Cooperative Spectrum Sharing in Cognitive Radio Networks

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Progress Report

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CERTIFICATE

This is to certify that the present research work entitled "Cooperative Spectrum Sharing in Cognitive Radio Networks" being submitted to NIIT University, Neemrana, Rajasthan, in the fulfillment of the requirements for the course at NIIT University, Neemrana, embodies authentic and faithful record of original research carried out by Prabhpreet Singh Dua, Ramkrishna G. Bihani, Madamsetty Anoop and Anirudh Joshi of B Tech (Area) at NIIT University, Neemrana. They have worked under our supervision and that the matter embodied in this project work has not been submitted, in part or full, as a project report for any course of NIIT University, Neemrana or any other university.

Dr. Sushanta Das

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Part I

Acknowledgement

We take this opportunity to thanks NIIT University on giving us the chance to work on this project which brought us a wide domain of experiences and learnings. In doing this project we were fortunate to receive the assistance of Dr. Sushanta Das who was generous with the time and provided us with exemplary guidance, monitoring and constant encouragement throughout the course of this research project. We would also like to thank Jetendra Joshi and Abhinaba Banerjee for his cordial support, valuable information and guidance We express our deepest gratitude to Shivam Vinayak and Paresh Nayyar who helped us in many ways in doing this project.

Part II

Rationale

Wireless spectrum is one of the most imortant resources required for radio communications. Spectrum utilizationis regulated so that essential services can be provided and also protected from harmful interferences. Traditiitonal spectrum governance across the world has tended toward static long term exclusivity of spectrum use in large geographical areas. While the more or less static spectrum allocation strategy has led to many successful apllications, it has also led to almost all of the prime available spectrum being assigned for various applications. It may thus seem that there is no or little or no spectrum available for emerging wireless products and services. On the other hand, there have been several studies and reports over the years that show that spectrum is in face vastly underutilised. Thus, to accomplish opportunistic spectrum use and also to alleviate the artificial scarcity of prime spectrum advanced radio and signal processing techniques armed with Cognitive Radio and Cooperative communication methods is employed.

1 Cognitive Radio

Cognitive Radio (CR) is an adaptive, intelligent radio and network technology that can automatically detect available channels in a wireless spectrum. It intelligently uses underutilized licensed spectrum, thereby addressing spectrum scarcity.

2 Cooperative Communications

- Primary User (PU): A user who is licensed to use the particular spectrum.
- Secondary User (SU): A user who doesn't own the licensed spectrum, but exploits the spectrum in such a way that it does not cause interference to primary users.

Cooperative Communication increases quality of service via cooperation of nodes. Every user can act as a "relay"- forwards the signal received from transmitter or an intermediary node to another intermediary node or receiver. Advantage: It brings Cooperative Diversity i.e. Multiple users bring spatial diversity

Techniques of cooperative communication.

1. Decode and Forward. The relay fully decodes primary user's signal, re-encodes the decoded bits and forwards the re-modulated symbols to the destination.

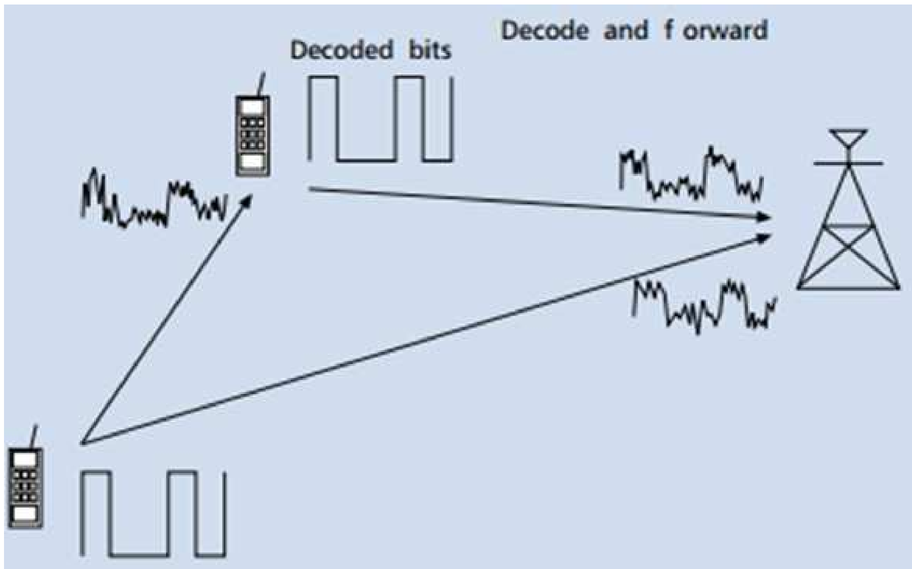

Figure 1: Decode and Forward[9]

2. Amplify and Forward. The amplify-forward scheme entails the relay not to decode, but to amplify and retransmit the received signal. However, the noise variance also gets amplified at the relay.

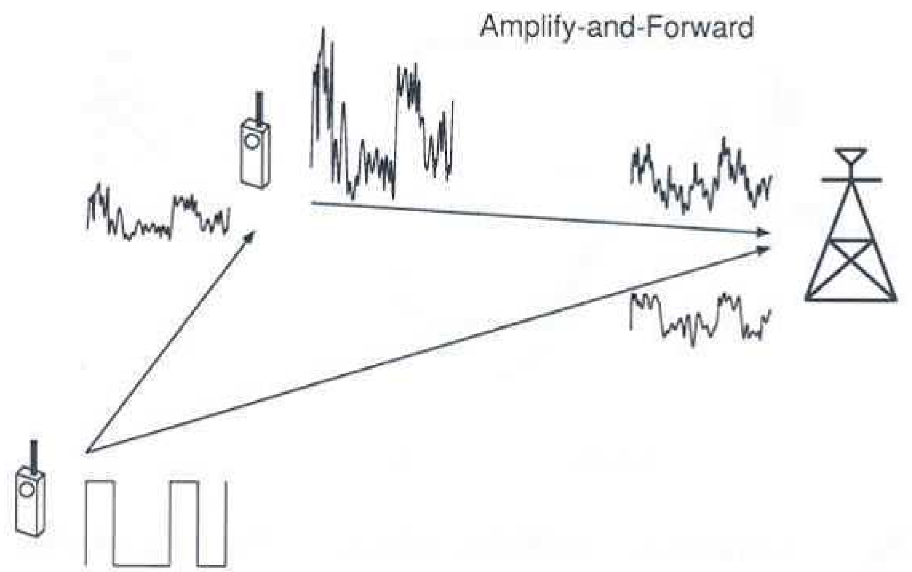

Figure 2: Amplify and Forward[9]

3. Partial Decode and Forward. The relay generates soft-value estimates of the received symbols and retransmits the estimated soft value symbols to the final destination.

3 Cooperative Spectrum Sharing

The secondary nodes extend cooperation to primary users by serving as a relay for the primary user system in exchange of its right to coexist in the primary user frequency band.

The different paradigms of CSS are

3.1 Interweave Paradigm

The interweave paradigm is based on the idea of opportunistic communication. There exist temporary space-time-frequency voids, reffered to as white spaces that are not in constant use in both the licensed and unlicensed bands. This paradigm allows secomdary user to exploit these spectrum holes, to operate in orthogonal dimensions of space, time or frequency relative to primary user. Thus, the utilisation of spectrum is improved by opportunistic reuse over the white spaces. ([1])

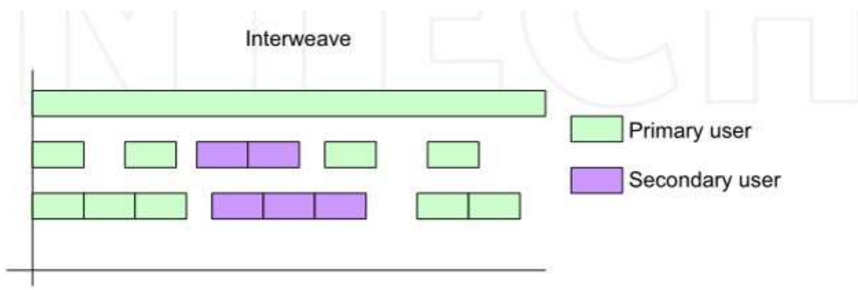

Figure 3: Interweave (Source: [6])

3.2 Underlay

The underlay paradigm mandates that concurrent primary and secondary transmissions may occur only if the interference generated by the secondary transmission at the primary receivers is below some acceptable threshold. ([1])

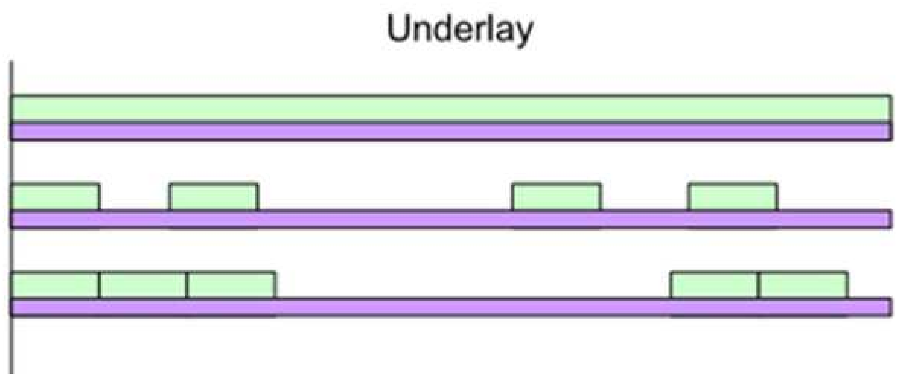

Figure 4: Underlay (Source: [6])

3.3 Overlay

The premise for overlay systems is that the secondary transmitter has knowldege of primary user's transmitted data sequence and how this sequence is encoded. Knowledge of a primary user's data sequence can be exploited by the secondary transmitter in a variety of ways to improve the performance of both the primary and secondary systems. ([1])

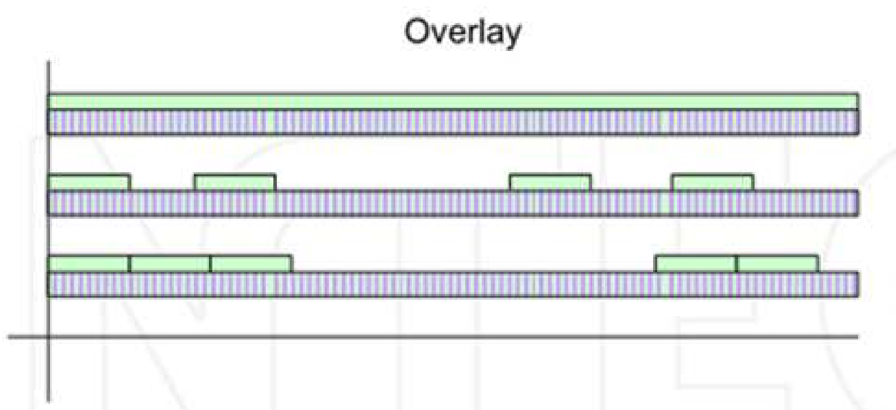

Figure 5: Overlay (Source: [6])

Part III
Objective

4 Introduction

4.1 Cognitive Radio

Cognitive radio is a generic term used to describe a radio that is aware of the environment around it ans can adopt its transmission according to the interface it sees. Cognitive radio can recognize the available systems around them and adjust their frequencies, waveforms and protocols to access those systems efficiently.

4.2 MIMO

MIMO is the core technology of modern wireless communication. MIMO tries to exploit multiple antennas at both the transmitter and receiver to improve the performances of wireless communication without additional radio bandwidth. These performances can be spectral efficiency, data throughput, link range, link reliability,QoS of multiuser situation, etc. MIMO is widely adopted as radio communication standards by IEEE 802.11, IEEE 802.16 and 3GPP LTE.

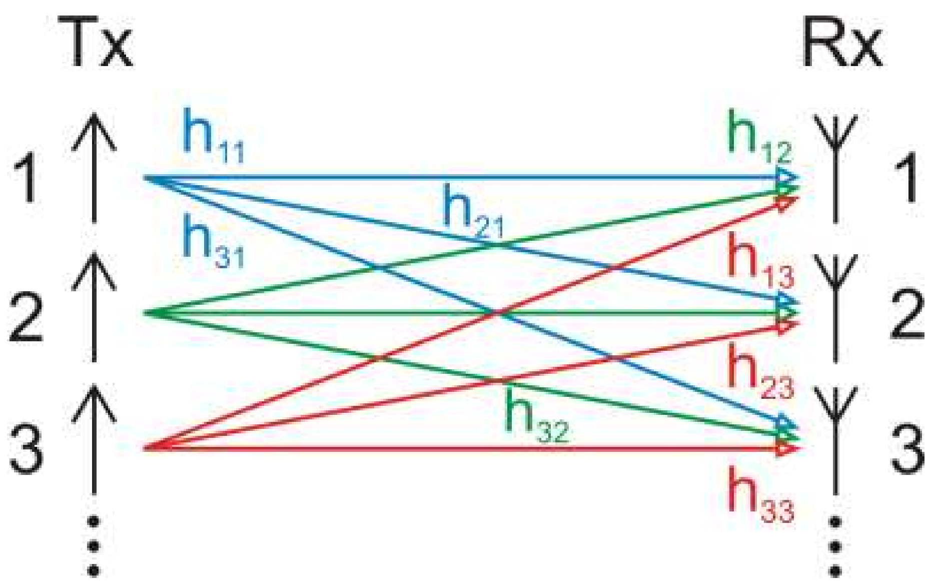

Figure 6: MIMO Channel Model
Image courtsey of Wikipedia.

Benefits of MIMO :

1. Diversity Gain: Diversity is used to combat fading in wireless communication. Multiple copies of the same signal can be transmitted through two or more different communication channels. The commonly used diversity schemes include: time diversity, space diversity,etc.

2. Multiplexing Gain: Multiplexing leads to anincrease in capacity due to the simultaneous transmission of different data streams on multiple spatial dimensions.

There is a fundamental tradeoff between diversty gain and multiplexing gain when MIMO is explored.

4.3 STBC

Space–time block coding is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer. A space time block code can be represented as

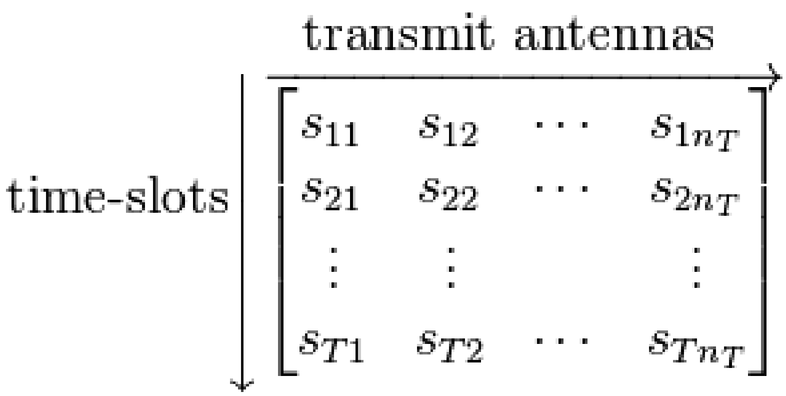

Figure 7: STBC Code
Image courtesy of Wikipedia

s_{ij} is the modulated symbol to be transmitted in time slot i from antenna j. There are to be T time slots and n_T transmit antennas.

If K symbols are encoded within T time slots by space time block code, then the code rate of space time block code is

$$r = \frac{K}{T}$$

5 Objective

The project aims to analyze a two-step hierarchical spectrum sharing protocol based on cooperative decode-forward and partial decode-forward cooperative relaying techniques. The secondary cognitive users can have multiple antennas, whereas the primary users are equipped with either single or multiple antenna(s). We explore the use of space-time block code with rate $R = \frac{6}{4}$ with multi-layer spatial diversity to study the performance of the primary as well as secondary users.

Part IV
METHODOLOGY

We started off with studying and covering the basics required for our project which included studying the course “Wireless Communications” ([8, 7]) and getting a broad idea of cognitive radio . We proceeded with investigating different cognitive radio paradigms that would best suit our model. In our case we chose the overlay technique in which the secondary user has an idea of primary user’s data sequence. We then went on to decide the relaying technique that was to be used in our model. The paper “Partial Decode-Forward Transmission and Channel Estimation Methods for Cooperative Communications” by Sushanta Das was referred to choose an appropriate PDF method. We have kept the implementation of the use of PDF as our future work. In our model we have worked with the assumption that the secondary user is perfectly able to decode the primry user’s data.

MIMO system is essential in our model since we work with STBC code. Thus, we have three antennas at the secondary transmitter while one each at primary transmitter, primary receiver and secondary receiver.

Our next step was analysing the STBC code that we had decided to use in our model. The code was taken from the paper Opportunistic Space-Time Block Codes by Sushanta Das. The given code has rate $R = \frac{6}{4}$ with two layers of diversity $3M_r$ and M_r for message sets A and C, respectively.

$$X_{a,c} = X_a + X_c = \begin{bmatrix} a(0) & -a^*(1) & -a^*(2) & \frac{c^*(0)}{k} \\ a(1) & a^*(0) & \frac{c^*(3)}{k} & -a^*(2) \\ a(2) & \frac{c^*(2)}{k} & a^*(0) & a^*(1) \end{bmatrix}$$

We then had to chose our model’s environment and consider the various simulation variables including SNR gains, the type of modulation of primary user’s data. For a direct communication between Primary transmitter and secondary transmitter we opted for BPSK modulation and, between secondary transmitter and primary user, QPSK modulation was used.

We considered three situationswhere the relay lies:

- near the source
- in the middle of link between source and destination
- near the destination

The path-loss (dB) between the links is reflected as additional SNR gain (loss) in respective receivers. For example, if the relay is closer to the source, the source-relay link would be stronger than the relay- destination and the source-destination links.

With the help of Dr. Sushanta Das we came up with a decoding algorithm that would be employed at primary receiver and secondary receiver and in this we made use of Matched filtering and ML decoding.

Part V
Literature Review

6 Cooperative relay to improve diversity in cognitive radio networks

Paper reference: [10]

This research paper gave us a basic idea about why cooperative communications can be incorporated in cognitive radio networks.

6.1 Cognitive radio and its challenges

Wireless spectrum around the world is allocated by governments and it isn't allocated to maximize the capacity of the particular spectrum. Thus, some spectrum frequencies are left underutilized while others such as the ISM band and the 2G/3G spectrum are experiencing spectrum scarcity. This problem is known as artificial spectrum scarcity.

With recent advancements in communication systems such as highly reconfigurable software defined radios, it is possible to design an intelligent radio system which can be programmed and configured to automatically detect available,unused channels in wireless spectrum and thus use spectrum more effectively. This is the idea of cognitive radio.

Cognitive radios have three main paradigms pertaining to how they use existing unused spectrum:

1. Interweave
2. Underlay
3. Overlay

This paper uses the interweave paradigm, where unused spectrum at a particular point in time is used for a channel at a particular frequency.

Currently, there are primarily two challenges when developing cognitive radio:

1. Primary User Detection: Detecting if there is a primary user already using the spectrum
2. Transmission Opportunity Exploitation: After detection of a white space, secondary users should utilize the given white space for transmission as close as to full capacity without interfering with the primary user.

Therefore, all secondary users can compete and cooperate amongst themselves to maximize efficiency and fairness of resources available (i.e. the white space).

6.2 Cooperative Communications

Wireless channels experience multiple channel impairments apart from additive white Gaussian noise experienced in all electronic devices. These include:

1. Path Loss
2. Multipath Fading
3. Shadowing
4. Interference

In communication systems, the reliability of a system is commensurate to the signal power to noise power ratio, i.e. if signal power is increased in a channel with the same noise power, the quality of service of the communication system will get better.

The basic idea behind cooperative communications is that every user can act as a "relay", i.e. the user re-transmits a signal to the intended destination improving signal power and thus increasing the quality of service. This helps mitigate the effect of channel impairments such as path loss and multipath fading.

6.3 Cooperative transmission to improve spatial diversity

Basic relay model is given as follows.

Relays combat signal fading (attenuation experienced by a signal due to destructive interference caused by multipath propagation) through spatial diversity, i.e. cooperation among distributed antennas (facing different interference environment) belonging to multiple terminals in the wireless network will provide different "copies" of each signal, thus increasing relaibility of a wireless system.

Cooperative communications can exist in the following scenarios in cognitive radio networks:

1. Between secondary users

   Secondary users act as relay for transmission of another secondary node. Here the secondary user must sense spectrum for possible transmission by primary users. The rationale here is to increase throughput for a given spectral holes (i.e. an unused channel in the spectrum).

2. Between primary user and secondary users

   Secondary users relay the traffic of the primary user towards intended destination. The rationale behind this is that primary user will finish its transmissions quicker (due to lesser packet retransmissions due to error) and thus will provide more transmission opportunities for a primary user.

6.4 Cooperative Relay to improve spectrum diversity

Cognitive radios, particularly in the interweave paradigm, have a severe resource imbalance when compared to traditional wireless networks. These are:

1. Spectrum availability is heterogenous

   In the interweave paradigm, unused spectrum at a particular time is exploited if a primary user isn't using the spectrum. Therefore, spectrum availaibilty depends on the following factors:

   (a) Location difference among users

   (b) Dynamic traffic of primary users

   (c) Opportunistic nature of spectrum access of secondary user

2. Traffic demands of different secondary users is different.

Cooperative relaying allows us to partially address the unbalanced spectrum usage. The basic premise of cooperative relaying is that some secondary users will not use the entire availaible spectrum due to low traffic demand. Utilizing such nodes as helpers to relay the other secondary users data thus improving the range, availability and reliability of the secondary network.

7 Partial Decode Forward Transmission and Channel Estimation Methods for Cooperative Communications

Paper Reference: [2]

7.1 Abstract

- A new transmission scheme for relay-based cooperative communication is proposed.
- The proposed partial decode and forward method renders better bit error rate performance at reduced complexity and lower power consumption at the receiver.
- The relay generates soft-value estimates of the received symbols and retransmits the estimated soft value symbols to the final destination.
- A novel channel estimation technique, in which a simple redesign of the preamble sequence at the relay enables the destination to concurrently estimate the product of the channel state information between source & relay, and relay & destination is introduced.

- Extensive numerical analyses and simulations show that the proposed scheme attains considerable performance gains against the conventional decode-forward and amplify-forward schemes, which proves to be a good trade-off.

7.2 Introduction

Most of the work that has been done on wireless communication is based on the assumption that in a wireless network, communication between two devices involve only those two devices and any other device is a potential interferer, but the concept of cooperative communications changes this basic assumption and investigates the effect of cooperation between multiple devices. The improvements in capacity, range and robustness have been analyzed for certain configurations. In the proposed work the relay performs partial decoding of the received signal, generates soft-value estimates of the received symbols and retransmits the estimated symbols to the final destination. The proposed method can operate with less computation power, and reduced decoding complexity. The performance is also at par with the AF and DF schemes.

A novel channel estimation method through partial decoding of the received signal is also proposed. By partial decoding, we mean that the relay decodes only the preamble sequence, and either AF or PDF is applied on the remaining data payload. The proposed method helps the destination to estimate the product of the channel state information between the source and the relay and between the relay and the destination.

7.3 System Description

In the partial decoding strategy at the relay, the relay does not fully decode the received signal, instead it generates soft- value estimates of the transmit symbols. Prior to retransmission, the relay can regenerate the signal in either one of following forms:

i) Soft-value estimates of received symbols, or

ii) Regenerate soft-value symbols with estimated channel state information at the relay.

In order to decode the received symbols from the relay, the destination can either

1. Combine the signal received from the relay with the signal from the source, or

2. Use only the signal received from the relay

The proposed methods have been mathemetically illustrated as follows. The system is described with the help of the following notations:

h_{sd}**:** Channel State Information between the source and the destination,

h_{sr}: Channel State Information between the source and the relay

h_{rd}: Channel State Information between the relay and the destination.

y_{sd}: Signal received at the destination from the source

y_{rd}: Signal received at the destination from the relay

y_{sr}: Signal received at relay.

z : additive white gaussian noise

$\bar{(.)}$: denotes conjugate (transpose) of a complex scalar (vector).

The signal received at the destination directly from the source:

$$y_{sd} = h_{sd}x + z_d$$

The signal received at the relay from the source:

$$y_{sr} = h_{sr}x + z_r$$

During the next signaling period, the relay adopts the Proposed Partial Decode and Forward (PDF) method.The relay partially decodes the received signal, which is the soft-value estimate of the transmitted symbols. The partial decoding of the received signal y_{sr} using a MMSE receiver at the relay generates the following signal:

$$\tilde{x} = \frac{|h_{sr}|^2 x + \bar{h_{sr}} z_r}{(|h_{sr}|^2 + N_0)}$$

The relay can then retransmit the signal in either one of the following three forms to the destination:

1. The relay can retransmit the normalized soft-value symbol estimate $\tilde{x}$ to the destination. The received signal at the destination is as follows:

   $$y_{rd} = h_{rd}\tilde{x} + z_{d\_pdf}$$

   The destination decodes the combined received signal and we get

   $$\frac{1}{|h_{sd}|^2 + |h_{rd}|^2}\left[\left(|h_{sd}|^2 + \frac{|h_{rd}|^2|h_{sr}|^2}{|h_{sd}|^2 + N_0}\right)x + \frac{|h_{rd}|^2\bar{h_{sr}}z_r}{|h_{sr}|^2 + N_0} + \bar{h_{sd}}z_d + \bar{h_{rd}}z_d\right]$$

   The noise variance is:

   $$\left(\frac{1}{|h_{sd}|^2 + |h_{rd}|^2} + \frac{|h_{rd}|^4|h_{sr}|^2}{(|h_{sr}|^2 + N_0)^2 + (|h_{sd}|^2 + |h_{rd}|^2)^2}\right)N_0$$

2. The relay can regenerate and retransmit the normalised signal $\hat{h_{sr}}\tilde{x}$, where $\hat{h_{sr}}$ is the channel estimate between source and relay. The received signal at the destination is as follows:

   $$y_{rd} = h_{rd}\hat{h_{sr}}\tilde{x} + z_d$$

Assuming that the relay has perfect knowledge of the channel state information between the source and the relay, i.e., $\hat{h_{sr}} = h_{sr}$ and substituting for $\tilde{x}$ the destination can process the combined received signal as follows:

$$x' = \frac{1}{|h_{sd}|^2 + |h_{rd}|^2|h_{sr}|^2}\left[\left(|h_{sd}|^2 + \frac{|h_{rd}|^2|h_{sr}|^4}{|h_{sr}|^2 + N_0}\right)x + \bar{h_{sd}}z_d + \frac{|h_{rd}|^2|h_{sr}|^2\bar{h_{sr}}z_r}{|h_{sr}|^2 + N_0} + \bar{h_{rd}}\bar{h_{sr}}z_d\right]$$

the noise variance is

$$\left[\frac{1}{|h_{sd}|^2 + |h_{rd}|^2|h_{sr}|^2} + \frac{|h_{rd}|^4|h_{rd}|^6}{\left(|h_{sd}|^2 + |h_{rd}|^2|h_{sr}|^2\right)^2\left(|h_{sr}|^2 + N_0\right)^2}\right]N_0$$

3. The relay can also remap symbols onto different constellations depending on the distance and channel gains between the source-relay and the relay-destination links.

7.4 Proposed Channel Estimation Method

1. To decode the regenerated signal from the relay, the destination requires the product of h_{sr} and h_{rd} which are estimated by the destination through the preamble sequence transmitted by the relay in the packets.

2. The preamble sequence used to estimate channel state information is designed to be more robust and gets more protection by giving it a lower order modulation (generally BPSK).

The sequence of operations at the relay is as follows:

1. The relay estimates the channel between the source and relay (h_{sr}) from the received preamble sequence. Suppose, the received preamble sequence at the relay is

$$s = h_{sr}p + z_r$$

2. Since the preamble sequence p is known at the receiver, the relay can estimate $\hat{h_{sr}}$. The relay redesigns the preamble as follows:

$$\hat{p} = \hat{h_{sr}}p$$

3. The actual received preamble at the relay is replaced by its cleaner version. Due to reduction in additive noise in the preamble, the destination can achieve a better estimation of the product of channel state information. The received preamble sequence at the destination is:

$$s' = h_{rd}\hat{p} + z_d \Rightarrow s' = h_{rd}\hat{h_{sr}}p + z_d$$

Since, p is a known sequence, the destination can estimate the product of the channel state information$\hat{h_{rd}h_{sr}}$ from s' .

Features Of The Proposed Method:

- The stringent requirement of error-free decoding as in DF scheme is relaxed in the proposed PDF strategy. In comparison to AF, the PDF shows improved performance with only a little additional computation cost. Hence, the PDF scheme can be regarded as a good trade-off.

- The proposed PDF strategy results in constellations expansion; however, the constellation expansion is also present in conventional AF strategy.

- The relay transmits soft-value (regenerated) estimates of the received symbols. The process reduces the noise at the relay, resulting in an observable performance gain.

- In the proposed channel estimation technique, the reliability of the estimation enhances due to reduction in the additive white noise in the preamble part of the received signal at the destination.

- The proposed channel estimation technique is unique in a sense that it avoids the complexity of designing and inserting additional preamble at the relay. Instead, the intelligently designed new preamble sequence estimates the product of channel state information between the source-relay and relay-destination pairs.

8 Opportunistic-Space Time Block Codes

Paper Reference: [3]

8.1 MIMO and STBC

MIMO, Multiple Input Multiple Output, is a modern wireless communication technique which uses multiple antennas at transmitter and recievers. At each recieve antenna, a sum of transmitted signals multiplied by the complex fading coefficients are recieved.

There are two types of MIMO techniques:

1. Spatial Multiplexing: Sending multiple bits on the same channel using different spatial links to increase the capacity of the system (thus increasing the rate).

2. Spatial Diversity: Sending same symbols over different spatial links to improve diversity in order to increase reliability of the system.

Space Time Block Code provides a trade-off between rate and diversity by dividing data streams into time blocks, encoding it into symbols and sending it repeatedly as specified by the block code. High-rate space-time codes come at a cost of lower diversity, and high reliability (diversity) imply a lower rate.

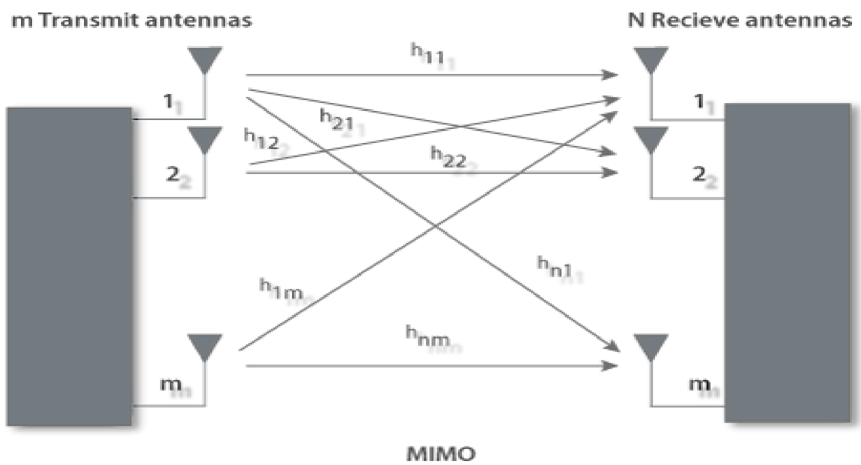

Figure 8: An illustration of MIMO with fading channels[4]

The idea of opportunistic space time block codes is to embed different message sets with different diversity so that the message sets which need higher reliability can be transmitted without compromising a higher data rate.

8.2 Transmission Model

Consider a quasi-static flat-fading channel where coded information is transmitted over M_t antennas and recieved by $M_r$recieve antennas. Assume that reciever has perfect channel knowledge. The channel is constant over a coherence interval of T symbols and changes independently from one coherence interval to the next. After demodulation and sampling, the recieved signal can be written as

$$Y = HX + Z$$

where Y is the recieved sequence, H is quasi-static channel fading matrix, X is the space-time block code matrix with transmit power P and Z is assumed to be additive white gaussian noise with variance σ^2.

Let A and B be two message sets from two different information streams. Let their rates be $R(A)$ and $R(B)$. Let the average error probability of the message set be $P_e(A)$ and $P_e(B)$. Then, the code is designed such that a certain tuple of rate and diversities, (R_a, D_a, R_b, D_b), are achievable where $R_a = \frac{log(|A|)}{T}$, $R_b = \frac{log(|B|)}{T}$ and $D_a = lim_{SNR\to\infty} \frac{logP_e(A)}{log(SNR)}$, $D_b = lim_{SNR\to\infty} \frac{logP_e(B)}{log(SNR)}$.

8.3 Opportunistic space time block code used in the project

The following space time code with message sets A and C was used in our project.

$$X_{a,c} = X_a + X_c = \begin{bmatrix} a(0) & -a^*(1) & -a^*(2) & \frac{c^*(0)}{k} \\ a(1) & a^*(0) & \frac{c^*(3)}{k} & -a^*(2) \\ a(2) & \frac{c^*(2)}{k} & a^*(0) & a^*(1) \end{bmatrix}$$

The diversity order of the code was $(\frac{3}{4}log|S|, 3M_r, \frac{3}{4}log|S|, M_r)$ where S is the set of all possible combinations of symbols.

Part VI
Proposed Model and Results

9 Proposed Model

For all models, we have assumed a flat-fading, narrowband channel which has a standard complex gaussian fading channel with additive white gaussian noise. We have assumed that the reciever has perfect knowledge of the channel state information for all symbols transmitted.

9.1 Direct Transmission Communication Model

The proposed relaying model should be compared to a standard. Generally, BPSK is chosen since it is the best modulation technique in terms of performance. Any improvement over that is substantial . The modulation is as follows:

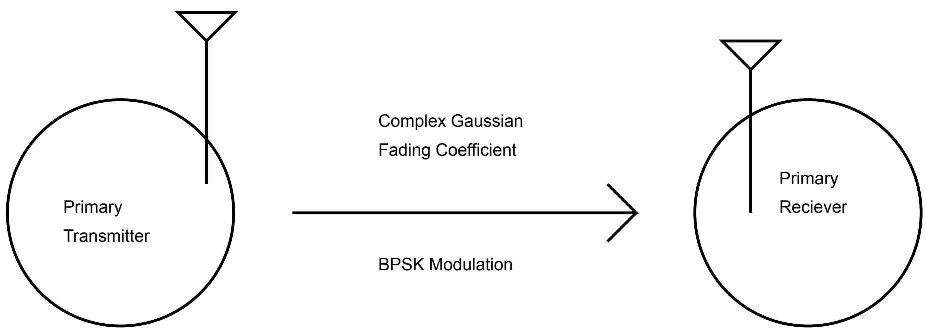

Figure 9: Direct Transmission Communication Model

9.2 Relaying Decode and Forward Model

In this model, the secondary system's transmitter acts as a relay. Notice that the secondary transmitter has three antennas on it in the figure below.

This system has two phases:

1. **Phase I**: Primary transmitter sends its symbols over to secondary transmitter for relaying in frames. All frames arriving at first phase will have error control check. Frames will be discarded if they have an error. For now, we have assumed perfect decoding here and we will evaluate the effect of imperfect decoding and discarding of frames in the future work.

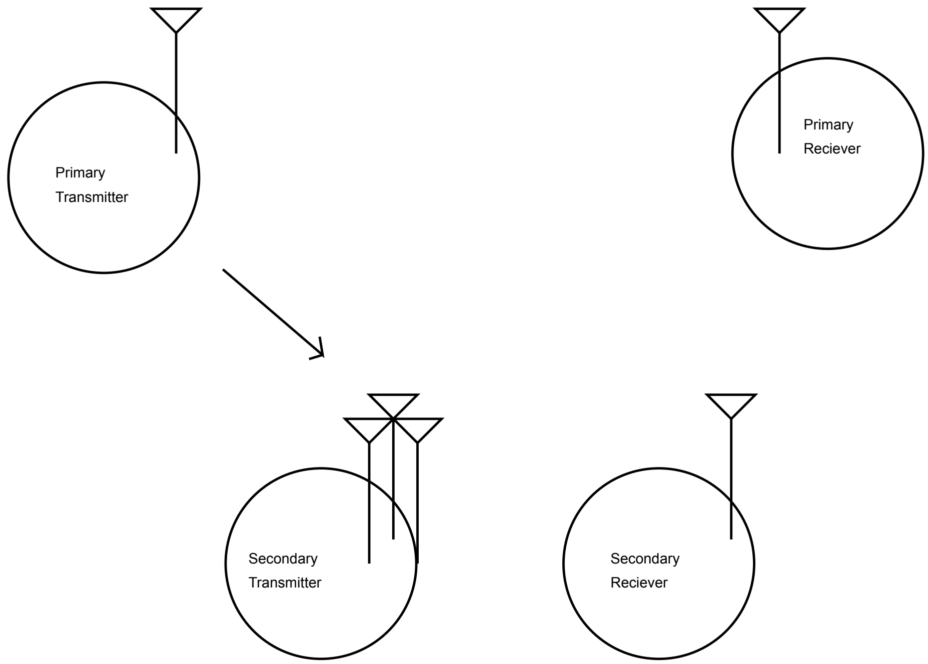

Figure 10: Phase I of Relaying Decode and Forward Model

2. **Phase II**: Once our secondary transmitter or the relay has the primary message, it relays the message over to primary receiver along with it's own data. It uses the opportunistic STBC code stated in Literature Review #3 over 4 time slots and uses QPSK modulation.

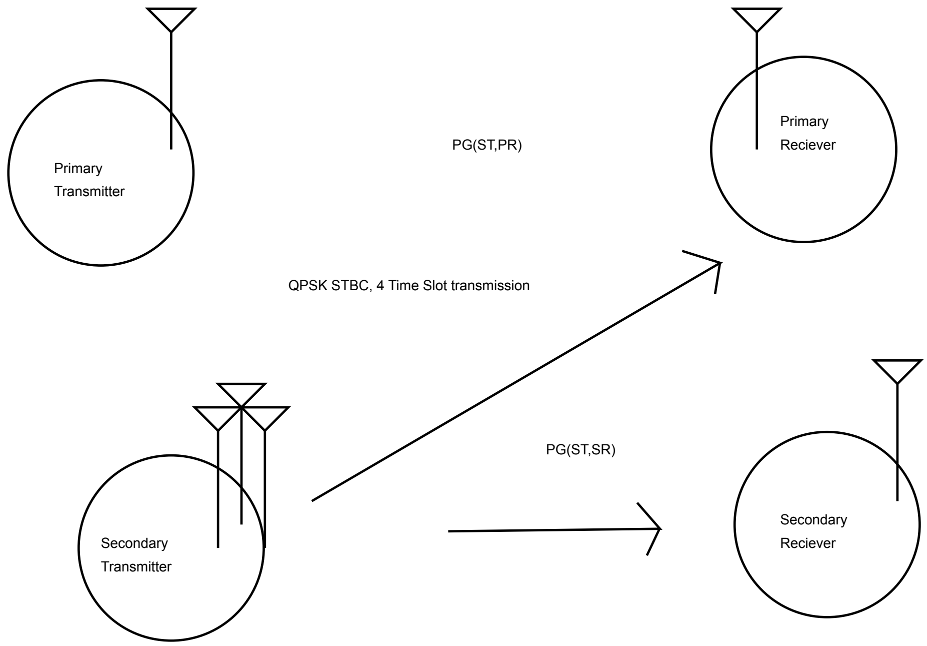

Figure 11: Phase II of Relaying Decode and Forward Model

For evaluating the performance of the system, path gains should be evaluated over each of these links. The path gain between secondary transmitter and secondary reciever,

$$PG_{ST,SR} = 0dB$$

For path gain between the secondary transmitter and primary reciever, $PG_{ST,PR}$, we have taken three cases:

1. When the secondary transmitter is close to the primary transmitter

$$PG_{ST,PR} = 5dB$$

2. When the secondary transmitter is in the middle of the primary transmitter and the primary receiver

$$PG_{ST,PR} = 7dB$$

3. When the secondary transmitter is far from the primary transmitter and close to the primary reciever

$$PG_{ST,PR} = 10dB$$

Model of Opportunistic STBC The opportunistic STBC consists of two message sets A and C, as given in the literature review [3], is given by

$$X_{a,c} = X_a + X_c = \begin{bmatrix} a(0) & -a^*(1) & -a^*(2) & \frac{c^*(0)}{k} \\ a(1) & a^*(0) & \frac{c^*(3)}{k} & -a^*(2) \\ a(2) & \frac{c^*(2)}{k} & a^*(0) & a^*(1) \end{bmatrix}$$

where k is the power factor and $k = 1.6$.
The resultant symbols after transmission are represented as

$$Y = X * H + N$$

$$\begin{bmatrix} y(0) \\ y(1) \\ y(2) \\ y(3) \end{bmatrix} = \begin{bmatrix} a(0) & a(1) & a(2) \\ -a^*(1) & a^*(0) & c^*(0) \\ -a^*(2) & c^*(1) & a^*(0) \\ c^*(2) & -a^*(2) & a^*(1) \end{bmatrix} * \begin{bmatrix} h(1) \\ h(2) \\ h(3) \end{bmatrix} + \begin{bmatrix} n(1) \\ n(2) \\ n(3) \\ n(4) \end{bmatrix}$$

Decoding Opportunistic STBC at the primary reciever We have used the maximum likelihood algorithm along with matched filtering to decode the STBC code at the primary reciever. The essence of maximum likelihood is to evaluate for all possible values of the message sets A and C, given perfect channel state information so as to find the minimum energy difference between the recieved symbols and the symbols evaluated with the given channel state information.

Mathematically, the resultant symbols after transmission are obtained as

$$Y = X * H + N$$

We evaluate all possible combinations of message set C symbols, where each possibility is denoted as $x(0)$, $x(1)$, $x(2)$.

For every set of the symbols, the following is done:

1. Remove the symbols of message set C and obtain

   (a)

$$Y_{remaining} = Y - \begin{bmatrix} 0 \\ h(3) * \frac{x^*(3)}{k} \\ h(2) * \frac{x^*(3)}{k} \\ h(1) * \frac{x^*(3)}{k} \end{bmatrix} = \begin{bmatrix} a(0)h(1) + a(1)h(2) + a(1)h(3) \\ -a^*(1)h(1) + a^*(0)h(2) \\ -a^*(2)h(1) + a^*(0)h(3) \\ -a^*(2)h(1) + a^*(1)h(2) \end{bmatrix}$$

2. Conjugate rows 2, 3 and 4 to obtain original symbol values of a

   (a)

$$Y' = \begin{bmatrix} y_{remaining}(0) \\ y^*_{remaining}(1) \\ y^*_{remaining}(2) \\ y^*_{remaining}(3) \end{bmatrix}$$

3. Apply matched filtering using complex equivalent channel matrix to obtain only symbols of message set A

   (a)

$$Y_{match} = \begin{bmatrix} h(1) & h(2) & h(3) \\ h^*(2) & -h^*(1) & 0 \\ h^*(3) & 0 & -h^*(1) \\ 0 & h^*(3) & -h^*(2) \end{bmatrix} * Y^{'}$$

   (b)

$$Y_{match} = (|h(1)|^2 + |h(2)|^2 + |h(3)|^2) * \begin{bmatrix} a(0) \\ a(1) \\ a(2) \end{bmatrix} + \tilde{N}$$

4. Quantize symbols to +1 or -1 for both real and imaginary parts. Then, multiply with a equivalent channel matrix to obtain the approximation of Y and take the difference from Y and its approximation to get a difference matrix. The minimum value of the differerence matrix is

   (a)

$$D = \begin{bmatrix} n_1 \\ n_2^* \\ n_3^* \\ n_4^* \end{bmatrix}$$

5. A frobenius norm of the difference matrix is taken.

For the given combination of symbols of message set having the minimum value of frobenius norm of the difference matrix is the maximum likelihood value. This symbol value is then decoded to obtain the recieved bits.

Decoding Opportunistic STBC Code at secondary reciever The secondary reciever is also assumed to have perfect knoweldge of the channel state. However, we also assume that the secondary reciever has perfect knowledge of the symbols sent by the primary reciever. Therefore, simple linear algebra is used to obtain the symbols of message set C.

$$A = \begin{bmatrix} y(1) \\ y(2) \\ y(3) \end{bmatrix} + \begin{bmatrix} -h(2) & h(1) & 0 \\ -h(3) & 0 & h(1) \\ 0 & -h(3) & h(2) \end{bmatrix} * \begin{bmatrix} a^*(0) \\ a^*(1) \\ a^*(2) \end{bmatrix}$$

$$\begin{bmatrix} c(0) \\ c(1) \\ c(2) \end{bmatrix} = \begin{bmatrix} \frac{h^*(3)}{|h(3)|^2} \\ \frac{h^*(2)}{|h(2)|^2} \\ \frac{h^*(1)}{|h(1)|^2} \end{bmatrix} * A$$

10 Results

We use the standard metric of Bit error rate vs. Signal to Noise Ratio for comparison of the primary and secondary systems for the Physical layer. The curve that gives a lower Bit Error Rate for a given SNR has a better performance. The scales here are logarithmic for BER, and SNR is in decibels.

We also show the goodput which is the number of correct bits recieved divided by all bits sent.

As mentioned in the Proposed Model Section, the results are for three cases.

10.1 When secondary transmitter is close to primary transmitter

$$PG_{ST,PR} = 5dB$$

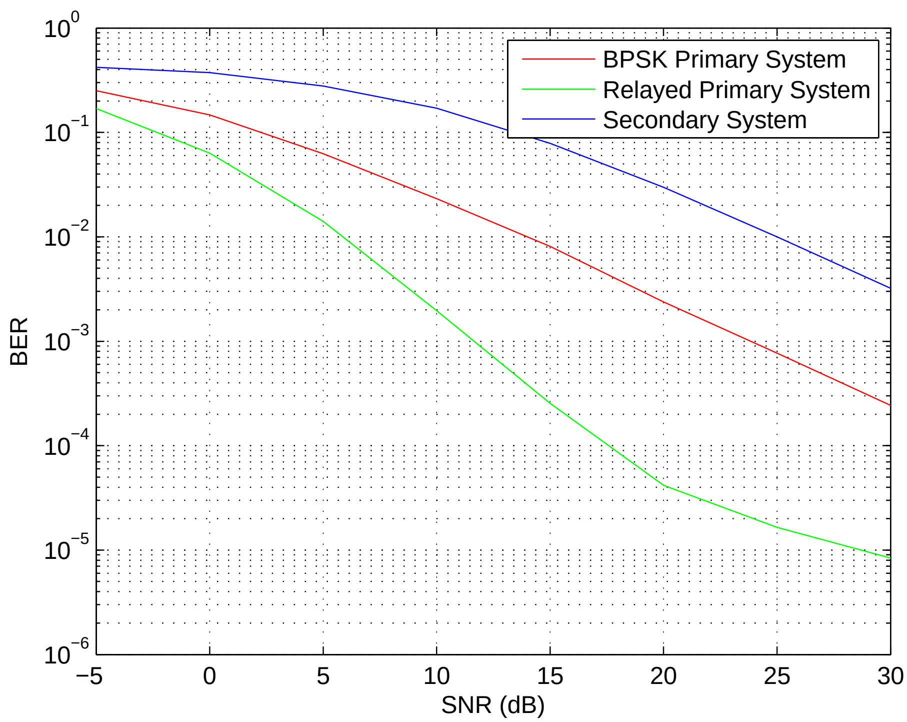

Figure 12: BER vs. SNR for when ST is close to PT

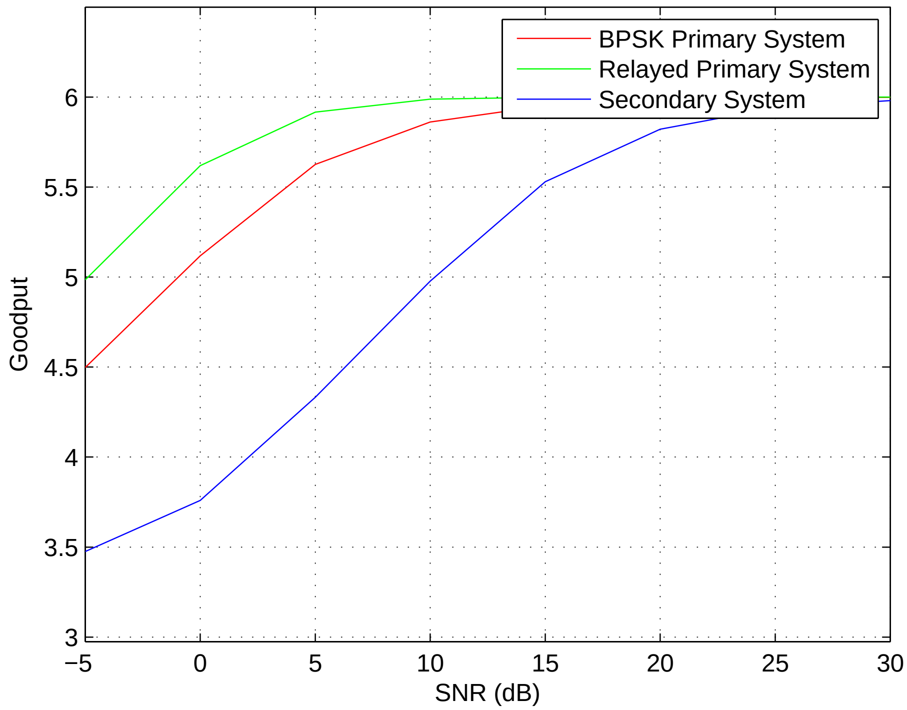

Figure 13: Goodput vs. SNR for when ST is close to PT

10.2 When secondary transmitter is in the middle of primary transmitter and primary reciever

$$PG_{ST,PR} = 7dB$$

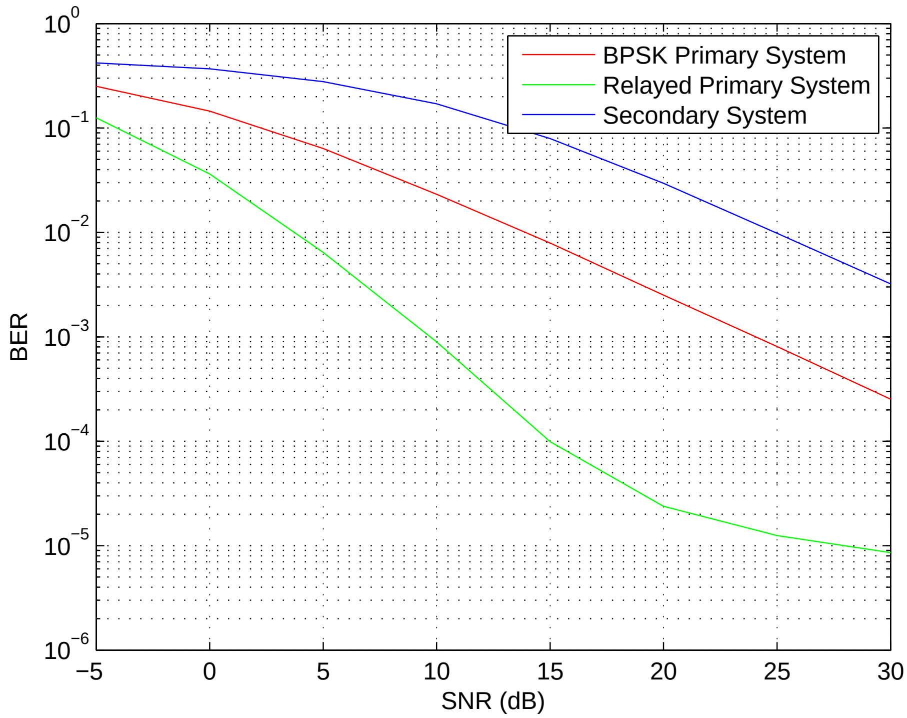

Figure 14: BER vs. SNR for when ST is in middle from PT

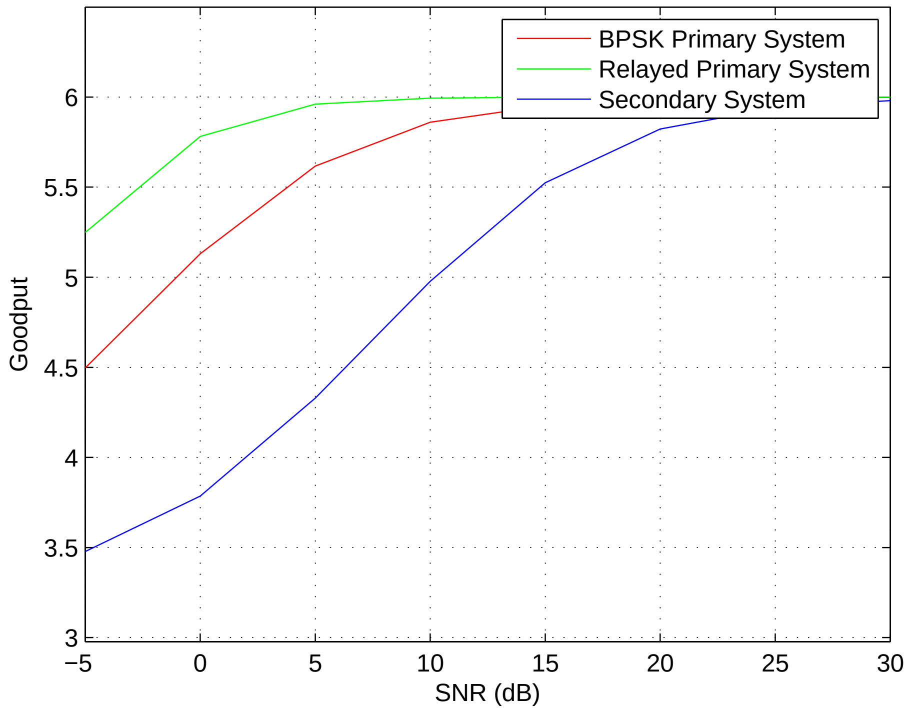

Figure 15: Goodput vs. SNR for when ST is in middle from PT

10.3 When secondary transmitter is far from primary transmitter

$$PG_{ST,PR} = 10dB$$

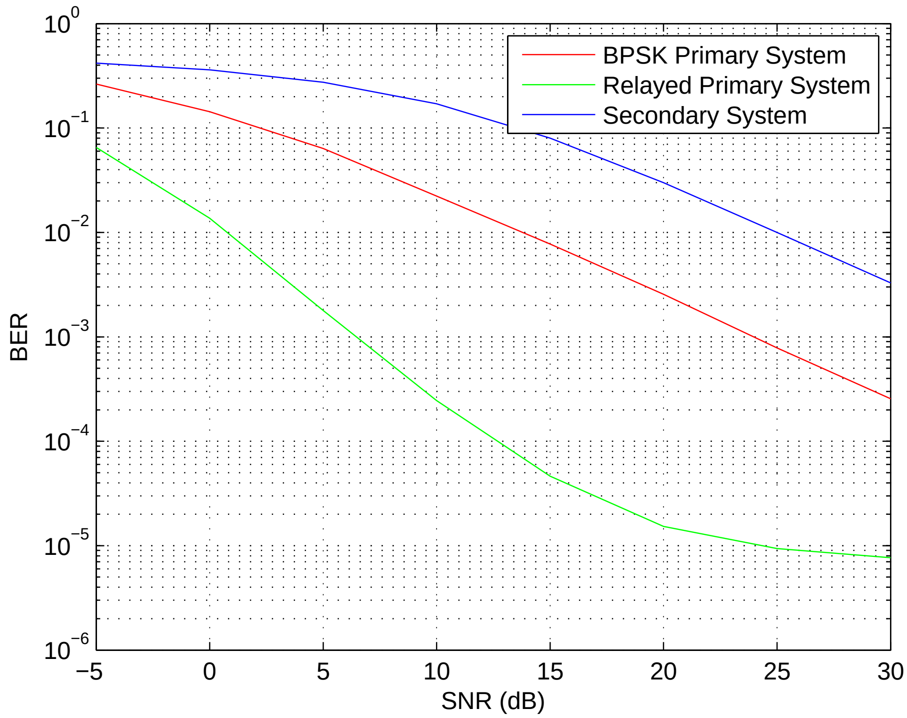

Figure 16: BER vs. SNR for when ST is far from PT

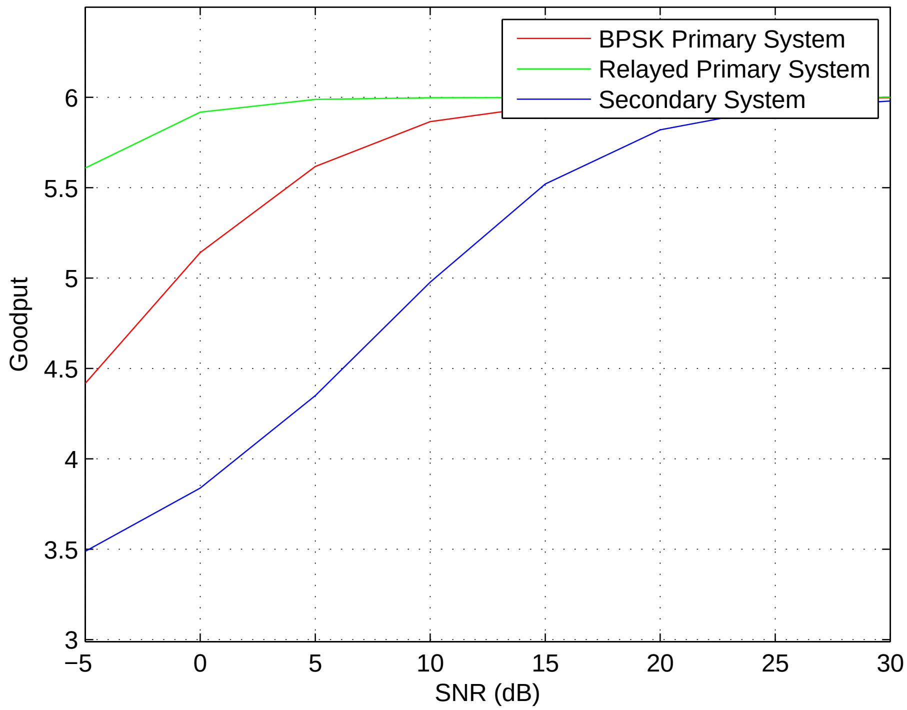

Figure 17: Goodput vs. SNR for when ST is far from PT

Part VII
Summary

Due to the way the RF spectrum is allocated, an artificial scarcity of spectrum has emerged. So, to combat this effect intelligent systems have to be developed which can make dynamic use of spectrum and alleviate the artificial scarcity. One such step towards it is the developement of cognitive radio. A cognitive radio is an intelligent radio that can be programmed and configured dynamically, adapting its way of communication to minimize the effects of interference at the primary user and make use of unused spectrum.

Cooperative communication is one of the fastest growing areas of research, and it is likely to be a key enabling technology for efficient spectrum use in future. The key idea in user-cooperation is that of resource-sharing among multiple nodes in a network. A three-node network is a fundamental unit in user cooperation. Indeed, a vast portion of the literature, especially in the realm of information theory, has been devoted to a special three-node channel, labeled the relay channel ([5]). The relay is treated as a secondary user who forwards PU's data along with its own data. In our R&D work, we studied "Partial Decode and Forward", in which the relay generates soft-value estimates of the received symbols and retransmits the estimated soft value symbols to the final destination. We also studied a scheme (novel channel estimation technique), in which a simple redesign of the preamble sequence at the relay enables the destination to concurrently estimate the product of the channel state information between source & relay, and relay & destination was introduced.

In a wireless communication scenario the transmitted signal must traverse a potentially difficult environment with scattering, reflection, refraction and so on and may then be further corrupted by thermal noise in the receiver. Thus, for a better reception of signal we make use of STBC. Space–time block coding is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer. For our work we studied opportunistic STBC wherein the code has different embedded diversity for for different message set.

We have analysed SNR vs BER for the relayed system, where the relay assumes three positions; near the primary transmitter,near the primary receiver, and in middle of primary transmitter and primary receiver. By varying the position of the secondary transmitter the pathloss changes and thus, the SNR gain between the links. For the simulation we compared the results of the SNR vs BER between the PT-PR direct communication, the ST-SR link and the relayed PT-PR communication. For all the three positions we find that the relayed system performs the best.

Part VIII

Future Work

We aim to work on the following as an extension to our work:

1. Partial Decode and Forward Simulation
2. Examining other cooperative spectrum sharing techniques and simulation of those techniques
3. Examining other opportunistic STBC codes
4. We would also like to come up with a new Cooperative Spectrum Sharing technique.

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Part IX
Appendix

A MATLAB Simulation Code

Generates stored .dat simulation files.

```
Notations
%$$Y = HX + N$$
%(except for STBC, which is $Y=XH + N$)
%Y: M_r * T
%H: M_r * M_t
%X: M_t * T
%N: M_r * T
Initialization
clear all;
close all;

%Specify extra stings to save .mat file as (leave no spaces)
version = 'pathLossNorm';
SNR and error parameters
 Set SNR and errors to be evaulated
errors_evaluated = 2000;

snr_dB = -5;


ber_pu_direct = zeros(1,length(snr_dB));
ber_pu_relay = zeros(1,length(snr_dB));
ber_su = zeros(1,length(snr_dB));
Pathloss Model
 Taking all pathlosses in dB
pl_pt_pr_dB = 0;
%pl_pt_st_dB = 10;
pl_st_pr_dB = 5;
pl_st_sr_dB = 0;
Primary Transmitter Setup
pt_direct_constellation = [-1 1];
pt_direct_average_symbol_energy = mean(abs(pt_direct_constellation).^2)
    ;
pt_direct_constellation = pt_direct_constellation./sqrt(
    pt_direct_average_symbol_energy);
pt_direct_average_symbol_energy = mean(abs(pt_direct_constellation).^2)
    ;


%Relay Phase: TODO- check
pt_bits = 6;
pt_M = 2.^pt_bits;
pt_relay_constellation = qammod([0:pt_M-1], pt_M, 0);
pt_relay_average_symbol_energy = mean(abs(pt_relay_constellation).^2);
pt_relay_constellation = pt_relay_constellation./sqrt(
    pt_relay_average_symbol_energy);
pt_relay_average_symbol_energy = mean(abs(pt_relay_constellation).^2);
STBC Setup
```

```
rng('default');
rng('shuffle');

%QPSK symbols
st_pu_const = (exp(1i.*[-3*pi/4 3*pi/4 7*pi/4 -7*pi/4])); %Unity magnitude and thus unity power
%st_pu_average_symbol_energy = mean(abs(st_pu_const).^2);


%scaled QPSK symbols
st_su_const = st_pu_const./1.6;  %Scaling down the unity amplitude by 1.6
% st_su_average_symbol_energy = mean(abs(st_su_const).^2);
%
% e = 4./((9*st_pu_average_symbol_energy) + (3*st_su_average_symbol_energy));
% st_pu_const = st_pu_const.*sqrt(e);
% st_su_const = st_su_const.*sqrt(e);



%create all combinations of two QPSK symbols
a=[1:4 1:4 1:4];
b=unique([nchoosek(a,3)],'rows');
    %nchoosek: produces all combinations of vector where 3 elements are chosen at a time. unique: Choose unique combinations, since each element was assumed to be unique in combination.
X = st_su_const(b((1:length(b)),:));
Loop section
 Set SNR here onwards for loop, when calculating BER
for m = 1:length(snr_dB)

    no_tx_pu = 0;
    no_tx_su = 0;
    errors_pu_direct = 0;
    errors_pu_relay = 0;
    errors_su = 0;

    pt_direct_pr_snr = snr_dB(m) + pl_pt_pr_dB;
    pt_direct_pr_snr = 10.^(pt_direct_pr_snr/10);
    pt_direct_pr_sigma = sqrt(1/pt_direct_pr_snr);

    st_pr_snr = snr_dB(m) +pl_st_pr_dB;
    st_pr_snr = 10.^(st_pr_snr/10);


    st_sr_snr = snr_dB(m) +pl_st_sr_dB;
    st_sr_snr = 10.^(st_sr_snr/10);


    while errors_pu_direct < errors_evaluated

        %%%%%%%%
        %Direct Transmission of PU
        %BSPK, 6 bits at a time. h constant for whole time interval.
        %%%%%%%%

```

```
        pt_direct_bits = randi([0 1], 1, 6);
        pt_direct_x = pt_direct_constellation(pt_direct_bits + 1);

        pt_direct_h = (randn(1, 6) + 1i.*randn(1,6))./sqrt(2);

        pt_direct_n = pt_direct_pr_sigma*((randn(1,6)+1i*randn(1,6))./
            sqrt(2));

        pt_direct_y = pt_direct_h.*pt_direct_x  + pt_direct_n;

        %Perfect CSI

        pt_direct_y = conj(pt_direct_h).*pt_direct_y./(abs(pt_direct_h)
            .^2);

        pt_direct_decoded = (sign(real(pt_direct_y))+1)./2;

        errors_pu_direct = errors_pu_direct + sum(pt_direct_bits ~=
            pt_direct_decoded);


        %%%%%%%%
        %Relayed System
        %Phase I: Assume perfect decoding.
        %%%%%%%%

        pt_symbols = randi([0 pt_M-1], 1,1);

        pt_bit_sequence = de2bi(pt_symbols,pt_bits);

        %At secondary transmitter

        pt_st_y_decoded = pt_symbols;

        pt_st_y_decoded_bits = de2bi(pt_st_y_decoded,pt_bits);

        %%%%%%%%
        %Phase II: ST, STBC Code
        %%%%%%%%

        %At secondary transmitter

            st_symbols = randi([1,4], 3, 1);
            st_bit_sequence = de2bi(st_symbols-1, 2);
            st_symbols = st_su_const(st_symbols);


            c = st_pu_const(bi2de(reshape(pt_st_y_decoded_bits, 3, 2))
                + ones(3,1));

            s = st_symbols;

            st_stbc_code = [c(1) c(2) c(3); -c(2)' c(1)' s(1)'; -c(3)'
                s(2)' c(1)'; s(3)' -c(3)' c(2)'];
                    %Conjugate: '
```

```
                %Row vectors: Instance of time, T= 4, Column vector : Tx Antennas M_t = 3;

        %At primary receiver
            st_pr_sigma = sqrt((norm(st_stbc_code,'fro')^2)/(4*st_pr_snr));
            h = (randn(3,1)+1i*randn(3,1))./sqrt(2); %Joint variance of complex Gaussian distribution is 1. Therefore, average value of magnitude of fading channel is 1.

            %the following complex equivalent channel matrix is for the ORTHOGONAL 3TX STBC
            H = [h(1) h(2) h(3); h(2)' -h(1)' 0; h(3)' 0 -h(1)'; 0 h(3)' -h(2)'];

            %the following complex equivalent channel is for the Embedded Diversity Code
            %for 3 TX
            H_eqv = [h(1) h(2) h(3) 0 0 0; h(2)' -h(1)' 0 h(3)' 0 0; h(3)' 0 -h(1)' 0 h(2)' 0; 0 h(3)' -h(2)' 0 0 h(1)'];

            N = st_pr_sigma.*((randn(4,1)+1i*randn(4,1))./sqrt(2));
                % T= 4, M_r = 1
                %Joint variance of complex Gaussian distribution is 1. Therefore, average value of magnitude of fading channel is 1.

              %received Signal
              Y = st_stbc_code * h  + N; %Code multiplied with h, not H i.e. multiplied with fading coefficients only.

              for k = 1:length(X)
                  %discard the effect of diversity 2 and 1 layer from total received
                  %signal to get Y_remaining, alias Y_rem
                  Y_rem = [Y(1); Y(2)-h(3)*X(k,1)'; Y(3)-h(2)*X(k,2)'; Y(4)-h(1)*X(k,3)'];

                  Y_prime = [Y_rem(1) Y_rem(2:4)'].';

                  %Apply matched filtering because the remaining received signal is
                  %due to the contribution from the Orthogonal Diversity 3 layer Only
                  Y_match = H' * Y_prime;

                  Sym = sign([real(Y_match); imag(Y_match)]);

                  S_tilde = Sym(1:3) + 1i*Sym(4:6);

                  Decoded_Symb{k} = [S_tilde.' X(k,1) X(k,2) X(k,3)];
                  %Now apply ML decoding using the overall equivalent channel matrix
                  %H_Eqv
                  diff = [Y(1) Y(2:4)'].' - H_eqv * Decoded_Symb{k}.';

```

```
                    metric(k) = norm(diff,'fro')^2;

                end

                [W, ind] = min(metric);

                st_pr_decoded_stbc = Decoded_Symb{ind};

                st_pr_decoded_symbols = st_pr_decoded_stbc(1:3);

                st_pr_decoded_bits = reshape([(sign(imag(st_pr_decoded_symbols))+1)/2;(sign(real(st_pr_decoded_symbols))+1)/2].', 1,6);

                errors_pu_relay = errors_pu_relay + sum(pt_bit_sequence ~= st_pr_decoded_bits);

                no_tx_pu = no_tx_pu + 1;

        % At secondary reciever
            st_sr_sigma = sqrt((norm(st_stbc_code,'fro')^2)/(4*st_sr_snr));
            st_sr_h = (randn(3,1)+1i*randn(3,1))./sqrt(2);
            st_sr_n = st_sr_sigma.*((randn(4,1)+1i*randn(4,1))./sqrt(2));

            st_sr_Y = st_stbc_code * st_sr_h + st_sr_n;

            %%%%%%%%%%%%%%%
            % Assume that we know all 6 bits of primary transmitter
            % perfectly.
            %%%%%%%%%%%%%%%

            st_sr_Y_dash = st_sr_Y(2:4);
            H_dash = [-st_sr_h(2) st_sr_h(1) 0;-st_sr_h(3) 0 st_sr_h(1); 0 -st_sr_h(3) st_sr_h(2)];
            H_prime = [st_sr_h(3)'./(abs(st_sr_h(3)).^2);st_sr_h(2)'./(abs(st_sr_h(2)).^2);st_sr_h(1)'./(abs(st_sr_h(1)).^2)];

            s_prime = (H_prime.*(st_sr_Y_dash + H_dash*(c')))';

            st_sr_decoded_bits = [(sign(imag(s_prime))+1)/2;(sign(real(s_prime))+1)/2].';


            errors_su = errors_su + sum(st_bit_sequence(:) ~= st_sr_decoded_bits(:));

            no_tx_su = no_tx_su + 1;

    end

        snr_dB(m)
        ber_pu_direct(m) = errors_pu_direct/(pt_bits*no_tx_pu)
        ber_pu_relay(m) = errors_pu_relay/(pt_bits*no_tx_pu)
        ber_su(m) = errors_su/(6*no_tx_su)
end
```

```
Save Data
save(strcat('values_', num2str(snr_dB(1)), '_' , num2str(snr_dB(end)), 'dB','_',num2str(errors_evaluated),'iterations', version,'.mat'));
```

B MATLAB Plot Graph Code

Creates plot from .dat files.

```
clear all;
close all;

snr_dB = -5:5:30;
%snr_dB = snr_dB + 5;

[filename, pathname] = uigetfile('*.mat', 'Select data files', 'Multiselect', 'on')
files = strcat(char(pathname), filename);
b = [];
x = [];
s = [];
for i = 1:size(files, 2)
    load(files{i},'ber*', 'pt_bits');
    b = [b,ber_pu_direct];
    x = [x,ber_pu_relay];
    s = [s,ber_su];

end
ber_pu_direct = b;
ber_pu_relay = x;
ber_su = s;

throughput_pu_direct = 6*(1-ber_pu_direct);
throughput_pu_relay = 6*(1-ber_pu_relay);
throughput_su = 6*(1-ber_su);

figure
semilogy(snr_dB, ber_pu_direct, 'r')
hold on
semilogy(snr_dB, ber_pu_relay, 'g')
hold on
semilogy(snr_dB, ber_su)
legend('BPSK Primary System', 'Relayed Primary System', 'Secondary System');
grid on;
xlabel('SNR (dB)')
ylabel('BER')
figure
plot(snr_dB, throughput_pu_direct, 'r')
hold on
plot(snr_dB, throughput_pu_relay, 'g')
hold on
plot(snr_dB, throughput_su)
```

```
axis([snr_dB(1) snr_dB(end) min([throughput_pu_direct throughput_pu_relay throughput_su])-0.5 max([throughput_pu_direct throughput_pu_relay throughput_su])+0.5])
legend('BPSK Primary System', 'Relayed Primary System', 'Secondary System');
grid on;
xlabel('SNR (dB)')
ylabel('Goodput')
```