightarrow$ SR, ST $\rightarrow$ SR, ST $\rightarrow PU_2$, and SR $\rightarrow PU_2$ are assumed to be Rayleigh flat fading with channel coefficients $h_1, h_2, h_3, h_4, h_5, h_6$ respectively. Here $h_i \sim \mathcal{CN}\left(0, d_i^{-v}\right)$ where i=1,2,3,4,5,6. v is the path loss exponent and d_i is the distance between the respective transmitter and receiver. All the nodes are assumed to be half duplex, and $\gamma_i = \left|h_i^2\right|$. x_{p_1}, x_{p_2} and x_s are the signals for first pri-

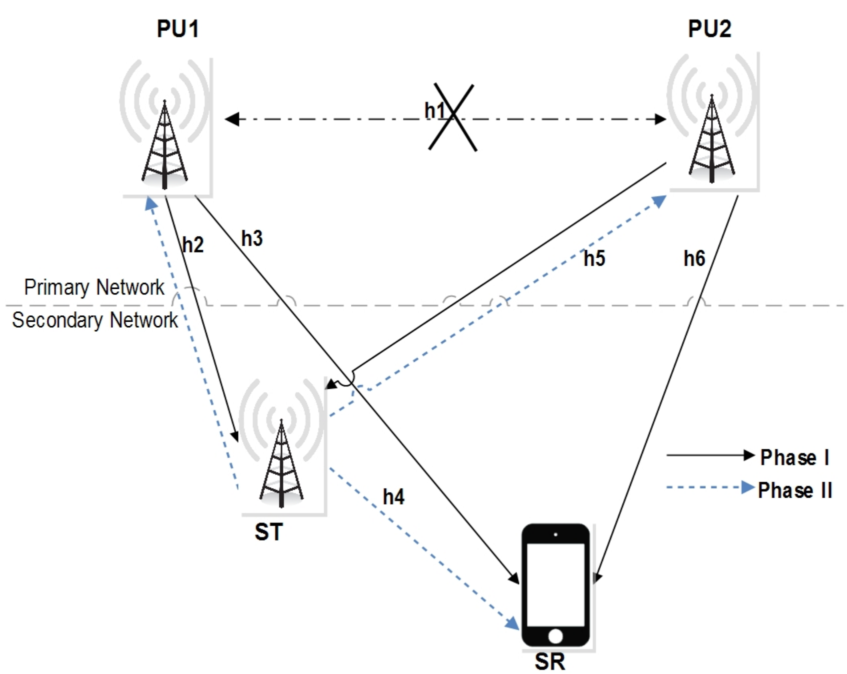

Figure 4.1: System Configuration

mary system, second primary system and secondary system respectively with zero mean and

[1]We have assumed that the direct link fails due to the adverse channel conditions between the two primary users.

$E\left\{x_{p_1}^* x_{p_1}\right\} = 1$, $E\left\{x_{p_2}^* x_{p_2}\right\} = 1$ and $E\left\{x_s^* x_s\right\} = 1$, where $*$ denotes the complex conjugate operation. P_{p_1}, P_{p_2} and P_s are the transmit power for first primary system, second primary system and secondary system respectively.
The above protocol can be described in the form of pseudo code as below,

Two phase two-way AF relaying protocol for CSS Schemes
If PU_1-PU_2 fails

1 Enters into two phase protocol.

2 Phase I: PU_1 and PU_2 broadcast x_{p_1} and x_{p_2} respectively which is received by both ST and SR.

3 Phase II: ST amplifies x_{p_1} and x_{p_2} and transmits it along with x_s with α and 1-α of the available power at ST.

4 As SR has prior knowledge of x_{p_1} and x_{p_2} from phase I so it will cancel out the interference signals x_{p_1} and x_{p_2} received in phase II.

else PU_1 will continue communication with PU_2 directly.

4.3 Outage Performance for Primary System

In phase I, PU_1 and PU_2 broadcast primary signals i.e. x_{p_1} and x_{p_2} respectively which is received by both ST and SR. Therefore, signal received at ST is given as,

$$y_{ST} = \sqrt{P_{p_1}} h_2 x_{p_1} + \sqrt{P_{p_2}} h_5 x_{p_2} + n_{12}, \tag{4.1}$$

where, $n_{ij} \sim \mathcal{CN}(0, \sigma^2)$ is the AWGN in i^{th} phase of transmission at j^{th} receiver and j=1,2,3 corresponds to PU_2, ST, SR respectively. In phase II, ST amplifies the primary signals and transmits it along with its own signal x_s, both of which are linearly combined with α and 1-α of the available power at ST. Transmit signal at ST is given as,

$$Z_s = \frac{\sqrt{\alpha P_s}}{\sqrt{P_{p_1}\gamma_2 + P_{p_2}\gamma_5 + \sigma^2}} y_{ST} + \sqrt{(1-\alpha) P_s} x_s. \tag{4.2}$$

As ST transmits the combined signal in phase II, which is received by all the nodes. Thus the signal received at PU_2 from ST is,

$$\begin{aligned} y_{PU_2} &= h_5 Z_S + n_{21}. \\ &= h_5 \frac{\sqrt{\alpha P_s}}{\sqrt{P_{p1}\gamma_2 + P_{p2}\gamma_5 + \sigma^2}} \left(\sqrt{P_{p1}} h_2 x_{p1} + \sqrt{P_{p2}} h_5 x_{p2} + n_{12}\right) + h_5 \sqrt{(1-\alpha) P_s} x_s + n_{21}. \end{aligned} \tag{4.3}$$

As x_{p_2} is already known by PU_2, thus after applying interference cancellation techniques [44], the signal received at PU_2 is given by,

$$y_{PU_2} = h_5 \frac{\sqrt{\alpha P_s}}{\sqrt{P_{p1}\gamma_2 + P_{p2}\gamma_5 + \sigma^2}} \left(\sqrt{P_{p1}} h_2 x_{p1} + n_{12}\right) + h_5 \sqrt{(1-\alpha) P_s} x_s + n_{21}. \tag{4.4}$$

The signal power at PU_2 is,

$$P_3 = \frac{\gamma_5 \alpha P_s P_{p_1} \gamma_2}{P_{p_1}\gamma_2 + P_{p_2}\gamma_5 + \sigma^2}. \tag{4.5}$$

The noise power at PU_2 is,

$$N = \frac{\gamma_5 \alpha P_s \sigma^2}{P_{p_1}\gamma_2 + P_{p_2}\gamma_5 + \sigma^2} + \gamma_5 (1-\alpha) P_s + \sigma^2. \tag{4.6}$$

Primary system outage probability occurs when,

$$P_{out}^{p} = Pr\left\{R_5 < R_{pt}\right\}. \tag{4.7}$$

where R_5 is the rate at PU_2, and R_{pt} denotes the target rate of primary system.

$$R_5 = \frac{1}{2}\log_2\left(1 + \frac{P_3}{N}\right). \tag{4.8}$$

The factor $\frac{1}{2}$ is due to the fact that the whole transmission is divided into two phases. Assuming $P_s = P_{p_1} = P_{p_2} = P$ and $P >> \sigma^2$,

$$R_5 = \frac{1}{2}\log_2\left(1 + \frac{\gamma_5 \alpha P \gamma_2}{\gamma_5 (1-\alpha) P (\gamma_2 + \gamma_5) + \sigma^2 (\gamma_2 + 2\gamma_5)}\right) \tag{4.9}$$

Solving for (4.7),

$$P_{out}^{p} = P\left\{\frac{\gamma_5 \alpha P \gamma_2}{\gamma_5 (1-\alpha) P (\gamma_2 + \gamma_5) + \sigma^2 (\gamma_2 + 2\gamma_5)} < \rho_1\right\} \tag{4.10}$$

where, $\rho_1 = 2^{2R_{pt}} - 1$.

$$P_{out}^{p} = P\left\{\alpha P - \rho_1 (1-\alpha) P < \frac{\sigma^2 \rho_1}{\gamma_5} + \frac{2\sigma^2 \rho_1}{\gamma_2} + \rho_1 (1-\alpha) P \frac{\gamma_5}{\gamma_2}\right\} \tag{4.11}$$

Thus the outage probability of the primary system is,

$$P_{out}^{p} = Pr\left\{\vartheta < \frac{\varepsilon}{\gamma_5} + \frac{2\varepsilon}{\gamma_2} + \delta\frac{\gamma_5}{\gamma_2}\right\}. \tag{4.12}$$

where, $\delta = \rho_1 (1-\alpha) P$, $\vartheta = \alpha P - \rho_1 (1-\alpha) P$, $\varepsilon = \rho_1 \sigma^2$. After simplifying (4.12), we will get,

$$P_{out}^{p} = \exp\left(\frac{-d_5^v \varepsilon}{\vartheta}\right) - d_5^v \exp\left(\frac{d_2^v \varepsilon}{\vartheta}\left(2 + \frac{\delta}{\vartheta}\right)\right)\Upsilon(\gamma_5). \tag{4.13}$$

For detailed derivation of (4.13), please refer to Appendix A.

4.4 Outage Probability of Secondary system

Assume that x_{p1}, x_{p2} are decoded at SR in phase I successfully so that interference cancellation can be done in the signal received at SR in phase II. The signal received at SR transmitted from ST, after interference cancellation in phase II can be given as,

$$y_{SR} = \frac{h_4\sqrt{\alpha P_s}}{\sqrt{P_{p1}\gamma_2 + P_{p2}\gamma_5 + \sigma^2}} n_{12} + h_4\sqrt{(1-\alpha) P_s} x_s + n_{23}. \tag{4.14}$$

If in phase I, links between PU_1-SR and PU_2-SR fail in decoding x_{p1} and x_{p2} respectively, interference cancellation at SR in phase II is not possible and hence the outage will be declared for secondary system. The outage probability for secondary system can be given as [32],

$$P_{out}^{s} = 1 - Pr\{R_3 > R_{pt}\} Pr\{R_6 > R_{pt}\} Pr\{R_4 > R_{st}\}, \tag{4.15}$$

where, R_3 and R_6 are rate achieved between PU_1-SR and PU_2-SR link respectively and R_4 is the rate at SR in phase II. R_{st} is defined as the target rate of secondary system.

$$R_3 = \frac{1}{2}\log_2\left(1 + \frac{P_{p_1}\gamma_3}{\sigma^2}\right). \tag{4.16}$$

Assuming $P_{p_1} = P_{p_2} = P_s = P$. Therefore,

$$Pr\{R_3 > R_{pt}\} = Pr\left\{\gamma_3 > \frac{\rho_1\sigma^2}{P_{p_1}}\right\} = \exp\left(-\frac{d_3^v \rho_1 \sigma^2}{P}\right). \tag{4.17}$$

Further,

$$R_6 = \frac{1}{2}\log_2\left(1 + \frac{P_{p_2}\gamma_6}{\sigma^2}\right). \tag{4.18}$$

Therefore,

$$Pr\{R_6 > R_{pt}\} = Pr\left\{\gamma_6 > \frac{\rho_1\sigma^2}{P_{p_2}}\right\} = \exp\left(-\frac{d_6^v \rho_1 \sigma^2}{P}\right). \tag{4.19}$$

Furthermore,

$$R_4 = \frac{1}{2}\log_2\left(1 + \frac{\gamma_4(1-\alpha)P_s}{\frac{\gamma_4 \alpha P_s \sigma^2}{P_{p_1}\gamma_2 + P_{p_2}\gamma_5 + \sigma^2} + \sigma^2}\right) \tag{4.20}$$

Assuming $P_{p_1} = P_{p_2} = P_s = P$ and $P >> \sigma^2$,

$$\begin{aligned} R_4 &= \frac{1}{2}\log_2\left(1 + \frac{\gamma_4(1-\alpha)P_s}{\frac{\gamma_4 \alpha P_s \sigma^2}{P_{P1}\gamma_2 + P_{P2}\gamma_5 + \sigma^2} + \sigma^2}\right) \\ &= \frac{1}{2}\log_2\left(1 + \frac{\gamma_4(1-\alpha)P\left(P\gamma_2 + P\gamma_5 + \sigma^2\right)}{\gamma_4\alpha P\sigma^2 + \sigma^2\left(P\gamma_2 + P\gamma_5 + \sigma^2\right)}\right) \\ &= \frac{1}{2}\log_2\left(1 + \frac{\gamma_4(1-\alpha)\left(P\gamma_2 + P\gamma_5 + \sigma^2\right)}{\gamma_4\alpha\sigma^2 + \gamma_2\sigma^2 + \gamma_5\sigma^2}\right) \end{aligned} \tag{4.21}$$

Therefore,

$$Pr\left\{R_4 < R_{st}\right\} = Pr\left\{\frac{\gamma_4(1-\alpha)\left(P\gamma_2 + P\gamma_5 + \sigma^2\right)}{\gamma_4\alpha\sigma^2 + \gamma_2\sigma^2 + \gamma_5\sigma^2} < \rho_s\right\}. \tag{4.22}$$

where, $\rho_s = 2^{2R_{st}} - 1$. After solving (4.22) we have,

$$P\left\{R_4 < R_{st}\right\} = \frac{d_5^v\left(\exp\left(-d_5^v\varsigma\right) - \exp\left(-d_2^v\varsigma\right)\right)}{d_2^v - d_5^v} - d_2^v d_5^v \Gamma\left(\gamma_2, \gamma_5\right). \tag{4.23}$$

where, $\varsigma = \frac{\varphi\alpha - \sigma^2}{P}$, $\Gamma\left(\gamma_2, \gamma_5\right) = \int_0^{\varsigma}\int_{\varsigma-\gamma_5}^{\infty} e^{-\frac{d_4^v\varphi(\gamma_2+\gamma_5)}{P\gamma_2+P\gamma_5+\sigma^2-\varphi\alpha}}$ $e^{-d_2^v\gamma_2}e^{-d_5^v\gamma_5}d\gamma_2 d\gamma_5$. For detailed derivation of (4.23), please refer to Appendix B. After substituting (4.17), (4.19) and (4.23) in (4.15), we have,

$$\begin{aligned} P_{out}^s =& 1 - \exp\left(-\frac{d_3^v\rho_1\sigma^2}{P}\right)\exp\left(-\frac{d_6^v\rho_1\sigma^2}{P}\right) + \exp\left(-\frac{d_3^v\rho_1\sigma^2}{P}\right)\exp\left(-\frac{d_6^v\rho_1\sigma^2}{P}\right) \\ & \left[\frac{\exp^{\left(-d_5^v\varsigma\right)} - \exp^{\left(-d_2^v\varsigma\right)}}{d_2^v - d_5^v} - d_2^v d_5^v \Gamma\left(\gamma_2, \gamma_5\right)\right]. \end{aligned} \tag{4.24}$$

4.5 Simulation results and discussion

In this section the simulation results for the proposed protocol has been presented. The graphs of the primary and secondary systems are plotted for the outage probability with respect to the power allocation factor (α). PU_1, PU_2, ST, SR nodes are assumed to be collinear [32], [33]. As shown in Fig. 4.2 the distance between PU_1 and PU_2 is fixed at $d_1 = 500m$. The distances between the remaining nodes is represented in terms of distance between PU_1 and ST (i.e. d_2), the distance between PU_1 to SR and ST to SR node is $d_3 = d_4 = d_2/2$ respectively. Further, the distance between PU_2 and ST is $d_5 = 500 - d_2$ and PU_2 to SR is $d_6 = 500 - d_2/2$. The graphs for the outage probability for primary and secondary system are plotted for different values of

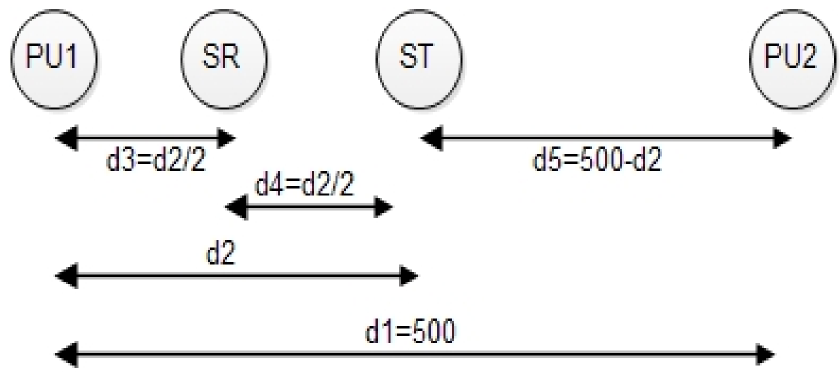

Figure 4.2: Distances between Nodes

d_2. The path loss exponent (v) is chosen to be 3. The power of both primary and secondary system is 10 dBm and the noise variance is assumed to be -100 dBm at all receivers. The target rate, R_{pt} and R_{st} is equal to 1 bits/sec/Hz. Fig. 4.3 presents the outage performance of the

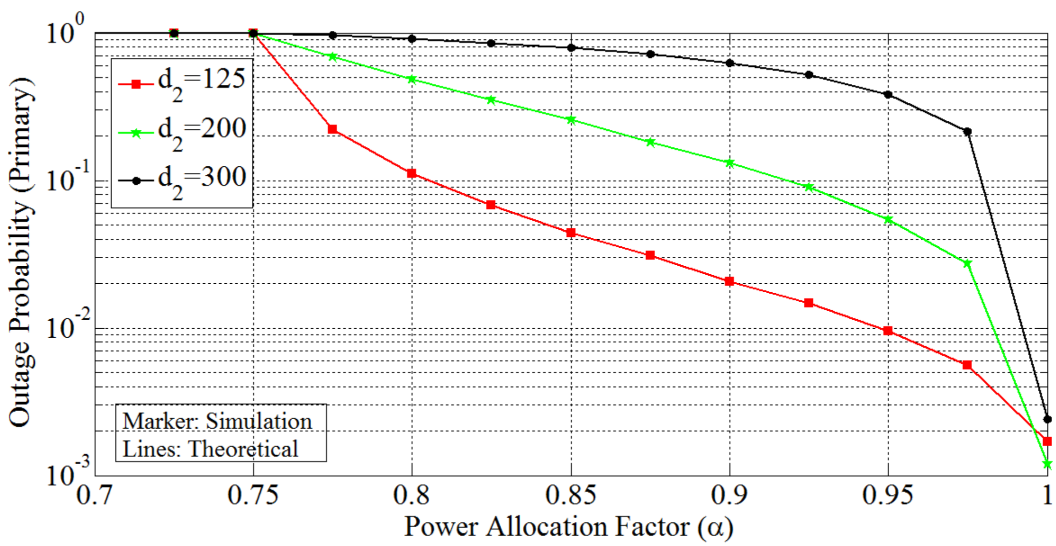

Figure 4.3: Outage Performance of Primary System

primary system with respect to the power allocation factor α for different values of d_2. From Fig. 4.3, it is quite obvious that as α increases, the outage probability of the primary system decreases. The reason can be explained as follows. With an increase in α, more power of ST is being allocated for relaying the primary signal and less power is allocated for the transmission of secondary signal (acting as an interference for the primary signal reception). Thus the outage probability of the primary transmission decreases with increase in α which leads to performance improvement.

Further, it is also visible from the Fig. 4.3 that as the distance between PU_1 and ST (d_2) increases the outage probability increases. It is due to the fact that with increasing d_2, the distance between the ST and PU_2 decreases, which leads to more interference in the signal received at ST in phase I. Thus with increasing d_2, the outage probability increases due to the enhancement in the interference levels in the signal received at SR.

Fig. 4.4 shows the outage probability of the secondary system with respect to α for various d_2. The figure depicts that as α increases, the outage probability also increases. This is because as α increases more power is allocated for the primary's signal transmission and less power is allocated for the relaying of secondary's signal which leads to an increase in the outage probability of secondary system.

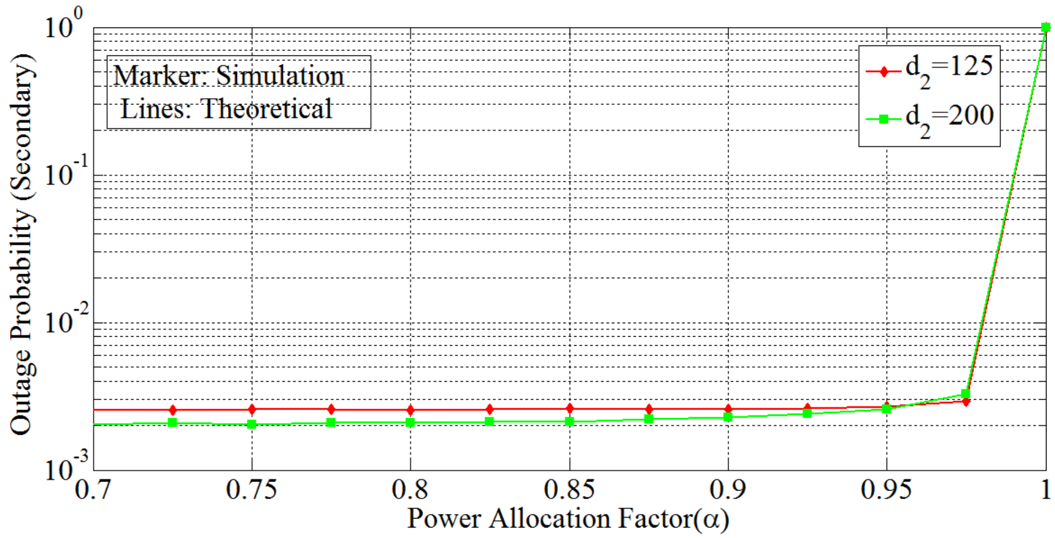

Figure 4.4: Outage Performance of Secondary System

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Cognitive radio is a promising technology to solve the problem of spectrum scarcity. Cooperative spectrum sharing scheme is an alternative framework to realize a cognitive radio network. Thus, the spectral efficiency and spectrum utilization have improved because of the emerging technologies like cooperative relaying, cognitive radio and cooperative spectrum sharing. But conventional CSS schemes have many existing issues, few of them are resolved in this thesis. The research work done in the thesis can be categorized into four parts.

In the first part, conventional CSS schemes and various wireless terminologies like diversity and combining techniques, spectrum sharing schemes, fading channels and different types of relays have been discussed.

In the second part, a two phase adaptive cooperative relaying protocol for cooperative cognitive radios has been proposed. It has been shown that using adaptive modulation at ST, significant performance gains can be obtained for the primary and secondary system. Furthermore, the BER performance of the primary system with BER-SC has also been analyzed. From the BER-SC analysis, the value of modulation size is selected which gives minimum BER for a given distance between PT-ST (d_2). The plots for outage probability for corresponding d_2 and M are plotted. For both the primary and secondary systems the outage performance improves with higher M (increased data rate). Further, for a fixed value of d_2 and M, as α increases, more and more power is being allocated to the primary signal and thus the outage probability of primary and secondary system decreases and increases, respectively.

In the third part, a three phase two-way CSS protocol in the presence of Nakagami-m fading has been proposed. The proposed technique utilizes two-way CSS protocol which shows that the primary network can achieve the desired QoS in exchange for allowing spectrum access to the secondary system. Furthermore, it was shown that even in the presence of severe fading ($m < 1$), two-way CSS protocol provides significant performance gains for primary users as compared to direct transmission. In addition to the above, it was also demonstrated that two-way relaying with CSS improves the spectral efficiency as compared to conventional CSS relaying.

In the fourth part, a new protocol for cooperative spectrum sharing scheme has been analyzed for cognitive Two-way AF relaying protocol. A cognitive ST "disguised" as a relay amplifies and forwards the data of PU_1 and PU_2, along with its own data to PU_1, PU_2 and SR thus, getting the spectrum access in exchange. It was also demonstrated that two-way relaying with CSS improves the spectral efficiency as compared to conventional one-way relaying protocol. Furthermore, two-way CSS protocol provides significant performance gains for primary and secondary systems.

The agreement between the simulations and the analytically obtained expressions validate the theoretical analysis presented in the thesis.

5.2 Future work

- The work can be extended for relay selection techniques in adaptive modulation environment in which out of all the existing relays, the best relay will be selected to transmit the data adaptively to the destination.
- In the proposed work (in chapter 3 and 4), the secondary user is equipped with a single antenna. Thus, the future work can be a scenario where the work of two-way relaying can be extended to multiple antennas at the secondary transmitter. This will help to achieve diversity and to improve the performance of both the primary and secondary systems.

Appendix

Appendix A

Expression for the outage probability of the primary system, from (4.12) we have,

$$\begin{aligned} P_{out}^{p} =& Pr\left\{\frac{\varepsilon}{\gamma_5} + \frac{2\varepsilon}{\gamma_2} + \delta\frac{\gamma_5}{\gamma_2} > \vartheta\right\}. \\ =& Pr\left\{\frac{2\varepsilon + \delta\gamma_5}{\gamma_2} > \vartheta - \frac{\varepsilon}{\gamma_5}\right\}. \\ =& Pr\left\{\gamma_2 < \frac{2\varepsilon + \delta\gamma_5}{\vartheta - \frac{\varepsilon}{\gamma_5}}\right\}. \end{aligned} \tag{5.1}$$

As $\gamma_2 \sim exp()$ thus the quantity $\frac{2\varepsilon+\delta\gamma_5}{\vartheta-\frac{\varepsilon}{\gamma_5}}$ needs to be always positive and further $2\varepsilon + \delta\gamma_5$ is a positive value. Therefore, we have $\gamma_5 > \varepsilon/\vartheta$. Thus the expression for the outage probability of the primary system is,

$$\begin{aligned} P_{out} &= \int_{\frac{\varepsilon}{\vartheta}}^{\infty} \int_{0}^{\frac{2a+b\gamma_5}{c-\frac{a}{\gamma_5}}} d_2^v \exp\left(-d_2^v\gamma_2\right) d_5^v \exp\left(-d_5^v\gamma_5\right) d\gamma_2 d\gamma_5 \\ &= \int_{\frac{\varepsilon}{\vartheta}}^{\infty} \left(1 - \exp\left(-d_2^v \frac{2a + b\gamma_5}{c - \frac{a}{\gamma_5}}\right)\right) d_5^v \exp\left(-d_5^v\gamma_5\right) d\gamma_5 \\ &= \int_{\frac{\varepsilon}{\vartheta}}^{\infty} d_5^v \exp\left(-d_5^v\gamma_5\right) d\gamma_5 - d_5^v \int_{\frac{\varepsilon}{\vartheta}}^{\infty} \exp\left(-d_2^v \frac{2a + b\gamma_5}{c - \frac{a}{\gamma_5}} - d_5^v\gamma_5\right) d\gamma_5. \end{aligned} \tag{5.2}$$

After simplifying (5.2) we will get,

$$\begin{aligned} P_{out} &= \exp\left(\frac{-d_5^v\varepsilon}{\vartheta}\right) - d_5^v \int_{\frac{\varepsilon}{\vartheta}}^{\infty} \exp\left(\frac{\left(-d_2^v\delta - d_5^v\vartheta\right)\gamma_5^2 + \left(d_5^v\varepsilon - d_2^v 2\varepsilon\right)\gamma_5}{\vartheta\gamma_5 - \varepsilon}\right) d\gamma_5 \\ &= \exp\left(\frac{-d_5^v\varepsilon}{\vartheta}\right) - d_5^v \int_{\frac{\varepsilon}{\vartheta}}^{\infty} \exp\left(\lambda\gamma_5 + \frac{d_2^v\varepsilon}{\vartheta}\left(2 + \frac{\delta}{\vartheta}\right) + \frac{\phi}{\vartheta\gamma_5 - \varepsilon}\right) d\gamma_5 \end{aligned} \tag{5.3}$$

where, $\lambda = -\frac{d_2^v\delta+d_5^v\vartheta}{\vartheta}$ and $\phi = -\frac{d_2^v\varepsilon^2}{\vartheta}(2 + \frac{\delta}{\vartheta})$. The final expression for the outage performance of the primary system is,

$$P_{out}^{p} = \exp\left(\frac{-d_5^v \varepsilon}{\vartheta}\right) - d_5^v \exp\left(\frac{d_2^v \varepsilon}{\vartheta}\left(2 + \frac{\delta}{\vartheta}\right)\right) \Upsilon\left(\gamma_5\right), \tag{5.4}$$

where, $\Upsilon\left(\gamma_5\right) = \int_{\frac{\varepsilon}{\vartheta}}^{\infty} \exp(\lambda\gamma_5 + \frac{\phi}{\vartheta\gamma_5 - \varepsilon})d\gamma_5$.

Appendix B

Solving for (4.22) where R_4 is the rate between ST-SR link, we have,

$$\begin{aligned} Pr\left\{R_4 < R_{st}\right\} &= Pr\left\{\frac{\gamma_4\left(1-\alpha\right)\left(P\gamma_2 + P\gamma_5 + \sigma^2\right)}{\gamma_4\alpha\sigma^2 + \gamma_2\sigma^2 + \gamma_5\sigma^2} < \rho_s\right\} \\ &= Pr\left\{\gamma_4 < \frac{\varphi\left(\gamma_2 + \gamma_5\right)}{P\gamma_2 + P\gamma_5 + \sigma^2 - \varphi\alpha}\right\}, \end{aligned} \tag{5.5}$$

where, $\varphi = \frac{\rho_s \sigma^2}{1-\alpha}$. Now as the term $\varphi\left(\gamma_2 + \gamma_5\right)$ is always positive thus from that we have, $\gamma_2 > \varsigma - \gamma_5$ where, $\varsigma = \frac{\varphi\alpha - \sigma^2}{P}$ and $\gamma_5 < \varsigma$. After solving (5.5) we have,

$$\begin{aligned} P\left\{R_4 < R_{st}\right\} &= \int_0^{\varsigma}\int_{\varsigma-\gamma_5}^{\infty}\int_0^{\frac{\varphi(\gamma_2+\gamma_5)}{P\gamma_2+P\gamma_5+\sigma^2-\varphi\alpha}} d_4^v e^{-d_4^v\gamma_4} d_2^v e^{-d_2^v\gamma_2} d_5^v e^{-d_5^v\gamma_5} d\gamma_4 d\gamma_2 d\gamma_5 \\ &= \int_0^{\varsigma}\int_{\varsigma-\gamma_5}^{\infty}\left(1 - e^{-\frac{d_4^v\varphi(\gamma_2+\gamma_5)}{P\gamma_2+P\gamma_5+\sigma^2-\varphi\alpha}}\right) d_2^v e^{-d_2^v\gamma_2} d_5^v e^{-d_5^v\gamma_5} d\gamma_2 d\gamma_5 \\ &= \int_0^{\varsigma}\int_{\varsigma-\gamma_5}^{\infty} d_2^v e^{-d_2^v\gamma_2} d_5^v e^{-d_5^v\gamma_5} d\gamma_2 d\gamma_5 \\ &\quad - d_2^v d_5^v \int_0^{\varsigma}\int_{\varsigma-\gamma_5}^{\infty} e^{-\frac{d_4^v\varphi(\gamma_2+\gamma_5)}{P\gamma_2+P\gamma_5+\sigma^2-\varphi\alpha}} e^{-d_2^v\gamma_2} e^{-d_5^v\gamma_5} d\gamma_2 d\gamma_5 \\ &= d_5^v e^{-d_2^v\varsigma}\int_0^{\varsigma} e^{\left(d_2^v - d_5^v\right)\gamma_5} d\gamma_5 - d_2^v d_5^v \Gamma\left(\gamma_2, \gamma_5\right), \end{aligned} \tag{5.6}$$

where $\Gamma\left(\gamma_2, \gamma_5\right) = \int_0^{\varsigma}\int_{\varsigma-\gamma_5}^{\infty} e^{-\frac{d_4^v\varphi(\gamma_2+\gamma_5)}{P\gamma_2+P\gamma_5+\sigma^2-\varphi\alpha}} e^{-d_2^v\gamma_2} e^{-d_5^v\gamma_5} d\gamma_2 d\gamma_5$. After solving (5.6) further we have,

$$Pr\left\{R_4 < R_{st}\right\} = \frac{d_5^v\left(\exp\left(-d_5^v\varsigma\right) - \exp\left(-d_2^v\varsigma\right)\right)}{d_2^v - d_5^v} - d_2^v d_5^v \Gamma\left(\gamma_2, \gamma_5\right).$$

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