Interference Cancellation and Energy Harvesting Techniques for Cooperative Spectrum Sharing Cognitive Radio Systems

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Certificate

This is to certify that the thesis titled **"Interference Cancellation and Energy Harvesting Techniques for Cooperative Spectrum Sharing Cognitive Radio Systems"** submitted by **Neha Jain** 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. This work has not been submitted anywhere else for the reward of any other degree.

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Abstract

With the exponential increase in wireless applications, there arises the need to utilize the spectrum more efficiently. Cooperative spectrum sharing (CSS) schemes have been proposed as a viable framework for cognitive radio where, an unlicensed (secondary) user can access the spectrum of licensed (primary) user, on the condition that unlicensed user will help the licensed user in achieving the target rate of communication. While sharing the spectrum, primary user always has higher priority.

In the proposed work, a two phase CSS scheme is proposed, where secondary's transmitter equipped with multiple antennas uses transmit antenna selection to improve the primary's performance by reducing the interference level of secondary signal at primary receiver. Moreover, a three phase interference cancellation CSS scheme using STBC (Space time block code) is also proposed. It has been shown that the proposed scheme helps in achieving diversity gain of three and two for primary and secondary system respectively.

Apart from above, we have also proposed a novel approach to solve the power issues in secondary user by utilizing technique such as RF (radio frequency) energy harvesting. Specifically, we have shown that significant performance gains can be obtained for both primary and secondary user by using RF energy harvesting.

Acknowledgments

Towards the end of my Master degree, I would like to pay my heartily gratitude to several individuals who contributed in many ways. First of all, I would like to express my deep gratitude to my thesis supervisor, Dr. Vivek Ashok Bohara for their support, guidance and motivation all along the way. I feel extremely fortunate to work with him. He has been great sources of inspiration to me and I thank him from the bottom of my heart. I would like to thank Dr. Pankaj Jalote and all my professors at IIITD for providing such a wonderful environment to work. I would like to express my gratitude towards my family for their kind co-operation and encouragement which give me a source of motivation. Last but not the least, I want to thank my friends for all thoughtful discussions we had, which prompted me to think beyond the obvious.

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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
CCTH	cooperative clear-to-help
CCTS	cooperative clear-to-send
CR	cognitive radio
CRTS	cooperative right to send
CSI	channel state information
CBS	central base station
CSS	Cooperative spectrum sharing
DF	decode and forward
EH	energy harvesting
FCC	Federal Communication Commission
LOS	line-of-sight
MRC	Maximum ratio combining
PT	primary transmitter
PR	primary receiver
PU	primary user
QoS	Quality of service
RF	radio frequency
R_{pt}	primary user's target rate
R_{st}	secondary user's target rate
SNR	signal to noise ratio
ST	secondary transmitter
SR	secondary receiver
STBC	space time block code
SU	secondary user
TAS	transmit antenna selection
WSN	Wireless sensor network
x_p	primary signal
x_s	secondary signal

Chapter 1

Introduction

1.1 Motivation and objective

Radio frequency (RF) spectrum, considered as the most limited resource for wireless communications, has been congested due to its diversified use. Most of the radio spectrum (3kHz to 300GHz) has already been allocated under the licensed band and is no longer available for new wireless systems [3]. Licensing the spectrum avoids the interference between the users. But recent studies have suggested that, the licensed spectrum is either unutilized or underutilized [3,4]. As a result of this inefficient spectrum utilization, researchers over the years have proposed alternative spectrum access techniques to improve spectral efficiency and capacity in radio communication, giving birth to "cognitive radios" (CR) [5–7]. Conceptually, in CR, an unlicensed user (also known as cognitive user) is allowed to coexist in licensed band of primary user.

Various spectrum sharing schemes can be classified in three forms:

- **Spectrum interweave/Interference avoidance**: In this scheme [8]- [9], spectrum access by the secondary user (SU) is only allowed when the radio spectrum allocated to the primary user (PU) is determined to be unused. This unused spectrum is known as "spec-

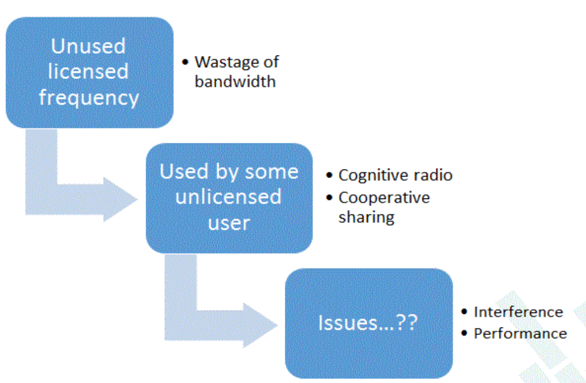

Figure 1.1: Motivation

trum holes” or “white spaces”. This scheme is also called detect and avoid cognitive radio schemes. 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**: Beside the interweave technique, in underlay cooperative spectrum sharing scheme, secondary user is allowed to transmit simultaneously in the primary user's frequency band with a constraint that the interference at the PU due to SU is below a designated threshold level [10, 11].

- **Interference mitigation/Overlay schemes**: In this scheme 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. This non-causal information of the PU helps the SU to mitigate the interference at the primary user's receiver due to secondary transmission [12, 13].

In this thesis, an overlay cooperative spectrum sharing scheme (CSS) is discussed in which, both primary and cognitive (secondary) user are allowed to coexist in the same frequency band with the assurance that secondary user will improve the performance of primary user. Moreover, while sharing the spectrum, primary user (PU) always has higher priority. In this architecture, primary and secondary system consists of transmitter receiver pair known as primary transmitter (PT) - primary receiver (PR) and secondary transmitter (ST) - secondary receiver (SR) respectively.

In the conventional CSS schemes [14, 15], whenever the instantaneous transmission rate of PU drops below the target rate, it seeks cooperation from the neighbouring terminals which may help it in achieving the target rate of communication, in exchange of it PU allows SU for opportunistic spectrum access. The whole system is divided into two phases as shown in Fig. 1.2. In phase I, Primary Transmitter (PT) broadcasts its data (represented as x_p) which is received by Primary Receiver (PR), Secondary Transmitter (ST) and Secondary Receiver (SR). After successful decoding, ST forwards the data received in phase I along with its own data (represented as x_s) to PR and SR. The data received at PR in transmission phases 1 and 2 is decoded using MRC, considering secondary data (i.e. x_s) as noise. At SR, after successful decoding of primary data in transmission phase 1, the interference component (primary's data) is cancelled out in transmission phase 2 to obtain the desired secondary data.

Although conventional CSS scheme helps the SU to access the PU spectrum but there are many issues in the conventional scheme which are mentioned below:

- These schemes are limited by interference at the PR due to ST's data.

- Moreover, the performance of SU depends on the successful decoding of PT's data by SR in the first transmission phase.

- Consequently, there is no diversity gain for secondary user.

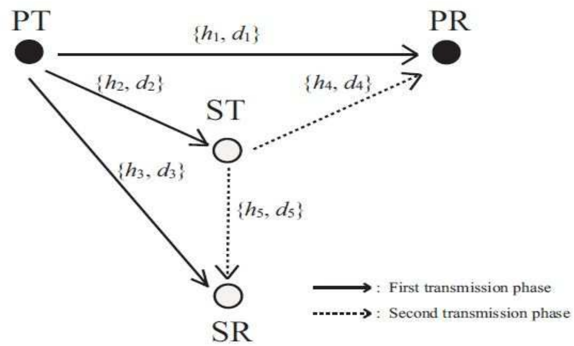

Figure 1.2: Conventional Scheme

- Providing some external battery mechanism at ST is also not possible in all scenario.

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

- To develop a new CSS protocol which can resolve interference problem at PR, power issues at secondary transmitter etc. with increment in performance of both the systems.
- 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.

Throughout this thesis, any complex Gaussian random variable (RV) say Z with mean μ and variance σ^2 is denoted as $Z \sim \mathcal{CN}(\mu, \sigma^2)$. An exponentially distributed RV say X with mean $\frac{1}{\lambda}$ is denoted as $X \sim \varepsilon(\lambda)$. A Gamma distributed RV say G with shape parameter k and scale parameter θ is defined as $G \sim Gamma(k, \theta)$. $\sim$ is used to indicate "has the distribution of" and i.i.d is used to represent independent and identically distributed. The transpose of a matrix A is denoted by A^T. $f_X(x)$ symbolizes the probability density function (PDF) of RV X and $f_{X,Y}(x, y)$ symbolizes the joint PDF of RVs X and Y. Moreover, $F_X(x)$ symbolizes the cumulative distribution function (CDF) of RV X and $F_{X,Y}(x, y)$ symbolizes the joint CDF of RVs X and Y.

1.2 Contribution

We have proposed a transmit antenna selection based CSS scheme with multiple antennas at ST node which helps in reducing the interference at PR due to secondary's signal [16].

- Neha Jain, Shubha Sharma, Ankush Vashistha, Vivek Ashok Bohara and Naveen Gupta, "Cooperative Spectrum Sharing using Transmit Antenna Selection for Cognitive Radio Systems" accepted in *Crowncom, Cognitive Radio for 5G network 2015.*

We have proposed a three phase CSS protocol using STBC code which provides high diversity gain as well as complete interference cancellation at both primary and secondary receiver

- Neha Jain, Ankush Vashistha and Vivek Ashok Bohara, "BER and outage analysis of an interference cancellation technique for cooperative spectrum sharing cognitive radio systems", submitted to *IET communication journal 2015.*

To solve the power and spectrum issues in wireless sensor network (WSN), we have proposed a CSS scheme where, WSN will act as SU and will harvest both spectrum and energy from primary transmission and simultaneously helps PU also to achieve the target rate of communication

- Neha Jain and Vivek Ashok Bohara, "Energy Harvesting and Spectrum Sharing Protocol for Wireless Sensor Networks", submitted to *IEEE Wireless communication letter, 2015.*

1.3 Terminologies

1.3.1 Fading channels

In this thesis, we have considered below mentioned fading channel:

- **Rayleigh fading** is used to simulate the rapid amplitude fluctuations where there is no direct ray component. Because of no Line of sight (LOS) component, it is often classified as the worst case fading type. Using a one ray model, this small scale distribution simulates the effects of rapid amplitude fluctuations when the receiver travels a distance of a few wavelengths. The one ray is scattered near the receiver resulting in a large number of rays arriving at the receiver from all directions. The signals add in and out of phase giving rise to amplitude fluctuations that vary at a rate that is dependent on the speed of the receiver. The statistical model used to describe the amplitude variations is the Rayleigh probability distribution function. Moreover, when there is dominant LOS component, Rayleigh fading becomes **Ricean fading**.

- **Nakagami fading**: Most of the experimental work has been done in Rayleigh fading channel but Nakagami fading is more accurate distribution for modelling the long distance fading effects which generally encounter in case of mobile communication. In [17] also, author shown that in urban multipath channel, Nakagami fading distribution is more preferred. Moreover, by changing the shape parameter (m) of Nakagami distribution various fading channel conditions can be obtained like for m=1 Nakagami fading converges into Rayleigh fading and m=0.5 into one side Gaussian fading [18].

1.3.2 Diversity and combining techniques

As in wireless communication systems, fading channel present between transmitter and receiver cause signal attenuation which can cause incorrect decoding of the signal at the transmitter. To overcome this problem, various diversity and combining techniques come in the picture.

Diversity

The three important features of fading channels i.e. time correlation, frequency correlation and space correlation, give birth to notation called diversity. Conceptually, diversity scheme provides two or more inputs at the receiver such that the fading phenomena among these inputs are uncorrelated. If one radio path undergoes deep fade at a particular point, another independent (or at least highly uncorrelated) path may have a strong signal at that input. Therefore, it increases the probability of correctly decoding a signal at receiver. For example, if probability of a deep fade in one channel is p, then the probability for N channels is p^N. The three main diversity schemes are explained as below:

- **Spatial Diversity**: The different diversity branches are spatially distributed and hence have different channel characteristics. This can be done by providing large antenna spacing.
- **Temporal Diversity**: Here diversity branches are uncorrelated on the basis of time selective property of channel.
- **Spectral Diversity**: Here diversity branches are uncorrelated on the basis of frequency selective property of channel.

Combining

After getting multiple uncorrelated replicas of a same signal we can combine it by following ways:

- **Selection Combining (SC)**: Select the strongest signal (signal having maximum SNR) as shown in Fig. 1.3(a).
- **Maximum Ratio Combining (MRC)**: Weight branches for maximum SNR as shown in Fig. 1.3(b).
- **Equal gain combining (EGC)**: Coherently combining of all the branches with equal gain as shown in Fig. 1.3(c).

1.3.3 Relay

As already discussed above, the ST node has relaying functionality that's why its able to relay the data of primary user. Depending on how the relay forwards the source information to the destination, relay can be classified mainly as [19]:

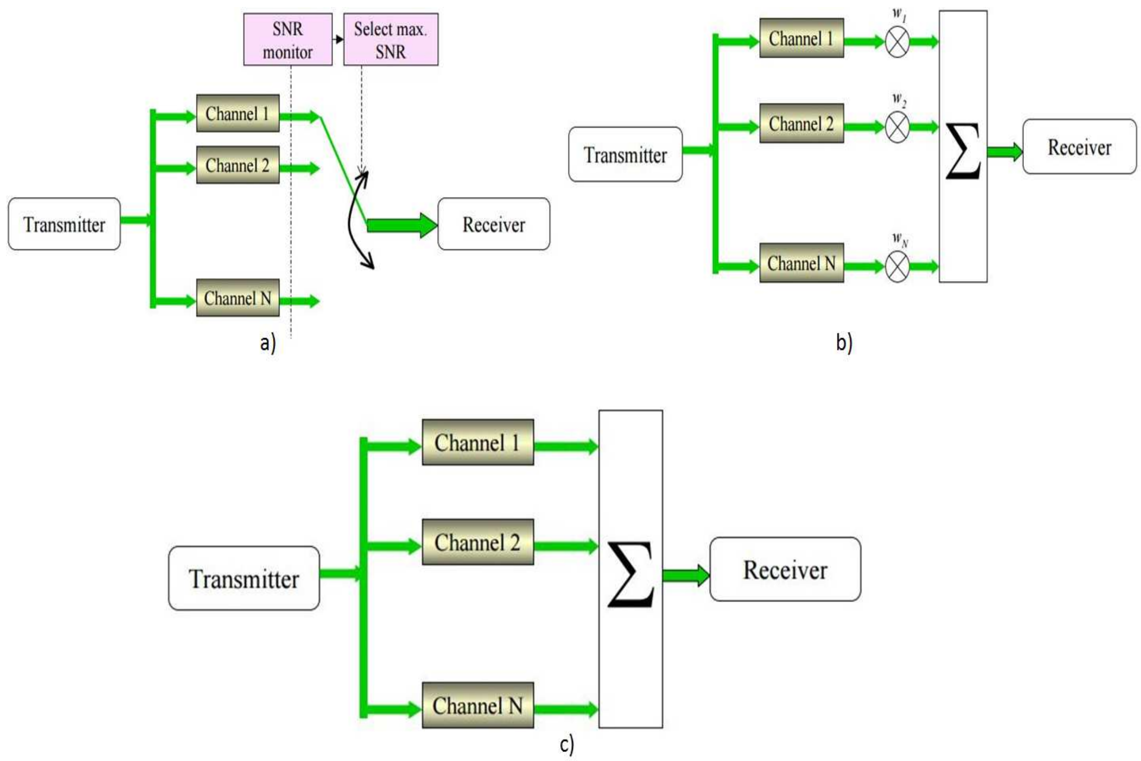

Figure 1.3: a) Selection Combining b) Maximum Ratio Combining c) Equal Gain Combining

- **Amplify and forward (AF) relay**: In AF, relay just amplifies and retransmits the source data to destination. It is very easy to implement. As there is no error correction facility in relay, the error from source to relay channel propagates to the destination
- **Decode and forward (DF) relay**: In DF, relay decodes and forwards the source data to the destination therefore due to regeneration of source's signal at relay, there is no error propagation to destination from the source-relay channel. However, this increases the complexity at relay node.

1.4 Outline

The remaining thesis is organised as below:

Chapter 2 deals with Proposed scheme 1 where, multiple antennas are used at ST. As already discussed above in conventional CSS scheme [14,15] interference is present at PR due to presence of SU's signal. So in the proposed scheme, by using transmit antenna selection, the level of interference at PR due to x_s get reduced. Closed form expression has been derived. We have also shown both analytical and simulated results in this chapter. The results are compared with pre-defined CSS schemes those are using multiple antennas at ST.

Chapter 3 deals with proposed scheme 2. Here a three phase interference cancellation scheme is defined by using Alamouti code with both analytical and simulated results. Closed form expressions are also provided. Moreover, a good comparison with conventional interference cancellation CSS scheme is also shown in simulation results.

Chapter 4 deals with proposed scheme 3. In case, when SU is some system (may be wireless sensor system) where multiple antennas can't be provided. Even providing external battery mechanism is also not possible. In such scenario SU neither able to help PU nor itself. Therefore in this chapter both energy and spectrum harvesting scheme from primary transmission is proposed. The closed form expression is also provided along with simulated results.

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

Chapter 2

CSS using Transmit Antenna Selection for CR Systems

2.1 Introduction

As already discussed, this scheme is proposed to decrease the interference at PR caused due to presence of secondary signal. Here we have used multiple antennas at ST node. Most of the CSS schemes have been confined to single antenna system. Recently, some work has also been proposed where multiple antenna CR system have been used to enhance the performance of both systems [20]- [1]. The authors in [20] proposed a scheme with multiple antennas at ST node which utilizes zero-forcing precoding technique in order to cancel the interference at PR caused due to presence of cognitive system. But the application of this precoding technique requires perfect transmit channel state information (CSI) at ST. Assuming that perfect transmit CSI is available at ST may not be practically feasible in the case of fading environment. Moreover, in [20], as ST is working as an amplify and forward relay, therefore while forwarding the data from PT to PR, it will amplify both the required signal as well as noise received from PT. In [1], authors have proposed a CSS scheme in which ST is equipped with two antennas. Both the antennas receive primary's data which is decoded at ST and then forward this data by selecting one of the two antennas randomly. This will improve the performance of primary system when compared to conventional CSS scheme because of increase in probability of successful decoding of primary's data. However it still suffers from the drawback on the amount of interference at PR due to presence of secondary system which is same as conventional CSS system.

In this chapter, we have proposed a transmit antenna selection [21] based scheme with multiple antennas at ST node which can alleviate the drawbacks of [14]- [15], [1]. Moreover, unlike [20], proposed scheme does not require perfect CSI, it just requires partial CSI feedback to select the best among the set of antennas at ST (that maximizes the post processing SNR at PR). This reduces the transmitter complexity and lowers the feedback bandwidth while preserving the gains from diversity [22]- [23]. In the proposed scheme, once primary and secondary system

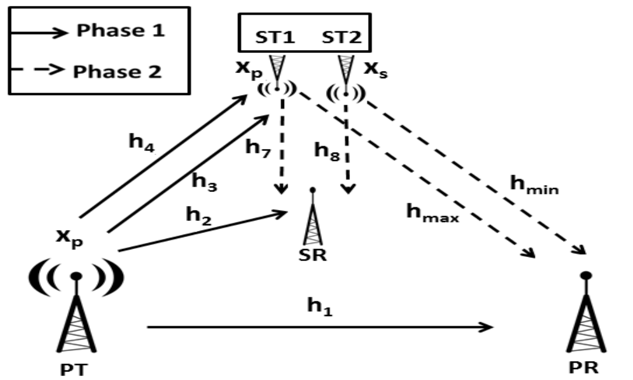

Figure 2.1: Transmission Phases

enter into CSS, PT broadcasts its data in half of the overall time slot (represented as phase 1) which is received by all the present nodes i.e. PR, ST and SR. After receiving primary's data ST will try to decode it. In the remaining half of the time slot (phase 2), ST chooses the antenna having larger instantaneous gain between ST and PR for primary's data transmission and secondary's data is transmitted via other antenna which has comparatively lower gain as shown in Fig. 2.1. Finally, the data received in both the phases, is decoded using maximum rate combining (MRC) at PR. However, if ST fails to decode primary's data, it will remain silent in phase 2. This technique is advantageous in two ways; first, we can improve the performance of primary system by reducing the interference caused due to secondary's data at PR. Second, the performance of secondary system is unaffected because of interference cancellation at SR. Moreover, when ST works as a pure relay and transfer only primary's data, in such a scenario, ST can also be seen as a selection combiner [24]. Consequently, PR will receive its signal from a selection combiner and a direct link (PT-PR).

2.2 Model Description with Performance Analysis

2.2.1 System Model

The primary and secondary system consists of transmitter receiver pair known as PT-PR and ST-SR respectively. We have considered multiple antennas at ST, named as ST1 and ST2. [1] Channels between the links are modeled as Rayleigh flat fading channels and the channel coefficients between PT-PR, PT-SR, PT-ST(1), PT-ST(2), ST(1)-PR, ST(2)-PR, ST(1)-SR, ST(2)-SR is $h_1, h_2, h_3, h_4, h_5,\ h_6, h_7, h_8$ respectively. Here, $h_i \sim \mathcal{CN}(0, d_i^{-v})$ where, v is the path loss component and d_i is the normalized distance between the corresponding link. The normalization is done with respect to the distance between PT-PR link therefore, $d_1 = 1$. The instantaneous gain of each channel is given as $\gamma_i = |h_i|^2$ where, $\gamma_i \sim \varepsilon(d_i^v)$.

[1]For ease of analysis, we have assumed that ST is equipped with two antennas, however the results obtained can be easily extrapolated to scenarios where ST is equipped with multiple (>2) antennas.

2.2.2 System Equations

In transmission phase 1, PT broadcasts primary signal i.e. x_p which is received by all the nodes. Therefore, signal received at PR is given as

$$y_{PR}^{(1)} = \sqrt{P_p} x_p h_1 + n_{11} \tag{2.1}$$

where, P_p is the power assigned to PT and $n_{ij} \sim \mathcal{CN}(0, \sigma^2)$ is the AWGN in i^{th} phase of transmission at j^{th} receiver and j=1,2,3 corresponds to PR, SR, ST respectively. The signal received at SR in phase 1 is given by

$$y_{SR}^{(1)} = \sqrt{P_p} x_p h_2 + n_{12}. \tag{2.2}$$

Since ST is equipped with two antennas, hence the signal received at ST can be given as

$$\begin{bmatrix} y_{ST}^{(1)} \\ y_{ST}^{(2)} \end{bmatrix} = \sqrt{P_p} \begin{bmatrix} h_3 \\ h_4 \end{bmatrix} x_p + n_{13}. \tag{2.3}$$

In transmission phase 2, ST decodes the primary signal (i.e. x_p) and transmits it along with its own signal (i.e. x_s). As ST has two antennas, in order to reduce interference at PR, it will transmit x_p and x_s from the antenna which provides maximum and minimum instantaneous gain between ST-PR respectively. Therefore, signal received at PR in phase 2 is given by

$$y_{PR}^{(2)} = \begin{bmatrix} h_{\max} & h_{\min} \end{bmatrix} z + n_{21} \tag{2.4}$$

where, $h_{\max} = \begin{cases} h_5 & \text{if } \gamma_5 > \gamma_6 \\ h_6 & \text{if } \gamma_5 \leq \gamma_6 \end{cases}$, $h_{\min} = \begin{cases} h_6 & \text{if } \gamma_5 > \gamma_6 \\ h_5 & \text{if } \gamma_5 \leq \gamma_6 \end{cases}$,
$z = \begin{bmatrix} \sqrt{\alpha P_s} x_p & \sqrt{(1-\alpha) P_s} x_s \end{bmatrix}^T$, α and $(1-\alpha)$ is the fraction of power provided by the secondary transmitter to transmit primary signal and secondary signal respectively. Therefore the signal received at PR in the both phases can be written as

$$\begin{bmatrix} y_{PR}^{(1)} \\ y_{PR}^{(2)} \end{bmatrix} = \begin{bmatrix} \sqrt{P_p} h_1 & 0 \\ \sqrt{\alpha P_s} h_{\max} & \sqrt{(1-\alpha) P_s} h_{\min} \end{bmatrix} \begin{bmatrix} x_p \\ x_s \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{21} \end{bmatrix}. \tag{2.5}$$

Now, the signal received at SR in phase 2 is given by

$$y_{SR}^{(2)} = [h_7 \quad h_8] z + n_{22} \tag{2.6}$$

where, $z = \begin{bmatrix} \sqrt{\alpha P_s} x_p & \sqrt{(1-\alpha) P_s} x_s \end{bmatrix}^T$. Using (2.2), SR will estimate the primary signal (i.e $\hat{x_p}$) which helps in cancelling the x_p signal received in phase 2 and hence the overall signal received at SR after applying interference cancellation is given as

$$y_{SR} = \sqrt{(1-\alpha)\,P_s} h_8 x_s + n_{22}. \tag{2.7}$$

2.2.3 Outage Probability of Primary System

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 1 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

$$P_{out}^{PR} = P[R_{11} < R_{pt}]P[R_{13} < R_{pt}] + P[R_{13} > R_{pt}]P[R_{MRC} < R_{pt}] \tag{2.8}$$

where, R_{11} is the transmission rate achieved in phase 1 between PT-PR link, R_{13} is the transmission rate achieved between PT-ST in phase 1 and R_{MRC} is the rate achieved at PR after applying MRC of both transmission phases. Solving for (2.8),

$$R_{11} = \frac{1}{2}\log_2\left(1 + \frac{P_p\gamma_1}{\sigma^2}\right). \tag{2.9}$$

The factor $\frac{1}{2}$ is due to the fact that the whole transmission is divided into two phases.

$$P[R_{11} < R_{pt}] = P\left[\gamma_1 < \frac{\sigma^2\rho}{P_p}\right] = 1 - e^{-\frac{\sigma^2\rho}{P_p}}. \tag{2.10}$$

as, $\rho = 2^{2R_{pt}} - 1, \gamma_1 \sim \varepsilon(1)$.

$$R_{13} = \frac{1}{2}\log_2\left(1 + \frac{P_p\gamma_3}{\sigma^2} + \frac{P_p\gamma_4}{\sigma^2}\right) \tag{2.11}$$

and

$$P[R_{13} < R_{pt}] = P\left[\gamma_3 + \gamma_4 < \frac{\sigma^2\rho}{P_p}\right]. \tag{2.12}$$

We assume that the distances between the antennas at ST is negligible as compare to distance between the nodes, hence $d_3 = d_4, d_5 = d_6, d_7 = d_8$. Therefore, γ_3 and γ_4 are i.i.d and hence $f_{\gamma_3,\gamma_4}(\gamma_3,\gamma_4) = f_{\gamma_3}(\gamma_3)f_{\gamma_4}(\gamma_4)$ where,

$$f_{\gamma_3} = \begin{cases} d_3^v e^{-d_3^v\gamma_3} & \gamma_3 > 0 \\ 0 & \text{otherwise.} \end{cases}$$

Therefore,

$$P[R_{13} < R_{pt}] = \int_0^{\frac{\sigma^2\rho}{P_p}} \int_0^{\frac{\sigma^2\rho}{P_p}-\gamma_4} f_{\gamma_3,\gamma_4}(\gamma_3,\gamma_4)d\gamma_3 d\gamma_4$$
$$= 1 - \left[\left(1+\frac{\sigma^2\rho}{P_p}d_3^v\right)e^{-\frac{\sigma^2\rho}{P_p}d_3^v}\right]. \quad (2.13)$$

Moreover,

$$P[R_{13} > R_{pt}] = \left[\left(1+\frac{\sigma^2\rho}{P_p}d_3^v\right)e^{-\frac{\sigma^2\rho}{P_p}d_3^v}\right]. \quad (2.14)$$

The rate at PR after MRC is obtained as

$$R_{\text{MRC}} = \frac{1}{2}\log_2(1+\text{SNR}_{\text{MRC}}) \quad (2.15)$$

where, $\text{SNR}_{\text{MRC}} = \frac{P_p\gamma_1}{\sigma^2} + \frac{\alpha P_s\gamma_{\max}}{(1-\alpha)P_s\gamma_{\min}+\sigma^2}$, $\gamma_{\max} = \max(\gamma_5,\gamma_6)$, $\gamma_{\min} = \min(\gamma_5,\gamma_6)$. Therefore,

$$P[R_{MRC} < R_{pt}] = P\left[\frac{P_p\gamma_1}{\sigma^2} + \frac{\alpha P_s\gamma_{\max}}{(1-\alpha)P_s\gamma_{\min}+\sigma^2} < \rho\right]. \quad (2.16)$$

After solving, we get

$$P[R_{MRC} < R_{pt}] = 1 - e^{-\frac{\sigma^2}{P_p}(\rho-\frac{\alpha}{1-\alpha})} + \frac{2}{n}e^{-\frac{d_5^v\sigma^2\rho}{\alpha P_s}+\frac{mp}{n}}$$
$$\left(Ei\left[\frac{p\sigma^2}{P_p}\left(\rho-\frac{\alpha}{1-\alpha}\right)-\frac{mp}{n}\right] - Ei\left[-\frac{mp}{n}\right]\right) \quad (2.17)$$

where, $\alpha \leq \frac{\rho}{\rho+1}$, $m = \left(\frac{1-\alpha}{\alpha}\right)\rho+1$, $n = \left(\frac{1-\alpha}{\alpha}\right)\frac{P_p}{\sigma^2}$, $p = \frac{d_5^v P_p}{\alpha P_s} - 1$ and Ei represents the exponential integral defined as $Ei(x) = -\int_{-x}^{\infty}\frac{e^{-t}}{t}dt$. For detailed derivation of (2.17), please refer to Appendix A. After substituting (2.10), (2.13), (2.14) and (2.17) in (2.8), we get

$$P_{out}^{PR} = (1-e^{-\frac{\sigma^2\rho}{P_p}})\left(1-\left[\left(1+\frac{\sigma^2\rho}{P_p}d_3^v\right)e^{-\frac{\sigma^2\rho}{P_p}d_3^v}\right]\right) + \left(\left[\left(1+\frac{\sigma^2\rho}{P_p}d_3^v\right)e^{-\frac{\sigma^2\rho}{P_p}d_3^v}\right]\right)$$
$$\left(1-e^{-\frac{\sigma^2}{P_p}(\rho-\frac{\alpha}{1-\alpha})} + \frac{2}{n}e^{-\frac{d_5^v\sigma^2\rho}{\alpha P_s}+\frac{mp}{n}}\left(Ei\left[\frac{p\sigma^2}{P_p}\left(\rho-\frac{\alpha}{1-\alpha}\right)-\frac{mp}{n}\right] - Ei\left[-\frac{mp}{n}\right]\right)\right) \quad (2.18)$$

Special case when α=1

ST acts as a selection combiner. In such senerio, $\text{SNR}_{\text{MRC}} = \frac{P_p\gamma_1}{\sigma^2} + \frac{P_s\gamma_{\max}}{\sigma^2}$. Therefore (2.16) reduces to,

$$P[R_{MRC} < R_{pt}] = P\left[\frac{P_p\gamma_1}{\sigma^2} + \frac{P_s\gamma_{\max}}{\sigma^2} < \rho\right] \quad (2.19)$$

After solving,

$$
\begin{aligned}
P[R_{MRC} < R_{pt}] =& e^{-g}\left(\frac{e^{((2\mu g)-2\psi)}}{2\mu-1} - \frac{2e^{((\mu g)-\psi)}}{\mu-1} - 1\right) \\
& - \left(\frac{e^{2\psi}}{2\mu-1} - \frac{2e^{-2\psi}}{\mu-1} - 1\right)
\end{aligned} \tag{2.20}
$$

where, g=$\frac{\rho\sigma^2}{P_P}$, $\psi = \frac{d_5^v\rho\sigma^2}{P_s}$ and $\mu = \frac{d_5^v P_p}{P_s}$. For detailed derivation of (2.20), please refer Appendix B.

2.2.4 Outage Probability of Secondary System

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 1, links between PT-ST and PT-SR fails in decoding x_p, interference cancellation at SR in phase 2 is not possible and hence outage will be declared for secondary system. The outage probability for secondary system can be given as [14]

$$
P_{out}^{SR} = 1 - P[R_{12} > R_{pt}]P[R_{13} > R_{pt}]P[R_2^{SR} > R_{st}] \tag{2.21}
$$

where, R_{12} is the transmission rate achieved between PT-SR link in phase 1, R_{13} is the transmission rate achieved at ST in phase 1 (given in (2.14)) and R_2^{SR} is the rate achieved at SR in phase 2. Solving for (2.21),

$$
R_{12} = \frac{1}{2}\log_2\left(1 + \frac{P_p\gamma_2}{\sigma^2}\right). \tag{2.22}
$$

Therefore,

$$
P[R_{12} > R_{pt}] = P\left[\gamma_2 > \frac{\rho\sigma^2}{P_p}\right] = e^{-\frac{d_2^v\rho\sigma^2}{P_p}}. \tag{2.23}
$$

Moreover,

$$
R_2^{SR} = \frac{1}{2}\log_2\left(1 + \frac{P_s(1-\alpha)\gamma_7}{\sigma^2}\right). \tag{2.24}
$$

Therefore,

$$
P[R_2^{SR} > R_{st}] = P\left[\gamma_7 > \frac{\rho_s\sigma^2}{P_s(1-\alpha)}\right] = e^{-\frac{d_7^v\rho_s\sigma^2}{P_s(1-\alpha)}} \tag{2.25}
$$

where, $\rho_s = 2^{2R_{st}} - 1$.

After substituting (2.23), (2.14) and (2.25) in (2.21), we get

$$
P_{out}^{SR} = 1 - \left[\left(\left(1 + \frac{\sigma^2\rho}{P_p}d_3^v\right)e^{-\frac{\sigma^2\rho}{P_p}d_3^v}\right)e^{-\frac{d_2^v\rho\sigma^2}{P_p}}e^{-\frac{d_7^v\rho_s\sigma^2}{P_s(1-\alpha)}}\right] \tag{2.26}
$$

2.3 Simulation Results and Discussion

In this section, we have discussed the analytical and simulation results for outage probability. We have compared our results with the scheme in [1], where they randomly pick an antenna at ST for transmission. Fig 2 shows the simulation model of the proposed scheme, in which for the ease of analysis all nodes are assumed to be collinear. The value of d (distance between PT-ST) is considered to be 0.5 and 0.8. The target rate chosen for primary and secondary system is 1 i.e. $R_{pt} = R_{st} = 1$, and we have considered $\frac{P_p}{\sigma^2} = 5$dB.

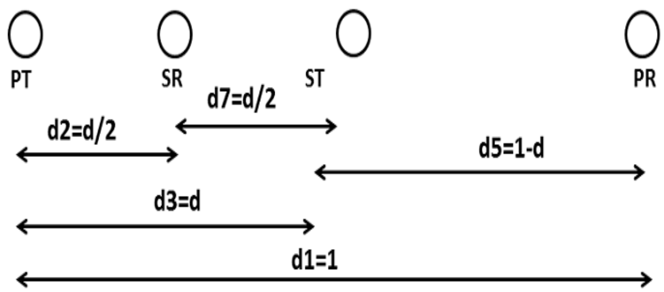

Figure 2.2: System Model

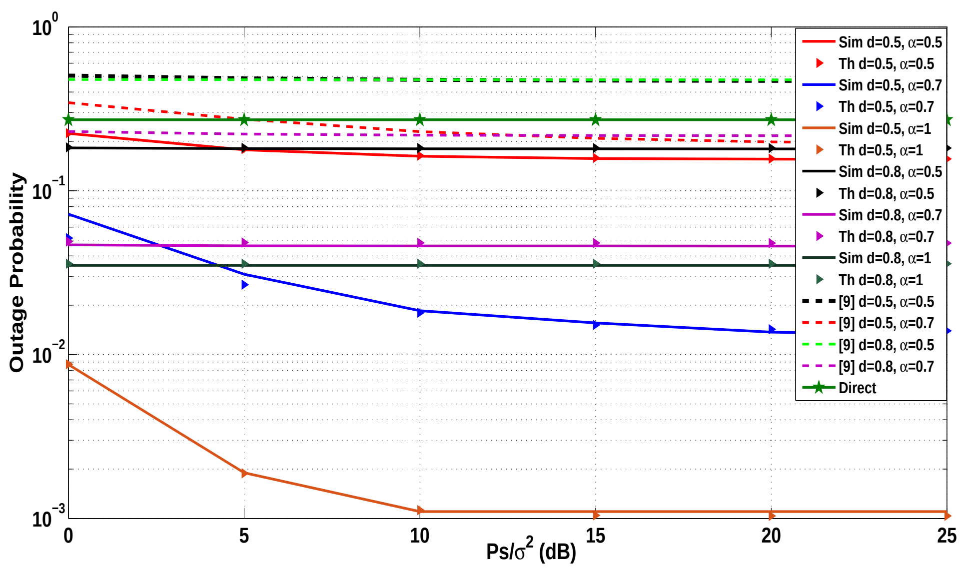

Figure 2.3: Outage Probability of Primary System

Fig. 2.3 and Fig. 2.4 shows the outage probability of primary and secondary system respectively with respect to $\frac{P_s}{\sigma^2}$. From the plots it is quite obvious, that the outage probability of both primary as well as secondary system is continuously decreasing with the increase in power at secondary transmitter. However this decrement gradually reduces after 10dB because the outage probability also depends on the successful decoding of primary's data at ST in phase 1 (from (2.8

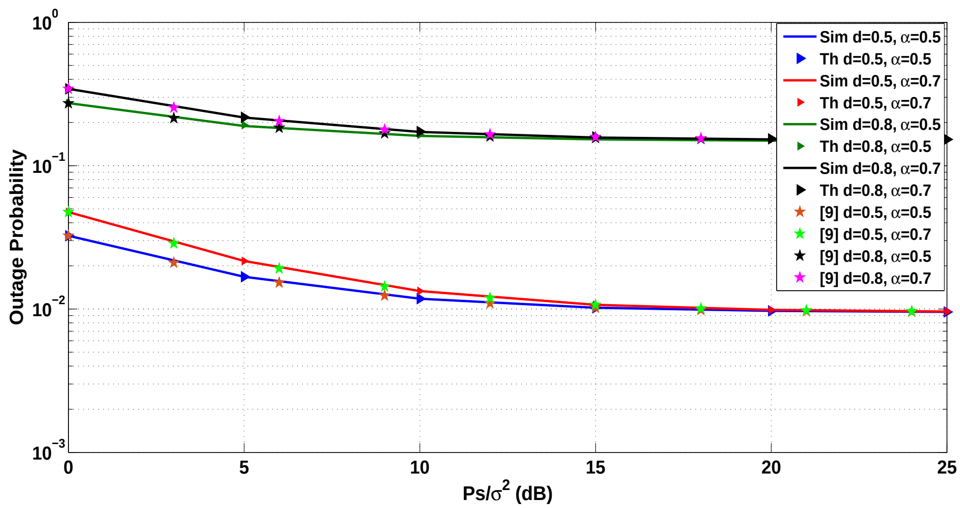

Figure 2.4: Outage Probability of Secondary System

and 2.21)). The results are shown for two different values of α i.e. 0.5 and 0.7. By transmitting x_s from channel having less instantaneous gain, interference level at PR get reduced which results in considerable improvement in the performance of primary system (approximately 10 times at d = 0.5 and $\alpha = 0.7$ for $\frac{P_s}{\sigma^2} = 5$dB) compared to [1]. Even when half of the power of ST ($\alpha = 0.5$) is allocated to secondary signal, the performance of proposed scheme is still far better than that of [1] with an improvement of approximately 5 times. It is also obvious from Fig. 2.4 that notwithstanding the improvement in the performance of primary system, we are still able to retain the performance of secondary system as in [1]. Furthermore, we also demonstrate the results for the case wherein ST acts as a pure relay ($\alpha = 1$) i.e. it is transmitting only primary's data with the channel having larger instantaneous gain. For such scenario the proposed scheme works as a selection combiner in phase 2.

Chapter 3

Interference cancellation technique for cooperative spectrum sharing cognitive radio systems

3.1 Introduction

In this chapter, we have proposed a complete interference cancellation CSS technique by using multiple antennas at ST node. Substantial amount of work is also available in which multiple antennas are utilized for primary and secondary systems. In [1], ST is using multiple antennas to receive signal from PT, thereby improving the probability of detection of primary signal at ST. However it is transmitting the superimposed primary and secondary signal by randomly selecting one of its antennas, thereby causing interference from one node to other. Furthermore, the schemes proposed in [1, 14, 15] were primarily concerned with the improvement of primary systems outage probability without much duo consideration to the improvement in performance of secondary system.

In [25], to reduce the interference at PR, due to presence of secondary system, multiple ST nodes are used and the one which causes minimum interference to the primary system is chosen for the transmission. Here, multiple antennas are utilized at all the nodes to achieve multiuser diversity by using STBC but ST doesn't help in primary signal transmission. In [26] multiple relays are used to enhance the performance of secondary system under three different strategies (i.e. selective amplify and forward, selective decode and forward and amplify and forward with partial relay selection) to transmit data of secondary system. However in [25]- [26] relays were primarily used to optimize the performance of secondary system without assisting the primary system's transmission. Moreover, these are cognitive underlay schemes, their performance is limited by amount of interference the primary system can tolerate from the secondary system for a predefined QoS.

Some recent works [2, 20, 27, 28] have also focused on interference cancellation at PR and SR due to secondary and primary signal respectively. For example in [27] and [20] interference cancellation is done at PR and SR by applying orthogonal beamforming and zero forcing pre-coding at ST. Both schemes required *a priori* transmit channel state information (CSI) which is complex to obtain as compared of received CSI. Moreover, [20] also uses amplify and forward relaying scheme at ST, which results in amplifying noise along with the signal received from PT. In [2] authors have proposed a cooperative spectrum sharing scheme based on STBC to cancel the interference from primary to secondary system and vice versa. However, in this, ST is transmitting and receiving simultaneously by using two different antennas which is practically difficult to realize as it requires proper shielding between the antennas and which may also result in cross-talk as well. In [28] , authors have proposed a three phase interference free scheme however it lacks in terms of performance. In first phase PT broadcasts its signal and in second phase after successful decoding, ST will transmit only x_p signal and then in third phase x_s is transmitted. Therefore, the amount of time used for primary transmission gets reduced. As a consequence, the diversity gain achieved at PR and SR is two and one respectively.

In this work we aim to mitigate the drawbacks of the above mentioned schemes and propose an overlay cooperative spectrum sharing scheme based on STBC in which there is no interference from one system to another. Moreover, as shown later, propose scheme helps in achieving a diversity order of 3 and 2 for primary and secondary system respectively. In the following we briefly describe the protocol description of the proposed scheme. Fig. 3.1 shows the system flow chart which illustrates step by step procedure, how secondary system get access over primary spectrum for transmission. When the QoS[1] between PT-PR link drops below the minimum target threshold, PT may require cooperation from neighbouring nodes. In such scenario, PT will broadcast CRTS (Co-operative right to send) message along with the desired QoS. In response to the CRTS message, PR sends CCTS (Co-operative clear to send) message to PT. ST overhears the CRTS and CCTS messages and decides to help primary system, if it can provide the desired QoS to the primary system. ST then works as a decode and forward relay and in exchange, is allowed opportunistic access to primary system's spectrum. ST then sends CCTH (cooperative clear to help) as a confirmation to primary system. Once PT and PR receive this message, it enters into three phase protocol as shown in Fig.3.2. In the 1^{st} phase, PT broadcasts its data which is received by all the nodes i.e. ST, SR and PR. In 2^{nd} phase, ST will try to decode primary signal correctly. If it fails, it will remain silent for the next phases and PR will receive signal directly from PT. In case of successful decoding in 2^{nd} phase, ST will transmit the decoded primary's data along with its own data from the two antennas equipped at ST as shown in Fig. 3.2. In third phase, conjugate of the data will be sent using STBC [29]. Finally, by using received CSI and applying MRC (Maximum ratio combining) after the three transmission phases, interference can be cancelled out at both the receivers. As a basic requirement of the proposed scheme we believe that both primary and secondary systems are advance systems which use multiple antenna such as IEEE 802.11n, IEEE 802.16m [30–32].

The advantages of the proposed scheme are summarized as follows:

[1] QoS can be defined as a target rate, required probability of bit error at PR etc.

- As there is no interference from one node to another, the performance of primary and secondary system is not limited by the presence of ST and PT respectively.
- As primary and secondary receiver is receiving its signal from three and two different channels hence the proposed scheme provides the diversity gain of 3 and 2 for primary and secondary system respectively, whereas in conventional schemes [1, 14, 15], [2]- [28] diversity gain achieved is only two and one respectively.
- We can achieve the required QoS for both systems just by increasing the transmission power of ST without any trade-off between primary and secondary system performance as against the schemes proposed in [1, 14, 15]
- In the proposed scheme, performance of both systems can be enhanced. Unlike [1, 14, 15] where main focus in on primary system performance and [25]- [26] which concern about performance of secondary system only.
- Unlike [1, 14, 15], in proposed scheme SR need not to decode the primary signal received from PT in the first phase.
- Here, received CSI is used to decode the signal and to cancel the interference at PR and SR contrary to [20, 27] where transmit CSI is used, which is more difficult to estimate.
- No shielding is required between multiple antennas of ST unlike [2] because in proposed scheme antennas are not transmitting and receiving simultaneously.
- Lastly, performance of secondary system can be maintained independent on availability of spectrum holes.

3.2 System model and protocol description

3.2.1 System model

The primary and secondary system consists of transmitter receiver pair known as PT-PR and ST-SR respectively. We have considered multiple antennas at ST, named as ST1 and ST2. Channels between the links are modeled as Rayleigh fading channels, the channel coefficient between PT-PR, PT-SR, PT-ST(1), PT-ST(2), ST(1)-PR, ST(2)-PR, ST(1)-SR, ST(2)-SR is $h_1, h_2, h_3, h_4, h_5, h_6, h_7, h_8$ respectively. Here, $h_i \sim \mathcal{CN}(0, d_i^{-v})$ where ν is the path loss exponent and d_i is the normalized distance between the corresponding link. The normalization is done with respect to the distance between PT-PR link therefore, $d_1 = 1$. The instantaneous gain of each channel is given as $\gamma_i = |h_i|^2$ where, $\gamma_i \sim \varepsilon(d_i^v)$.

3.2.2 System equations

In transmission phase 1, PT will broadcast the primary signal i.e. x_p which will be received by ST, SR and PR. Signal received at PR in phase1 is given by $y_{PR}^{(1)} = \sqrt{P_p} x_p h_1 + n_{11}$. Here

$n_{ij} \sim \mathcal{CN}(0,\, \sigma^2)$ is the additive white Gaussian noise (AWGN) in the i^{th} phase of transmission at the j^{th} receiver. $j = 1, 2, 3$ corresponds to PR, SR, ST respectively and P_p is the transmitted power of the primary transmitter. The direct transmission rate at PR in phase 1 is given by

$$R_{PR}^1 = \frac{1}{3}\log_2\left(1 + \frac{P_p\gamma_1}{\sigma^2}\right). \tag{3.1}$$

The factor $\frac{1}{3}$ in the above equations is due to the fact that the whole transmission is divided into three phases. Signal received at ST after first phase is thus given as $y_{ST}^{(1)} = \sqrt{P_p}x_ph_3 + \sqrt{P_p}x_ph_4 + n_{13}$. Therefore, the rate achieved at ST is given by

$$R_{STT}^1 = \frac{1}{3}\log_2\left(1 + \frac{P_p\gamma_3}{\sigma^2} + \frac{P_p\gamma_4}{\sigma^2}\right). \tag{3.2}$$

In transmission phase 2, after successfully decoding the signal received from PT in first transmission phase, ST transmits the primary's data along with its own data. Signal received at PR in second phase is given by $y_{PR}^{(2)} = \begin{bmatrix} h_5 & h_6 \end{bmatrix} z + n_{21}$ where, $z = \begin{bmatrix} \sqrt{\alpha\frac{P_s}{2}}x_p & \sqrt{(1-\alpha)\frac{P_s}{2}}x_s \end{bmatrix}^T$, P_s is the total transmitted power of ST, α and $(1-\alpha)$ are the power allocation factor assigned to both the antennas at ST. In $y_{PR}^{(2)}$, power of secondary system is divided by the factor 2, this is due to the fact that ST is transmitting information in two time slots. In the proposed scheme, power at ST is equally divided between both the antennas i.e. $\alpha = \frac{1}{2}$. Therefore, $y_{PR}^{(2)}$ can be written as,

$$y_{PR}^{(2)} = \sqrt{\frac{P_s}{4}}h_5x_p + \sqrt{\frac{P_s}{4}}h_6x_s + n_{21}. \tag{3.3}$$

As both primary and secondary systems are using STBC and receivers have channel state information, therefore multiplying (3.3) with received CSI h_5^*, we get

$$y_{PR}^{(2)} = \sqrt{\frac{P_s}{4}}h_5^*h_5x_p + \sqrt{\frac{P_s}{4}}h_5^*h_6x_s + n_{21}h_5^*. \tag{3.4}$$

The signal received at SR in second phase is given as $y_{SR}^{(2)} = [h_7 \quad h_8]z + n_{22}$. Substituting z and multiplying $y_{SR}^{(2)}$ with the received CSI h_8^* , we get,

$$y_{SR}^{(2)} = \sqrt{\frac{P_s}{4}}h_8^*h_7x_p + \sqrt{\frac{P_s}{4}}h_8^*h_8x_s + n_{22}h_8^*. \tag{3.5}$$

In transmission phase 3, signal transmitted from different antennas at ST (using STBC) can be combined and given by $z_1 = \sqrt{\frac{P_s}{4}}\begin{bmatrix} -x_s^* \; x_p^* \end{bmatrix}^T$. Signal thus received at PR in phase 3 is given by $y_{PR}^{(3)} = [h_5 \quad h_6]z_1 + n_{31}$. This after multiplying with z_1, taking conjugate and multiplying with the received CSI h_6 is given by

$$y_{PR}^{(3)*} = \sqrt{\frac{P_s}{4}}h_6^*h_6x_p - \sqrt{\frac{P_s}{4}}h_5^*h_6x_s + n_{31}^*h_6 \tag{3.6}$$

Signal received at SR is given by $y_{SR}^{(3)} = [h_7 \quad h_8]z_1 + n_{32}$ Taking conjugate of $y_{SR}^{(3)}$ and multiplying it with the received CSI $-h_7$, we get

$$y_{SR}^{(3)*} = \sqrt{\frac{P_s}{4}} h_7^* h_7 x_s - \sqrt{\frac{P_s}{4}} h_8^* h_7 x_p - h_7 n_{32}^*. \tag{3.7}$$

The signal at PR after all the transmission phases is given by

$$y_{PR} = \begin{bmatrix} y_{PR}^{(1)} \\ y_{PR}^{(2)} \\ y_{PR}^{(3)*} \end{bmatrix} = \begin{bmatrix} \sqrt{P_p} h_1 & 0 \\ \sqrt{\frac{P_s}{4}} h_5 h_5^* & \sqrt{\frac{P_s}{4}} h_6 h_5^* \\ \sqrt{\frac{P_s}{4}} h_6 h_6^* & -\sqrt{\frac{P_s}{4}} h_6 h_5^* \end{bmatrix} \begin{bmatrix} x_p \\ x_s \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{21} h_{5^*} \\ n_{31}^* h_6 \end{bmatrix}. \tag{3.8}$$

The signal received at PR in all the transmission phases are combined using MRC and therefore the SNR is given by $\text{SNR}_{\text{PR}}^{\text{MRC}} = \frac{P_p |h_1|^2}{\sigma^2} + \frac{\left|\sqrt{\frac{P_s}{4}}|h_5|^2 + \sqrt{\frac{P_s}{4}}|h_6|^2\right|^2}{E[\left|n_{21} h_5^* + n_{31}^* h_6\right|^2]}$. This can be further simplified as

$$\text{SNR}_{\text{PR}}^{\text{MRC}} = \frac{P_p \gamma_1}{\sigma^2} + \frac{P_s \gamma_5}{4\sigma^2} + \frac{P_s \gamma_6}{4\sigma^2}. \tag{3.9}$$

Similarly, signal received at SR is given as

$$y_{SR} = \begin{bmatrix} y_{SR}^{(2)} \\ y_{SR}^{(3)*} \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{P_s}{4}} h_7 h_8^* & \sqrt{\frac{P_s}{4}} h_8 h_8^* \\ -\sqrt{\frac{P_s}{4}} h_7 h_8^* & \sqrt{\frac{P_s}{4}} h_7 h_7^* \end{bmatrix} x_s + \begin{bmatrix} n_{22} h_{8^*} \\ -n_{32}^* h_7 \end{bmatrix}. \tag{3.10}$$

After solving the above expression, we have

$$y_{SR} = \left(\sqrt{\frac{P_s}{4}} |h_8|^2 + \sqrt{\frac{P_s}{4}} |h_7|^2 \right) x_s + (n_{22} h_8^* - n_{32}^* h_7). \tag{3.11}$$

The signal received at SR in all the transmission phases are combined using MRC and therefore the SNR is given by $\text{SNR}_{\text{SR}}^{\text{MRC}} = \frac{\left|\sqrt{\frac{P_s}{4}}|h_8|^2 + \sqrt{\frac{P_s}{4}}|h_7|^2\right|^2}{E[\left|n_{22} h_8^* - n_{32}^* h_7\right|^2]}$. This can be further simplified as

$$\text{SNR}_{\text{SR}}^{\text{MRC}} = \frac{P_s \gamma_7}{4\sigma^2} + \frac{P_s \gamma_8}{4\sigma^2}. \tag{3.12}$$

3.3 Analysis on Bit Error Rate

In this section bit error rate (BER) for primary and secondary system is calculated. BER is chosen as one of the performance metric for the proposed scheme as it assesses the end to end performance of a system including the transmitter, receiver and the medium between them.

3.3.1 For Primary System

In this section, we have calculated the probability of bit error for primary system. The modulation scheme used is Binary phase shift keying (BPSK). Using Moment generating function (MGF) and Craig's expression of Q function [33], probability of bit error is given by

$$\overline{P_b} = \frac{1}{\pi}\int_0^{\pi/2}\prod_{i=1}^{M} M_{\gamma_i}\left(\frac{-1}{sin^2\phi}\right)d\phi \tag{3.13}$$

where, M is the number of independent channels between transmitter and receiver pair and $M_{\gamma i}$ is the moment generating function of the given channel. Moreover, MGF for Rayleigh fading is given by $M_\gamma(s) = (1 - s\overline{\gamma})^{-1}$, where, $\overline{\gamma}$ is the average SNR of Rayleigh faded branch [33]. If ST fails to decode the primary signal in the first phase, it will remain silent for the next two phases and only direct link between PT-PR exists. Therefore, for this case probability of bit error is given by

$$P_b^{direct} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\psi_1}}{\overline{\psi_1}+1}}\right) \tag{3.14}$$

where $\overline{\psi_1}$ is the average SNR of branch PT-PR and given by $\overline{\psi_1} = \frac{P_p}{\sigma^2}$. On the other hand, if ST successfully decodes the primary signal, received in phase 1, then it is concluded that PR is receiving signal from three independent channels using (3.9) and hence M=3. From (3.9) and (3.13), probability of bit error at PR is given by

$$\overline{P_b^p} = \frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{\overline{\psi_1}}{sin^2\phi}\right)^{-1}\left(1+\frac{\overline{\psi_5}}{4d_5^v sin^2\phi}\right)^{-1}\left(1+\frac{\overline{\psi_6}}{4d_6^v sin^2\phi}\right)^{-1}d\phi \tag{3.15}$$

where, $\overline{\psi_1} = \frac{P_p}{\sigma^2}, \overline{\psi_5} = \overline{\psi_6} = \frac{P_s}{\sigma^2}$. We assume that the distances between the antennas at ST is negligible as compare to distance between the nodes, and hence $d_3 = d_4, d_5 = d_6, d_7 = d_8$. So, (3.15) reduces to

$$\overline{P_b^p} = \frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{\overline{\psi_1}}{sin^2\phi}\right)^{-1}\left(1+\frac{\overline{\psi_5}}{4d_5^v sin^2\phi}\right)^{-2}d\phi. \tag{3.16}$$

After solving (3.16), we get

$$\begin{aligned}\overline{P_b^p} =& \frac{1}{2} - \frac{1}{2((4d_5^v)\overline{\psi_1}-\overline{\psi_5})^2}\left(\frac{\overline{\psi_5}}{\overline{\psi_5}+4d_5^v}\right)^{\frac{3}{2}}(\overline{\psi_5^2} - 40\overline{\psi_1}d_5^{2v} + (6-8\overline{\psi_1})\overline{\psi_5}d_5^v)\\ &- \frac{8\overline{\psi_1}^{5/2}d_5^{2v}}{\sqrt{\overline{\psi_1}+1}\left(4\overline{\psi_1}d_5^v - \overline{\psi_5}\right)^2}.\end{aligned} \tag{3.17}$$

3.3.2 For Secondary System

Probability of bit error for secondary system using (3.12) and (3.13) is given as

$$\overline{P_b^s} = \frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{\overline{\psi_7}}{4d_7^v sin^2\phi}\right)^{-1}\left(1+\frac{\overline{\psi_8}}{4d_8^v sin^2\phi}\right)^{-1} d\phi \tag{3.18}$$

where $\overline{\psi_7} = \overline{\psi_8} = \frac{P_s}{\sigma^2}$ and $d_7 = d_8$. Therefore (3.18) reduces to

$$\overline{P_b^s} = \frac{1}{\pi}\int_0^{\pi/2}\left(1+\frac{\overline{\psi_7}}{4d_7^v sin^2\phi}\right)^{-2} d\phi. \tag{3.19}$$

After solving (3.19), we get

$$\overline{P_b^s} = \frac{1}{2}\left[1-\frac{\sqrt{\overline{\psi_7}}(\overline{\psi_7}+6d_7^v)}{(\overline{\psi_7}+4d_7^v)^{\frac{3}{2}}}\right]. \tag{3.20}$$

3.4 Analysis on Outage probability

In this section outage probability for 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 primary and secondary system is denoted by R_{pt} and R_{st} respectively.

3.4.1 For Primary System

Outage for primary system is declared when PR is unable to receive its signal with target rate (R_{pt}). When ST fails to decode the primary signal correctly in phase 1, it will remain silent in the next two phases. In this case, PR can still decode primary signal from the direct link between PT-PR. Therefore, outage can be expressed as $P[R_{PR}^1 < R_{pt}]P[R_{STT}^1 < R_{pt}]$. Moreover, if ST decodes x_p correctly in 1^{st} phase then also outage can occur, if the total rate achieved after three transmission phases is less than R_{pt}. Therefore the overall outage probability expression for the primary system is given as

$$P_{out}^{PR} = P[R_{PR}^1 < R_{pt}]P[R_{STT}^1 < R_{pt}] + P[R_{STT}^1 > R_{pt}]P[R_{PR}^{MRC} < R_{pt}] \tag{3.21}$$

From (3.1)

$$P[R_{PR}^1 < R_{pt}] = P\left[\gamma_1 < \frac{\sigma^2\rho}{P_p}\right] = 1 - e^{-\frac{\sigma^2\rho}{P_p}} \tag{3.22}$$

where, $\rho = 2^{3R_{pt}} - 1, \gamma_1 \sim \varepsilon(1)$. From (3.2)

$$P[R_{STT}^1 < R_{pt}] = P\left[\gamma_3 + \gamma_4 < \frac{\sigma^2\rho}{P_p}\right] \tag{3.23}$$

As, γ_3 and γ_4 are i.i.d and hence $f_{\gamma_3,\gamma_4}(\gamma_3,\gamma_4) = f_{\gamma_3}(\gamma_3) * f_{\gamma_4}(\gamma_4)$ where,

$$f_{\gamma_3} = \begin{cases} d_3^v e^{-d_3^v \gamma_3} & \gamma_3 > 0 \\ 0 & \text{otherwise.} \end{cases}$$

Therefore, (3.23) reduces to

$$\begin{aligned} P[R_{STT}^1 < R_{pt}] &= \int_0^{\frac{\sigma^2\rho}{P_p}} \int_0^{\frac{\sigma^2\rho}{P_p}-\gamma_4} f_{\gamma_3,\gamma_4}(\gamma_3,\gamma_4) d\gamma_3 d\gamma_4 \\ &= 1 - \left[\left(1 + \frac{\sigma^2\rho}{P_p} d_3^v\right) e^{\frac{\sigma^2\rho}{P_p} d_3^v}\right]. \end{aligned} \tag{3.24}$$

The overall achieved rate at primary receiver after MRC is given by

$$R_{PR}^{MRC} = \frac{1}{3}\log_2(1 + \mathrm{SNR}_{\mathrm{PR}}^{\mathrm{MRC}}). \tag{3.25}$$

Using (3.9) and (3.25)

$$\begin{aligned} P[R_{PR}^{MRC} < R_{pt}] &= P\left[\frac{P_p\gamma_1}{\sigma^2} + \frac{P_s\gamma_5}{4\sigma^2} + \frac{P_s\gamma_6}{4\sigma^2} < \rho\right] \\ &= \int\int\int f_{\gamma_1}(\gamma_1) f_{\gamma_5}(\gamma_2) f_{\gamma_6}(\gamma_3) d\gamma_1 d\gamma_5 d\gamma_6. \end{aligned} \tag{3.26}$$

Since, $\gamma_1 \sim \varepsilon(1), \gamma_5 \sim \varepsilon(d_5^v), \gamma_6 \sim \varepsilon(d_5^v)$. Using [34], $P[R_{PR}^{MRC} < R_{pt}]$ can be solved as

$$\begin{aligned} = &\int_0^{\frac{4\rho\sigma^2}{P_s}} \int_0^{\frac{4\rho\sigma^2}{P_s}-\gamma_6} \int_0^{\left(\rho\sigma^2 - \frac{P_s\gamma_5}{4} - \frac{P_s\gamma_6}{4}\right)\frac{1}{P_p}} d_5^{2v} \\ &e^{-\gamma_1} e^{-d_5^v\gamma_5} e^{-d_5^v\gamma_6} d\gamma_1 d\gamma_5 d\gamma_6. \end{aligned} \tag{3.27}$$

Solving (3.27), we get the final expression as

$$= 1 - e^{-ad_5^v} - ad_5^v e^{-ad_5^v} - \frac{d_5^{2v} e^{\frac{-\rho\sigma^2}{P_p}}}{b^2}(1 - e^{-ab} - abe^{-ab}) \tag{3.28}$$

where, $a = \frac{4\rho\sigma^2}{P_s}$ and $b = d_5^v - \frac{P_s}{4P_p}$.

3.4.2 For Secondary System

For secondary system, outage will occur when the link between ST-SR fails in providing desired target rate for secondary system (i.e. R_{st}). Therefore outage probability expression is given as

$$P_{out}^{SR} = P[R_{SR}^{MRC} < R_{st}] \tag{3.29}$$

where R_{SR}^{MRC} is the rate achieved between ST-SR link and is given by $R_{SR}^{MRC} = \frac{1}{2}\log_2(1 + \mathrm{SNR}_{\mathrm{SR}}^{\mathrm{MRC}})$. Factor $\frac{1}{2}$ in this expression represents that secondary system is using only last two phases for the transmission. Using (3.12), (3.29) can be written as

$$P_{out}^{SR} = P\left[\gamma_7 + \gamma_8 < \frac{4\sigma^2 \rho_s}{P_s}\right] \tag{3.30}$$

where, $\rho_s = 2^{2R_{st}} - 1$. As γ_7, γ_8 are i.i.d and $d_7 = d_8$ we get,

$$P_{out}^{SR} = 1 - e^{-td_7^v} - td_7^v e^{-td_7^v} \tag{3.31}$$

where, $t = \frac{4\sigma^2 \rho_s}{P_s}$.

3.5 Simulation results and discussion

In this section, different results are plotted for bit error rate and outage probability for primary and secondary system, with respect to $\frac{P_s}{\sigma^2}$. For the ease of presentation, all the nodes are considered to be collinear as shown in Fig. 3.3 for the system topology. The value of d (i.e. the distance between PT and PR) is considered to be 0.5 and 0.8 for the simulations. The path loss exponent, v is 4 and target rate for both systems is chosen to be 1 (i.e. $R_{pt} = R_{st} = 1$).

3.5.1 BER

Fig. 3.4 and Fig. 3.5 shows the bit error rate of primary and secondary system with respect to $\frac{P_s}{\sigma^2}$. For comparison, BER of the scheme proposed in [1] is also plotted. Moreover, in Fig. 3.4 we are also showing the BER of the direct link between PT-PR when no secondary system is present. One important point that needs to be mentioned here is that all the results plotted are for the case when ST decodes the primary signal correctly in first phase. If ST fails in decoding primary signal it will be silent in next phases and all the results (proposed and [1]) will converges into the case when no secondary system is present which is shown by BER_{Direct} in the graph. From Fig. 3.4 we can observe at $\frac{P_s}{\sigma^2}$=20dB when d=0.5, the proposed scheme has BER of approximately 10^{-7} whereas, for [1] BER achieved is nearly 10^{-1} and 10^{-4} for α=0.5 and 0.75 respectively. Similarly, when d=0.8, proposed scheme has BER of approximately 10^{-10} and [1] has BER of nearly 10^{-1} and 10^{-6} for α= 0.5 and 0.75 respectively. This huge improvement is also observed in secondary system performance. In Fig. 3.5 proposed scheme provides the BER of 10^{-8} and 10^{-7} at d=0.5 and d=0.8 whereas, in [1], BER of nearly 10^{-5} is observed when d=0.5 and nearly 10^{-4} for d=0.8. It is quite obvious this improvement is due to interference cancellation at the respective receivers. Moreover, PR is receiving its signal i.e. x_p from three different channels i.e h_1, h_5, h_6 and SR is also receiving its signal from two different channels i.e. h_7 and h_8, thereby providing a good diversity gain for both PR and SR. Moreover, in [1] to increase the performance of primary system, α (fraction of ST power assigned to x_p) should be large which in turn effects the performance of secondary system. To prove this we have plotted results of [1] for two different values of α i.e. 0.5 and 0.75. This trade-off is completely removed in proposed scheme as power is equally divided between both the systems. Moreover, we can also observe that by increasing the power of ST (P_s), performance of both systems can be improved, hence the performance of secondary system is not compromised in order to attain better performance of primary system.

3.5.2 Outage probability

Fig. 3.6 and 3.7 shows the outage probability analysis of proposed scheme for primary and secondary system respectively. On comparing it with scheme presented in [1], we can observe approximately 10 times improvement in outage probability. Moreover, proposed scheme (where power is always equally divided among both signals) works better for both primary and secondary system even when 75% of the power at ST is allocated to primary signal and remaining 25% to secondary system in [1].

Fig. 3.8 and 3.9 shows the outage probability of the proposed scheme and compares it with scheme proposed in [2] for primary and secondary system respectively. Although [2] is also an interference cancellation technique but due to achievement of high diversity gain at primary and secondary receiver, proposed scheme outperforms the scheme presented in [2]. Moreover, in [2], spectrum sharing works until the distance between PT-ST (i.e. d) is less than 0.75 whereas in proposed scheme by utilizing multiple antennas at ST, the probability of decoding of primary signal at ST can be increased and thus proposed scheme works even for larger distances $d > 0.75$.

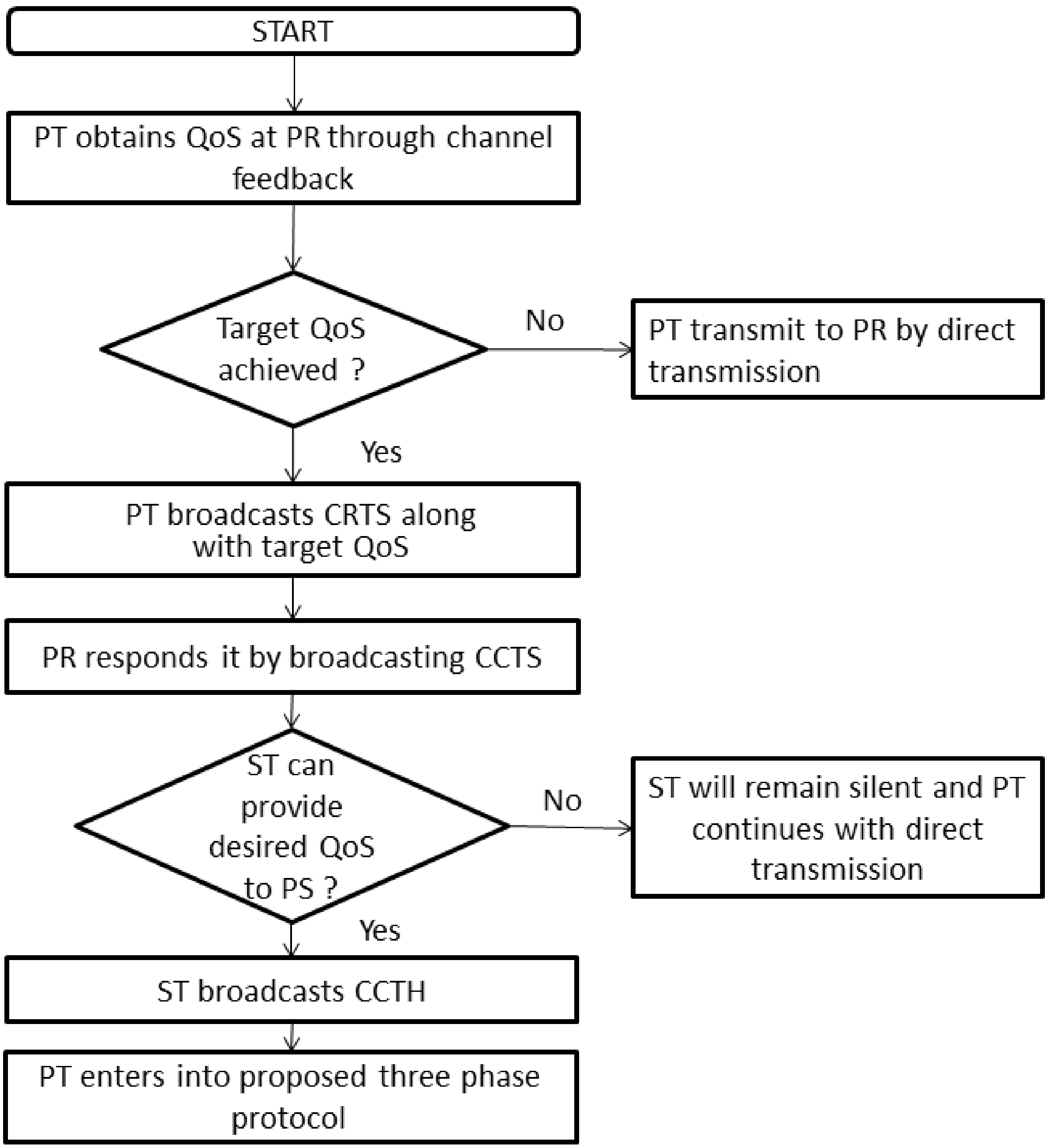

Figure 3.1: Sytem Flowchart

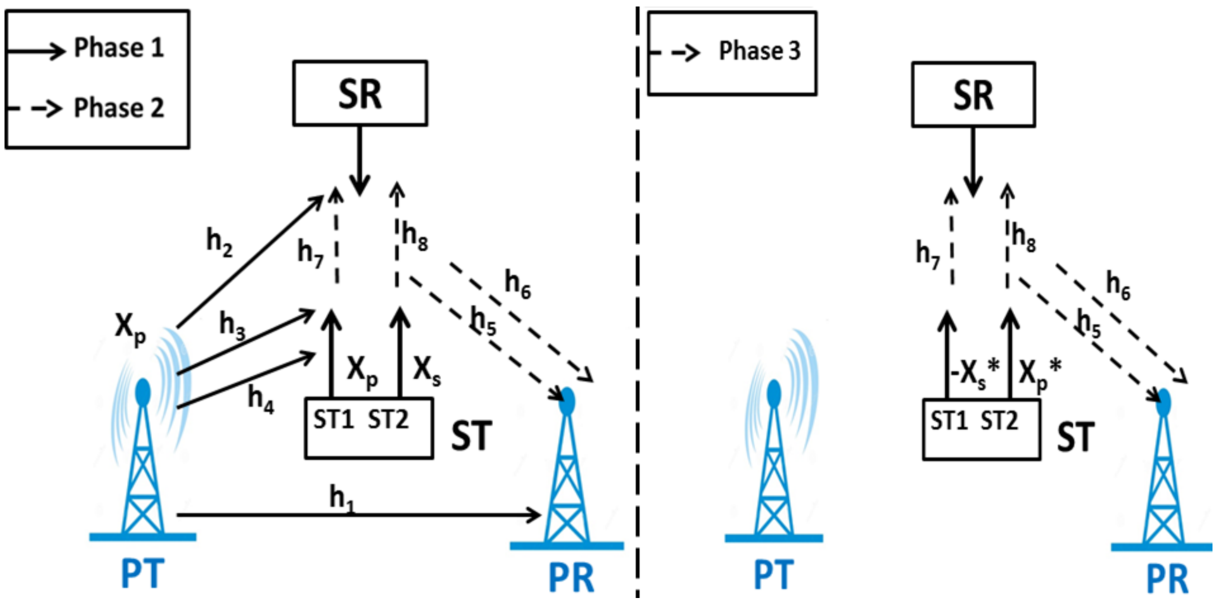

Figure 3.2: Transmission Phases

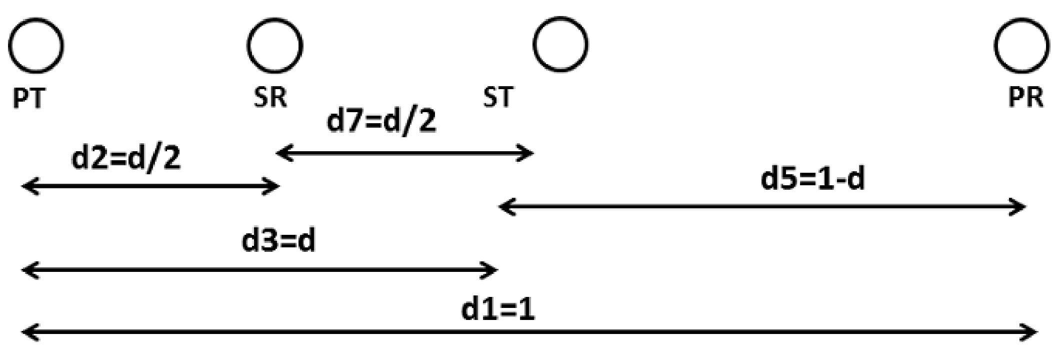

Figure 3.3: Simulation Model

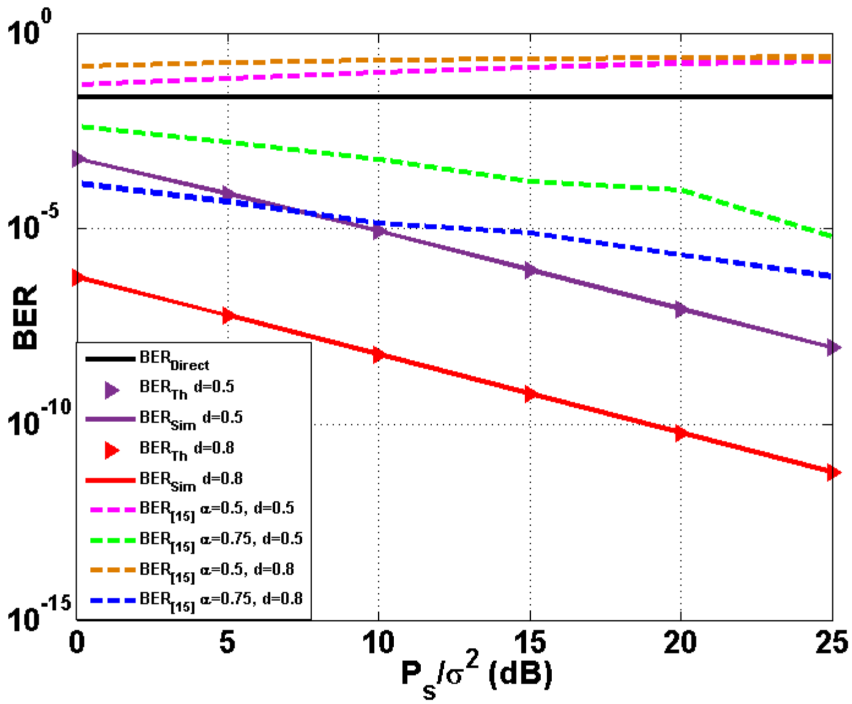

Figure 3.4: BER of primary system and its comparison with the scheme proposed in [1]

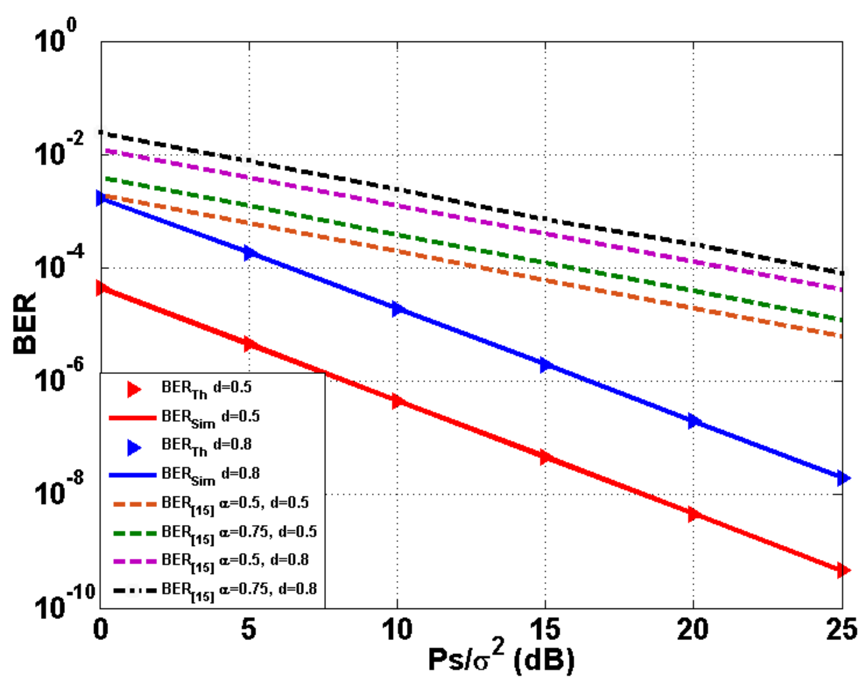

Figure 3.5: BER of secondary system and its comparison with the scheme proposed in [1]

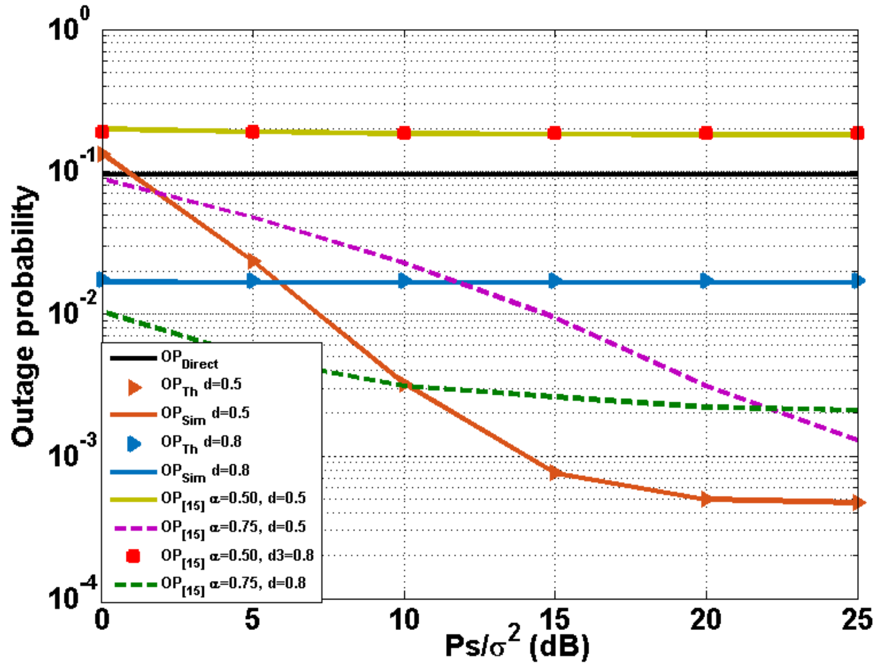

Figure 3.6: Outage probability of primary system and its comparison with the scheme proposed in [1]

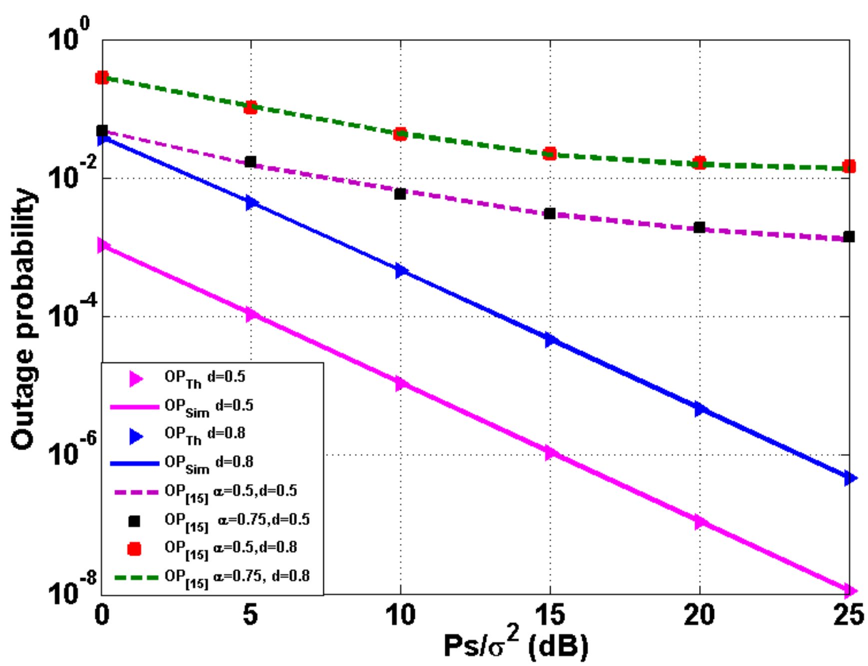

Figure 3.7: Outage probability of secondary system and its comparison with the scheme proposed in [1]

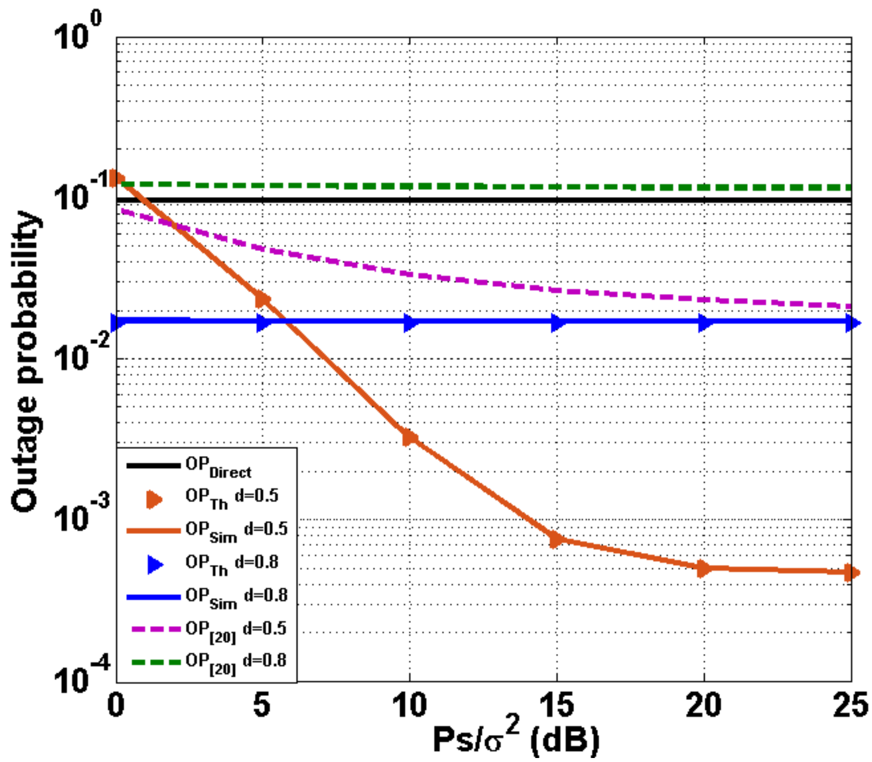

Figure 3.8: Outage probability of primary system and its comparison with the scheme proposed in [2]

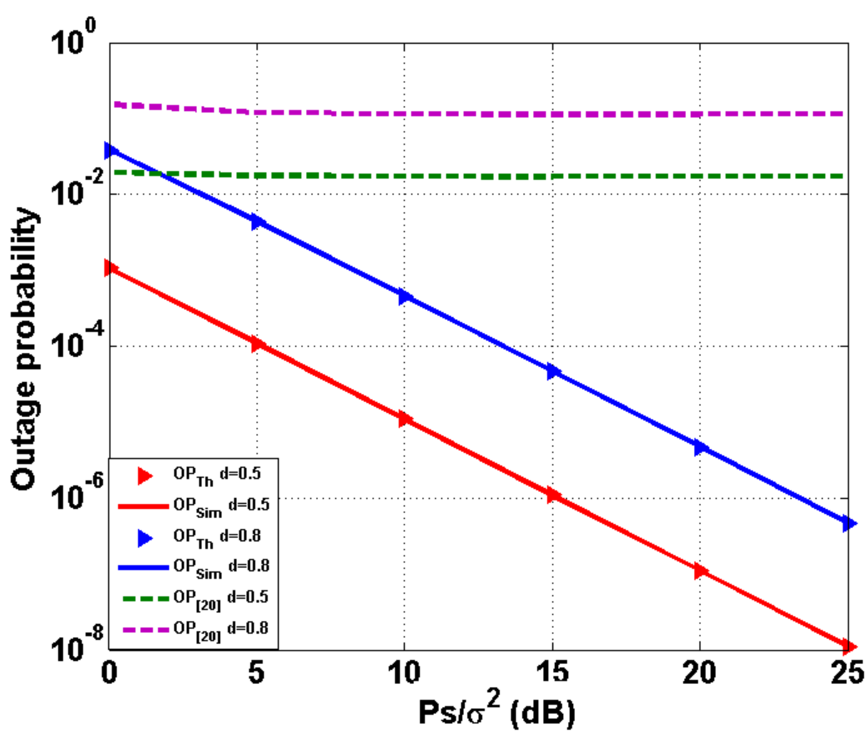

Figure 3.9: Outage probability of secondary system and its comparison with the scheme proposed in [2]

Chapter 4

Cooperative spectrum sharing with Energy Harvesting Capability for Wireless Sensor Networks

4.1 Introduction

Recently there has been growing impetus on developing smart cities thorough out the world [35]-[36]. Smart city is an intelligent city that is able to integrate and synthesize data for many purposes which helps in improving the quality of life in cities. The Smart city is an innovation of ICT (Information and communication technology), which is based upon IoT (Internet of thing), where the motivation is to connect different parts of the city by using sensors which will be useful in real-time monitoring of the public infrastructures such as bridges, roads, buildings as well as climate conditions [35]. Apart from above, the concept of ”smartness” has also been brought in technologies such as smart meters, smart grid, energy conservatism, recycling, waste management etc. [35]. To further boost the above technology, countries such as India has recently approved a proposal to invest heavily in smart city development [36]. For effective development of smart city, sensors have to be deployed in very large numbers and they have to be interconnected, so that the collected data can be transmitted to a CBS, where intelligent decisions based on this data can be made [35]. There are few issues identified in the aforementioned definition i.e. deployment of sensors throughout the city and transfer the collected information to the CBS which require both power and frequency spectrum. As the sensor nodes do not need to send the data all the time, therefore providing a dedicated spectrum to WSN is not an economically viable approach. Furthermore in case of WSN, providing energy storage mechanism is a critical issue in terms of size and location [37]. In this chapter, to alleviate the above issues, we propose a self-sustaining wireless sensor network that will utilize advance techniques such as cooperative spectrum sharing (CSS) [15] and RF energy harvesting (EH) to satisfy its requirement of spectrum and power respectively. In CSS, an unlicensed (secondary/cognitive) user is allowed to coexist in licensed spectrum of primary user (PU) on the condition that secondary user (SU) will assist the PU to achieve its target rate of communication [15]. Moreover, instead of using an internal battery or external recharging mechanism for its operation, it will prefer other sources of renewable energy like thermal, solar, wind, mechanical etc. The most reliable one, in case of WSN, is harvesting energy from the RF signals present in the environment, commonly known as RF or wireless EH. Various studies have shown that the wireless EH is the viable solution in solving the issues of energy constrained systems [38]. Hence in the proposed work, we characterize WSN as an energy-constrained SU, which will harvest energy and spectrum from PU, in return, it will ensure that PU meets its target rate of communication.

Some recent work have incorporated RF EH in cooperative relaying [39–41] where a single node operates for both EH and information processing. In [39] two relaying protocols are discussed for Rayleigh fading channel, namely PSR (Power switching relay) and TSR (Time switching relay). In PSR, relay utilizes fraction of signal power coming from source for EH and remaining power for information processing. In TSR, relay will harvest energy in EH period and remaining time is used for information processing. Here, relay is used to amplify the source data and forward it to the destination. No spectrum sharing has been discussed. Both [40]- [41] have discussed spectrum sharing protocol with EH but in underlay mode. Moreover, SU is not helping the PU in achieving the target rate of communication. In underlay mode, some power constraint on SU is superimposed so that SU will cause only an acceptable amount of interference at PU.

In this chapter, a two phase protocol for energy as well as spectrum harvesting along with information transmission in overlay mode has been proposed for Nakagami fading channel. In the proposed protocol, a sensor node which acts a s a decode-and-forward relay for the PU [42] will harvest energy from primary transmission and will use that harvested energy to assist the PU in achieving the required rate of communication by transmitting its data to the destination. Moreover, part of the harvested energy will also be utilized by the node to send its own data to CBS. However, as compared to underlay mode of transmission, the proposed overlay protocol does not suffer from power constraint at the relay node [42].

4.2 System Model with Mathematical Analysis

In this architecture, primary and secondary system consists of transmitter receiver pair known as Primary Transmitter-Primary Receiver (PT-PR) and Secondary Transmitter-Secondary Receiver (ST-SR) respectively as shown in Fig. 4.1a). For simplicity, we assume that the link between PT-PR fails, and primary user is not able to achieve its target rate of communication, R_p (due to physical obstacles, poor channel conditions etc. [8]), in such case PT will require some cooperation from neighbouring nodes to forward its data to PR with target rate of R_{pt}. ST node (if it can) will assist PT by forwarding its data to PR and simultaneously transfer its own data to SR. As ST is self-sustaining sensor node, it will harvest the required energy from signal it received from PT. Therefore the whole protocol works as follow: In first phase, PT will broadcast PU's signal (x_p) which will be received by ST and SR only. After receiving the signal, ST will utilize ρ amount of signal power to harvest energy and remaining for signal decoding. In second phase, this harvested energy will be used to transfer both primary as well as secondary signal (x_s). ST will assign some (α) amount of power to x_p and remaining to x_s, so that target rate at PR is met. As SR has prior knowledge of x_p from phase 1, so it can cancel the interference received in phase 2 and will extract only the required signal i.e. x_s. The above protocol can be described in the form of pseudo code [1] as below

CSS with EH in two phase protocol
If PT-PR fails
If ST can help PT by forwarding x_p to PR

1 Enters into two phase protocol.

2 Phase1:

a PT will broadcast x_p which will be received by ST, SR.

b ST will harvest ρ amount energy from above transmission and will use remaning energy for x_p signal decoding.

3 Phase2: ST will use α fraction of power from harvested energy to transmit x_p and reaming to transmit ST's signal i.e. x_s.

4 As ST has prior knowldge of x_p from phase1 so it will cancel out the interfere signal x_p received in phase2.

else ST will keep silent.
else PT will continue transmission with PR directly.

The channels between the nodes are modeled as frequency non-selective Nakagami block fading. The channel coefficient between PT-ST, ST-PR, ST-SR, PT-SR, is h_1, h_2, h_3, h_4 respectively. Here, $h_i \sim$ Nakagami (m,Ω_i) where, m is the shape parameter and Ω is the controlling parameter. $\Omega_i = d_i^{-v}$ where, v is the path loss exponent and d_i is the distance between the corresponding link. The instantaneous gain of each channel is given as $\gamma_i = |h_i|^2$. γ_i is the random variable given by Gamma (k,θ_i) where, k=m and θ_i is the scale parameter, defined as $\theta_i = \frac{\Omega_i}{m}$. The additive white Gaussian noise (AWGN) at receiver is represented as $r \sim \mathcal{CN}(0, \sigma^2)$ which indicates 0 mean and σ^2 variance. x_p and x_s denotes the information-bearing symbol sent by PT and ST respectively, which is assumed to be independently circularly-symmetric complex Gaussian (CSCG) distributed with zero mean and unit variance, i.e. $x_p \sim \mathcal{CN}(0, 1)$ and $x_s \sim \mathcal{CN}(0, 1)$. R_{pt} and R_{st} represents the target rate at primary and secondary receiver respectively.

The information signal received at ST during the first phase is given by $y_{st} = \sqrt{P_p} h_1 x_p + n_{st}$ where, P_p is the transmission power of PT and $n_{st} \sim \mathcal{CN}(0, \sigma_{st}^2)$ is the AWGN received at ST. Here, ST works as a power splitting based relay as shown in Fig. 4.1b), the power is split in the ratio of $\rho : (1-\rho)$. ρ is for energy harvesting and $(1-\rho)$ for information processing, $0 \le \rho \le 1$. Signal received by energy harvester is given by $\sqrt{\rho} y_{st} = \sqrt{\rho P_p} h_1 x_p + \sqrt{\rho} n_{st}$. The harvested energy at ST for half of the block time of length T can be given by $E_h = \frac{\eta \rho P_p |h_1|^2 T}{2}$ where, $0 \le \eta \le 1$ is the energy conversion efficiency. The power will be dispensed for remaining T/2 time and hence given by

$$P_h = \frac{E_h}{T/2} = \eta \rho P_p \left| h_1 \right|^2. \quad (4.1)$$

The signal received by information receiver is given by

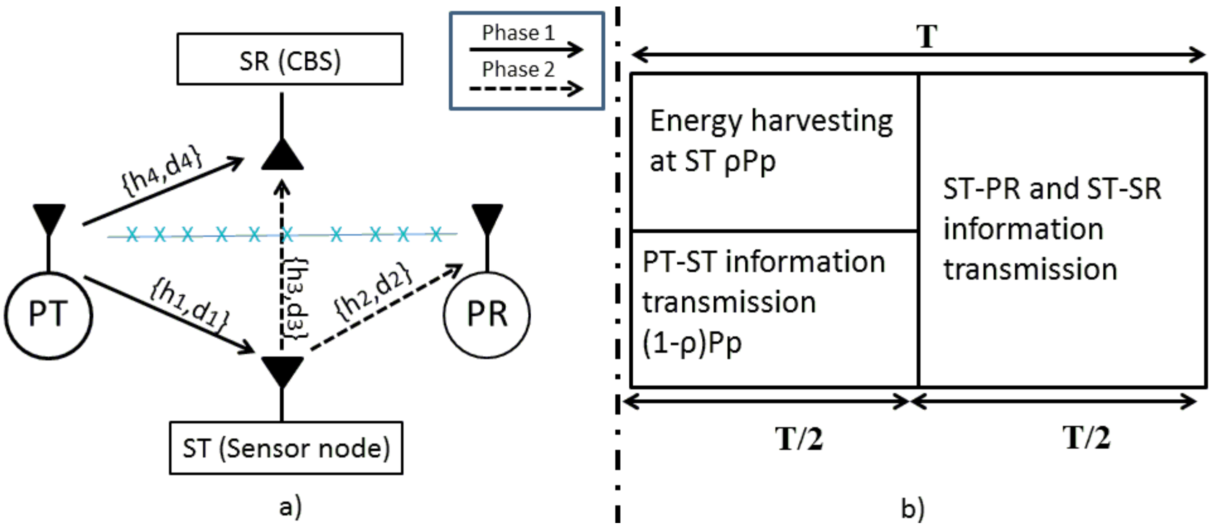

Figure 4.1: a) System Model b) Proposed protocol illustration for energy harvesting and information transmission at ST

$$\sqrt{(1-\rho)} y_{st} = \sqrt{(1-\rho) P_p} h_1 x_p + \sqrt{(1-\rho)} n_{st} + n_{rf} \quad (4.2)$$

where, $n_{rf} \sim \mathcal{CN}(0, \sigma_{rf}^2)$ is the sampled AWGN due to RF band to baseband signal conversion. Therefore, total AWGN noise at information receiver is $n_{ir} = \sqrt{(1-\rho)} n_{st} + n_{rf}$ and $\sigma_{ir}^2 = (1-\rho)\sigma_{st}^2 + \sigma_{rf}^2$. Consequently, the rate achieved at information receiver of ST can be given by

$$R_{ir} = \frac{1}{2} \log_2(1 + SNR_{ir}) \quad (4.3)$$

where, $SNR_{ir} = \frac{(1-\rho) P_p \gamma_1}{\sigma_{ir}^2}$. In transmission phase 2, ST decodes the received signal (x_p) at information receiver and transmits it along with x_s by providing fraction of α and $(1-\alpha)$ power respectively. The signal received at PR is given by $y_{pr} = \sqrt{\alpha P_h} x_p h_2 + \sqrt{(1-\alpha) P_h} x_s h_2 + n_{pr}$ where, $n_{pr} \sim \mathcal{CN}(0, \sigma_{pr}^2)$ is the AWGN received at PR and P_h is defined in(4.1). After substituting P_h, we get $y_{pr} = \sqrt{\alpha \eta \rho P_p \left| h_1 \right|^2} x_p h_2 + \sqrt{(1-\alpha) \eta \rho P_p \left| h_1 \right|^2} x_s h_2 + n_{pr}$. The rate achieved at PR is given by

$$R_{pr} = \frac{1}{2} \log_2(1 + SNR_{pr}) \quad (4.4)$$

where, $SNR_{pr} = \frac{\alpha \eta \rho P_p \gamma_1 \gamma_2}{(1-\alpha) \eta \rho P_p \gamma_1 \gamma_2 + \sigma_{pr}^2}$.

4.3 Outage Probability of Primary System

The outage probability for the primary system can be given as

$$P_p^{out} = 1 - P\left[R_{ir} > R_{pt}\right] P\left[R_{pr} > R_{pt}\right]. \tag{4.5}$$

(4.5) shows that outage at PR will be declared if either ST or PR fails in decoding primary's signal with target rate of R_{pt}. Using (4.3)

$$P\left[R_{ir} > R_{pt}\right] = 1 - P\left[\gamma_1 < \frac{\psi_p \sigma_{ir}^2}{(1-\rho)P_p}\right] = 1 - \frac{\Gamma(k, \frac{\psi_p \sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)} \tag{4.6}$$

where, $\psi_p = 2^{2R_{pt}} - 1$, $\Gamma(.,.)$ is the lower incomplete gamma function[1] and $\Gamma(.)$ is the complete gamma function[2]. Using (4.4),

$$P\left[R_{pr} > R_{pt}\right] = 1 - P\left[\frac{\alpha\eta\rho P_p \gamma_1\gamma_2}{(1-\alpha)\,\eta\rho P_p\gamma_1\gamma_2 + \sigma_{pr}^2} < \psi_p\right] \tag{4.7}$$

where, $z = \frac{\psi_p \sigma_{pr}^2}{\eta\rho P_p[\alpha - \psi_p(1-\alpha)]}$. (4.7) can be rewritten as,

$$P\left[R_{pr} > R_{pt}\right] = \begin{cases} 1 - P[\gamma_1\gamma_2 < z] & \psi_p < \frac{\alpha}{1-\alpha} \\ 1 - P[\gamma_1\gamma_2 > z] = 0 & \text{otherwise} \end{cases} \tag{4.8}$$

The second equality in (4.8) is because of the fact that for $\psi_p > \frac{\alpha}{1-\alpha}$, the z term will be negative and the probability of gamma distribution greater than a negative number is always 1. Moreover for $\psi_p = \frac{\alpha}{1-\alpha}$, z tends to $+\infty$ and the probability of product of gamma distribution less than $+\infty$ is also 1. Now solving for first equality when z is positive, using concept of product of two RVs, we obtain

$$\begin{aligned} P[\gamma_1\gamma_2 < z] &= \int_0^\infty f_{\gamma_1}(x) P(\gamma_2 \le z/x)dx \\ &= \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)} e^{-\frac{x}{\theta_1}} \Gamma\left(k, \frac{z}{x\theta_2}\right) dx. \end{aligned} \tag{4.9}$$

Using (4.7), (4.8) and (4.9) we get,

$$P\left[R_{pr} > R_{pt}\right] = \begin{cases} 0 & 0 \le \alpha \le \hat{\alpha} \\ 1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)} e^{-\frac{x}{\theta_1}} \Gamma\left(k, \frac{z}{x\theta_2}\right) dx & \hat{\alpha} < \alpha \le 1 \end{cases} \tag{4.10}$$

[1] $\Gamma(k, x) = \int_0^x t^{k-1} e^{-t} dt$
[2] $\Gamma(k) = \int_0^\infty t^{k-1} e^{-t} dt$

where, $\hat{\alpha} = \frac{\psi_p}{\psi_p + 1}$. Using (4.5), (4.6) and (4.10) we get,

$$P_p^{out} = \begin{cases} P_{p_1}^{out} = 1, & 0 \leq \alpha \leq \hat{\alpha} \\ P_{p_2}^{out}, & \hat{\alpha} < \alpha \leq 1 \end{cases} \tag{4.11}$$

where,

$$P_{p_2}^{out} = 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p \sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)}\right)\left(1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)} e^{-\frac{x}{\theta_1}} \Gamma\left(k, \frac{z}{x\theta_2}\right) dx\right). \tag{4.12}$$

Eq.(4.12), can be obtained in closed form using ([43], eq.(7)),

$$P_{p_2}^{out} = 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p \sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)}\right)\left(1 - \frac{1}{(\Gamma(k))^2} G_{1,3}^{2,1}\left[\frac{z}{\theta_1\theta_2} \mid \begin{matrix} & 1 & \\ k & k & 0 \end{matrix}\right]\right) \tag{4.13}$$

where, G[.] is the Meijer G-function as defined in ([44], eq.(9.301)). For m=1 Nakagami fading reduces to Rayleigh Fading Channel and (4.13) reduces to

$$P_{p_2}^{out} = 1 - \left(e^{-\frac{\psi_p \sigma_{ir}^2}{\theta_1(1-\rho)P_p}}\right)\left(\sqrt{\frac{4z}{\theta_1\theta_2}} K_1\left(\sqrt{\frac{4z}{\theta_1\theta_2}}\right)\right) \tag{4.14}$$

where, $K_1(.)$ is the first order modified bessel function of second kind [44]. Here we have used $\int_0^\infty e^{\left(-\frac{\beta}{4x} - \gamma x\right)} dx = \sqrt{\frac{\beta}{\gamma}} K_1(\sqrt{\beta\gamma})$ from [44].

4.4 Outage Probability of Secondary system

The signal received by SR in transmission phase 1 is given by

$$y_{sr_1} = \sqrt{P_p} h_4 x_p + n_{sr} \tag{4.15}$$

where, $n_{sr} \sim \mathcal{CN}(0, \sigma_{sr}^2)$ is the AWGN received at SR. At SR, an estimate of x_p is obtained as $\widehat{x_p} = \frac{y_{sr_1}}{\sqrt{P_p} h_4} = x_p + \frac{n_{sr_1}}{\sqrt{P_p} h_4}$. In transmission phase 2, signal received at SR from ST is given by

$$y_{sr_2} = \sqrt{\alpha P_p \eta \rho \left|h_1\right|^2} h_3 x_p + \sqrt{(1-\alpha) P_p \eta \rho \left|h_1\right|^2} h_3 x_s + n_{sr} \tag{4.16}$$

The estimate $\widehat{x_p}$ is used to cancel the interference component from (4.16), to obtain $\widehat{y}_{sr_2} = \sqrt{(1-\alpha) P_p \eta \rho \left|h_1\right|^2} h_3 x_s + n_{sr}$. The achieved rate between ST and SR, conditioned on successful decoding of x_p at both ST and SR in the first transmission phase, is given by

$$R_{sr} = \frac{1}{2} \log_2 \left[1 + SNR_{sr}^{df}\right] \tag{4.17}$$

where, $SNR_{sr}^{df} = \frac{(1-\alpha)\eta\rho P_p\gamma_1\gamma_3}{\sigma_{sr}^2}$. Moreover, using (4.15) the rate achieved at SR in phase 1 is given by

$$R_{sd} = \frac{1}{2}\log_2\left[1 + \frac{P_{pt}\gamma_4}{\sigma_{sr}^2}\right]. \tag{4.18}$$

Outage is declared if ST and SR are not able to decode x_p, and therefore the outage probability of the secondary signal transmission with target rate R_{st} is given as

$$P_s^{out} = 1 - P\left[R_{ir} > R_{pt}\right]P\left[R_{sd} > R_{pt}\right]P\left[R_{sr} > R_{st}\right]. \tag{4.19}$$

Using (4.18),

$$P\left[R_{sd} > R_{pt}\right] = 1 - P\left[\gamma_4 < \frac{\psi_p\sigma_{sr}^2}{P_p}\right] = 1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{sr}^2}{\theta_4 P_p})}{\Gamma(k)}. \tag{4.20}$$

Using (4.17),

$$P\left[R_{sr} > R_{st}\right] = 1 - P\left[R_{sr} < R_{st}\right] = 1 - P\left[\gamma_1\gamma_3 < y\right]$$

where, $y = \frac{\psi_s\sigma_{sr}^2}{(1-\alpha)\eta\rho P_p}$ and $\psi_s = 2^{2R_{st}} - 1$. Therefore,

$$\begin{aligned} P\left[R_{sr} > R_{st}\right] &= 1 - \int_0^\infty f_{\gamma_1}(x)P(\gamma_3 \leq y/x)dx \\ &= 1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\Gamma\left(k, \frac{y}{x\theta_3}\right)dx. \end{aligned} \tag{4.21}$$

Using (4.6), (4.19), (4.20) and (4.21) we get,

$$\begin{aligned} P_s^{out} =& 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)}\right)\left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{sr}^2}{\theta_4 P_p})}{\Gamma(k)}\right) \\ &\left(1 - \frac{1}{\theta_1^k(\Gamma(k))^2}\int_0^\infty x^{(k-1)}e^{-\frac{x}{\theta_1}}\Gamma\left(k, \frac{y}{x\theta_3}\right)dx\right). \end{aligned} \tag{4.22}$$

Eq.(4.22), can be obtained in closed form using ([43], eq.(7)),

$$P_s^{out} = 1 - \left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p})}{\Gamma(k)}\right)\left(1 - \frac{\Gamma(k, \frac{\psi_p\sigma_{sr}^2}{\theta_4 P_p})}{\Gamma(k)}\right)\left(1 - \frac{1}{(\Gamma(k))^2}G_{1,3}^{2,1}\left[\frac{y}{\theta_1\theta_3}\,\middle|\,\begin{matrix} & 1 & \\ k & k & 0\end{matrix}\right]\right) \tag{4.23}$$

where, G[.] is the Meijer G-function as defined in ([44], eq.(9.301)).

For m=1 i.e. Rayleigh Fading Channel, (4.23) can be re-written as

$$\begin{aligned} P_s^{out} =& 1 - \left(e^{-\frac{\psi_p\sigma_{ir}^2}{\theta_1(1-\rho)P_p}}\right)\left(e^{-\frac{\psi_p\sigma_{sr}^2}{\theta_4 P_p}}\right) \\ &\left(\sqrt{\frac{4y}{\theta_1\theta_3}}K_1\left(\sqrt{\frac{4y}{\theta_1\theta_3}}\right)\right). \end{aligned} \tag{4.24}$$

where, $K_1(.)$ is the first order modified bessel function of second kind [44]. Here we have used

$\int_0^\infty e^{\left(-\frac{\beta}{4x}-\gamma x\right)}dx = \sqrt{\frac{\beta}{\gamma}}K_1(\sqrt{\beta\gamma})$ from [44].

4.5 Simulation results and discussion

In this section we have plotted outage probability for primary and secondary system with respect to location of the nodes in Fig. 4.2 and 4.3 respectively. We have considered $\frac{P_p}{\sigma_{ir}^2} = \frac{P_p}{\sigma_{pr}^2} = \frac{P_p}{\sigma_{sr}^2} =$ 40 dB. The path loss exponent (i.e. v) is considered to be 3. The target rate for both systems are considered to be 1 i.e. $R_P = R_S = 1$. The results are shown for:

- two different values of m i.e. $m = 0.5$ (half Gaussian pulse), 1 (Rayleigh fading)
- two different values of ρ i.e. $\rho = 0.25$, 0.75
- two different values of η i.e. $\eta = 0.5$, 1
- for $\alpha = 0.8$
- distance of d (where, $0.1 \leq$ d ≤ 0.9) between PT-ST node and (1-d) between ST-PR, ST-SR links. PT-SR distance is assumed to be 1.

It is very obvious that with increasing value of m, fading will become less severe; therefore outage probability decreases when m changes from 0.5 to 1 in both Fig.4.2 and 4.3.

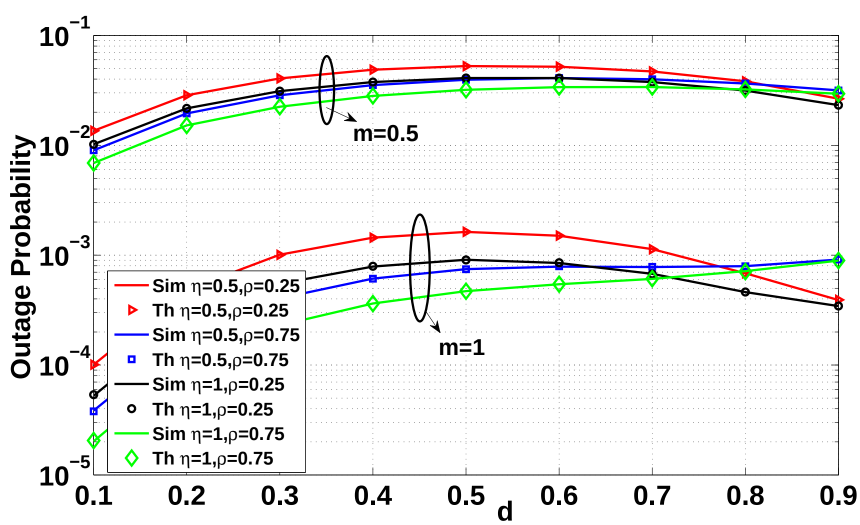

Figure 4.2: Outage probability for Primary System

From Fig. 4.2, it can be observed that when d is small, outage probability decreases with increasing ρ, as less value of d indicates PT and ST are closed enough and hence more energy can be saved by using large ρ. However, when d $\geq$0.8, we need to choose small value of ρ in order to have less outage probability. The reason for this is, as ST is moving away from PT, it will require more power for decoding the signal correctly. So proper choice of ρ depends

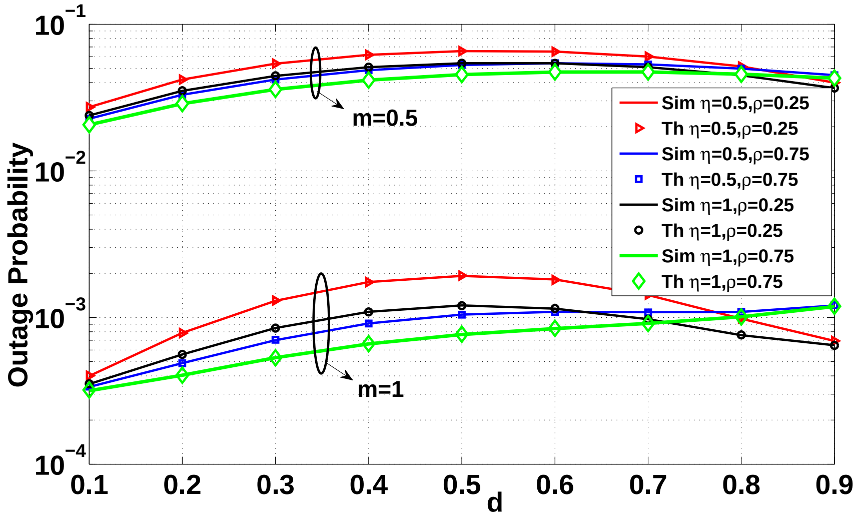

Figure 4.3: Outage probability for Secondary System

on the location of nodes. Similarly, Fig. 4.3 illustrates the outage probability of secondary system with respect to d. The trend observed in secondary system is quite similar to that of primary system. This can be explained as follows. Since the outage probability of secondary system is also dependent on the successful decoding of primary signal by ST in Phase 1, hence as d (i.e.. distance between PT-ST) increases the probability of successful decoding of primary signal reduces hence the outage increases. Furthermore, when d $\geq$ 0.8, more power is required for decoding and less for transmission, hence outage probability decreases for $\rho = 0.25$.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Cognitive radio is a promising technology to solve spectrum scarcity problem. Cooperative spectrum sharing scheme is an alternative framework to realize a cognitive radio network. But conventional CSS schemes have many issues, few of them are resolved in this thesis. The research work done in the thesis can be categorized into four parts. In first part, conventional CSS schemes and various wireless terminologies have been discussed.

In second part, a two phase cooperative spectrum sharing scheme with decode and forward relay at secondary system has been proposed. The proposed technique utilizes transmit antenna selection scheme at secondary transmitter in order to reduce interference at primary receiver due to presence of secondary signal.

In third part, a three phase cooperative spectrum sharing scheme with decode and forward relay at secondary system has been proposed. The proposed technique utilizes STBC to cancel interference at primary as well as secondary receiver. As power is divided equally among primary and secondary signals at ST, therefore performance of secondary system is drastically improved without affecting the performance of primary system. It has also been shown that by using the proposed scheme it is possible to achieve a diversity of 3 and 2 for primary and secondary system respectively.

In fourth part, a new protocol for wireless sensor nodes has been discussed. In this protocol, WSN which is characterized as a secondary user can harvest both energy and spectrum from primary signal transmission. Simultaneously it will also help primary user in achieving the target rate of communication.

The excellent agreement between simulated results and the analytically obtained closed form expressions validated the theoretical analysis presented in the thesis.

5.2 Future work

- The work can be extended for adaptive modulation techniques. In which time duration of each phase can be based upon the channel condition, instead of equally dividing the time block.
- In the proposed work (in chapter 2 and 3), overall time was constant but ST is keep on increasing the power to provide better performance. The future work can be the scenario where overall time and power, both are fixed for entire communication. In such scenario by using some transmit CSI, PT can estimate the channel between PT-ST and based upon channel conditions, it will use only the amount of power by which ST can decode the x_p signal correctly and remaining power is assigned to ST for further transmission.

Appendix

Appendix A

Derivation for the probability by which R_{MRC} fails to achieve target rate [34]. According to (2.16)

$$\begin{aligned} P[R_{MRC} < R_{pt}] &= P\left[\frac{P_p\gamma_1}{\sigma^2} + \frac{\alpha P_s\gamma_{\max}}{(1-\alpha)P_s\gamma_{\min} + \sigma^2} < \rho\right] \\ &= \int_0^{\frac{\sigma^2}{P_p}(\rho - \frac{\alpha}{1-\alpha})} P\left[\gamma_{\max} < c + b\gamma_{min}\right] f_{\gamma_1} d_{\gamma_1} \end{aligned} \tag{5.1}$$

where,

$$b = \left(\frac{\alpha}{1-\alpha}\right)\left(\rho - \frac{P_p\gamma_1}{\sigma^2}\right), c = \frac{\sigma^2}{\alpha P_s}\left(\rho - \frac{P_p\gamma_1}{\sigma^2}\right). \tag{5.2}$$

Moreover, $\gamma \sim \varepsilon(1)$, therefore PDF of γ_1 is given as

$$f_{\gamma_1}(\gamma_1) = \begin{cases} e^{-\gamma_1} & \gamma_1 \geq 0 \\ 0 & \text{Otherwise} \end{cases} \tag{5.3}$$

Solving for,

$$P\left[\gamma_{\max} < c + b\gamma_{\min}\right] = \int\int f_{\gamma_{\max},\gamma_{\min}}(w,z)dwdz \tag{5.4}$$

where, $f_{\gamma_{\max},\gamma_{\min}}(w,z)$ is the joint pdf of $\gamma_{\max}$ and $\gamma_{\min}$. Moreover, joint CDF is given by

$$\begin{aligned} F_{\gamma_{\max},\gamma_{\min}}(w,z) &= P[\gamma_{\max} \leq w, \gamma_{\min} \leq z] \\ &= P[\max(\gamma_5,\gamma_6) \leq w, \min(\gamma_5,\gamma_6) \leq z]. \end{aligned} \tag{5.5}$$

Considering following mention cases:

Case 1: $w > z$ as shown in Fig. 5.1, (5.5) can be rewritten as,

$$
\begin{aligned}
&= P[\max(\gamma_5, \gamma_6) \le w] - P[\min(\gamma_5, \gamma_6) \le z] \\
&= P[\gamma_5 \le w]P[\gamma_6 \le w] - P[z \le \gamma_5 \le w]P[z \le \gamma_6 \le w] \\
&= (P[\gamma_5 \le w])^2 - (P[z \le \gamma_5 \le w])^2 \\
&= (1 - e^{-wd_5^v})^2 - \left(\int\limits_z^w d_5^v e^{-xd_5^v} dx \right)^2 \\
&= 1 - 2(e^{-wd_5^v}) - e^{-2zw} + 2e^{d_5^v(w+z)}.
\end{aligned} \tag{5.6}
$$

Differentiating (5.6) to get joint PDF,

$$
f_{\gamma_{\max},\gamma_{\min}}(w,z) = \frac{\partial^2}{\partial z \partial w} F_{\gamma_{\max},\gamma_{\min}}(w,z) = 2d_5^{2v} e^{-d_5^v(w+z)}. \tag{5.7}
$$

Case 2: $w \le z$ as shown in Fig. 5.1

$$
P[\max(\gamma_5, \gamma_6) \le w] = (P[\gamma_5 \le w])^2 = (1 - e^{-wd_5^v})^2. \tag{5.8}
$$

Differentiating (5.8) to get joint PDF,

$$
f_{\gamma_{\max},\gamma_{\min}}(w,z) = \frac{\partial^2}{\partial z \partial w} F_{\gamma_{\max},\gamma_{\min}}(w,z) = 0. \tag{5.9}
$$

Therefore,

$$
f_{\gamma_{\max},\gamma_{\min}}(w,z) = \begin{cases} 2d_5^{2v} e^{-d_5^v(w+z)} & w > z \\ 0 & \text{Otherwise} \end{cases} \tag{5.10}
$$

From (5.4),

$$
P\left[\gamma_{\max} < c + b\gamma_{\min}\right] = \int\limits_0^{\infty} \int\limits_z^{c+bz} 2d_5^{2v} e^{-d_5^v(w+z)} dw dz. \tag{5.11}
$$

On solving,

$$
P\left[\gamma_{\max} < c + b\gamma_{\min}\right] = 1 - \frac{2e^{-cd_5^v}}{b+1}. \tag{5.12}
$$

As probability always lies between 0 and 1. Therefore, (5.12) gives b≥1 and c≥0. Using this, $\gamma_1 \le \frac{\sigma^2}{P_p}(\rho - \frac{\alpha}{1-\alpha})$. Therefore, (5.1) can be written as

$$
P[R_{MRC} < R_{pt}] = \int_0^{\frac{\sigma^2}{P_p}(\rho - \frac{\alpha}{1-\alpha})} \left(1 - \frac{2e^{-cd_5^v}}{b+1}\right) f_{\gamma_1} d_{\gamma_1}. \tag{5.13}
$$

After putting value of b and c using (5.2) and PDF of γ_1 from (5.3), (5.13) can be solved and

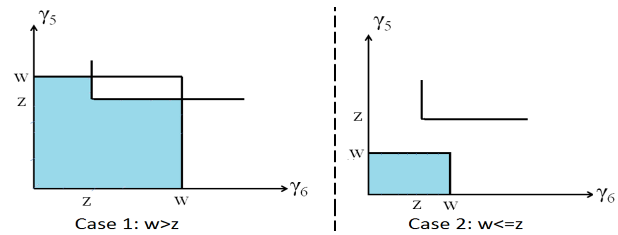

Figure 5.1: Different Cases

written as,

$$P[R_{MRC} < R_{pt}] = 1 - e^{-\frac{\sigma^2}{P_p}(\rho - \frac{\alpha}{1-\alpha})} + \frac{2}{n} e^{-\frac{d_5^v \sigma^2 \rho}{\alpha P_s} + \frac{mp}{n}}$$
$$\left(Ei\left[\frac{p\sigma^2}{P_p}\left(\rho - \frac{\alpha}{1-\alpha}\right) - \frac{mp}{n}\right] - Ei\left[-\frac{mp}{n}\right]\right)$$

where, $\alpha \leq \frac{\rho}{\rho+1}$, $m = \left(\frac{1-\alpha}{\alpha}\right)\rho + 1$, $n = \left(\frac{1-\alpha}{\alpha}\right)\frac{P_p}{\sigma^2}$, $p = \frac{d_5^v P_p}{\alpha P_s} - 1$ and Ei represents the exponential integral defined as $Ei(x) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} dt$.

Appendix B

Derivation for the *Special case (when α=1)*: ST acts as a selection combiner. Solving for (2.19),

$$\begin{aligned} P[R_{MRC} < R_{pt}] &= P\left[\frac{P_p \gamma_1}{\sigma^2} + \frac{P_s \gamma_{\max}}{\sigma^2} < \rho\right] \\ &= \int_0^{\frac{\rho\sigma^2}{P_p}} \int_0^{\frac{\rho\sigma^2}{P_s} - \frac{P_p\gamma_1}{P_s}} f_{\gamma_1}(\gamma_1) f_{\gamma_{max}}(\gamma_{max}) d\gamma_{\max} d\gamma_1. \end{aligned} \tag{5.14}$$

As already defined $\gamma_1 \sim \varepsilon(1)$ and $\gamma_{\max} = \max(\gamma_5, \gamma_6)$. Moreover, $f_{\gamma_1}(\gamma_1)$ is defined as the PDF of γ_1 and is given by $f_{\gamma_1}(\gamma_1) = \begin{cases} e^{-\gamma_1} & \gamma_1 > 0 \\ 0 & \text{otherwise} \end{cases}$ and PDF of $\gamma_{\max}$ is given by $f_{\gamma_{\max}}(\gamma_{\max}) = \begin{cases} 2d_5^v e^{-d_5^v \gamma_{\max}}(1 - e^{-d_5^v \gamma_{\max}}) & \gamma_{\max} > 0 \\ 0 & \text{otherwise} \end{cases}$. Therefore, (5.14) can be written as,

$$\begin{aligned} P[R_{MRC} < R_{pt}] =& e^{-g}\left(\frac{e^{((2\mu g) - 2\psi)}}{2\mu - 1} - \frac{2e^{((\mu g) - \psi)}}{\mu - 1} - 1\right) \\ & - \left(\frac{e^{2\psi}}{2\mu - 1} - \frac{2e^{-2\psi}}{\mu - 1} - 1\right) \end{aligned}$$

where, g=$\frac{\rho\sigma^2}{P_P}$, $\psi = \frac{d_5^v \rho\sigma^2}{P_s}$ and $\mu = \frac{d_5^v P_p}{P_s}$.

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