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# Performance Analysis of Selected Cooperative Relaying Techniques

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# ABSTRACT

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Recently, cooperative communication has gained significant interest due to the fact that it exploits spatial diversity and provides capacity/performance gain over conventional single-input single-output (SISO) systems. A mobile node with single antenna can cooperate with a nearby mobile node having single antenna in multi-user environment to create the effect of virtual multiple antenna system. Hence, reducing the complexity associated with actual multiple antenna systems. Despite the small size and power constraints, a mobile node can still benefit from spatial diversity by employing cooperation, thus saving transmission power and increasing the coverage range of the network. In this thesis, we have selected some of relaying protocols, namely, amplify-and-forward, decode-and-forward, detect-and-forward, and selective detect-and-forward that are studied and implemented for two different relaying geometries, i.e. equidistant and collinear. Results are studied and compared with each other to show the performance of each protocol in terms of average symbol error probabilities. The considered system model has three nodes, i.e. source, relay, destination. Communicating nodes are considered to be half-duplex with single antenna for transmission and reception. The source, when communicating with the destination, broadcasts the information, which is heard by the nearby relay. The relay then uses one of the cooperation protocols. Finally, the relayed signal reaches the destination, where it is detected by maximal ratio combiner (MRC) and combined with the direct transmission for possible diversity gains. The transmission path or the channel is modeled as a frequency non-selective Rayleigh fading in the presence additive white Gaussian noise (AWGN).

The effect of path loss has been observed on cooperation for collinear arrangement with exponential decay up to four. Considering equidistant arrangement, decode-and-forward shows good performance at high signal-to-noise ratio (SNR) while amplify-and-forward is very promising for very low SNR. A selective relaying scheme called selective detect-and-forward is also presented which outperforms its fixed counterparts for a wide range of SNR.



# DEDICATION

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*We dedicate this thesis to our parents and family who supported us throughout our thesis work and made it possible to achieve this milestone.*



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First of all we are thankful to Almighty Allah who gave us potential and courage to undertake and complete this thesis.

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# 1. INTRODUCTION

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## 1.1 Motivation

Cooperative communication has recently received significant attention in various communication communities. Much of the work in cooperative communication shows great improvement in the performance of wireless network. It exploits the spatial diversity, hence providing a great deal of room for design of network architectures that integrates cooperation. Research has shown that nodes with a single antenna when provided with channel coding and cooperation could achieve similar diversity to those of multiple antenna systems. A single mobile station with a single antenna can cooperate with similar mobile station in multiuser environment to create the effect of virtual multiple antenna systems. Multiple antenna systems can achieve sufficient diversity gain but its implementation is not feasible due to some constraints in wireless systems. Therefore, virtual antenna systems in the form of cooperative communications are gaining more attention.

Our focus is to analyze selected relaying protocols in different channel conditions. These protocols are applied to different relaying geometries and the results are studied for possible diversity gains.

## 1.2 Context and Concepts

Today mankind is living in information age. A lot of information is generated and utilized by the people all over the world. So the main focus for the research community is to convey the information correctly and within time, as information delayed is information denied. To meet this challenging demand we need a quick, efficient, and reliable communication system. The researchers are continuously striving to improve the communication systems in all aspects. We cannot deny the importance of communication system in our daily life.

Communication systems can use different mediums to transfer data from one place to another. This medium can be wired or wireless. Nowadays wireless communication is far more popular than wired communication. Researchers contributed a lot in the field of wireless communication systems. Existence of the radio waves was predicted by James Clark Maxwell in 1864. Another scientist Heinrich Hertz showed its physical existence. With the help of work done by these two researchers, Oliver Lodge demonstrated the first wireless communication over short distance of 150 meters [1]. This is how series of great achievements started that we see nowadays in the form of communication systems. Communication systems play a very important role in our daily lives. Wireless communication has many applications, i.e. in the field of military, healthcare, business, telephony and education. Cellular communication is one of the most common uses of wireless communication which utilizes radio waves for the propagation of information.

When a signal propagates through wireless channel, it encounters different challenges associated with the varying nature of the wireless channel. This varying nature of the wireless channel impairs the performance of a communication system especially when there is only a single path from source to destination. The transmitted signal going through different phenomena, i.e. scattering, reflection, diffraction, and refraction etc. has different delays when arriving at the receiver. Every path has its own delay depending upon the above mentioned characteristics. This causes fading: a change due to destructive and constructive interference of the several copies of the transmitted signal.

Diversity is a technique which can combat multipath fading and channel variations. Diversity provides various independent signal paths between source and destination. Each of the multiple paths will show independent fading. There will be less probability for all the signal paths to show deep fades simultaneously [2]. Different types of diversity techniques for providing multiple independent paths are space, time, frequency, and cooperative diversity.

In frequency diversity several independent fading paths are provided by sending the copies of the same signal over different carrier frequencies. If the transmitting frequencies are largely apart, replicas of the signal will experience different and

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independent fading [6]. In time diversity, multiple copies of the same signal are transmitted at different times. It is expected that not all copies will experience deep fades [5], [6]. Space diversity can be achieved when the signal is transmitted over different propagation paths using multiple transmitter and/or multiple receiving antennas. Due to the transmission/reception antennas located at different locations the signal will experience different fades [5], [6]. When there are multiple antennas for transmission and reception the technique is referred to as multiple-input multiple-output (MIMO) [4], sometimes it is also termed as multiple-transmit multiple-receiver (MTMR).

In cooperative diversity, users share their antennas with one another to create the effect of MIMO. Cooperative diversity attains the spatial diversity due to the fact that received signal at the destination arrives from different propagation paths and experiences different fades [7]. Cooperative diversity is suitable for the conditions where providing multiple transmit or multiple receive antennas is not feasible. Research has shown the performance of communication network greatly improves with the help of cooperative communication.

The aim of the project is to carry out performance analysis of selected cooperative schemes for two different relaying geometries, namely, equidistant and collinear. Relaying protocols can be broadly classified as decode-and-forward (DF) and amplify-and-forward (AF) [3]. These relaying protocols are implemented for the generic system that uses binary phase shift keying (BPSK). MATLAB is used for the simulation of different results.

In amplify-and-forward, the relay node receives the signal from source and amplifies it according to some power constraints, then forwards it to the destination. AF involves no signal processing and it is also termed as non-regenerative relaying. Decode-and-forward is performed in two time slots. The signal received during first time slot by the relay is decoded while in the second time slot the decoded signal is re-encoded by the relay and forwarded to the destination.

A simpler version of DF is also considered in this thesis which is referred as detect-and-forward (DtF). In this strategy, the source symbols are estimated by the relay

through just hard decisioning, without full decoding. Depending upon the channel conditions, if the source relay channel is bad the relay may choose not to cooperate or when the relay receives severely distorted signal. Such type of scheme is termed as selective detect-and-forward (S-DtF).

### **1.3 Thesis Organization**

The rest of this document is organized in the following pattern:

- Chapter 2 Explains the background study that is required to understand this thesis.
- Chapter 3 Explains the actual work carried out in this thesis.
- Chapter 4 Explains the simulation results and performance analysis of selected cooperative protocols in this thesis.
- Chapter 5 Conclusions.

## 2. BACKGROUND

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This chapter explains the related theory in detail about the thesis, mainly focuses on the modulation technique used, wireless channel, and diversity.

### 2.1 Modulation

The process of converting information so it can be sent through a medium (wired or wireless) is termed as modulation. In other words modulation is the process of encoding source data on to a carrier frequency. All modulation techniques involve operation on one or more of three fundamental frequency domain parameters namely phase, amplitude, and frequency [8]. Modulation helps in noise immunity, can combat attenuation but it strictly depends upon the medium used.

#### 2.1.1 Binary Phase Shift-Keying

In binary phase shift-keying (BPSK) the phase of the constant amplitude carrier signal is switched between two values according to the two possible signals  $m_1$  and  $m_2$  corresponding to binary 1 and 0 respectively. Two phases are separated by  $180^\circ$ . If the sinusoidal carrier has an amplitude  $A_c$  and energy per bit  $E_b = \frac{1}{2} A_c T_b$ , then the transmitted BPSK signal is either

$$x(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta_c) \quad 0 \leq t \leq T_b \text{ (binary 1)} \quad (2.1)$$

$$x(t) = -\sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta_c) \quad 0 \leq t \leq T_b \text{ (binary 0)} \quad (2.2)$$

We consider bit 0 and bit 1 that is represented as phase of  $\pi$  and 0 radians respectively; the BPSK signal can take the form [8]

$$x(t) = \begin{cases} A \cos(2\pi f_c t) & \text{for bit} = 1 \\ -A \cos(2\pi f_c t + \pi) & \text{for bit} = 0 \end{cases} \quad (2.3)$$

As we know that  $\cos(\theta + \pi) = -\cos(\theta)$ , so the transmitted signal becomes

$$x(t) = \begin{cases} A \cos(2\pi f_c t) & \text{for bit} = 1 \\ -A \cos(2\pi f_c t) & \text{for bit} = 0 \end{cases} \quad (2.4)$$

As  $P$  is power per symbol given by  $P = \frac{A^2}{2}$  then

$$A = \sqrt{2P} = \sqrt{\frac{2E_s}{T}} \quad (2.5)$$

where  $E_s$  denotes energy per symbol.

Constellation diagram is used for the representation of phase shift keying. Vectors are used to represent symbols. Angle of the vector shows the phase of the symbol while magnitude of the vector represents its amplitude. The constellation diagram of BPSK symbols is shown in Figure 2.1.

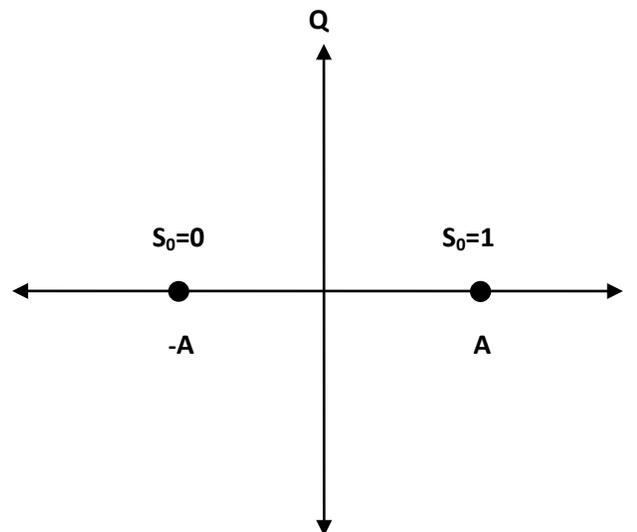


Figure 2.1 Constellation diagram for BPSK.

## 2.2 Wireless Channel

Wireless channels are different from wired channels because of their unreliable behavior. In wireless channel, the state of the channel may vary with respect to time. Such kind of random and unreliable behavior of the wireless channel greatly effects the communication.

### 2.2.1 Additive White Gaussian Noise

Noise is any unwanted portion of the signal that is not the original signal but corrupts the desired signal. Noise can be originated from different sources. It can be natural or manmade. Noise generated by the natural sources is not possible to eliminate, e.g. thermal noise.

Thermal noise is due to the thermal agitation of electrons in electronic components. This type of noise is statistically modeled as Gaussian random process having probability density function (PDF) given by

$$P(n) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{n}{\sigma}\right)^2} \quad (2.6)$$

where  $\sigma^2$  represents the variance of noise. Spectral density for noise can be written as  $S_n(f) = N_0/2$  Watts/Hz that is same for all frequencies up to  $10^{12}$ Hz [1]. The noise is additive because the received signal is equal to the transmit signal with the addition of noise, power spectral density is flat and the samples have Gaussian distribution. The channel responsible for introducing such kind of noise to transmitted signal is known as additive white Gaussian noise (AWGN) channel.

AWGN can be modeled as Gaussian random variable which is circular symmetric complex and is represented by  $Z$

$$Z = Z_r + jZ_i \quad (2.7)$$

where both  $Z_r$  and  $Z_i$  show zero-mean real valued Gaussian random variables respectively [10]. If the signal transmitted is represented by  $x(t)$ , then the received signal with AWGN can be written as

$$y(t) = x(t) + z(t) \quad (2.8)$$

where  $y(t)$  and  $z(t)$  show received signal and AWGN respectively.

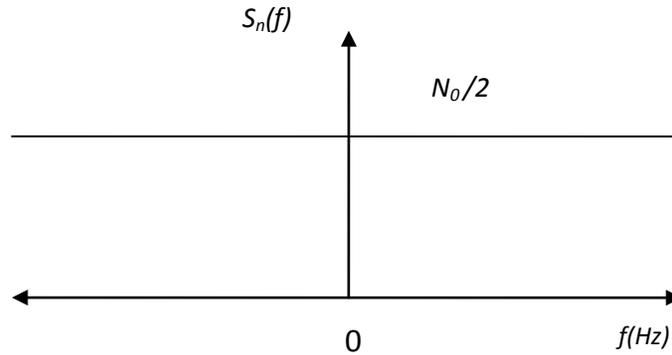


Figure 2.2 White noise.

### 2.2.2 Path Loss

The attenuation in the transmitted signal while propagating from the source to the destination is referred to as path loss. The factors due to which path loss occurs are the dissipation of the radiated power and also the effects of the propagation channel such as absorption due to moisture. Typical path loss models consider distance dependence attenuation, i.e. the received power depends on the distance between the source and the destination.

The simplest path loss model corresponds to propagation in free space, i.e. line-of-sight (LOS) link between the source and the destination. According to this model, the received signal power is given as [8]

$$P_R = P_T G_T G_R \frac{\lambda^2}{4\pi d^2} \quad (2.9)$$

where  $P_T$  denotes the transmitted power,  $G_R$  and  $G_T$  show the receive and transmit antenna gains respectively,  $\lambda$  represents the wavelength of the transmitted signal, and  $d$  denotes the distance between the source and the destination. Therefore, there is a decrease in the received power with a factor of distance-squared under free space propagation. This model also shows that path loss is dependent on carrier wavelength.

Hence, shorter wavelength or equivalently higher transmitter frequency leads to higher path loss.

### 2.2.3 Fading

Multipath fading is one of the basic characteristics of wireless channels. Wireless communication systems can have multiple signal paths between sender and receiver. These multiple paths are due to the occurrence of different phenomena such as reflection, scattering, and diffraction. Thus multiple replicas of the same signal known as multipath components are received by the receiver. These multipath components arrive to the receiver from varying directions having different phases and amplitudes. They combine to give a resultant received signal. They may sometimes combine destructively due to which there is a significant possibility of severe fades.

A short review of this topic is given as follows. Consider the transmit signal to be

$$x(t) = \Re\{x_B(t)e^{j2\pi f_c t}\} \quad (2.10)$$

where  $x_B(t)$  represents the baseband equivalent of the transmitted signal  $x(t)$  and  $f_c$  gives the carrier frequency as described in [11]. Since there are multiple propagation paths, that give rise to multipath components. As discussed earlier that each multipath component is having its own characteristics such as amplitude, propagation delay, path length, and attenuation of its path. All these properties vary with respect to time because of the alterations in the medium structure and the movement of transmitter/receiver. The received multipath signal  $y(t)$  can then be given as

$$y(t) = \sum_n \alpha_n(t)x(t - \tau_n(t)) \quad (2.11)$$

where,  $\alpha_n(t)$  represents attenuation factor of nth path and  $\tau_n(t)$  shows the propagation delay of nth path. The number of multiple paths at a particular time t varies with time.

Substituting 2.11 in 2.10 gives

$$y(t) = \sum_n \alpha_n(t)\Re[x_B(t - \tau_n(t))e^{j2\pi f_c t}] \quad (2.12)$$

$$y(t) = \Re\left[\left\{\sum_n \alpha_n(t)e^{-j2\pi f_c \tau_n(t)}x_B(t - \tau_n(t))\right\}e^{j2\pi f_c t}\right] \quad (2.13)$$

By comparing 2.13 with 2.10, it is obvious that resultant low pass signal for received signal is:

$$y_B(t) = \sum_n \alpha_n(t) e^{-j2\pi f_c \tau_n(t)} x_B(t - \tau_n(t)) \quad (2.14)$$

This gives the channel response for the resultant baseband signal  $x_B(t)$ . Substituting the transmit signal by unit impulse gives the impulse response of the channel, that is

$$h(\tau; t) = \sum_n \alpha_n(t) e^{j2\pi f_c \tau_n(t)} \delta(t - \tau_n(t)) \quad (2.15)$$

We get the resultant band-pass impulse response of the channel. So considering  $x_B(t) = 1$ , i.e. when the carrier frequency is not modulated

$$y_B(t) = \sum_n \alpha_n(t) e^{j2\pi f_c \tau_n(t)} \quad (2.16)$$

$$y_B(t) = \sum_n \alpha_n(t) e^{j2\pi f_c t} x \quad (2.17)$$

where  $\theta_n(t) = 2\pi f_c \tau_n(t)$  gives the phase of  $n$ th multipath component. Hence the received signal is a vector sum of phasors.  $\alpha_n(t)$  gives the path loss effect or large scale fading, therefore, variations in the received signal because of  $\alpha_n(t)$  arise over relatively large distances, whereas, small variations in  $\tau_n(t)$  give rise to a considerable change in  $\theta_n(t)$ . For example  $1/f_c$  variation in  $\tau_n(t)$  varies  $\theta_n(t)$  by  $2\pi$  radians. Hence for large  $f_c$ , that is mostly the case for wireless communication, small variations in the medium structure will change  $\theta_n(t)$  symbolically.  $\tau_n(t)$ , i.e. the propagation delay related to different paths varies at different rates and unexpectedly gives rise to unpredicted fluctuations in the resultant signal. Hence the received signal may be modeled as a random process. In Figure 2.3 every tap shows a path for a signal. Every path has its own delay  $\tau_i$  and faces channel  $h_i$ , where  $i = 1, 2, 3, \dots, N$ .

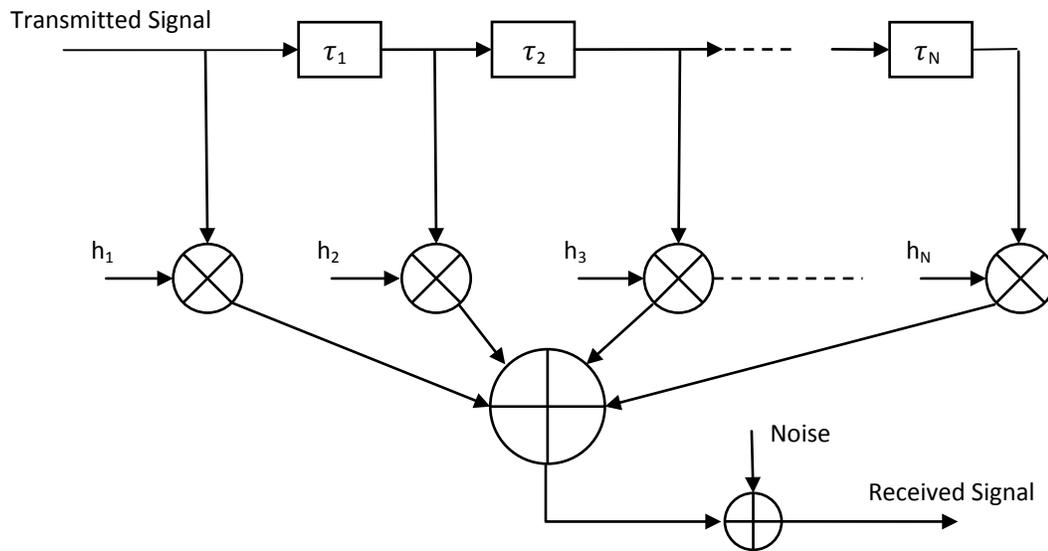


Figure 2.3 Tap delay structure of multipath channel.

Hence fading is a random phenomenon caused due to alterations of multipath components  $\theta_n(t)$  and phases. Multipath components having different phases add constructively and destructively giving rise to alterations in amplitude of the received signal. Fading mostly depends upon time and frequency [10].

The power delay analysis is given by the autocorrelation function of the channel response  $h(\tau; t)$  that is the average output power of the varying channel with time delay  $\tau$ . The range of  $\tau$  where the channel's average output power has non-zero value is called multipath spread or delay spread,  $T_m$ . The measure of coherence bandwidth of the channel given by delay spread is

$$\Delta f_c \approx 1/T_m \quad (2.18)$$

where,  $\Delta f_c$  represents the channel's coherence bandwidth. This is the frequency range for which channel gains alter inconsiderably. All the frequency components go through similar fading if transmission bandwidth is smaller than the channel's coherence bandwidth. Such type of fading is known as frequency non-selective or flat fading. On the other hand if signal bandwidth is larger than coherence bandwidth, then the fading in

that case is called frequency selective fading. This type of channel shows extreme distortion to the signal because different frequency components go through different fading.

### 2.2.4 Rayleigh Fading

Multipath reception is the main cause of Rayleigh fading. It is the case of non line-of-sight propagation when the propagating signal is reflected, diffracted, or refracted and finally reaches the receiver. Because of this variation in the signal, the output signal is random and the received power becomes random variable. If there are several multipath components in a channel, then the central theory of statistics is applied and the channel can be designed circular symmetric zero-mean Gaussian complex random process [10] which can be denoted as

$$H = H_r + jH_i \quad (2.19)$$

where  $H_r$  and  $H_i$  are zero mean Gaussian random variables, respectively. The envelope of these random variables follows Rayleigh distribution and is given by

$$R = |H| = \sqrt{H_r^2 + H_i^2} \quad (2.20)$$

Also, we have probability density function given as

$$P_R(r) = \frac{2r}{\Omega} e^{-\frac{r^2}{\Omega}} \quad r \geq 0 \quad (2.21)$$

Above described model is termed as Rayleigh fading channel. When there is a narrow-band transmission, then the multipath components cannot be separated. Hence the delay spread becomes very small and the channel follows flat fading. Channel mode for such a case is single-tap as shown in Figure 2.4.

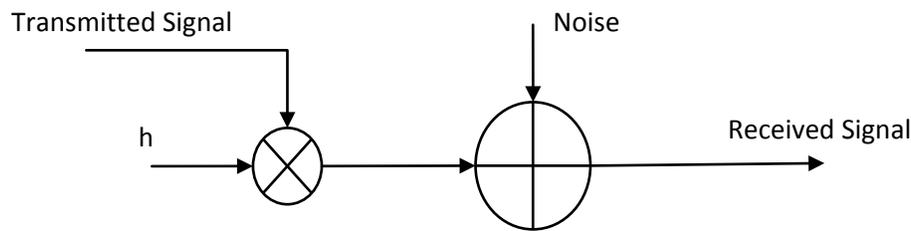


Figure 2.4 Flat-fading channel.

Channel for such a scenario follows the Gaussian distribution with zero-mean.

Received signal with AWGN can take the form

$$y(t) = h(t)x(t) + z(t) \quad (2.22)$$

where  $h(t)$  is the impulse response in the time domain for the Rayleigh channel,  $y(t)$  is the received signal,  $x(t)$  denotes the transmitted signal whereas  $z(t)$  denotes additive white Gaussian noise.

### 2.3 Diversity

When the signal travels from a transmitter to a receiver by a number of routes, it gives rise to a multipath fading. This is due to the signal being reflected from objects, or being influenced by atmospheric effects as it passes through layers of air with varying temperature and humidity. Signal arrives at the receiver through multiple paths. It means that the receive antenna will receive the signal at different phases, some at crest and some at trough. Here we can see that some signal will add together to form strong signal while some will subtract causing a weak signal.

The performance can be improved by providing multiple independent propagation paths. Because of the independent paths all the signals will experience different fades. Hence the error rates and the performance of the communication system may be greatly improved by combing the independently fading signals. Technique of providing multiple independent fading paths for the propagation of signal is known as diversity. Diversity makes use of the varying nature of the wireless channel. In telecommunication systems, we have many techniques by which we can achieve diversity. It can be

categorized as time, frequency, polarization, space, and cooperative diversity [5], [6]. Depending upon the channel conditions, any of the diversity techniques can be used to obtain diversity gain. Diversity is defined as the variation in the error probability slope. Generally the average error probability of a diversity system can be expressed as

$$\bar{P} = c\bar{\gamma}^{-M} \quad (2.23)$$

where  $\bar{P}$  denotes the average error probability,  $c$  is a constant which depends upon the modulation technique and coding scheme used whereas  $\bar{\gamma}$  represents the received SNR. Exponential  $M$  is the order of the diversity.  $M$  shows the variation of probability error slope in diversity system [13].

In time diversity, the same signal is transmitted over the same channel at different times. Channel coding when combined with interleaving is termed as time diversity, as the signals are spread in time. If the coded signal is spread wider than the coherence time, then time diversity is achieved.

Frequency diversity exploits the fact that the different frequencies will experience different fades, so it is not correlated. Hence if one frequency experience fades when travelling through propagation path the other may not experience fade. Frequency diversity can be achieved with frequency selective fading, since different frequencies have different channel fading. If the separation between sub-channels is larger than coherence bandwidth, frequency diversity can be obtained by the use of orthogonal frequency division multiplexing (OFDM) breakdown frequency selective channel into parallel flat fading sub-channels [27].

When the antennas of different polarizations (i.e. horizontal and vertical) are used for the diversity gain at the reception, this is termed as polarization diversity. Such kind of method uses signal polarization to create multiple paths. Polarization diversity provides vertically and horizontally polarized paths [13], [6].

### 2.3.1 Cooperative Diversity

The unreliable and varying nature of the wireless channel makes communication difficult but despite of varying nature the multiprotocol layers in the network architecture offers great opportunities for improving network performance. The energy efficient class of cross layer network called cooperative diversity which takes advantage

of the broadcast network and inherent spatial diversity of the channel [14]. With the help of cooperative diversity, wireless nodes can cooperate with each other by relaying messages for each other hence sending multiple copies of the same signal over the multiple paths to the receiver. At the receiver side, with the help of this redundant signal, system can achieve enough diversity gains. Cooperative diversity can provide full spatial diversity [15].

Cooperation can counter the shadowing effect by relaying the transmitted signal. Relaying nodes can restore the power of the signal by amplifying the signal with some defined factor. So it is helpful against path loss and network coverage extension. Figure 2.5 shows the case of uplink; Node A sends signal to the base station, Node B also hears this transmission so it acts as a relay and thus forwarding the signal to the base station.

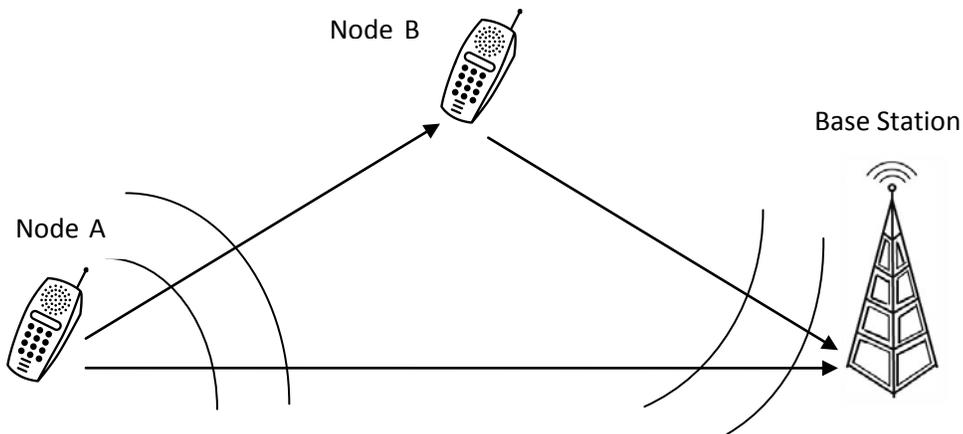


Figure 2.5 Cooperative communication.

## 2.4 Diversity Combining Types

Diversity combining is the technique used to combine various signals received by diversity reception device into a resultant and improved signal.

Various diversity combining techniques are discussed in the sequel.

### 2.4.1 Equal Ratio Combining

In this type of diversity combining technique, all the received signals are simply combined when it is difficult to estimate the channel quality. Though this technique is the easiest one, it does not give satisfactory performance in most cases. The combined signal at the destination is denoted as

$$y_d[n] = \sum_{i=1}^k y_{i,d}[n] \quad (2.24)$$

where  $y_d[n]$  is the combined signal at the destination and  $y_{i,d}[n]$  is either the signal from the source or the relay.

For our considered model, i.e. one relay node, the above equation can be written as

$$y_d[n] = y_{s,d}[n] + y_{r,d}[n] \quad (2.25)$$

where,  $y_{s,d}[n]$  represents the signal received at destination through direct path while  $y_{r,d}[n]$  represents the signal received through relayed path [32].

### 2.4.2 Fixed Ratio Combiner

This type of technique gives much better performance. In this technique, the incoming signals are weighted with a constant ratio instead of just combining them. The ratio represents the average channel quality and does not consider influences on the channel that are caused by fading or other effects. Only those influences on the channel, which vary the average channel quality, such as distances between different stations, are taken into account. The fixed ratio combining technique can be expressed as [32]

$$y_d[n] = \sum_{i=1}^k d_{i,d} \cdot y_{i,d}[n] \quad (2.26)$$

where,  $d_{i,d}$  represents weighting of the incoming signal  $y_{i,d}$ . For a system, using one relay node, the above equation can be given as

$$y_d[n] = d_{s,d} \cdot y_{s,d}[n] + d_{s,r,d} \cdot y_{r,d}[n] \quad (2.27)$$

---

### 2.4.3 Maximal Ratio Combiner

This combining technique obtains the best possible performance by multiplying each input signal with its corresponding conjugated channel gain. It takes into account that the receiver has perfect knowledge of channel's phase shift and attenuation.

$$y_d[n] = \sum_{i=1}^k h_{i,d}^*[n] \cdot y_{i,d}[n] \quad (2.28)$$

where  $y_d[n]$  is the combined signal at the destination and  $y_{i,d}[n]$  is either the signal from the source or the relay.

For a system having one relay node, the above equation can be rewritten as [32]:

$$y_d[n] = h_{s,d}^*[n]y_{s,d}[n] + h_{r,d}^*[n]y_{r,d}[n] \quad (2.29)$$

## 3. COOPERATIVE RELAYING SCHEMES

---

This chapter focuses on the research carried out and the actual work done. The first portion briefly describes the different diversities. Then there is a section that describes in detail the cooperative relay communications. Finally, the considered cooperative system models, i.e. equidistant and collinear are presented and all the selected cooperative strategies are explained.

### 3.1 The Different Diversities

In digital mobile radio, multipath reception is used to improve transmission. Each extra transmission path is used to reach a receiver node which increases reception performance and improves Signal-to-Noise ratio (SNR). Multipath reception mitigates the effects of the strong receive level variations that a single transmission channel is exposed to in mobile operation. The possibility that many channels are impassable at the same time is usually smaller than if only one channel is used.

Another method namely frequency hopping is used in the global system for mobile communications (GSM) standard to minimize strong receive level variations and hence increasing the transmission quality. In addition to that, proper coding (e.g. interleaving) minimizes the effects of short interruptions in transmission [12].

The use of additional antennas at the receiver and/or transmitter end is also a way of achieving diversity and hence improving the transmission quality [24]. As already discussed in the previous chapter that diversity techniques assists minimize the effects of fading by providing multiple replicas of the same signal through different paths (in time, frequency, or space) so that the possibility that all the paths will experience the same amount of fading is greatly reduced. Therefore, the destination node can be provided with improved signal via one or more paths. Frequency and time diversity techniques need additional spectral and temporal resources to make sure that the replicas

of the signal are sent through paths or channels conditions. This situation is bypassed by using the extra space dimension. Wireless propagation media have mostly scattering nature, so bringing in some degree of orthogonality between channel elements. This channel property can be employed using spatial diversity to send replicas of signals through multiple paths to the receiver node. Different types of diversity combiners are then used to combine the copies to maximize the SNR at the output [30].

### 3.1.1 Single-Input Single-Output

The communication model gives the simplest picture of a communication link between a single transmit antenna and a single receive antenna. It includes a source that encodes the data using half-rate convolution encoder, which is then modulated by a modulator using BPSK. The channel is designed as frequency non-selective Rayleigh faded in the presence of AWGN. So the noise is complex random process having Gaussian distribution with zero mean and variance  $N_0/2$ .

The communication model clearly shows that spatial diversity cannot be applied in this case. Yet, this basic scheme is included to evaluate its performance in fading channels and to highlight the obvious advantage of spatial diversity schemes that make use of multiple antennas.

The system is described as follows:

$$y_{s,d} = a_{s,d}x_s + n_{s,d} \quad (3.1)$$

where,  $y_{s,d}$  denotes the received signal,  $x_s$  is the transmitted signal, and  $n_{s,d}$  denotes an AWGN component.

Simulation results for all the selected relaying schemes have been compared with this non-cooperative scheme. This assists a good comparison and understanding the behavior of relaying protocols.

### 3.1.2 Multiple-Input Single-Output

MISO communication systems use multiple antennas at the transmitter and a single antenna at the receiver. It is also referred to as transmit diversity. In this thesis, we consider 2x1 MISO, i.e. a second order diversity which shows two transmit and one receiver antenna. This kind of arrangement is used for diversity gains.

Signal is encoded with channel encoder, then modulated using BPSK and finally propagated over flat fading Rayleigh channel.

In this thesis, theoretical performance of the second order diversity is considered for comparison. It is assumed that the channel conditions are known to the receiver. Simulation results for all the relaying protocols are also compared with the theoretical curves of the second order diversity [24].

### **3.2 Cooperative Communication**

In a multi-hop relay network, the communication between source and destination take place with the help of a relay. The broadcast nature of the wireless networks may cause the relay to intercept this transmission. The relay then retransmits the received information to the destination after varying it according to proper technique. Depending upon the relaying scheme used, and by combining the source and relay transmissions, the destination can outperform the single hop transmission. The major benefit is to obtain diversity against fading without the use of an antenna array at any terminal [9].

### **3.3 Relaying Geometry**

Relaying geometry shows the relative position of the relay in the network. Two different kinds of arrangements are considered in this thesis.

#### **3.3.1 Equidistant geometry**

This kind of arrangement assumes that distance between source to relay, relay to destination, and source to destination is same which considered as one in this thesis for simplicity reasons. Similar arrangement is also considered by other works e.g. [16] [17] [18], with single relay communication with source destination pair. Figure 3.1 shows the equidistant arrangement which is considered for this thesis.

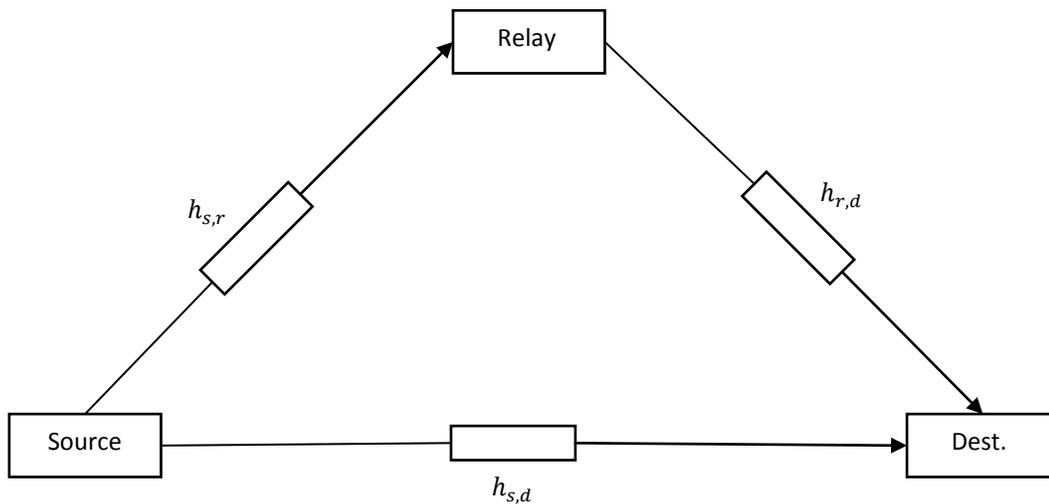


Figure 3.1 Equidistant geometry.

In Figure 3.1,  $s$ ,  $r$ , and  $d$  show source, relay, and destination nodes, respectively.  $h_{s,r}$  is the channel between source and relay,  $h_{r,d}$  is the channel between relay and destination, while  $h_{s,d}$  is the channel between source and destination. In this thesis, the channel  $s-r$  will be termed as inter-user channel,  $r-d$  as relay-uplink channel, while  $s-d$  as a source-uplink channel. All the nodes have single transmit and receive antenna.

Furthermore, it is assumed that the relay perfectly knows about the relay uplink channel and the destination has the perfect knowledge about all the channels, i.e.  $s-r$ ,  $r-d$ ,  $s-d$  channels, respectively. All the communicating nodes are considered to be half-duplex which means that they are able to either receive or transmit at a given time. The considered model shows that the source and relay are two users in a wireless network and they are placed in the same cell, they cooperate with each other using one of the cooperation schemes to obtain diversity gains.

In this thesis, the only case of uplink is considered, i.e. source communication with the base station but because of the system's omni-directional behavior, a nearby user can also hear this transmission so it is willing to cooperate with the source and it is considered as a relay. So due to the broadcast nature of the transmission, the relay receives the signal and modifies it according to one of the cooperation schemes and

forwards it to the receiver which is the base station. At the receiver side both the signals are combined using MRC combiner and the necessary information is extracted.

### 3.3.2 Collinear Geometry

This kind of arrangement shows the relay is half way between the source and destination. Source and relay cooperate with each other using one of the cooperation schemes and transmit to the destination. Similar arrangement is widely applied in the literature [19], [20], [21], [22]. Message is first encoded by the source and transmitted to the destination. Transmission is heard by the relay it decodes and modifies the signal according to one of the cooperation protocols. Figure 3.2 shows the collinear geometry.

The channel model consists of the effects of path loss with distance and the addition of AWGN having spectral density  $N_0/2$ .

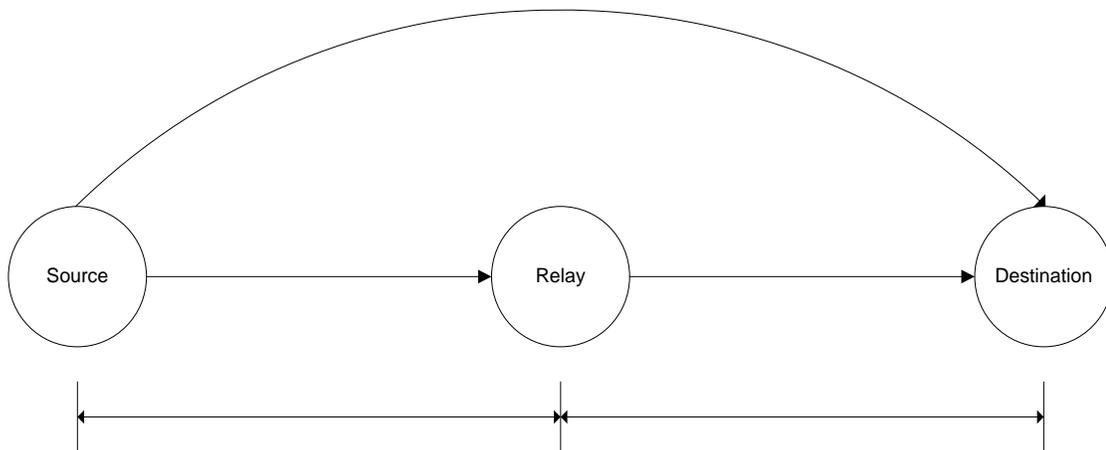


Figure 3.2 Collinear geometry.

### 3.4 Channel Model

In this thesis, the wireless channel is supposed to be frequency non-selective Rayleigh faded in the presence of AWGN. The channel is statistically independent and identically distributed complex Gaussian random process, that has zero mean and variance equal to unity. Noise is a complex random process denoted as

$$Z = Z_i + jZ_r \quad (3.2)$$

where  $Z_i$  shows the real part while  $Z_r$  is the imaginary part of the noise. Hence, the noise follows the Gaussian distribution with zero mean and variance

$$\sigma^2 = N_0/2 \quad (3.3)$$

where  $N_0$  is the power spectral density of the noise. Further, it is assumed that the channel is slowly faded, so that we have constant fading coefficients for any symbol period. Figure 3.3 shows the channel model.

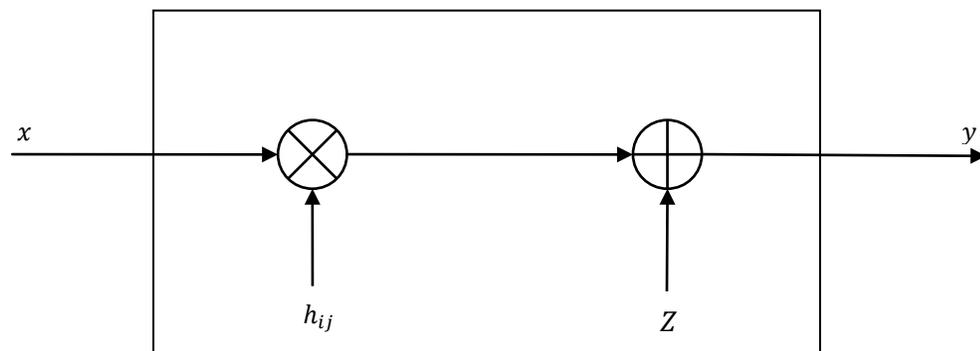


Figure 3.3 Channel model.

In Figure 3.3,  $x$  is the input signal or the transmitted signal which then passes through a noisy channel and fades during propagation whereas  $y$  is the corresponding output at the destination. So, we can mathematically express the transmission of each symbol as

$$y_{ij} = \sqrt{P_t} h_{ij} x + Z_{ij} \quad (3.4)$$

where  $y_{ij}$  denotes the symbol when  $x_{ij}$  is transmitted, and  $h_{ij}$  is channel response which is multiplicative channel fading coefficient.  $Z_{ij}$  is the AWGN while  $P_t$  being the transmit power.

### 3.5 Source Model

In this thesis, the source is assumed to generate random information which is a sequence of bits that is achieved by random generator. Data obtained from random generations is

then encoded using channel encoder which is half rate convolution encoder in this case. Finally the encoded data is modulated with BPSK. Transmission power is taken as normalized power  $P_t = 1$ .

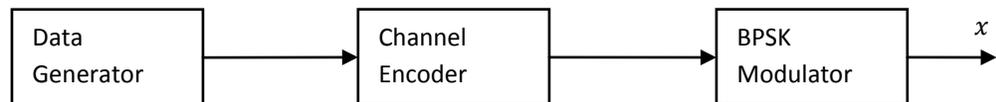


Figure 3.4 Source model.

### 3.5.1 Half - Rate Convolution Encoder

Source data is encoded using  $\frac{1}{2}$  rate convolution encoder. Sequence of bits is applied to the encoder, for every single data bit it generates two bit symbol. Figure 3.5 shows the channel encoder.

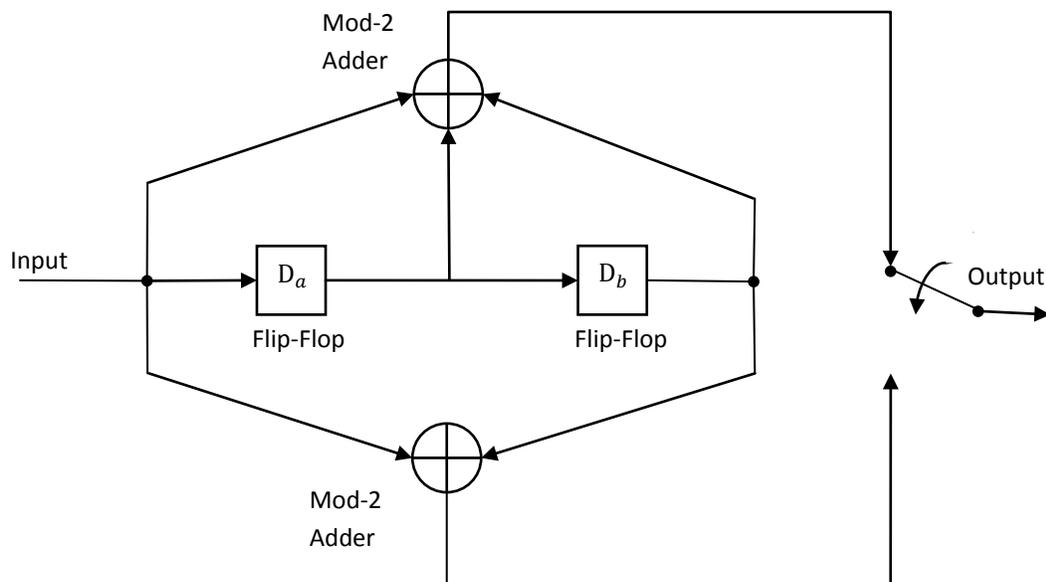


Figure 3.5 Half-rate convolution encoder.

In Figure 3.5,  $D_a$  and  $D_b$  are two stage shift registers with constraint length of 3.  $1+D+D^2$  is the generator polynomial to upper and  $1+D^2$  for the lower branch, respectively. Hence we have a (5,7) convolution encoder [1].

Transmission from source and relay is in the form of blocks which is considered as one symbol for this thesis.

### 3.6 Relay Model

Relay transmit power is normalized and taken as  $P_t = 1$ , it uses BPSK for signal modulation, so the relayed signal is similar to that of the source which is a sequence of 1's and 0's. Relay is assumed to have perfect knowledge about the inter-user channel. Effect of S-R channel can be equalized by the relay and it uses maximum likelihood (ML) detector for the detection of source signal. At the relay, the receiver signal is processed according to one of the cooperation schemes and sent to the destination. Figure 3.6 shows the block diagram of the relay node.

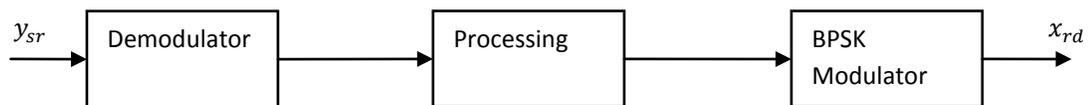


Figure 3.6 Relay model.

### 3.7 Destination Model

Destination receives two types of transmissions, i.e. one from the direct path (source) and second the relayed signal from the relay. Both the signals are then combined using MRC. In this thesis, it assumed that the destination has the full knowledge about the fading on all the channels. After the MRC, the symbol error rate is calculated by comparing it with the transmitted signal. Figure 3.7 shows the destination model.

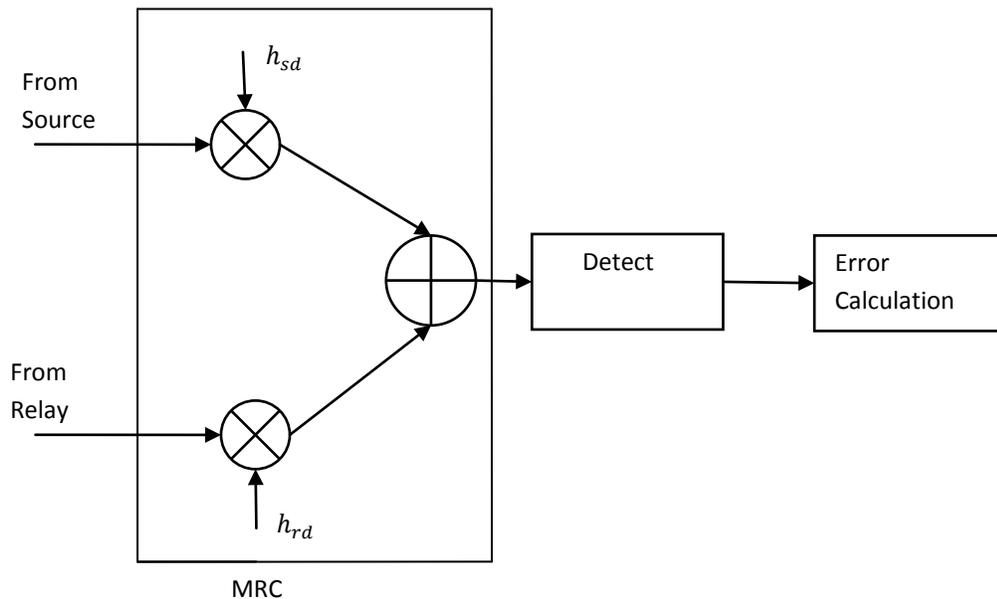


Figure 3.7 Destination model.

### 3.8 Modes of Relaying

Relaying schemes can be categorized as fixed and selective schemes. When the relay node attempts to cooperate in all conditions it is termed as fixed scheme but when it cooperates conditionally then it is termed as selective scheme [2]. In this thesis, three fixed and one selective scheme are studied and compared on the basis of symbol error rate.

#### 3.8.1 Amplify-and-forward

In this scheme, the source transmits to relay, the relay amplifies the received signal according to some amplification factor and the power constraints are considered. Amplification factor has inverse relation to the power received. From 3.4, the signal at relay is given by

$$y_{s,r} = \sqrt{P_t} h_{s,r} x + Z_{s,r} \quad (3.5)$$

Normalizing the power to  $P_t = 1$  gives

$$y_{s,r} = h_{s,r} x + Z_{s,r} \quad (3.6)$$

Received power is given as

$$\begin{aligned}
 E[y_{s,r}^2] &= E[(\sqrt{P_t}h_{s,r}x + Z_{s,r})^2] \\
 &= E[(\sqrt{P_t}h_{ij}x)^2] + E[Z_{s,r}^2] \\
 &= P_t|h_{s,r}|^2 + N_0
 \end{aligned} \tag{3.7}$$

where  $N_0 = 2\sigma^2$  is the average noise power. Amplification coefficient can be given by

$$\beta = \sqrt{\frac{P_t}{P_t|h_{s,r}|^2 + N_0}} \tag{3.8}$$

When the power constraint is considered, 3.8 takes the form

$$\beta = \sqrt{\frac{1}{|h_{s,r}|^2 + N_0}} \tag{3.9}$$

Thus the fading amplitude and noise are considered by amplification coefficient. Some other amplification coefficients are proposed in [22]. Amplification coefficient similar to this thesis are also suggested by [2], [19], [25], and [26]. This kind of amplification factor considers the channel response of inter-user channel and effect of noise when added to the received signal.

Signal after amplification becomes

$$\begin{aligned}
 x_r &= \beta y_{s,r} \\
 &= \beta(x_s h_{s,r} + Z_{s,r})
 \end{aligned} \tag{3.10}$$

Relayed signal when received at destination is given by

$$\begin{aligned}
 y_{r,d} &= h_{r,d}x_r + Z_{r,d} \\
 &= h_{r,d}(\beta(h_{s,r}x_s + Z_{s,r})) + Z_{r,d}
 \end{aligned} \tag{3.11}$$

Composite signal at destination is given as

$$\begin{aligned}
 y_d &= h_{s,d}x_s + h_{r,d}x_r + Z_{r,d} + Z_{s,d} \\
 &= h_{s,d}x_s + h_{r,d}\beta(x_s h_{s,r} + Z_{s,r}) + Z_{r,d} + Z_{s,d}
 \end{aligned}$$

$$\begin{aligned}
&= h_{s,d}x_s + h_{r,d}\beta(x_s h_{s,r} + Z_{s,r}) + Z \\
&= h_{s,d}x_s + \beta h_{r,d}h_{s,r}x_{r,s} + \beta h_{r,d}Z_{s,r} + Z_{r,d} + Z_{s,d} \\
&= h_{s,d}x_s + \beta h_{r,d}h_{s,r}x_s + Z
\end{aligned} \tag{3.12}$$

where  $Z$  represents the composite noise. Amplify-and-forward is a simple cooperation scheme, in which relay does not require extra processing capability but still it can achieve full diversity [19]. The only drawback in this scheme is that it amplifies the received signal along with inter-user channel noise. It means that it cannot eliminate the noise from the received signal. In literature it is also termed as non-regenerative relaying protocol.

### 3.8.1.1 Derivation of Effective SNR for Collinear Geometry

This derivation was first proposed by Laneman [27]. In AF source transmits a noisy version of a signal to relay. Relay amplifies this noisy signal and re-transmits to the destination. Destination combines the information from direct and relayed transmission and a final decision is taken by the destination. As we can see that the noise is also amplified by the relay but the destination makes better decisions on the received information as it receives two independent copies of the faded signal.

Signal received by the relay and destination in the first time slot can be represented as

$$y_{s,r} = a_{s,r}x_s + n_{s,r} \tag{3.13}$$

$$y_{s,d} = a_{s,d}x_s + n_{s,d} \tag{3.14}$$

where  $y_{s,r}$  and  $y_{s,d}$  represent the signal received by the relay and destination, respectively. Normalizing the transmit power so it becomes unity, i.e.  $P_t = 1$ . The path loss exponent considered is 2 so according to the equation  $a_i = 1/r_i^n$ , the path loss for source to destination link is unity, i.e.  $a_{s,d} = 1$ . In the first time slot the signal power  $P_t$  received at the destination will be unity and the noise power received at the destination is  $N_0$ . Hence, the SNR in the first time slot at the destination is  $1/N_0$ .

As the relay is placed half way between source and destination and this thesis considers free space model. So we assume the link distances from source to relay and

relay to destination equal to 0.5. The path loss exponent considered is 2 so according to the equation  $a_i=1/r_i^n$ , the path loss for source to relay link and relay to destination link is 4. Hence the path loss is four times less than that of the destination. Accordingly,  $r_{s,d} = 1$  then  $a_{s,d} = 1$  for single-hop link. Similarly if  $r_{s,r} = r_{s,d}/2$  then  $a_{s,r}, a_{r,d} = 4$  for two hop-link when free space model is considered with path loss exponent  $n = 2$ .

When the signal is received at the relay, it retransmits it to the destination after amplifying in the second time slot. For sending the data the relay uses a gain of ' $\beta$ ' or simply an amplification factor, which is

$$\beta = \sqrt{\frac{1}{4+N_0}}$$

$$\beta^2 = \frac{1}{4+N_0} \quad (3.15)$$

The received signal power  $P_r$  is  $\left(\sqrt{|a_{s,r}x_{s,r}|}\right)^2 = 4$  at relay whereas  $N_0$  represents the noise variance. In the second time slot, the signal received at the destination can be expressed as

$$y_{r,d} = a_{r,d}\beta(a_{s,r}x_s + n_{s,r}) + n_{r,d} \quad (3.16)$$

In relay's transmission the signal power is

$$P_r = \frac{4}{4+N_0} \quad (3.17)$$

In the second time slot, the noise power in relay's transmission is

$$P_n = \frac{N_0}{4+N_0} \quad (3.18)$$

As path loss between the relay and destination link is  $a_{r,d} = 4$ , signal power received at destination from relay is given by

$$P_{r,d} = \frac{16}{4+N_0} \quad (3.19)$$

Noise power amplified by relay, which is received at the destination, is given by

$$P_n = \frac{4N_0}{4+N_0} \quad (3.20)$$

As there is a noise in transmission environment,  $N_0$ , therefore,  $n_{s,r} = n_{r,d} = n_{s,d}$ . In the second time slot, the combined noise received at the destination is given by

$$P_n = \frac{4N_0}{4+N_0} + N_0 \quad (3.21)$$

Dividing 3.19 by 3.21 gives the effective SNR for collinear geometry, which is

$$SNR_{s,r,d} = \frac{16}{8N_0+N_0^2} \quad (3.22)$$

### 3.8.2 Decode-and-Forward

In this scheme, the original data is extracted from the received signal by using Viterbi decoder. Decoded data is further encoded by the relay in the similar way as encoded by the source. Encoded signal is finally sent to the destination. In literature, decode-and-forward is termed as re-generative relaying protocol [19]. The signal received by the relay is given by 3.7. Signal is decoded and further re-encoded by the relay to  $\hat{x}_s$ . Relayed signal at destination is given by

$$y_{r,d} = h_{r,d}\hat{x}_r + Z_{r,d} \quad (3.23)$$

At destination, the combined signal can be given by

$$\begin{aligned} y_d &= h_{s,d}x_s + h_{r,d}x_r + Z_{r,d} + Z_{s,d} \\ &= h_{s,d}x_s + h_{r,d}\hat{x}_s + Z_{r,d} + Z_{s,d} \end{aligned} \quad (3.24)$$

In this scheme, the relay must possess more processing capabilities, as the relay has to fully decode the signal. Decode-and-forward is regenerative process, so it can eliminate the S-R noise from the inter-user signal. At low SNR if the decoding at the relay is unsuccessful then the performance of DF will be degraded. As the relay can fully decode the signal, therefore, the security threats are also associated with this protocol. To combat with security threats there must be some mechanism of encryption of data which can help us protect the integrity of data.

### 3.8.3 Detect-and-Forward

In this scheme, the signal is demodulated/detected by the relay and sent to the destination. The channel encoded signal is not fully decoded by the relay whereas  $\bar{x}_s$  represent the detected signal by the relay, hence the signal at destination is given as

$$y_d = h_{s,d}x_s + h_{r,d}\bar{x}_s + Z_{r,d} + Z_{s,d} \quad (3.25)$$

It can be concluded that this scheme is less complex as compared to DF. In literature, it is also termed as re-generative scheme as the signal is detected and re-generated before transmission.

In literature, DtF and DF belong to the same category of relaying schemes. DtF is also termed as fixed DF which provides coding gain instead of diversity gain and acts as a repetition code [29]. DF fully decodes the received signal while DtF retransmits the symbols without fully decoding them; it just investigates the received symbols.

Exact definition of DF depends upon its implementation, i.e. superposition block Markov encoding/decoding [28], virtual Alamouti [29]. It can be concluded that the performance of DF depends upon the coding scheme employed.

### 3.8.4 Selective Detect-and-Forward

In this scheme, the relay detects the source transmission; if the detection is error free then it is forwarded to the destination. To detect the source transmission correctly there must be some error detection mechanism like cyclic redundant check (CRC) implemented at the relay. This thesis considers an ideal scenario in which symbol-by-symbol error is detected and the relay can easily discover about the error in the received symbol. This kind of scheme eliminates the problem of error propagation.

## 4. SIMULATION RESULTS AND ANALYSIS

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In this chapter results of the Monte Carlo simulation of selected cooperative schemes are presented for both the previously described relaying geometries, namely, equidistant collinear.

For equidistant geometry two reference rate SER curves are used for the analysis of the results. One is the curve for single hop transmission, namely, SISO, while other is for transmit diversity with two antennas, namely, 2x1 MISO.

For collinear geometry with a relay half way between the source and destination, the three cooperative schemes, i.e. AF, DF, and DtF, are analyzed. These cooperative schemes are compared for two different path loss exponents.

### 4.1 Equidistant Geometry with Similar Channel Conditions

Figure 4.1 compares the relayed signal for the three protocols AF, DF, and DtF. It is obvious from the figure that the relayed signal for DF is comparatively better than AF and DtF at mid-high SNR. For AF the relayed signal arrives in worse condition as compared to other protocols and direct transmission. Similarly in DtF the relayed signal contains more errors as compared to single hop transmission.

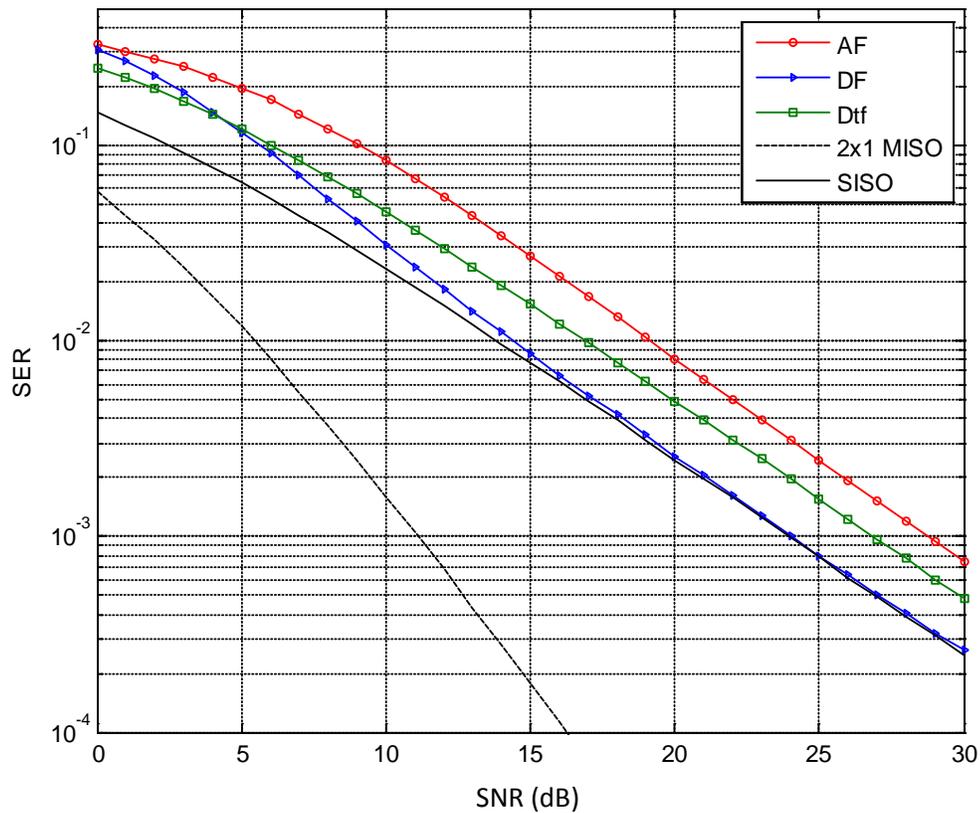


Figure 4.1 Relayed signal for equidistant geometry with similar channel conditions.

Figure 4.2 compares the results of cooperation, i.e. the MRC combined signal for the three protocols at the destination. The relayed signal is combined with the direct transmission at the destination for possible diversity gains. Figure 4.2 shows that the AF and DF provide better performance as compared to DtF. DF shows worse performance at low SNR, because if the inter-user channel is bad the relay cannot decode the signal efficiently and the error remains in the relayed signal. When this error is further propagated by the relay, it limits benefits of cooperation with DF at low SNR. In the Figure 4.2 we can see that AF and DF attain the diversity order 2 while DtF shows similar behavior as that of diversity order 1. DF has more errors at low SNR as compared to AF but higher SNR it outperforms AF. Relayed signal for DF has less errors as compared to AF but after MRC combiner both the protocols show somewhat

similar performance and attains full diversity. It may be because of MRC detection which is optimal for AF [31].

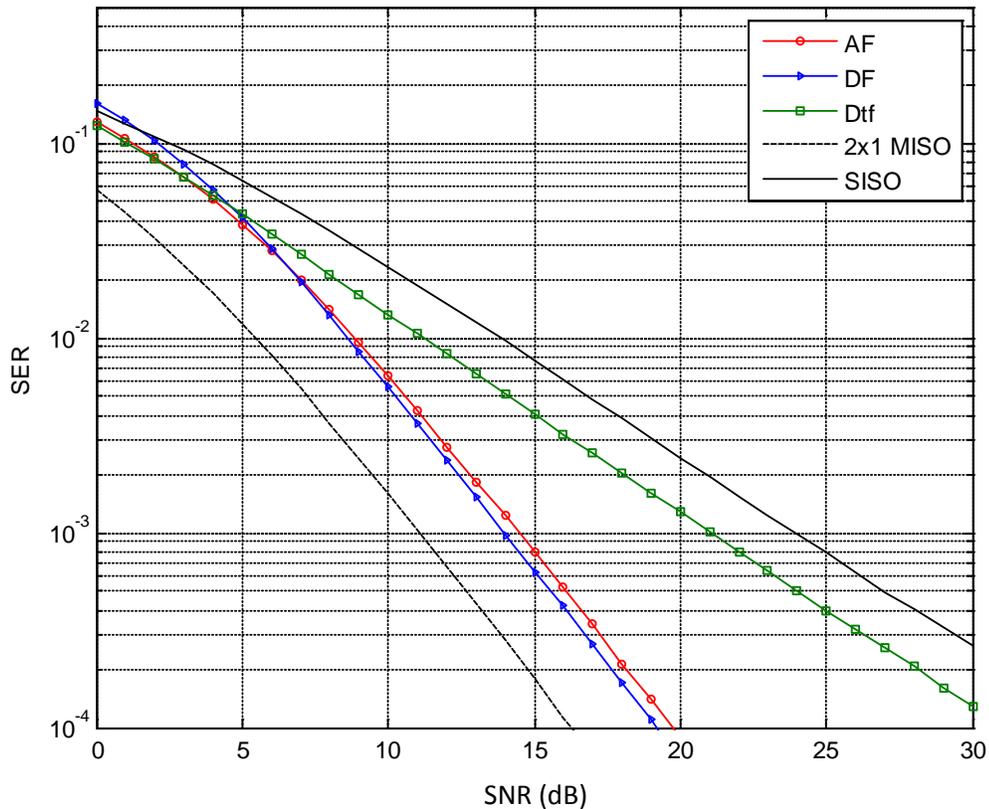


Figure 4.2 MRC combined signal for equidistant geometry with similar channel conditions.

## 4.2 Inter-user Channel

Inter-user channel refers to the path or channel between the source and relay. The channel is established between the two users which cooperate with each other using one of the cooperation schemes for possible diversity gain. Here we will investigate the effects of inter-user channel on cooperation.

### 4.2.1 Better Inter-user Channel

Figure 4.3 shows SER versus mean SNR curves of the uplinks. Better inter-user channel is when it is 10dB better than relay and source uplink channels. It is similar to a scenario when source and relay are in the same street or very near to each other. Better inter-user

channel conditions reduce the error propagation in DtF and DF, which in turns improves their performance. From Figure 4.3 it can be seen that both AF and DF attains full diversity when compared to theoretic curves for 2x1 MISO. Here we can see improvement in the performance of DtF. Errors of the first hop are eliminated with better inter-user channel and channel coding, therefore, DF acts like 2x1 MISO.

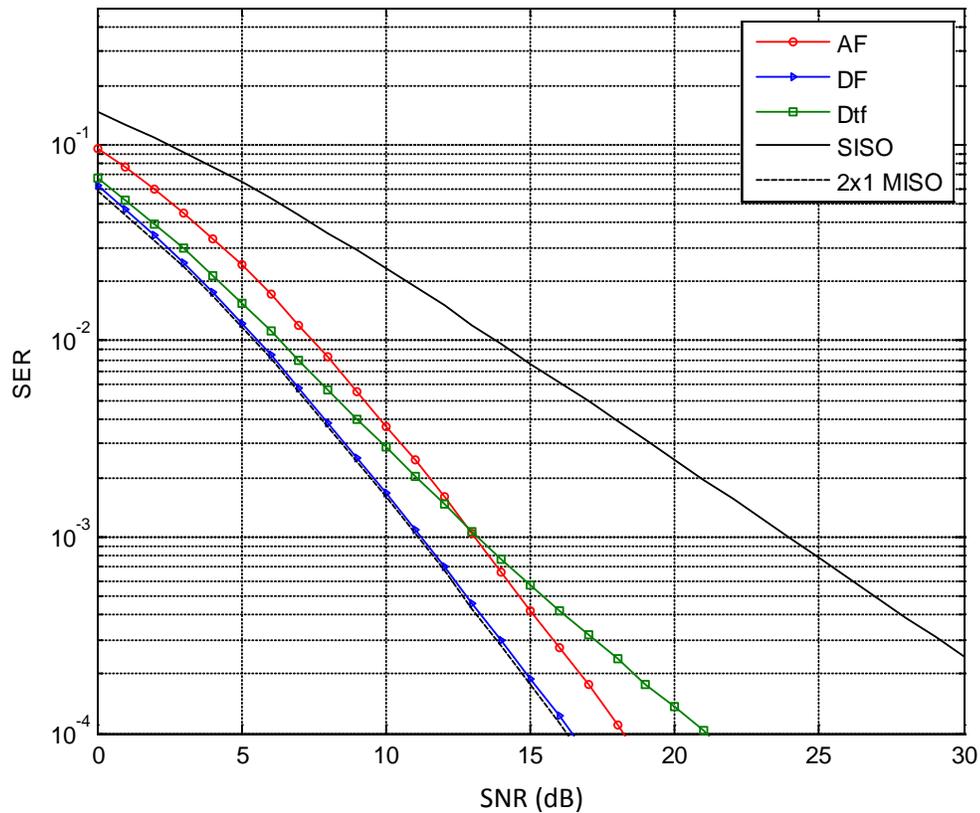


Figure 4.3 MRC combined signal with 10dB better inter-user channel.

### 4.2.2 Worse Inter-user Channel

Inter-user channel is worse when it is 10dB weaker than relay and source uplinks. Figure 4.4 shows the performance of cooperative schemes while inter-user channel is 10dB less than both the uplinks. This scenario can be taken equivalent to a presence of a building or any kind of obstacle on the inter-user channel.

It is obvious from the results that when the inter-user channel is bad then both DF and DtF show poor performance. It is because when the inter-user channel is bad the

relay node cannot decode/detect correctly. AF performs better than other two protocols in this case. Figure 4.4 shows better performance for the direct transmission at low-mid SNR. Results also show the dependence of all the cooperation schemes on inter-user channel. Bad inter-user channel means a lot of errors at the relay. When this error is propagated in the relayed signal, it is then combined with direct transmission at the receiver, which leads to the high error rates at the destination. On the other hand, AF protocol amplifies the noise along with the received signal. Low SNR at relay means that the relay will receive a very noisy signal. When this noisy signal is further forwarded in the second hop it further degrades the signal quality. Highly distorted relayed signal means high error rates at the destination. However, AF still performs better than DF and DtF because the noise is considered in amplification factor instead of decoding/detection. Amplification factor is inversely proportional to noise in the signal received.

Here we can conclude that if the inter-user channel is bad the cooperation does not provide diversity gains, so the direct path should be used for communication.

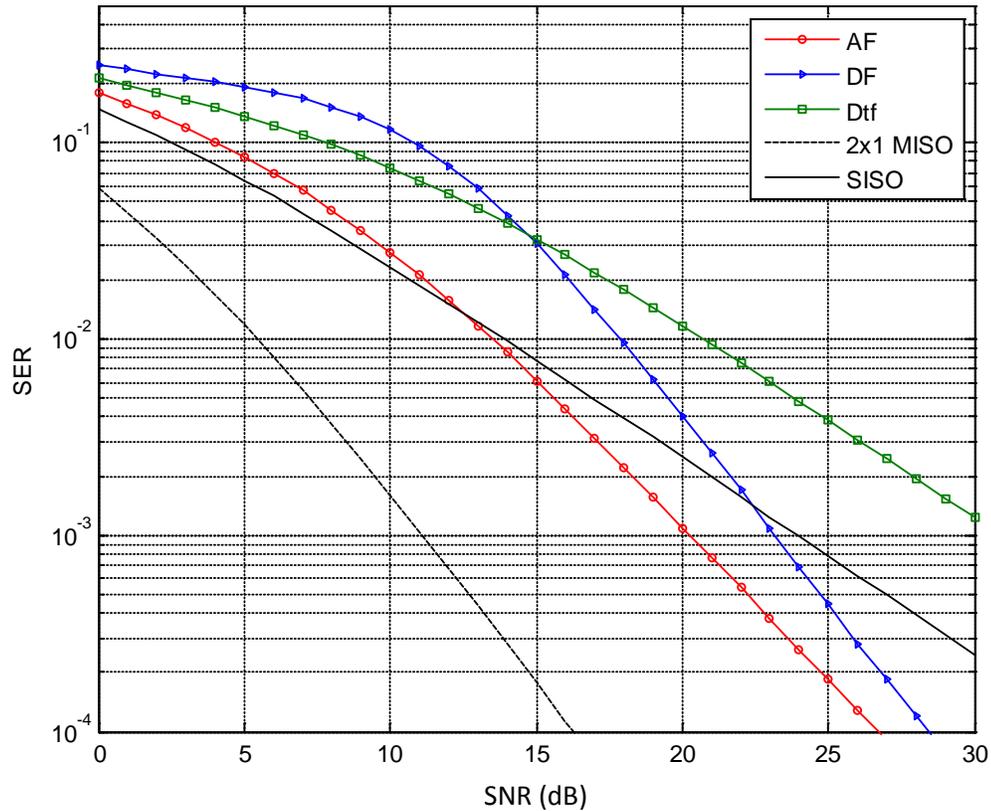


Figure 4.4 MRC combined signal with 10dB worse inter-user channel

### 4.3 Relay Uplink Channel

Relay uplink refers to the path or channel between relay and destination. The channel is established between the relay and destination by which the relayed signal reaches the destination. Now we will investigate the effect of relay uplink channel on cooperation by assigning different SNR values to this channel.

#### 4.3.1 Better Relay Uplink

Better relay uplink means when it is 10dB better than the source uplink and inter-user channel. Figure 4.5 shows the relative cooperation curves when relay uplink is 10dB better than the other two channels. Results show good diversity gains for AF and DF whereas; DtF provides coding gain in this case. At low SNR, AF shows better performance than DF because at low SNR there will error propagation and unsuccessful

decoding by DF. For particular range of SNR AF performs better than DF but it can be seen that at higher SNR DF can outperform AF and can be selected better candidate for application which require high SNR for operation.

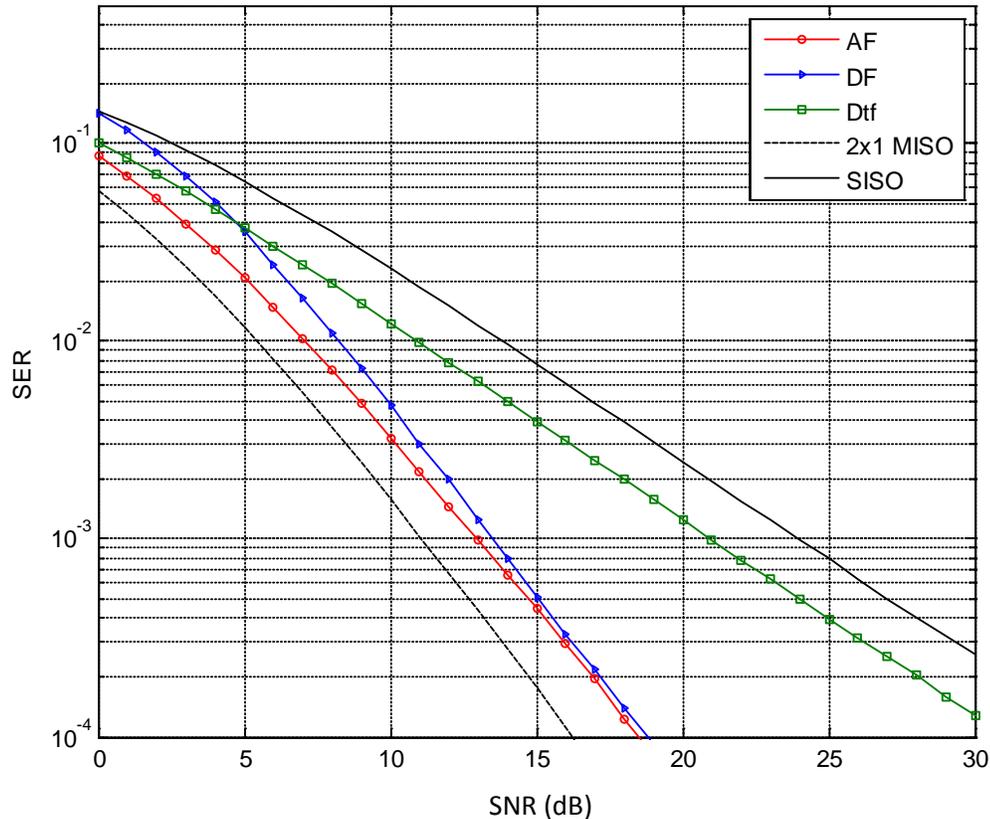


Figure 4.5 MRC combined signal with 10dB better relay uplink.

### 4.3.2 Worse Relay Uplink

Cooperative communication makes use of the idea that if source uplink channel is bad then diversity gain can be achieved by the cooperation of other node with better uplink. So it can be concluded that relay with poor uplink should not be considered for cooperation. Here such kind of scenario is considered for the sake of comparison. Relay uplink is worse when it is 10dB weaker than other two channels. Figure 4.6 shows the relative cooperation curves when relay uplink has 10dB weaker link than the other two channels. Results show better performance for DF compared to AF and DtF. As we can

see good diversity gains for AF and DF at high SNR while DtF provides slight performance gain. None of the cooperation schemes provides diversity gains at low-mid SNR. Here we can conclude that cooperation is not recommended when the relay uplink is bad. However, for applications which require higher power to operate, performance gain can be achieved from cooperation. In such case, DF will perform better than other two protocols.

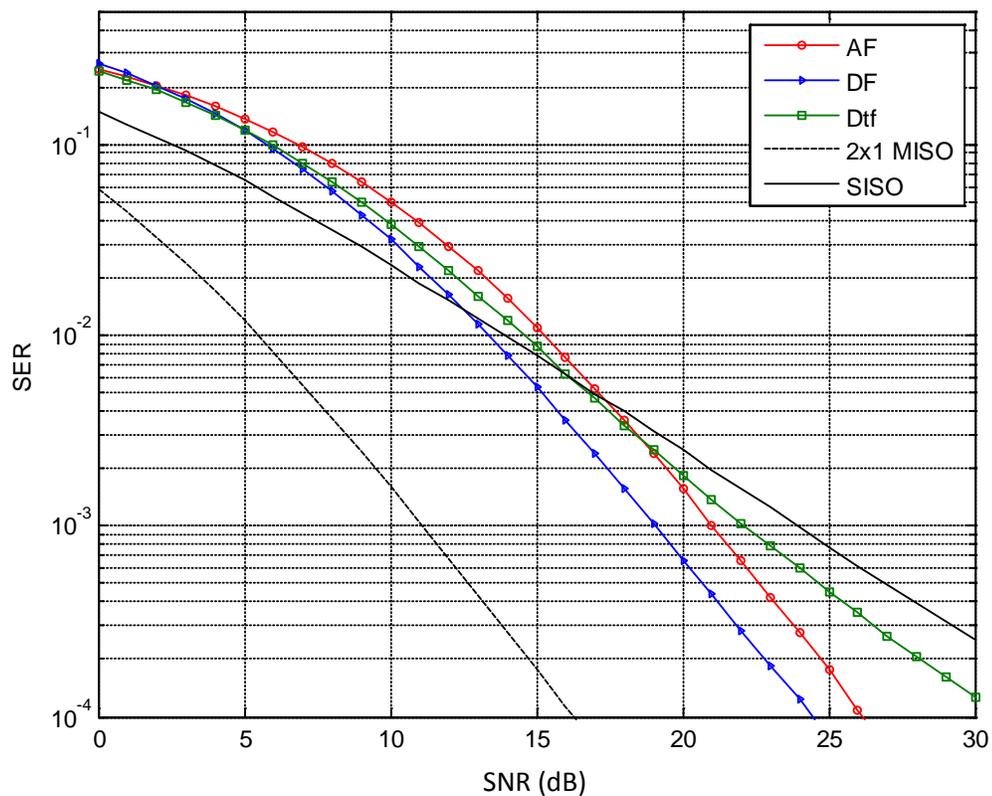


Figure 4.6 MRC combined signal with 10dB worse relay uplink.

#### 4.4 Source Uplink Channel

Source uplink refers to a path or channel between the source and destination. This is also called as the direct path between the source and destination. Here we will investigate the effects of source uplink on cooperation.

### 4.4.1 Better Source Uplink

Better source uplink is when it is 10dB better than relay uplink and inter-user channel. Figure 4.7 shows the cooperation curves when source uplink has 10dB better link than other two channels. This scenario can be considered similar to a case when the source is closer to the base station as compared to the relay. The signal through direct path faces fewer obstructions as compared to the relayed path. Results show better performance for the direct path at low SNR as compared to cooperation schemes. When comparing cooperation schemes in this case the AF performs better than DF and DfF.

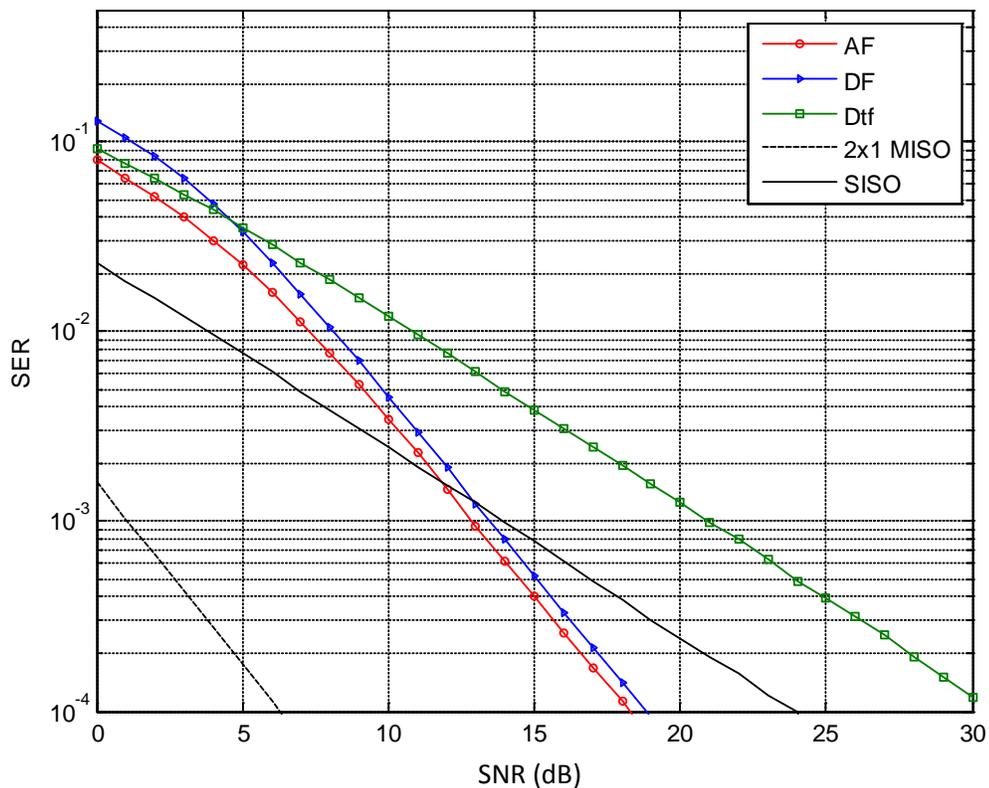


Figure 4.7 MRC combined signal with 10dB better source uplink.

### 4.4.2 Worse Source Uplink

The idea of the cooperative communication lies in the fact that if the source uplink is bad then the cooperative node can provide sufficient diversity gains with better uplink channel. Worse source uplink means that it is 10dB less than the relay uplink and inter-

user channel. Figure 4.8 shows the simulation results for worse source uplink as compared to other channels. Here we can see more error rates for direct transmission. Simulation results show substantial diversity gains for all the cooperative schemes at low-mid SNR. DF performs better than DtF and AF. Here we can see that a low complexity protocol like DtF is also providing significant diversity gain. Results show better performance for DF as compared to 2x1 MISO which seems incorrect at first glance because DF cannot outperform 2x1 MISO. Better performance for DF is due to the fact that 2x1 MISO is simulated with the link which is 10dB worse than the other two links, means 2x1 MISO is for the link which is -10dB. If 2x1 MISO is simulated with comparable SNR then it will outperform all the cooperation schemes. With this reasoning the performance of DF can be justified.

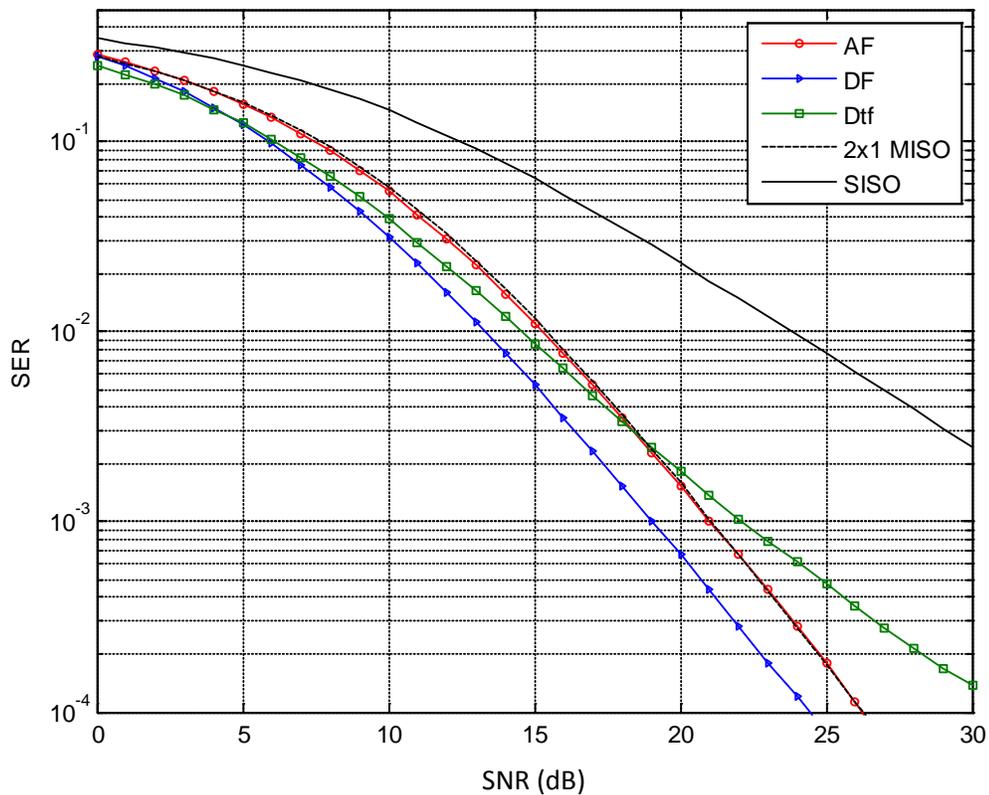


Figure 4.8 MRC combined signal with 10dB worse source uplink.

## 4.5 Selective-Detect and Forward

Figure 4.9 shows the symbol error rate for S-DtF. All channels have same average SNR in this case. Result shows better performance for S-DtF over its fixed counterparts, as it achieves full diversity starting from very low range of SNR. S-DtF shows promising performance as compared to other protocols because relay forwards those symbols which are detected correctly. It means there will be no error propagation in the relayed signal. Considered error detection is based on ideal error detection, which can detect all the errors at relay node in the received signal. In practice, the performance of the S-DtF depends upon the error detection scheme used. Better the error detection capability better will be the performance of S-DtF. We can conclude that the performance of the practical S-DtF will be worse as compared to one considered in this thesis.

Figure 4.9 shows the comparison of relative cooperation curves for S-DtF with previously discussed relaying protocols. All the channels have the same average SNR that can be seen from the results that S-DtF outperforms all the protocols for all the SNR values and achieves full diversity.

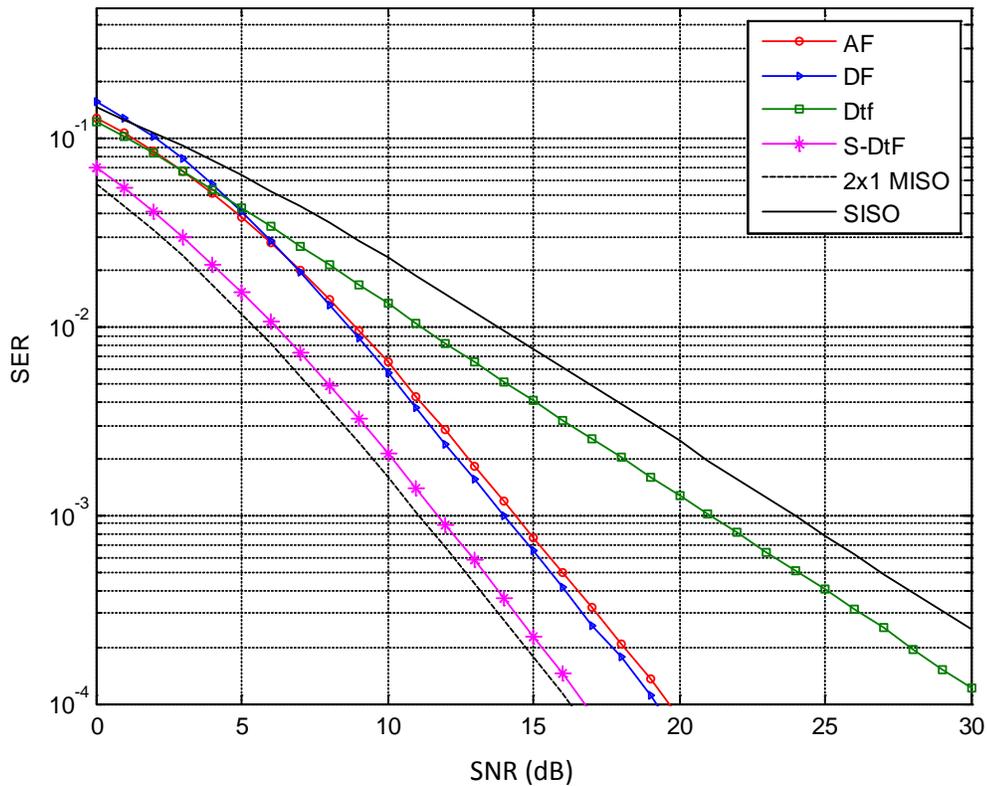


Figure 4.9 MRC combined signal for equidistant geometry with similar channel conditions.

#### 4.6 Collinear Geometry with Relay between Source and Destination

So far, the three nodes were located equidistantly and, therefore, all three channels had the same average SNR. In this section the results for AF, DF, and Dtf are analyzed when the relay is positioned halfway between the source and destination. Time division technique is used by the source and relay to cooperate with each other. In the first time slot the source encodes and transmits the message. The relay then forwards the message to the destination after implementing a particular protocol in the second time slot.

The channel propagation model includes path loss with distance and AWGN having two-sided power spectral density  $N_0/2$ . The base-band equivalent output of the demodulator of a receiver (relay or destination) for the BPSK modulation technique is hence modeled as:

$$y_i = a_i x_i + n_i \quad (4.1)$$

where  $a_i x_i$  shows the attenuated signal contribution, and  $x_i = E_i b_i$  denotes the BPSK symbols,  $E_i$  shows the energy per symbol and  $n_i$  is the noise distribution. The considered propagation model is the free space model, therefore,  $a_i = 1/r_i^n$ , where  $n$  is the path loss exponent and  $r_i$  is the link distance. The noise factor  $n_i$  is complex Gaussian having variance  $\sigma^2 = N_0/2$ .

In this thesis the selected cooperative protocols are analyzed for two different path loss exponents, i.e. for path loss exponent two and four.

#### 4.6.1 Path Loss Exponent 2

Since the relay is halfway between the source and destination so we assume the link distances from source to relay and relay to destination equal to 0.5. The path loss exponent considered is 2 so according to the equation  $a_i = 1/r_i^n$ , the path loss for source to relay link and relay to destination link is 4. The direct link distance from source to destination is assumed to be unity so the path loss for this link will be unity as well.

It is obvious from the calculations that the noise power on the direct link is four times greater than the noise power on the relay links, which tends to the fact that the SNR for the relay links is four times greater than that for the direct link. Thus the signal strength on the relay links is much greater than that on the direct link.

Among the selected cooperative protocols the DF shows the best result for the path loss exponent two. DF has the lowest error rate and achieves diversity sooner than the other two cooperative protocols.

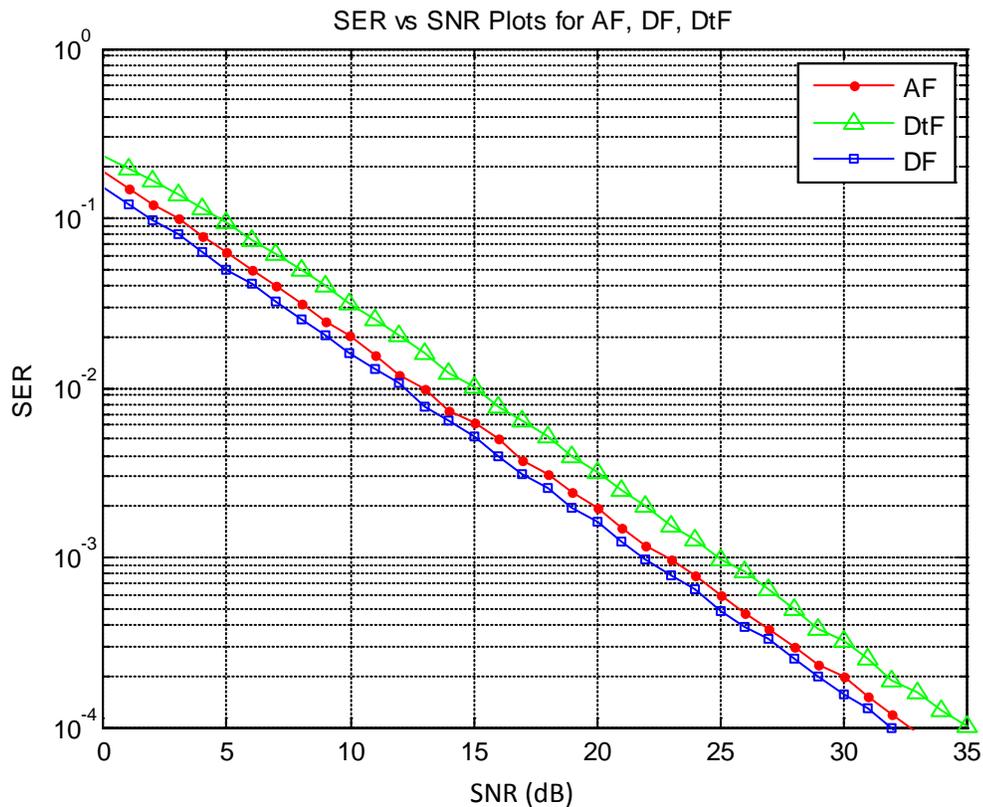


Figure 4.10 SER vs SNR curves for path loss exponent 2.

#### 4.6.2 Path Loss Exponent 4

In this case the relay is again halfway between the source and destination but the path loss exponent considered is four this time. So according to the equation  $a_i=1/r_i^n$  the path loss for source to relay and relay to destination link is 16. The path loss on the direct link is unity because the distance between the source and destination is unity.

In this case the noise power on the direct link is sixteen times greater than the noise power on the relay link, which tends to the facts that the SNR for the relay link is sixteen times greater than that for the direct link. Thus the signal strength on the relay links is much greater than that on the direct link.

When comparing the curves for path loss exponent two with the curves for path loss exponent four, it is obvious that all the selected cooperative protocols perform better in the later case. There is around a 3dB advantage on each selected protocol for path loss exponent four.

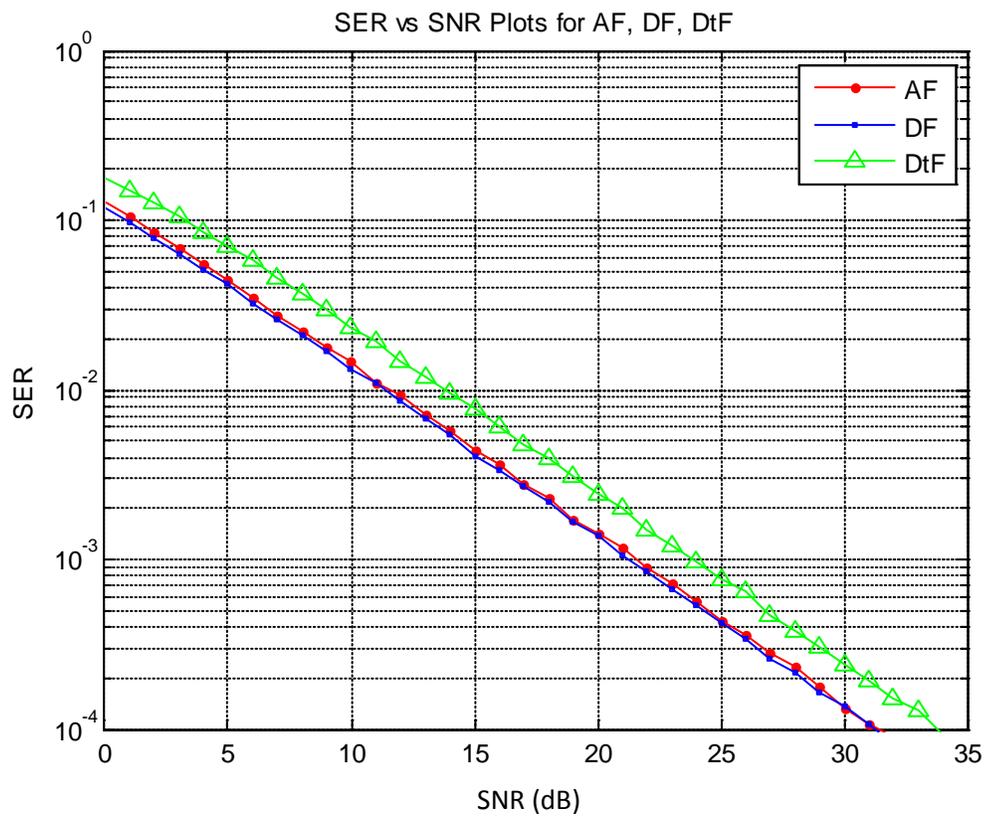


Figure 4.11 SER vs SNR curves for path loss exponent 4.

## 5. CONCLUSIONS

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### 5.1 Summary

This thesis is focused on the performance of selected relaying protocols when applied to different relaying geometries (equidistant and collinear). Great improvements in the performance of network can be seen by employing cooperative communication. Data reaches the destination through two different paths, i.e. a direct path from source to destination and a relayed path where different relaying protocols are applied to the data which finally reaches the MRC combiner at the destination. Above described system has been simulated to see the performance of selected diversity protocols namely AF, DF, DtF, and S-DtF. DtF can also be called as low complexity DF depending upon the relay involvement. Considering equidistant geometry the AF and DF has shows promising results. Good diversity gains can be seen for AF in most of the cases. DF contains high error rates at low SNR but it greatly improves with the channel conditions, thus a diversity order 2 can be seen for DF at high SNR. DtF does not provide high performance in various scenarios. In fact it provides a coding gain at high SNR. Performance of DtF greatly improves with selective relaying thus S-DtF outperforms the above mentioned protocols for a wide range of SNR.

Considering collinear arrangement DF performs better than AF and DtF. DF achieves diversity faster and contains lower error rates as compared to AF and DF. It is because when the inter-user channel is good DF can perfectly encode/decode the signal without errors. So there will be no error propagation in the received signal. Collinear arrangement has been simulated with two different path loss exponents, i.e. for two and four. Results show greater the path loss exponent; better will be the performance of the selected protocols. As path loss exponent has inverse relation with the noise power.

Higher the path loss exponent, lower will be the noise power. Hence better diversity gains for these protocols.

## 5.2 Future Work

This thesis provides basis for many other research works and it can be taken further in many ways. In this thesis we have seen that the performance of DtF greatly improves with selective relaying, so we can further investigate this trend by considering selective relaying AF and DF as well. This work presents the comparison of relaying protocols for generic system that uses BPSK. This helps us in understanding the pros and cons of relaying protocols. This study can be extended to a realistic communication system, where the actual cooperative signal construction, spreading codes, and channel estimation can be considered.

Considered models use MRC for signal combining. Research shows that MRC is best suitable for AF; hence it is not the optimal combining technique for DF and DtF. To further investigate the performance of these protocols, other types of combining techniques like FRC and EGC combining can be used. With this knowledge another class of cooperative relaying schemes like coded cooperation can also be studied.

Wireless communication involves the movement of mobile station. Sometimes we have well placed mobile station that can cooperate and act as a relay but this is not always the case. Most of the time the relay node is not placed optimally, it can be very near or too far from away from the sender. This work can also be used to further investigate the overall performance of mobile relay in more complicated systems.

This thesis can be further enhanced by employing more than one relay node with intelligent antenna selection. It is expected to have higher diversity gains for such kind of systems.

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## 7. APPENDIX

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### 7.1 Derivation of Effective SNR for Path Loss Exponent 4

Effective SNR for path loss exponent two has been derived earlier in Section 3.8.1.1. For the derivation of effective SNR for path loss exponent four the signal received by the relay and destination in the first time slot can be represented as

$$y_{s,r} = a_{s,r}x_s + n_{s,r} \quad (7.1)$$

$$y_{s,d} = a_{s,d}x_s + n_{s,d} \quad (7.2)$$

where  $y_{s,r}$  and  $y_{s,d}$  represent the signal received by the relay and destination respectively. Normalizing the transmit power so it becomes unity, i.e.  $P_t = 1$ . Now normalizing the path loss between the source and destination, i.e.  $a_{s,d}=1$ . In the first time slot the signal power  $P_t$  received at the destination will be unity and the noise power received at the destination is  $N_0$ . Hence, the SNR in the first time slot at the destination is  $1/N_0$ .

As the relay is placed half way between source and destination and this thesis considers free space model. Hence the path loss is sixteen times less than that of the destination. Accordingly,  $r_{s,d} = 1$  then  $a_{s,d} = 1$  for single-hop link. Similarly if  $r_{s,r} = r_{s,d}/2$  then  $a_{s,r}, a_{r,d} = 16$  for two hop-link when free space model is considered with path loss exponent  $n = 4$ .

When the signal is received at the relay it retransmits it to the destination after amplifying in the second time slot. For sending the data the relay uses a gain of ' $\beta$ ' or simply and amplification factor which is

$$\beta = \sqrt{\frac{1}{16+N_0}}$$
$$\beta^2 = \frac{1}{16+N_0} \quad (7.3)$$

As we know that the received signal power  $P_r$  is  $\left(\sqrt{|a_{s,r}x_{s,r}|}\right)^2 = 16$  at relay whereas

$N_0$  represents the noise variance. In the second time slot the signal received at the destination can be expressed as

$$y_{r,d} = a_{r,d}\beta(a_{s,r}x_s + n_{s,r}) + n_{r,d} \quad (7.4)$$

In relay's transmission the signal power is

$$P_r = \frac{16}{16+N_0} \quad (7.5)$$

In second time slot the noise power in relay's transmission is

$$P_n = \frac{N_0}{16+N_0} \quad (7.6)$$

Path loss between the relay and destination link is  $a_{r,d} = 16$ , signal power received at destination from relay is given by

$$P_{r,d} = \frac{256}{16+N_0} \quad (7.7)$$

Noise power amplified by relay which is received at the destination is given by

$$P_n = \frac{16N_0}{16+N_0} \quad (7.8)$$

As there is a noise in transmission environment,  $N_0$ , therefore,  $n_{s,r} = n_{r,d} = n_{s,d}$ . In the second time slot the combined noise received at the destination is given by

$$P_n = \frac{16N_0}{16+N_0} + N_0 \quad (7.9)$$

Dividing equation (7.7) by equation (7.9) gives the effective SNR for collinear geometry, which is

$$SNR_{s,r,d} = \frac{256}{32N_0+N_0^2} \quad (7.10)$$