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POWER ALLOCATION ALGORITHM FOR MIMO BASED MULTI-HOP CO-OPERATIVE SENSOR NETWORK

Master´s thesis for the degree of Master of Science in Technology submitted for inspection, Vaasa, 10 May, 2013.

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ABSTRACT:

Cooperative transmission is a new breed of wireless communication systems that enables the cooperating node in a wireless sensor network to share their radio resources by employing a distributed transmission and processing operation. This new technique offers substantial spatial diversity gains as the cooperating nodes help one another to send data over several independent paths to the destination node. In recent times, an extensive effort has been made to incorporate these systems in the future wireless networks like LTE (*Long Term Evolution*), IEEE 802.16j (*Mobile Multi-hop Relay (MMR) Networks*) and IEEE 802.16m (*Mobile WiMAX Release 2 or WirelessMAN-Advanced*). But, there are few technical issues which need to be addressed before this promising technique is integrated into future wireless networks. Among them, managing transmission power is a critical issue, which needs to be resolved to fully exploit the benefits of cooperative relaying. *Optimal Power Allocation*, is one such technique that optimally distributes the total transmission power between the source and relaying nodes thus saving a lot of power while maintaining the link quality. In the first part of the thesis, mathematical expressions of the received signals have been derived for different phases of cooperative transmission. Average-Bit-error-rate (ABER), has been taken as a performance metric to show the efficiency of cooperative relaying protocols. In the second part of this Chapter, a multi-hop framework has been presented for the power allocation algorithm with *Amplify-and-Forward* relaying protocol. The efficiency of the power allocation algorithm has been discussed with different scenarios i.e. First for a three node (*2-Hop*) wireless network configuration and then for a four node (*3-Hop*) wireless network configuration. The transmission scenarios (*2-Hop and 3-Hop*) have been further categorized into multiple cases on the basis of channel quality between source-to-destination, source-to-relay, relay-to-relay and relay-to-destination links.

KEYWORDS: Cooperative Communication, Relaying Strategies, Power Allocation

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Abstract

Cooperative transmission is a new breed of wireless communication systems that enables the cooperating node in a wireless sensor network to share their radio resources by employing a distributed transmission and processing operation. This new technique offers substantial spatial diversity gains as the cooperating nodes help one another to send data over several independent paths to the destination node. In recent times, an extensive effort has been made to incorporate these systems in the future wireless networks like LTE (*Long Term Evolution*), IEEE 802.16j (*Mobile Multi-hop Relay (MMR) Networks*) and IEEE 802.16m (*Mobile WiMAX Release 2 or WirelessMAN-Advanced*). But, there are few technical issues which need to be addressed before this promising technique is integrated into future wireless networks. Among them, managing transmission power is a critical issue, which needs to be resolved to fully exploit the benefits of cooperative relaying. *Optimal Power Allocation*, is one such technique that optimally distributes the total transmission power between the source and relaying nodes thus saving a lot of power while maintaining the link quality. In the first part of the thesis, mathematical expressions of the received signals have been derived for different phases of cooperative transmission. Average-Bit-error-rate (ABER), has been taken as a performance metric to show the efficiency of cooperative relaying protocols. In the second part of this Chapter, a multi-hop framework has been presented for the power allocation algorithm with *Amplify-and-Forward* relaying protocol. The efficiency of the power allocation algorithm has been discussed with different scenarios i.e. First for a three node (*2-Hop*) wireless network configuration and then for a four node (*3-Hop*) wireless network configuration. The transmission scenarios (*2-Hop and 3-Hop*) have been further categorized into multiple cases on the basis of channel quality between source-to-destination, source-to-relay, relay-to-relay and relay-to-destination links.

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1. Introduction

1.1 Background

Over the past few years, cooperative communication has achieved a reputation of an emerging strategy for the future wireless networks. These promising strategies efficiently take advantage of the broadcasting nature of wireless networks. The core idea is that communicating users/nodes share their data and transmit cooperatively forming a virtual antenna array resulting in a diversity gain that can drastically improve systems performance. In cooperative transmissions the relay nodes are utilized such that to help a source/sender node to help forwarding its data to the destination/receiver node. Therefore the destination node gets several copies of the same data via independent channels.

In Wireless Sensor Network (WSNs) nodes spend most of their power in communication either sending their own data or relaying other nodes data. Therefore, designing a power efficient algorithm is a major concern for these networks. More over power allocation has always been regarded as an efficient way to combat fluctuations in wireless channels and to reduce co-channel interference in the network. Power control constantly adjusts the transmission power so as to maintain a required received link quality. The benefits of the cooperative transmission have been investigated for the various communications layers. The problem to enhance the link between the source and destination node falls into the optimization for the physical layer. In this thesis, an effort has been made to analyze the power allocation for the physical layer to optimize the performance of the system.

The key subject is to optimize the capacity of the network, minimize the Bit-Error-Rate (BER) and improve the link quality with help of a solid power control strategy. A multiple node cooperative system is investigated to reduce the BER and improve the network coverage using one of the well-known cooperative relaying strategies i.e amplify-and-forward & decode-and-forward. In a nut shell, the main goal is to find out a source transmission power and transmission powers of the relays involved to optimize the BER for the source to relay and relay to destination channels.

1.2 Thesis Strategy

The simulation section of the thesis has been divided into two phases. In Phase-I, a comprehensive framework is presented for a single relay scenario taking into account both of the well-known/proven cooperative relaying strategies i.e amplify-and-forward (AF) & decode-and-forward (DF). The performance of diversity combining (MRC:Maximal Ratio Combining) based multi-antenna relay for both amplify-and-forward (AF) and decode-and-forward (DF) relaying protocols will also be investigated.

For Phase-II, there is an investigation of the performance of Power Allocation algorithm designed for a Cooperative Relay network with Amplify-and-Forward (AF) relaying protocol over a Rayleigh Fading Channel. Precisely, the aim is to answer the fundamental question:

"*What should be the transmission power assigned to source-to-relay links and to relay-to-destination links?*"

The implementations will be based on the Physical Layer using MATLAB as a simulation platform. The thesis will be organized as follows:

A) First, the Co-operative relaying system will be implemented for Amplify-and-Forward relaying protocol over a Rayleigh fading channel.

B) Second, the Co-operative relaying system will be implemented for Decode-and-Forward relaying protocol over a Rayleigh fading channel.

C) Third, a closed form expression for the moment generating function (MGF) of the destination signal-to-noise ratio (SNR) for a 2-Hop MIMO-relay links in a Rayleigh fading channel is derived. Moreover, expression for the performance metric of power allocation algorithm i.e., average-bit-error-rate (ABER) will be derived and implemented.

D) Fourth, a closed form expression for the moment generating function (MGF) of the destination signal-to-noise ratio (SNR) for a 3-Hop MIMO-relay links in a Rayleigh fading channel is derived. Moreover, expression for the performance metric of power allocation algorithm i.e. average-bit-error-rate (ABER) will be derived and implemented.

1.3 Objective

In cooperative wireless networks, transmission power is a sacred resource. Therefore power allocation is a significant design problem in these modern wireless communication systems. In general the power allocation constitutes different techniques and algorithms that are used to manage and adjust the transmitted power of the cooperating nodes. The primary objective of power allocation in wireless networks is to constantly control the power such that to guarantee a certain link quality. In order to achieve this it is mandatory to keep the SINR above a threshold level. In addition to this power allocation performs numerous other operations like reduction in co-channel interference, maintain link quality, maximizing coverage area, minimizing the mean transmit power of nodes.

In the early developmental stages of cooperative networks it was assumed that the overall transmit power should be uniformly allocated among the source and relay terminals. Whereas from the recent researches, it has been shown that the performance of cooperative relaying systems can be considerably improved by distributing the power, in an optimal manner among the cooperating nodes. The optimal power allocation scheme depends on specific quality-of service (QoS) measures such as the outage probability and BER. The main objective is to find the optimal power allocation of the source node and relays involved to maximize the QoS performance at the destination node with a total power constraint. The reverse optimization can be also considered in which the total power is minimized when given some conditions of constraint on the QoS performance like BER or outage probability.

1.4 Literature Survey

Transmission using cooperative relaying is a promising technique that has been proven to help in extending coverage area and at the same time in reduction of wireless channel impairments. Relaying information on multiple hops reduces also the need to use a high power at the transmitter resulting in extended battery life and lower level of co-channel interferences (Laneman & Wornell 2000). In this context and considering the fact that power is a critical resource Chiang (Chiang, ONeill, Julian & Boyd 2001) also considered the problem of optimizing resource allocation in cooperative based wireless sensor networks.

Power allocation in Cooperative Relay networks has also been studied recently. Most of these focus on the single-relay case, and solve for the optimal power division between the source and relay nodes to maximize capacity (Liang & Veeravalli 2004) (Serbetli &Yener 2005), minimize transmission power (Yao, Cai & Giannakis 2005) (Madsen & Zhang 2005), minimize outage probability (Deng & Haimovich 2005), (Brown 2004) or probability of error (Hasna & Alouini 2004). However, the extension of these algorithms to multiple relays is not obvious. Power allocation in multi-hop systems was discussed in (Hasna & Alouini 2004), where the relay nodes are used to extend the coverage area, rather than to provide diversity for improving throughput or reducing outage probability.

1.5 Thesis Outline

In this section, the contents of each chapter are outlined.

1.5.1 Cooperative Communication (Chapter 2)

In Chapter 2, section 2.1 introduces the term cooperative communication and familiarizes the readers with such systems Section 2.2 gives a short historical background of cooperative communication systems and this is followed by evolution of cooperative communication strategies in the recent years and how these systems have transformed into a standard in Section 2.5. Finally the chapter is concluded in Section 2.4.

1.5.2 Cooperative MIMO Networks (Chapter 3)

In Chapter 3, section 3.1 introduces the concept of MIMO based cooperative networks Section 3.2 explains various types of wireless channel characteristics. A brief discussion of different spatial diversity techniques is presented in Section 3.3. Section 3.4 addresses multi-hop transmission which is one of key features of cooperative networks. Section 3.5 discusses the core idea of relaying technology i.e. cooperative relaying protocols (amplify-and-forward & decode-and-forward) and this is followed by the different phases/processes a cooperative network under goes to transmit information from source node to the destination node in Section 3.6. Section 3.7 discusses the need and role of power allocation in cooperative networks and how they make the network energy efficient. Finally the chapter is concluded in Section 3.8.

1.5.3 Cooperative Relaying Strategies & Power Allocation (Chapter 4)

Chapter 4, deals with the mathematical aspect of the topic under discussion. Section 4.1 gives more detailed information on relaying strategies/protocols and shows how power allocation techniques are key factors for the proper functioning of the network with help of derived closed-form expressions. In the later sections three typical scenarios have been discussed for a cooperative network transmission and this is done with help of network models and related mathematics. Section 4.2 explains the first scenario of direct transmission of data without using any relaying protocol. Second scenario explaining transmission using amplify-and-forward protocol is presented in Section 4.3 and this is followed by the third scenario where transmission is occurring using decode-and-forward protocol in Section 4.4. In Section 4.5 expressions for various performance metrics of power allocation algorithm for the relaying protocol (amplify-and-forward) with multiple nodes are derived and discussed with help of a system/network model. Finally the chapter is concluded in Section 4.6.

1.5.4 Simulations & Results (Chapter 5)

In Chapter 5, results of the above mentioned scenarios are presented in form of BER performance curves made with help of MATLAB Simulation platform. Section 5.1 presents the BER performance curve of cooperative transmission when Amplify and Forward Protocol is incorporated. In Section 5.2 the BER performance curve of cooperative transmission with Decode and Forward Protocol is presented. This follows by the BER performance curve of Power Allocation Algorithm for 2-Hop Scenario in Section 5.3. In the last section 5.4 the BER performance curve of Power Allocation Algorithm for 3-Hop Scenario is presented.

1.5.5 Conclusions & Future Work (Chapter 6)

In chapter 6 the thesis is concluded by discussing the findings from various performance curves of cooperative transmission scenarios. In the end some of the features/techniques which were not touched in this thesis and which can be further taken up as future work are discussed.

2. Cooperative Communication

2.1 Introduction

In a multi-node communication scenario, cooperative communication makes use of the neighboring node's antenna in a way to facilitate the process of cooperative transmission. In this way a virtual multi-antenna transmission environment is created which offers the combined advantages of both relay and diversity technologies. It also helps in achieving spatial diversity gains and the overall transmission performance can be improved without adding any more antennas to the nodes. These benefits of cooperative communication come at cost of sharing the node's transmission power and computation resources with others. But in the broader perspective this loss of own power is neutralized when the cooperating node sends its own signal which is then relayed by other nodes, potentially leading to substantial resource savings for the whole network.

Unlike regular point-point communication systems, these multi-hop networks use a form of cooperation by enabling intermediate nodes to transmit the message from source to destination node. The destination node receives multiple copies of the same information from both the source and one or more relays and then combines these to get a more reliable estimate of the transmitted information as well as higher data rates.

Cooperative communications offers many advantages like: *Spatial Diversity Gain*, as it is highly resistant to both small scale fading and shadowing effect. *Higher Throughputs*, as the resources of all cooperating nodes have been pooled together. *Energy Efficient*, as the cooperating nodes operate on efficient power allocation algorithms. *Reduced Interference*, as the cooperative relays used orthogonal channels for transmissions. *Better Coverage*, as multiple nodes provide scalability and connectivity. *Flexible Deployment*, as the configuration is easy to implement and offers a degree of freedom.

Therefore, it is one of the hot research topics these days that holds a huge potential and will have a huge impact on the development of future wireless technologies. Since, it is flexible in deployment and needs no fixed infrastructure these systems can be integrated easily with other technologies without posing a threat to their respective advantages. Cooperative communication finds its application in wide range of communication systems like Cellular

Mobile Communication, Wireless Sensor Networks (WSNs), Wireless Local Area Networks (WLANs) and Wireless Ad-hoc Networks (WANs). Moreover, it has the ability to combat frequency selective fading rather well when incorporated with Orthogonal Frequency Division Multiplexing (OFDM) technology. When integrated with Cognitive Radio technology, it can vastly improve chances of spectrum detection eventually helping to get more spectrum access.

2.2 Brief History of Cooperative Communication Systems

Communication between a source and a destination node without the help of any other node is called *direct or point-to-point* communication. Cooperative communication is possible only when there is at least one additional node willing to aid in communication. The oldest form of cooperation is perhaps *multi-hop* technique that was nothing but several point-to-point links from the source to the destination.

The main idea of cooperative communication stemmed with the three node relay channel which was introduced by Meulen in [1968-1971]. Originally, Meulen discovered upper and lower bounds for the capacity of the relay channel and made numerous findings that led to improvement of his results in later years.

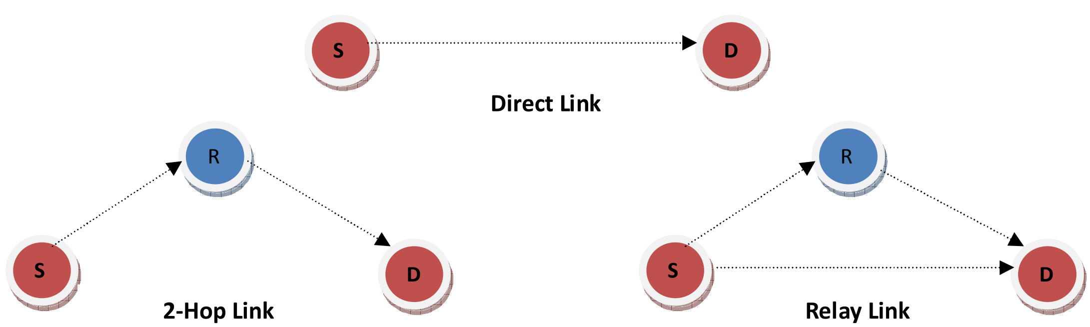

Figure 1 A) Direct link B) 2-Hop Link C) Relay Link

There is no doubt that the research work of Cover and El Gamal has set the most solid foundation for the recent works in this field. Many research ideas of theirs are still un-challengeable and are up to date. In the early 80's, there was an increased interest in research of relay channel.

Many attempts were made to generalize the findings of Cover and El Gamal. Also an effort was made to generalize their ideas for networks involving multiple relays like Aref in 1980. But due to lack of new findings from the domain of information theory and the technological challenges that were involved for implementing user-cooperation, the interest in cooperative relaying systems was diminished in 1980's.

In the 90's era some outstanding progress was made in field of digital and wireless communications, such as enhancement in capacity with the use of multiple antennas, knowledge of fading channels, new channel coding schemes. Advancements like these set the stage for an enhanced wave of research on relaying by providing a whole new perspective and new tools to handle the problem.

The field of information and theory helped to progress further towards the development of cooperative systems when in 2001 Schein considered a relay channel where there was no point-to-point link between source and destination nodes; communication took place with the involvement of two relay nodes. The work contributions of Laneman and his other colleagues proved to be a major break-through; from 2001- 2004 he conducted and published several papers that helped in strengthening the cause of cooperative systems.

Here it is worth mentioning the crucial help that was provided by Sendonaris in 2003 to draw attention to user-cooperation in. In his work, he utilized the concept of user-cooperation to exploit diversity in a mobile uplink scenario and showed its advantages using various performance metrics. In 2003, Gupta & Kumar also investigated that the transmission capacity can be increased extensively by the use of enhanced multiple user schemes. Afterwards in 2004, Xie and Kumar presented a practical data rate for a degraded AWGN channel when used with multiple relays. In the same year Reznik also performed similar research on the transmission capacity but with a total average power constraint.

As the technology advancements over the last two decades are quite impressive, this thing has lead the cooperative relaying systems to become very real. A huge volume of research is being under taken for the development of multiple user cooperation schemes that can actually utilize the gains predicted by information theory. For example, a committee has been established under the supervisions of Wireless World Research Forum (WWRF) to study cooperative relaying networks and has actually circulated several research papers. In 2004, a project named Wireless World Initiative New Radio (WINNER) was initiated in Europe for developing a universal wireless system which can outperform existing communication systems in terms of network performance, coverage area and deployment flexibility. Relay based communication is being given due importance in this research platform.

In addition to this, numerous international periodicals and conferences have also initiated a lot many symposiums, seminars and workshop for the on-going on cooperative communication technology. These include many well know names like IEEE International Conference on Communications (ICC), IEEE Communication Magazine, IEEE Wireless Communications and Networking Conference (WCNC), and IEEE Global Telecommunications Conference (GlobleCom). EU has also initiated a project by the name of Resource Management and Advanced Transceiver Algorithms for Multi-hop Networks (ROMANTIK).

Up till now, several relay and cooperative relaying schemes have been established based on the earlier efforts and studies conducted. Rapid development has been seen in the signal processing domain which is evident from several researches going on for medium access control, routing and network's quality of service.

2.3 Types of Cooperation

The term Cooperation can be categorized into two different paradigms: ***Cooperation for heterogeneous networks*** and ***Cooperation for a homogeneous networ***k. The first category is more related to telecommunication networks. One can clearly see these days that with the upcoming telecommunication networks an effort has been made to unify all networks on a common Internet Protocol (IP) platform and cooperation has been adopted for different access networks. The idea behind this cooperation is mobility management among heterogeneous networks i.e., inter-network handover and roaming. This has been done to provide a diversified set of services to the user.

But in this discussion we are more interested in the later type i.e. Cooperative communication for Homogeneous Network. It means that all involved nodes belong to the same network. It can further be categorized into two schemes: ***Fixed Relaying*** and ***User Cooperation***. The fixed relaying scheme is identical to the relay channel proposed by El Gamal and it has been shown earlier in this chapter. Here, a fixed relay node is placed in between the source and the destination node and this node acts as a communication bridge between the two nodes. The relay node is a passive node that does not transmit its own rather forwards the information it receives.

On the other hand, user cooperation is a much more dynamic scheme. In the network any node can act as a relay node. The node acting as a relay can forward the information of cooperative partners as well as it can transmit its own data. Therefore, these nodes have both the capabilities of signal forwarding and signal processing. The user cooperation can be further be categorized into the following schemes: ***Amplify-and-Forward***, ***Decode-and-Forward*** and ***Selective Relaying***. In the literature there are more schemes proposed but the above mentioned are the most generic and widely adopted ones. In the section we will discuss these schemes briefly as they will be discussed in a more detailed fashion in Chapter 3 and Chapter 4.

Amplify-and-forward is a 3 phase communication scheme. When this scheme is employed, the relay simply amplifies the signal received and forwards it to the destination node without any further processing. This scheme is the simplest of all and it can achieve full diversity gain. Decode-and-forward is also a 3 phase scheme in which the relay will decode and generate a new message signal for the destination to receive. This scheme requires some channel coding like a CRC check, if not then it can achieve full diversity gains.

Selective relating scheme is a bit different in execution as the relays are selected pre hand based on their link reliability. The link quality is compared with a threshold. Communication will take place only if the value exceeds the threshold. The selective relaying scheme can also be employed with both amplify-and-forward and decode-and-forward schemes to achieve better diversity gains.

2.4 Standardization of Cooperative Networks: Relay Technology

The cooperative communication along with the relaying technology has progressively merged into today's wireless standards like LTE (Long Term Evolution), IEEE 802.16j (Mobile Multi-hop Relay (MMR) Networks) and IEEE 802.16m (Mobile WiMAX Release 2 or WirelessMAN-Advanced).

The IEEE 802.16j standard is a further enhancement of IEEE 802.16e (WiMAX) that will support mobile multi-hop relay (MMR) technology. This has been done to achieve more throughputs and enhance overall system coverage. This standard utilizes multi hop wireless connectivity and the data between a base station (BS) and a subscriber station (SS) is relayed through a relay station (RS). The RS can be either fixed infrastructure based or it can be a mobile access relay station. Two types of relay modes have been defined in the standard ***Transparent mode*** and ***Non-transparent mode***. The transparent mode is used to enhance the throughput in the base station coverage while the non-transparent mode is used to extend the coverage area of base station. The relaying schemes proposed for the standard are amplify-and-forward, demodulation-and-forward and selective decode-and-forward.

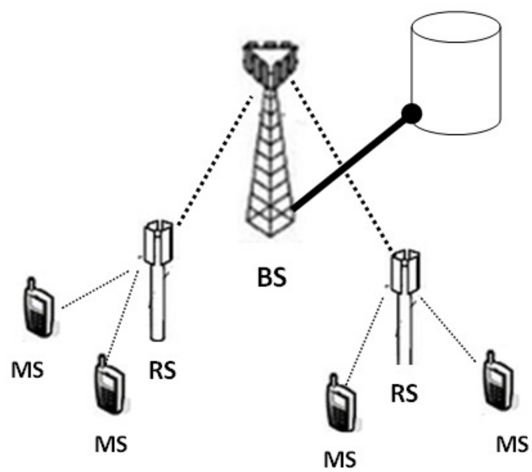

Figure 2 IEEE 802.16j Network Architecture

Cooperative communication is also being incorporated in the recent LTE-Advanced standard. Relay Nodes (RNs) are being deployed in LTE-advanced systems to facilitate the transmission between the e-NodeB(e-NBs) and the User Equipment (UEs). In comparison to an e-NodeB, Relay Node (RNs) uses a lower transmission power and therefore covers smaller areas.

The placement of Relay Node introduces low power coverage areas within a large coverage area of a conventional macro-Base Stations in the cellular network. The User Equipment has the choice to either communicate directly with the e-NodeB (e-NB) or through these deployed low power Relay Nodes (RNs). These Relay Nodes have some particular properties i.e. each of these Relay Nodes (RNs) appears to User Equipment (UE) as a separate cell distinct from the Base Stations cell. These cells provided by the Relay Nodes (RNs) have their own cell Identifiers.

The Relay Node (RNs) transmits its own synchronization channels, reference symbols, and other radio resources. The User Equipment (UE) receives scheduling information and Hybrid-ARQ feedback directly from the Relay Node and correspondingly they send their control channel to the Relay Nodes (RNs). In this manner the User Equipment (UE) at the edge of cell can be better served and the network coverage and capacity can both be increased.

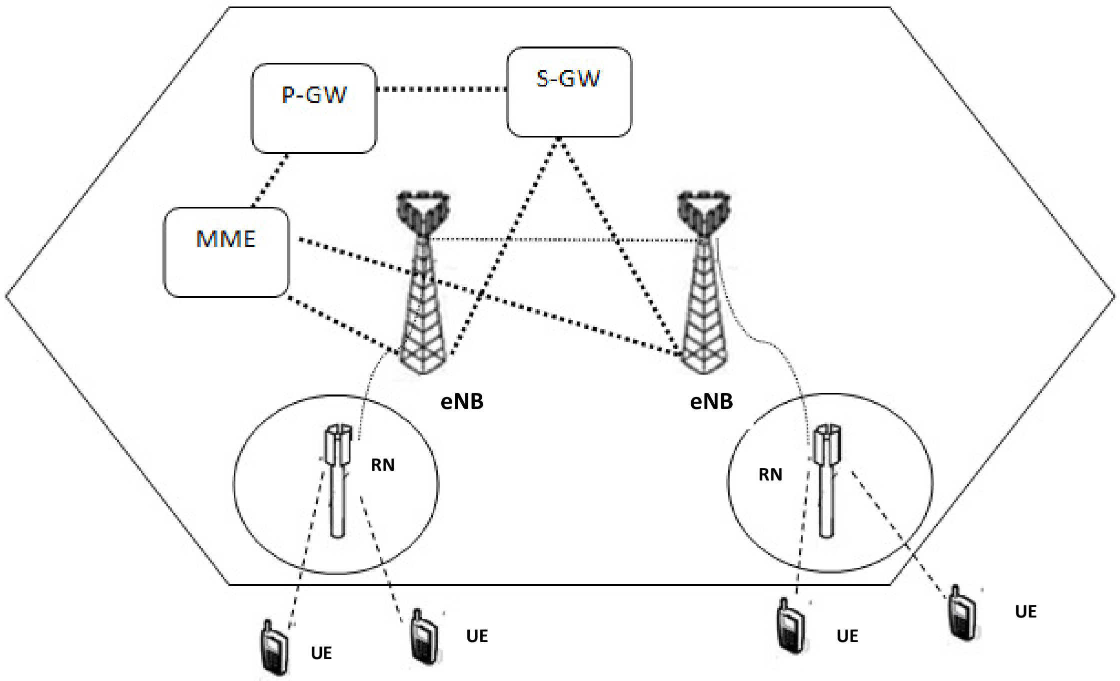

Figure 3 LTE-Advanced Network Architecture

Cooperative relaying has been used in IEEE 802.16m to enable throughput and reliability improvement. In this standard cooperative relaying can be used within sectors in which Relay Stations are deployed. Cooperative relaying is being used both in downlink and uplink transmissions. In downlink, the Base Station and multiple Relay Stations transmit the same data to the corresponding Mobile Station utilizing cooperative techniques.

In uplink, the Base Station and multiple RSs receive transmission from the corresponding Mobile Station in a similar manner. A non-transparent relay mode has been defined by IEEE 802.16m where the Advanced Relay Station (ARS) has the distinctive cell Identifier in every sector that it control. The Relay Node uses the decode-and-forward relaying scheme. Moreover in this standard, cooperative relaying is encapsulating some Multiple Input

Multiple Output (MIMO) modes. MIMO techniques are being used to exploit both transmit and receive diversity. These modes include both open-loop MIMO techniques and closed-loop MIMO techniques. For example, some of the cooperative relaying modes include Distributed Space Time Block Coding (DSTBC), Space Frequency Block Coding (SFBC) and Cooperative Beam-forming (CB).

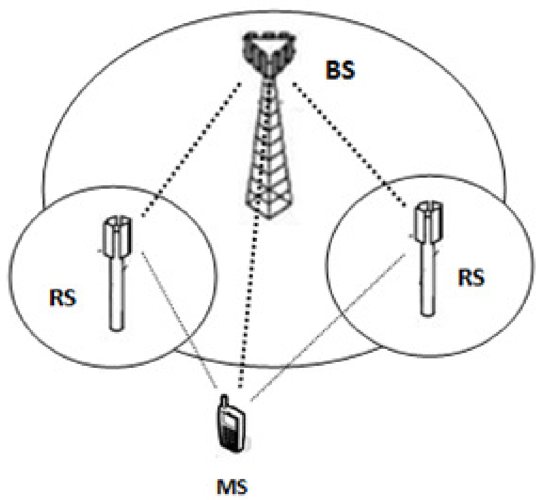

Figure 4 IEEE 802.16m Network Architecture

2.5 Summary

Cooperative communication has been of keen interest to wireless system researches for the past couple of years. The key idea is to have user cooperation in nodes for sending data instead of independent node operation. This concept has radically modernized the wireless network design making it more robust and increased throughputs. In the recent years these systems have also made their way to future wireless standards like LTE-Advanced, IEEE 802.16j and IEEE 802.16m. The chapter discusses a brief history of these systems and a shows its role in the future wireless standards. The discussion in this chapter provides a basis for further study in Chapter 3, which focuses on Cooperative MIMO networks.

3. Cooperative MIMO Networks

3.1 Introduction

In recent times, Cooperative Networks have made their way to become an evolving strategy for future wireless communication systems. These networks exploit efficiently the broadcasting nature of wireless networks. With a help of a cooperating relay node, a sender is facilitated to send its information to the recipient node. In this way the recipient gets multiple copies via independently channels. Like all infrastructure-less wireless networks, energy consumption is the most critical issue as each node has a limited power. Therefore, increasing the lifetime of the network is of utmost importance and a crucial design problem. During a cooperative transmission all the protocol stack layers, from physical layer to the application layer consume energy. But the energy consumed in the physical layer during long and medium range transmission has the most dominant effect on the lifetime of the network.

Therefore, in this thesis an optimal power allocation strategy with cooperative relaying scheme will be employed in a wireless sensor network to enhance the performance of the network. ABER performance analysis and optimum power allocation are provided for a Wireless Sensor Network with Amplify-and-Forward cooperative relaying protocol. The optimal power allocation strategy will be derived based on the objective of having minimal transmission power while maintaining the best possible link quality.

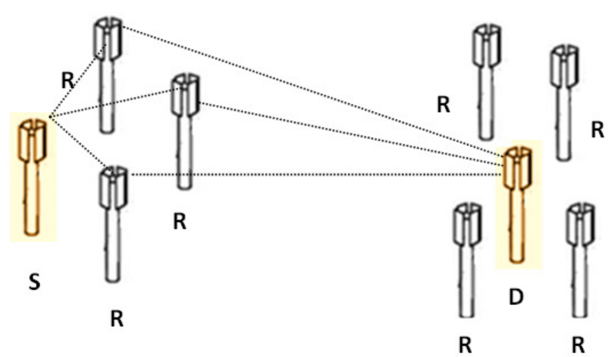

Figure 5 Cooperative Communication Network

In a cooperative MIMO network, the involved relays can jointly form a virtual antenna array and exploit traditional MIMO spatial diversity gains thus helping in enhancing system's performance. Moreover, as more and more relays are added there is an increased augmentation of the radio resource and more resources can be pooled together to facilitate the transmission of source node. Other than this, cooperative MIMO networks employ 3 different techniques like: ***Multi-hop Technique***, ***Relaying Technique*** and a ***Cooperative Transmission Technique***.

Multi-hop Transmission Technique saves the transmission energy by breaking down long transmission path into several small transmissions paths. Because when a signal is transmitted wirelessly by a source node to the destination node, then this signal gets attenuated on its way. The degraded received power is defined as the function of transmission distance. The factor of path loss varied from the minimum value of 2 (*Free Space*) to the maximum value of 6 (*Concrete Structures*).

Cooperative Relaying Technique achieve a virtual diversity gains with help of a virtual MIMO configuration based on the cooperation of nodes rather than using multiple antennas on a single node. These virtual antenna arrays are very simple to implement and have outstanding performance in deep fades. Therefore, we have a network with enhanced throughput capacity and less energy requirement.

Cooperative Transmission Technique employ a special case of MIMO systems i.e. Space-time MIMO configuration to avoid using more energy. These systems exploit space time diversity gains to require less power as compared to a traditional SISO (*Single-Input-Single-Output*) for the same Bit-Error-Rate requirements.

Before discussing the proposed idea of the thesis it is necessary to have the knowledge background about Cooperative MIMO Networks. So, in the chapter the discussion will start from spatial diversity techniques, then there will be a detailed study of a multi-hop technique, then the relaying strategies will be discussed in detail. After that cooperative MIMO techniques are presented and in the end power allocation techniques will be discussed.

3.2 Wireless Channel Characteristics

There has been a tremendous growth in wireless communication mainly because of the extreme potential that it holds. Along with all the benefits these systems offer they do have some limitations like propagation delays, signal attenuations and distortions. These problems are generally caused by one of the following issues, i.e. path loss, multi-path fading and shadowing effect.

3.2.1 Path Loss

Let's take a direct wireless connection in which a signal is transmitted by a source node to the destination node, this signal on its way get attenuated. The signal strength decreases and is inversely proportional to the propagation distance. This degradation can be defined in terms of a mathematical ratio of transmitted power (Pt) and the received power (Pr). This ratio is a quantitative measure of the path loss effect and its value depends on the variety of factors like height of transmitter/receiver, propagation environment, wavelengths etc. The path loss is generally represented in dB scale:

$$P_L\,(\mathrm{dB}) = 10\log_{10}\left(\frac{Pt}{Pr}\right)$$

Path loss models can vary according to certain conditions. If the transmission occurs in free space with a line-of-sight (LOS) and with no reflections, path loss model takes the following shape:

$$P_R = P_T\, G_T\, G_R \left(\frac{\lambda c}{4\pi d}\right)^2$$

Here, G_T and G_R are the transmitter and receiver antenna gains, d is the distance between the two and λ is the wavelength of the signal. A generic path loss model has been

3.2.2 Shadowing Effect

Besides power degradation due to path loss models, a signal may also be distorted when an obstacle is in between the transmission path. These obstacles cause signal degradation and random scattering as they absorb part of signal's power. The effect varies with time due to the relative motion between the two communicating nodes. This slow varying power is called shadowing effect. The obstacles can be anything like aircrafts, trees and buildings etc. A model for the random attenuation due to shadowing effects is also needed. The most common model is the log-normal shadowing model. The signal variations can be modeled as log-normal random variable with the PDF:

$$F\,(\Psi) = \frac{\xi}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(10 log \Psi - \mu)\hat{}2}{2\sigma\hat{}2}\right)$$

3.2.3 Multi-path Fading

If in a wireless transmission a signal gets scattered or reflected by an object the destination node will receive multiple copies of the signal. These multiple versions of the signal cause interference since those versions arrive at different time instants. The signal interference can be constructive or destructive therefore the strength of the signal varies with factors like time and frequency. Therefore multi path fading causes both amplitude and phase distortions. The diagram on the next page shows the combined causes of path loss, multi-path fading and shadowing.

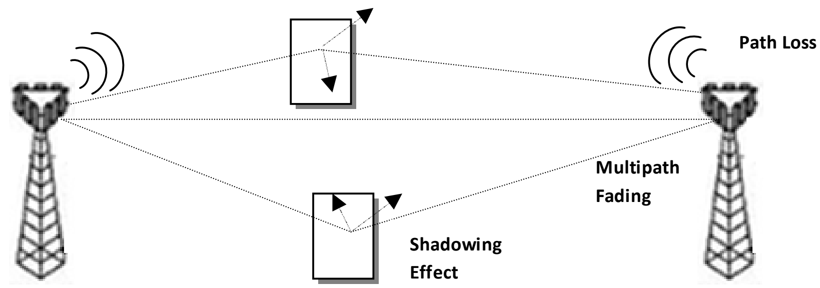

Figure 6 Causes of Path Loss, Shadowing and Multi-path Fading

3.3 Diversity Techniques

The key idea of diversity techniques is that copies of a transmitted signal are sent by multiple mediums like through different time slots, using several frequencies, changed polarizations or multiple transmit/receive antennas, this all is done to reduce the effect of fading. These multiple copies of the transmitted signal have independent fades so there is very less possibility that all these transmitted signals undergo a deep-fade at the same time. Therefore, using any of the above mentioned diversity technique the receiver can get the reliable data that was actually transmitted by the sender and the bit-error-rate will be a bare minimum.

Just by transmitting several copies of the signal through these fading channels which are independent, a higher diversity gain of the transmitter is achieved. The diversity gain Gd is defined below where Pe is the bit-error probability of the received signal and γ is the received SNR.

$$G_d = \lim_{\gamma \to \infty} \frac{log(Pe)}{log(\gamma)}$$

The diversity gain can be achieved in several ways. Few of them like, when different time slots are being used for the transmission, it is called ***Time Diversity***. Basically, multiple versions of the same transmitted signal are being sent in several time-slots. In order to have independent fades, it must be guaranteed that the time difference between any two consecutive time slots should always be greater than the coherence time Tc of the channel.

The second type is ***Frequency Diversity***, which uses multiple carrier frequencies to transmit the information. . In order to have independent fades, it must be guaranteed that these carrier frequencies are be separated by more than the coherence bandwidth Bc of the channel. Like time diversity, frequency diversity is not efficient when it comes to bandwidth requirement and in order to get the received signal correctly the receiver needs to have perfect signal synchronization.

The third type of diversity is ***Antenna diversity***. It is a technique that uses different characteristics of antenna's radiation pattern to transmit the information. Antenna diversity is further categorized into two types. *Angular diversity*, uses special directional antennas to achieve diversity in transmission. The transmitting antenna sends signal at varying angles and in the same way these signals are received at different angles on the receiver side too. *Polarization diversity*, on the other hand uses the polarization aspect of antenna's radiation pattern to achieve diversity in transmission. It uses either vertical or horizontal polarizations. Correspondingly, the received signal can be also be separated into two above mentioned polarizations.

3.3.1 Spatial Diversity Techniques

Unlike the earlier mentioned diversity techniques this fourth type of diversity technique does not lack bandwidth efficiency. ***Spatial diversity***, uses a combination of multiple antennas both at the transmitter and receiver side to send information. In order to have independent fades, it must be guaranteed that these antennas must be separated more than half of the wavelength of the carrier frequency. Spatial diversity is further categorized into two types. *Receive diversity*, exploits diversity gain by having multiple antennas at the receiver side. Since the received signals at multiple antennas have independent fades so they are combined to achieve the diversity gain. The diversity gain offered by this technique is approximately equal to the number of antennas deployed at receiver. Moreover this gain is a function of independent fading at the channels. *Transmit diversity*, exploits diversity gain by having multiple antennas at the receiver side. Same data is divided into multiple streams and then transmitted over multiple antennas simultaneously. Now there is a brief explanation of this spatial diversity technique for three configuration scenarios i.e. single-input-multiple-output, multiple-input-single-output and multiple-input-multiple-output.

3.3.1-A Single Input Multiple Output (SIMO)

In this scenario, the receiver is having more than one antenna so one can exploit spatial diversity to enhance performance of the system. The transmitter side can choose anyone other diversity type but it is bound to use a single antenna. At the receiver side, more than one antenna are used to achieve spatial diversity gain which leads to a robust system having a high signal-to-noise ratio (SNR) and low probability of bit error rate (BER). The signal received at the i-th antenna can be expressed as:

$$Y_i[n] = \sqrt{P}\, h_i\, x[n] + w_k[n]$$

Here, P is the transmitted power, h_i is the channel characteristic and w_k is the AWGN at the i-th antenna. The SNR is given by:

$$\gamma_i[n] \triangleq \frac{P|hi|^2}{\sigma^2}$$

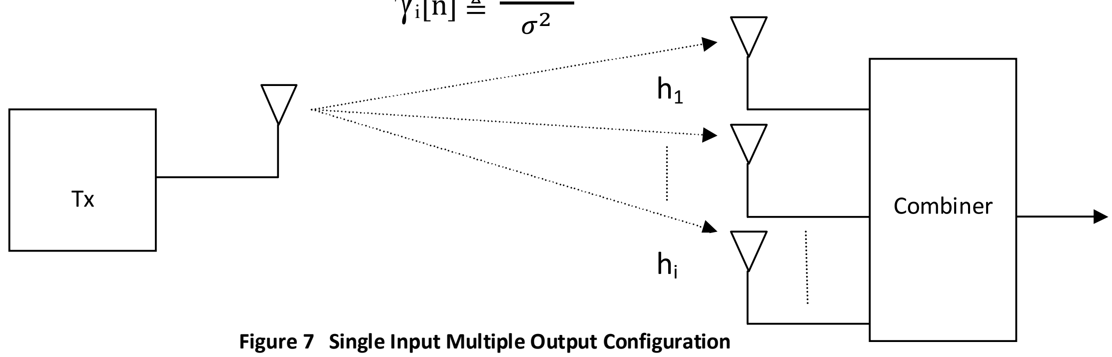

Figure 7 Single Input Multiple Output Configuration

3.3.1-B Multiple Input Single Output (MISO)

In this scenario, the transmitter is having more than one antenna so one can exploit spatial diversity to enhance performance of the system. The reason behind using this scheme of multiple antennas at the transmitter is to reduce the overall processing and to make less complex receiver. But this concept is not easily implemented and is not good as the other schemes when it comes to exploiting diversity gain. Still there is a considerable amount of processing involved both at the transmitters and receiver for accurate decoding of information. One more thing is that since the transmitter does not have any knowledge about the channel conditions, a fed back channel is used to provide the transmitter with that information. The signal received at the receiver is given by:

$$Y_i[n] = \sum_{k=1}^{Ni} \sqrt{P}\; h_i\, s_i[n] + w[n]$$

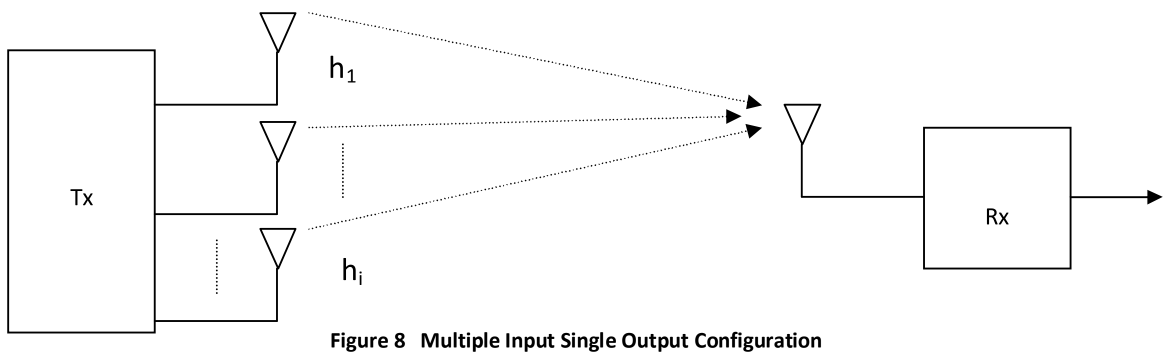

Figure 8 Multiple Input Single Output Configuration

Here, P is the transmitted power, s_i is the transmitted symbol vectors, h_i is the channel characteristic and w is the AWGN at the i-th antenna. The SNR is given by:

$$\gamma \triangleq \frac{\mathrm{P}|\sum_{k=1}^{N} hi|^2}{\sigma^2}$$

3.3.1-C Multiple Input Multiple Output (MIMO)

In this scenario, both the transmitter and receiver are having more than one antenna so one can exploit spatial diversity to enhance performance of the system. The signal is being pre-coded at the transmitter side and is being combined at the receiver. The main motivation of MIMO scheme is to achieve a higher throughput while having the largest possible diversity gain. Many researches in the domain of information theory have shown that the channel capacity and the performance of the system is considerably enhanced by using a MIMO scheme.

The MIMO schemes can be broadly categorized into two types: ***Spatial Multiplexing***, is a multi-layered design that uses multiplexing technique to enhance the data rate but it lacks any diversity gain. ***Space-time Coding***, on the contrary exploits the factor of diversity gain to make the communication system more robust and spectral efficient. The signal received at the receiver is given by:

$$\mathrm{Y[n]} = \sqrt{P}\mathrm{Hs[n]} + \mathrm{w\,[n]}$$

Here, P is the transmitted power, s is the transmitted symbol vectors, H is the channel matrix and w is the AWGN at the i-th antenna. The SNR is given by:

$$\gamma \triangleq \sum_{i=1}^{N} . \sum_{j=1}^{N} . \frac{P|h\ i,j|^2}{M\sigma^2}$$

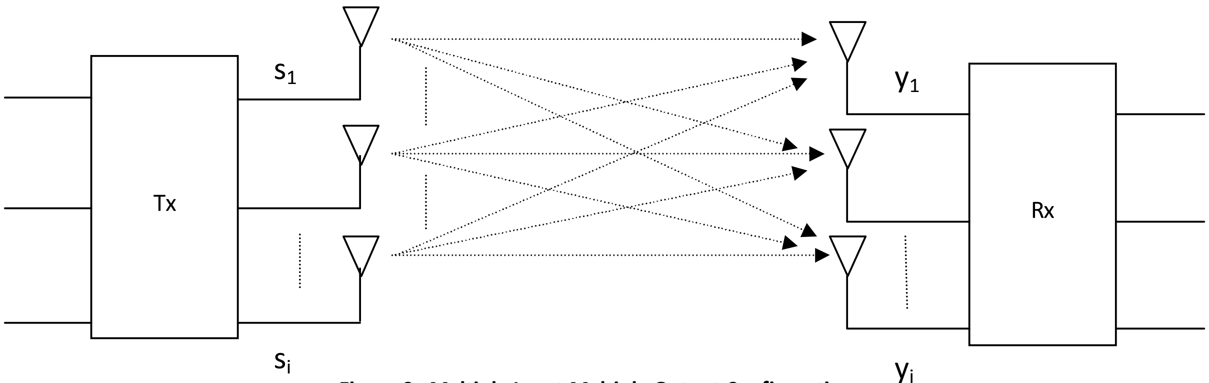

Figure 9 Multiple Input Multiple Output Configuration

3.3.2 Receiver Diversity Combining

The system performance is increased by increasing the signal-to-noise ratio (SNR), this is only possible if the receiver combines all the multiple version of the transmitted data. This increase in performance varies with the number of signals combined and the technique which was used for combining. Receiver diversity combining particularly targets small-scale fading. For this reason, the simulation will be implemented using flat Rayleigh fading channel as it is the easiest one to implement and easily controllable. There are numerous signal combining techniques defined in the literature like: *Maximum Ratio Combining*, *Equal Gain Combining* and *Selection Combining*. For every technique the end objective is to calculate the weights which will reduce the effect of fading. These techniques are different in the way they choose these weight vectors.

3.3.2-A Maximum Ratio Combining

From the above mentioned receiver diversity schemes it is known for a fact that the E_b/N_o performance of *Maximum-Ratio-Combining* (MRC) is better than the other two techniques for a given value of bit-error-rate (BER). But this technique adds a bit complexity to the receiver as well. In order to find the process involved in a MRC technique, take a system that receives multiple N copies of the transmitted signal s. The channels are fading independently here. The received signal is given by:

$$y_k = \alpha_k . s + w_k$$

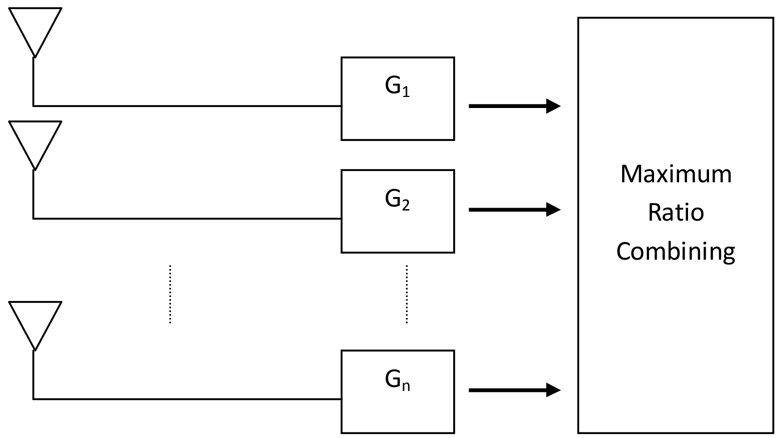

Figure 10 Maximum Ratio Combining

Here, α_k is the channel fading factor that is independent, s is the transmitted signal and w_k is the AWGN associated with the copy of signal. At the receiver side a maximum likely-hood (ML) decoder is employed to combines the N copies of signals. The receiver needs to find the best approximated transmitted signal which will minimize:

$$\sum_{k=1}^{N} ||yk - \alpha k.s||$$

As with the help of ML detector the transmitted signal has been found out so the signals at the N independent paths can be combined as:

$$\check{\tilde{s}} = \sum_{k=1}^{N} (\alpha_k . s + w_k) . \alpha_k^* = \sum_{k=1}^{N} ||\alpha_k|| \, s^2 + \sum_{k=1}^{N} \alpha_k^* . w_k$$

The SNR at the output of the maximum ratio combiner is

$$\gamma = \sum_{k=1}^{N} ||\alpha_k|| \, s^2 . \frac{Es}{No} = \sum_{k=1}^{N} \gamma_k$$

So, the final SNR is the summation of all the received SNR of N paths. If we consider that every independent path has a approximately same average SNR $\ddot{Y}$. The output of the maximum ratio combiner will be:

$$\gamma' = N \times \ddot{Y}$$

The MRC technique with N independent paths has diversity gain equal to N, as it has been shown above. *Equal-Gain-Combining* (EGC), is a unique case of MRC in which the signal combination is based on equal weights. The SNR performance of EGC and the gains associated with diversity are smaller than those of a MRC technique. The output of the EGC combiner will be:

$$\gamma' = [1+\frac{\pi}{4}(N-1)]\,\ddot{\Upsilon}$$

3.4 Multi-Hop Technique

Multi-hop techniques support many types of applications and facilitate the process of network deployment .In a multi-hop technique, a long transmission path from source node to destination node is divided into multiple transmission paths. For example, in figure a multi-hop model of a wireless transmission is presented. A multi-hop transmission works in a step-by-step manner as one node decodes the signal received from the previous node and then the signal is forwarded to the next node. This technique of transmission depends on certain factors like the distance between communicating nodes and index of path loss.

A multi-hop network has numerous benefits like the network can be expanded because of the multi-hop forwarding technique and at the same time throughput can also be increased as the hops are small. This technique is also very energy efficient as low transmission power is required resulting in extended battery life of the node. Consider a wireless sensor network as shown in the figure below. d_j, denotes the transmission path between two nodes and the total transmission path between the source and destination nodes consists of N hops. This network is comprised of N–1 cooperating sensor nodes. The total distance can be expressed as:

$$d_{total} = \sum_{j=1}^{N} d_j$$

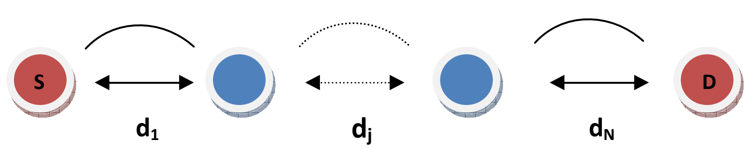

Figure 11 Multi-Hop Transmission

Since, it has been discussed earlier that the multi-hop wireless transmission depends critically on the path loss index. So the path loss in this scenario is given by:

$$P(dj) = P(do)(\frac{dj}{do})^{\alpha}$$

Here, α is the exponent of path loss for the multi-hop channel, $P(d_j)$ is the total power and $P(d_0)$ is the reference power. The total power required for a successful transmission is a exponentially proportional function of the path loss exponent. By dividing the long transmission path into several multi-hop paths, a linear relation is established instead of an exponential one between the path loss exponent and the transmission distance. This is so as the total transmission power is the summation of power consumed by single hop transmissions. As this technique reduces the usage of transmission power so the power consumption gain is defined as:

$$Power\ Gain = \frac{P(d)}{\sum_{j=1}^{N} P(dj)} = \frac{(\sum_{j=1}^{N} dj)^{\alpha}}{\sum_{j=1}^{N} dj^{\ \alpha}}$$

3.5 Relay Strategy Techniques

When considering wireless sensors, which are energy constrained entities the advantages offered by relaying strategies cannot be ignored. It has been discussed earlier that relaying technique employed in a sensor network reduces the exponent of path loss resulting in an increased performance of the wireless channel. At the same time it also reduces the required signal-to-noise ratio (SNR) to achieve a particular bit-error-rate making the network energy efficient. Relaying implementation is categorized into the following techniques:

The first one ***Fixed Protocols***, in this protocol cooperative relaying is always used irrespective of any condition. The receiver node decodes the message only when it receives the messages from both the source node and relaying nodes. A lot many methods defined belong to this category of protocols.

The second ***Adaptive Protocols***, in this protocol cooperative relaying is used only if the link quality between the relaying node and the destination node is known to have fewer errors. The relaying node performs link estimation and the transmission is authorized only if the link quality is above a threshold. If after the link estimation process no link is found with acceptable quality the direct transmission will take place instead of a relaying one. But diversity gains cannot be achieved as in the case of retransmission only the source node will retransmit.

The third ***On-demand Protocols***, in this protocol cooperative relaying is used only on if requested by the destination node. In case of repeated unsuccessful transmissions the receiver requests this protocol, so relaying nodes are involved in the communication.

The fourth ***Opportunistic Protocols***, this protocol is a special case of on-demand protocols. Unlike multi-hop transmissions the message is not decoded at each intermediate relaying node. They avoid weak link quality relaying nodes in order to guarantee a good end-to-end communication channel.

Relaying strategies employed in wireless sensor networks make sure that possibility of deep fading is at minimal level since the signal received at destination comes from various independent fading channels. The gain achieved due to diversity offers advantages like reduction in both error rate and requires transmission power. In figure a relaying strategy model for a wireless transmission is presented. The model comprises of a source node, relay node and a destination node. For the purpose of explaining the relaying technique is broken down in two time instants.

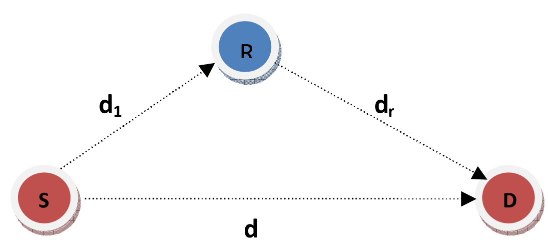

Figure 12 A single Relay Configuration

First Time Instant:

For the first time instant, signals are broadcasted by the source node to the neighboring nodes. So the transmitted signal is received by both the destination node and the involved relay nodes at the same instant. The signal received at the destination node and the relay node will be expressed as r_{D1} and r_R respectively:

$$r_{D1} = P_S \,.\, G_{SD} \,.\, X + n_{D1} \qquad (3.1)$$

$$r_R = P_R \,.\, G_{SR} .\, X + n_R \qquad (3.2)$$

Here, G_{SD} and G_{SR} are the channel gain from source to destination and channel gain from source to relay respectively.

n_{D1} and n_R are noise at the destination node and relay node respectively. P_R is the gain due to power factor as the distance between relay and destination is shorter than that between source and destination and P_S is the transmission power of source node.

Second Time Instant:

For the second time instant, only the relay node transmits signal to the destination node. The signal received by the destination nodes is given as:

$$r_{D2} = G_{RD} \, . \, X^{*} + n_{D2} \qquad (3.3)$$

Here, G_{RD} is the channel gain from relay to destination. n_{D2} is noise at the destination node. X^{*} is the processed signal which the relay received in the first time instant. As the receiver has now received multiple copies of independent fading channel so the process of diversity combination will be performed for the received signal r_{D1} and r_{D2}. Here in order to avoid any type of interferences the source-destination link and the relay-destination link are made orthogonal i.e. different frequency bands are used for both channels. As discussed earlier in chapter 2, the relaying techniques can be mainly categorized into these types: ***Amplify-and-Forward*** and ***Decode-and-Forward***.

3.5.1 Amplify and Forward

One of the most basic relaying techniques is *Amplify-and-Forward*. It has been shown in (Laneman, Tse, & Wornell 2004) that this relaying method accomplishes a diversity gain of second order. This order of diversity gain is considered the highest achievable result at higher signal-to-noise ratios. In an amplify-and-forward technique, the relay node just amplifies and re-transmits the signal received by it as shown by the figure below. The relay does not perform any digital signal processing technique.

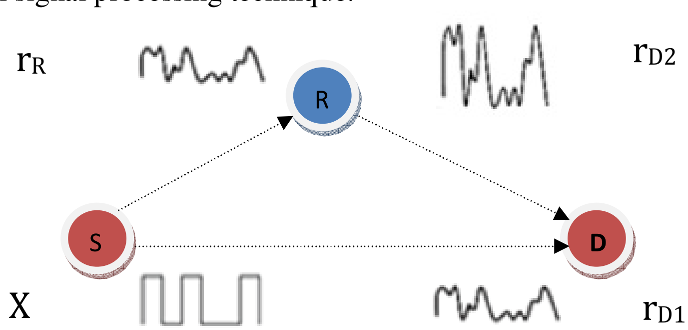

Figure 13 Amplify-and-forward Configuration

From equation 3.3 the received signal at the relay node is given as:

$$X^{*} = G_{SR} . X + (n_R / P_R)$$

Now the signal received at the destination node will be:

$$r_{D2} = G_{RD} . (G_{SR} . X + (n_R / P_R)) + n_{D2} \qquad (3.4)$$

At the destination, the node has received two copies of the same signal one sent by the source node while the second one is an amplified version of the signal been sent by the relay node. This scheme does have a small problem i.e. If there is some noise present at the source-relay link so at the amplification phase this noise will also get amplified. But since the destination node receives two copies of the same transmitted signal which have undergone independent fading. Thus, it can utilize these multiple copies to achieve the best diversity gain and decode the signal correctly. The destination node uses maximum-ratio-combing to get the final signal Y, the expression will be given below using equations 3.1 and equation 3.4:

$$Y = r_{D1} \ (G_{SD}^{*}) + r_{D2} \ (G_{RD}^{*} \ G_{SR}^{*}) \qquad (3.5)$$

$$Y = (G_{SD} .X + n_{D1}) \ (G_{SD}^{*}) + (G_{RD} . (G_{SR} .X + (n_R / P_R)) + n_{D2}) \ (G_{RD}^{*} \ G_{SR}^{*})$$

$$Y = X \ (||G_{SD}||^2 + ||G_{RD} G_{SR}||^2) + (n_{D1} . G_{SD}^{*}) + (n_{D2} . G_{SR}^{*} G_{RD}^{*}) + \ldots$$

$$(||G_{RD}||^2 . G_{SR}^{*} (n_R / P_R))$$

3.5.2 Decode and Forward

Other than the AF technique described above, one more common relaying technique is *Decode-and-Forward*. In this technique, the relay node decodes the signal and then retransmits/regenerates a totally new signal for the destination node to receive rather than just using analog amplification. The process is shown in the figure below.

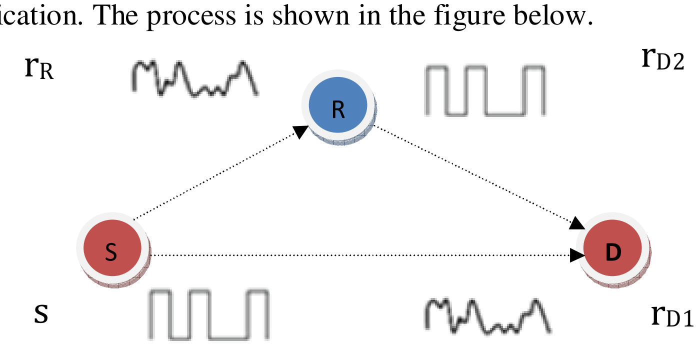

Figure 14 Decode-and-forward Configuration

Therefore, the signal received at the destination node using equation 3.3:

$$r_{D2} = G_{RD} . X^* + n_{D2} \tag{3.6}$$

Or $$r_{D2} = G_{RD} . X + n_{D2}$$ [Assuming decoding is correct $X^* = X$]

At the destination, the node has received two copies of the same signal one sent by the source node while the second one is a regenerated version of the signal been sent by the relay node.As the destination node has received two copies of the same transmitted signal which have undergone independent fading. Thus, it can utilize these multiple copies to achieve the best diversity gain and decode the signal correctly. The destination node uses maximum-ratio-combing to get the final signal Y, the expression will be given below using equations 3.1 and equation 3.6:

$$Y = r_{D1} (G_{SD}^*) + r_{D2} (G_{RD}^*) \tag{3.7}$$

$$Y = (G_{SD} . X + n_{D1}) (G_{SD}^*) + (G_{RD} . X + n_{D2}) (G_{RD}^*)$$

$$Y = X (||G_{SD}||^2 + ||G_{RD}||^2) + (n_{D1} . G_{SD}^*) + (n_{D2} . G_{RD}^*)$$

Decode-and-Forward technique relies totally on the process of decoding performed by the relay node. If the decoding is not accurate it degrades the results of the maximum-ratio-combiner too. Other than this if an error is present in the source to relay link the performance will be poor. These two factors make this technique less favorable when compare to the Amplify-and-Forward technique. Therefore, the deciding factor between the two techniques is the link between source node and relay node. For a generic scenario, Amplify-and-Forward technique is employed if the distance between relay and source node is large. On the other hand if the distance is small then Decode-and-Forward technique is used. Since, in Wireless Sensor Networks (WSNs) the nodes are deployed at far distances so for this reason Amplify-and-Forward technique is more preferred there.

3.6 Cooperative MIMO Techniques

As, it has been discussed in the previous section of this chapter that the relaying techniques offer advantages like reduction in bit-error-rate and increased energy efficiency. These techniques manage to offer the above mentioned benefits only because they achieve higher diversity gains. It is also known that the spatial diversity gain makes a Multi-Input-Multi-Output system much more energy efficient than a Single-Input-Single-Output system (Zhouhua, Yangdacheng, Qiweishi & MaMin 2003). With Cooperative MIMO techniques an effort has been made to combine the advantages of both ***Relaying*** and ***MIMO*** techniques.

Since the Wireless Sensor Networks are critically energy constrained so MIMO techniques can be of much help. But WSN nodes have a small physical size which makes it nearly impossible to allow the usage of more than one antenna. Therefore, instead of using multiple antennas on a single node cooperative MIMO technique can be used by a node to relay information of other nodes, making a virtual MIMO scenario as shown in the figure below. This ***Virtual MIMO***, offers similar spatial diversity gains like of a MIMO system and increases the network capacity too (Jayaweera & S.K 2005).

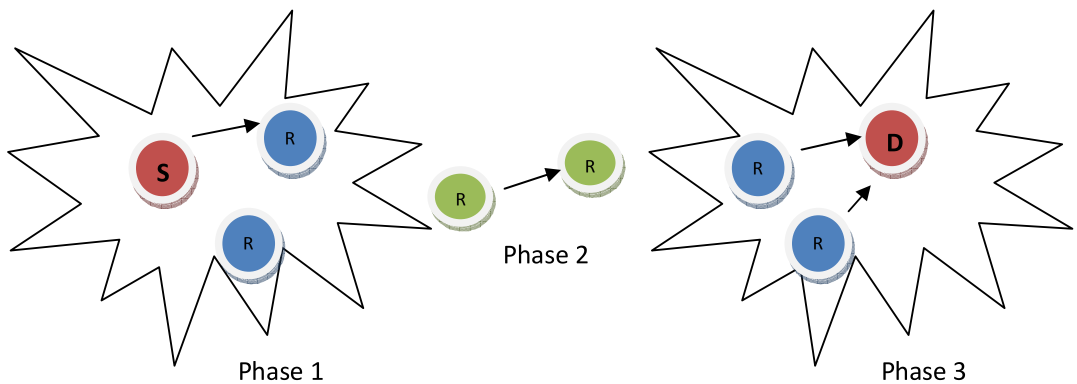

Figure 15 Cooperative MIMO Phases

The cooperative MIMO technique is composed of 3 phases, namely:

1. Local Transmission,
2. Virtual MIMO Transmission,
3. Cooperative reception.

3.6.1 Local Transmission

At the transmitter end, the source node S must cooperate with its neighboring nodes and should exchange data with them. It does so by broadcasting the information to the N nodes present in its surroundings. This phase uses much lesser power as distance between source node and its neighboring node will be small compared to the distance between source node and the receiver node.

3.6.2 Cooperative MIMO Transmission

Afterwards, these N nodes process the received signal i.e. either amplification or decoding is performed. After processing these signal are encoded into corresponding modulation symbols and then these N nodes transmit these symbols to destination node at the same time. In this way this scheme is similar to a multi-stream MIMO system but here these cooperating nodes generate these multiple streams instead of a single source.

3.6.3 Cooperative Reception

At the receiver end, the neighboring nodes of receiver first receive the modulated symbols. Then they re-transmit the information to the receiver in a sequential manner so that these multiple streams can be combined together to decode the information.

3.7 Power Allocation in Cooperative Networks

Power allocation is a significant design problem in these modern wireless communication systems. In general the power allocation constitutes different techniques and algorithms that are used to manage and adjust the transmitted power of the cooperating nodes. At macro-level, an optimal power allocation is determined on two factors i.e. minimizing the total transmitted power and maximizing the network capacity. At a micro-level, the primary objective of power allocation in wireless networks is to constantly control the power such that to guarantee a certain link quality. In order to achieve this it is mandatory to keep the SINR above a threshold level.

The implementation of the Cooperative Relaying network is based on virtual MIMO technique as discussed earlier. But in reality the power allocation techniques in Cooperative networks are not similar to those used in MIMO systems. Unlike MIMO systems, in a cooperative relay network every cooperating relay node has its own transmission channel whereas in the case of MIMO configuration, several antennas perform transmission and reception over the same channel.

In case of a Wireless Sensor Network (WSN), the maximum transmitted power is limited by the battery powered wireless nodes. So it has to be made sure that the transmission power is not high enough. Moreover these nodes have small computational power so the power allocation scheme should be as simple as possible so that it does not burden the processing power of the node. In the light of this, the ultimate aim should be to have a power allocation scheme that maximizes the throughput rate and minimizes the outage probability (OP) or bit-error-rate (BER) which ever performance metric is chosen.

In general the power allocation categories are based on the deployed wireless network types and configurations. In case of the network infrastructure, the power allocation schemes can be categorized into these types: ***Centralized or Distributed***. In case of cellular network deployment, the power allocation schemes can be categorized into the following types: ***Forward link or Reverse link***. In case of networks where feedback exists, the power allocation schemes can be categorized into these types: ***Open loop or Closed loop***.

3.7.1 Power Allocation Techniques

In addition to advantages of power allocation discusses earlier, it also performs numerous other operations like reduction in co-channel interference, maintain link quality, maximizing coverage area, minimizing the mean transmit power of nodes. The power allocation has no trivial solution there will be some trade-off and a lot constraints have to be met. Many power allocation schemes require accurate knowledge of SINR or BER. A comprehensive power allocation technique for a cooperative relay network must address the following three fundamental issues:

1. Transmission power in Phase-1 (*Broadcasting*) and Phase-2 (*Relaying*).
2. Transmission powers of source node and cooperating relay node in Phase-2 (*Relaying*).
3. Transmission power for each hop during transmission.

In a traditional ***Equal Power Allocation*** scheme for Amplify-and-Forward scheme all the nodes present in the surrounding of source and destination node take part in the data transmission one way or the other. Therefore equal power is assigned to all the cooperating nodes in order to make the network situation less complex. But this scheme can make the network heavy on power usage and therefore a lot of useful power resource is wasted to achieve a particular performance. Moreover, this scheme is simple to implement since it has no requirement of channel state information at any time. But there is a drawback to this scheme that it has no provision of optimization. A general case of optimization for EPA scheme is given below:

$$\min P_S + \min \sum_{i=1}^{N} P_{Ri}$$

Given condition, $$P_{max} \geq P_S, P_{Ri} \geq 0$$

Here, P_S is the transmission power of source node, P_{Ri} is the transmission power of the cooperating relay nodes and P_{max} is the total power constraint.

By simply distributing the total power between the source and relaying nodes a substantial sum of power can be saved with no effects on transmission quality. So, in an ***Optimal Power Allocation*** scheme the destination node wants a comprehensive knowledge of channel state information i.e., channel gains for source-relay link, source-destination link and for relay-destination link be available. Only after this knowledge it can assign transmission powers to the cooperating relay nodes. The way in which it gets this knowledge is out of scope of this thesis. A cooperating node is to remain in stand-by state if it gets zero power assignment from the destination node. A general case of optimization for OPA scheme is given below:

$$P_{Out} = P\{\gamma_{req} \leq \gamma_{th}\}$$

$$\min \quad P_{Out}$$

Given condition, $$\sum_{i=1}^{N} P_{Ri} = P_T$$

And $$P_{Out} \leq P_{max}$$

Here, P_{out} is the outage probability, γ_{req} is the required end-end SNR , γ_{th} is the threshold SNR, P_{max} is the transmission power of single hop, P_{Ri} is the transmission power of the cooperating relay nodes and P_T is the total power budget. The two power allocation models explained above are totally situation dependent. This will be explained with the help of the figure below, where two different scenarios have been shown each having a 3-node relay network. In the first scenario, the relay is located closer to the source node and is far from destination node. Here the link quality of source-to-relay path is better and robust than the link quality of relay-to-destination path. In this situation *Equal Power Allocation* will be suitable for the network and both source and relay get equal powers.

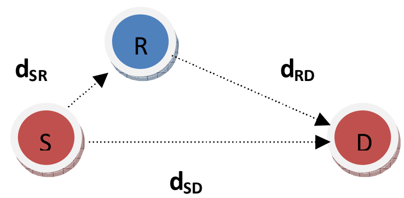

Figure 16 Equal Power Allocation Scenario

Whereas in the second scenario, the relay node is closer to the destination node and far from the source node making the link quality of source-to-relay path weaker than that of the relay-to-destination path. In this situation the source node needs more power as the link quality of source-to-relay path is weak and the link is not robust. Here, *Optimal Power Allocation* is more beneficial. Practically, more network configuration resembles this scenario because choosing a relay that is closer to a source will not help in the cause of relaying. Moreover, this scheme can be optimized to any limits within a suitable and practical network constraint.

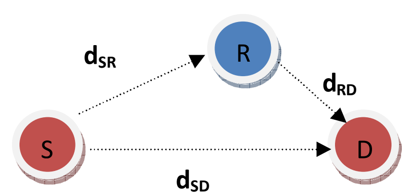

Figure 17 Optimal Power Allocation Scenario

In the earlier sections of this chapter two common cooperative relaying schemes were discussed namely, Amplify-and-Forward (AF) and Decode-and-Forward (DF). Out of these two, Amplify-and-Forward scheme uses a simple technique of amplifying the signal. Hence, the transceivers are less complex and consume less power as there is no signal processing involved.

So the optimal power allocation method proposed in this thesis will be based on Amplify-and-Forward relaying protocol. The power allocation schemes vary according to the network configuration, availability of channel state information and relaying strategy employed. So a more detailed study on the Optimal Power Allocation scheme for the Amplify-and-Forward relay network will be presented in Chapter 4 with a network model and related mathematics.

3.8 Summary

In this chapter it has been shown how cooperative transmission forms a virtual MIMO configuration with the help of cooperating relay nodes. This, actually increase the performance of a network and makes it energy efficient. There were separate sections discussing the multi-hop technique, cooperative relaying strategies and cooperative MIMO transmissions in detail. It was also shown that how power allocation scheme affects the lifetime of a network. A mathematical background has been built for the Chapter 4 in which the simulation scenarios will be discussed along with their network models.

4. Cooperative Relaying Strategies & Power Allocation

4.1 Introduction

Besides the clear significance for *Wireless Sensor Networks* where relaying strategies provide a vital role due to the absence of a network infrastructure, cooperative relaying is expected to play even a more crucial role in the evolution of future wireless networks like LTE-A (Long Term Evolution Advanced), IEEE 802.16j (Mobile Multi-hop Relay (MMR) Networks) and IEEE 802.16m (Mobile WiMAX Release 2 or WirelessMAN-Advanced). These wireless networks of the future are envisioned to have features like high-speed transmissions and large coverage spans. In order to achieve these features a radical change has to come to the existing network design. The multi-hop cooperative relay design is an effort in this direction. As the *Cooperative Relaying Strategie*s supports flexible deployment and has a potential to increase network's capacity, the above mentioned features for the future wireless networks can be achieved by incorporating these strategies with the existing networks. The most basic advantage of the cooperative relaying strategies comes from reduction of long transmission paths between the source and destination nodes into smaller paths. Moreover, there is a huge need to make the modern wireless systems energy efficient as power is a limited resource. Therefore, it is of utmost importance to integrate *Optimal Power Allocation*, schemes in the network by using the information of link qualities, in order to increase the network life time and reduce the power usage of nodes.

In the first part of this Chapter, a three node (*One Relay*) wireless network configuration is considered. The efficiency of such network configuration has been discussed first with a direct transmission scenario then with the two known cooperative relaying strategies i.e. *Amplify-and-Forward* & *Decode-and-Forward* respectively. The mathematical expressions of the received signals have been derived correspondingly at different phases of transmission. Bit-error-rate (BER), has been taken as a performance metric to show the efficiency of cooperative relaying protocols.

In the second part of this Chapter, a multi-hop framework has been presented for the power allocation algorithm with *Amplify-and-Forward* relaying protocol. The efficiency of the power allocation algorithm has been discussed with different scenarios i.e. First for a three node (*One Relay*) wireless network configuration and then for a four node (*Two Relays*) wireless network configuration.

Considering Average-bit-error-rate (ABER), as the performance metric the efficiency of the power allocation algorithm has been discussed for a multi-node network configuration. Unlike the equal power allocation discussed in the previous chapter where equal power was being assigned to both source and relay for the relay-destination link and source-destination link, the optimal power allocation algorithm calculates the transmitting power with the sole objective of minimizing the bit-error-rate for each cooperating relay node and the source.

4.2 Direct Transmission (DT)

In this section, a simple point to point transmission will be modeled between the source node and the destination node to establish a base line performance. For this case no cooperative relaying scheme will be employed in the network. The source node transmits the message with its transmission power to the destination. The received signal model will be designed with some assumptions. i.e. The channel is assumed to be a Rayleigh fading channel and is normalized so that the fading coefficient matrix is complex Gaussian with zero-mean and variance σ^2.

4.2.1 System Model

For this scenario the network configuration is shown in the figure below. The network comprises of just two nodes, a source node *S* and a destination node *D*. Since we are interested in analyzing the direct transmission with no relay node we consider the scenario where destination is located in the communication range of source node. The source node transmits the data *X* having unit energy with its transmission power P_S .G_{SD}, is the channel gain between source and destination link. *n*, is the AWGN The signal received y at the destination will be expressed as:

$$Y[n] = G_{SD} \,.\, X[n] + n \qquad (4.1)$$

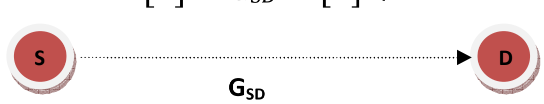

Figure 18   Direct Transmission

With direct link between the two communicating nodes and no involvement of any cooperating relay node the expression of signal-to-noise ratio will be:

$$\Gamma_{DT} = \frac{P_S|G_{SD}|^2}{\sigma^2} \tag{4.2}$$

Here σ^2, is the noise power which is assumed to be equal for all the links and the channel characteristics remain same for individual transmission frame. The result of the performance analysis of direct transmission links will be presented in the next chapter.

4.3 Transmission Using Amplify and Forward Protocol (AF)

In this section, amplify-and-forward cooperative relaying with spatial multiplexing is being employed in network. The transmitter is equipped with a single antenna but when several nodes with single antennas are used cooperatively, a virtual antenna array is formed. The source transmits similar signal to both destination and involved relays. The relay amplifies the received signal with a gain factor G_v and forwards it to the destination. The equations for signal received at the destination node are derived in the next section.

The signal model in the next section will be designed with some assumptions. i.e. The channel is assumed to be a Rayleigh fading channel and is normalized so that the fading coefficient matrix is complex Gaussian with zero-mean and varianceσ^2. Every communicating node in the network will obey rules of half duplex transmission which means it will either transmit or listen at any given instant. The knowledge of channel state information is not provided to the transmitter nodes but it is available at the receiver nodes. The multiple signals received by the receiver node will be combined using Maximal Ratio Combining (MRC) technique in order to maximize the signal-to-noise ratio (SNR). In this technique, weights will be assigned to the received signals and they will be added up to get the maximum signal-to-noise ratio received.

4.3.1 Transmission Model

For this scenario the network configuration is shown in the figure below. The network comprises of three nodes; a source node *S*, destination node *D* and a cooperating relay node *R*. Since we are interested in analyzing the transmission using relay node we consider the scenario where destination is not in the communication range of source node.

So we will employ Amplify-and-Forward relaying protocol. As it has been discussed in earlier chapters that cooperative relaying is performed in two phases in general.

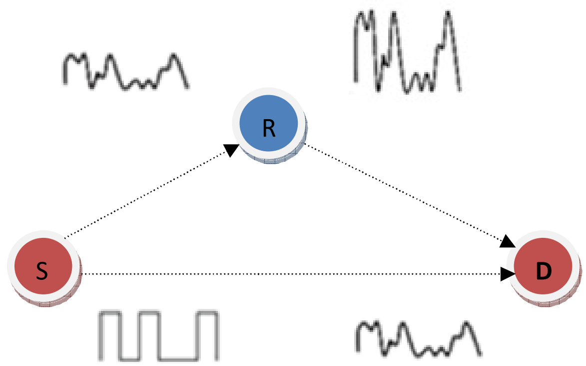

Figure 19 Transmission Using Amplify-and-forward Configuration

In the first phase the source node S broadcasts the data X with its transmission power P_S to both relay and destination node. The channel gains for the source-relay and source-destination links are G_{SR} and G_{SD} respectively. The AWGN present at the destination and relay node will be n_D and n_R respectively. The equation of received signals in the phase-I at the relay and destination node will be expressed as Y_R and Y_D respectively.

$$Y_D[n] = \sqrt{P_S}\; G_{SD}.X[n] + n_D[n] \tag{4.3}$$

$$Y_{Ri}[n] = \sqrt{P_S}\; G_{SR}.X[n] + n_R[n] \tag{4.4}$$

In phase-II, the relay amplifies the received signal Y_{Ri} and then forwards it to the destination with its transmission power P_{Ri}. The signal transmitted is the normalized version of the signal received Y_{Ri}. Here, P_R is the transmission power of the relay node. G_{RD} is the channel gain for relay-destination link and n'_D is the noise at the receiver in phase-II. Now the signal received at the destination from the relay is:

$$\dot{Y}_{Ri}[n] = \sqrt{P_R}\; G_{RD}.\dot{X}[n] + n'_D[n] \tag{4.5}$$

Since the transmitted signal $\dot{X}$ is the normalized version of the signal Y_{Ri}. So it is expressed as:

$$E[\dot{X}[n]^2] = \frac{Y_{Ri}[n]}{|Y_{Ri}[n]|} \tag{4.6}$$

$$E[\dot{X}[n]^2] = \frac{\sqrt{P_S}\ \ G_{SR}\ .X[n]\ + n_R[n]}{|\sqrt{P_S}\ \ G_{SR}\ .X[n]\ + n_R[n]|}, \quad \text{where } E[\dot{X}[n]^2] = 1$$

Now based on our assumption, the channel state information (Annavajjala, Cosman & Laurence 2007) is available at the receiver node. The relay node will multiply the received signal with a *Variable Gain* G_f: As it can be seen in the below expressions that the gain factor depends on the link quality between source and relay node. Therefore it varies in different transmission frame intervals.

$$G_f = \frac{1}{E[|Y_{Ri}[n]|^2 |G_{SR}|^2]}$$

Or

$$G_f = \frac{\sqrt{P_R}}{\sqrt{P_S|G_{SR}|^2 + \sigma^2}} \tag{4.7}$$

Therefore, the data $\dot{X}$ which is transmitted by the relay node in phase-II is given as:

$$\dot{X}[n] = G_f . Y_{Ri}[n]$$

$$\dot{X}[n] = G_f . (\sqrt{P_S}\ \ G_{SR}. X[n] + n_R[n])$$

$$\dot{X}[n] = \frac{\sqrt{P_S}}{\sqrt{P_s|G_{SR}|^2 + \sigma^2}} G_{SR}. X[n] + \frac{1}{\sqrt{P_S|G_{SR}|^2 + \sigma^2}}\ n_R[n] \tag{4.8}$$

Putting, equation (4.8) into (4.5) we get the signal received by the destination from relay node in Phase-II.

$$\dot{Y}_{Ri}[n] = \frac{\sqrt{P_R P_S}}{\sqrt{P_s|G_{SR}|^2 + \sigma^2}} G_{SR}. G_{RD}.X[n] + \frac{\sqrt{P_R}}{\sqrt{P_s|G_{SR}|^2 + \sigma^2}} . G_{RD}.n_R[n] + n'_D[n] \tag{4.9}$$

4.3.2 Reception Model

Since the cooperative relaying nodes are synchronized and send the data at the same time, the receiver node will get multiple copies of the message. The multiple copies can be used for detection or they can be combined using maximum-ratio-combiner (MRC). Therefore the reception transmission can be carried out in two ways i.e, *Using Spatial Diversity Combining* and *Not Using Spatial Diversity Combining*.

For the first case diversity combining is not used. The receiver node uses only the signal $\dot{Y}_{Ri}[n]$ which was transmitted by the relay node in phase-II for the purpose of detection. So the final signal-to-noise ratio will be expressed as:

$$\Gamma_{AF} = \frac{\frac{P_S P_R}{P_S|G_{SR}|^2+\sigma^2} \quad |G_{SR}|^2|G_{RD}|^2}{\frac{P_R\,\sigma^2}{P_S|G_{SR}|^2+\sigma^2} \quad |G_{RD}|^2 + \sigma^2} \tag{4.10}$$

As $$\Gamma_{SR} = \frac{P_S|G_{SR}|^2}{\sigma^2};\ \Gamma_{RD} = \frac{P_R|G_{RD}|^2}{\sigma^2}$$

$$\Gamma_{AF} = \frac{\Gamma_{SR}\Gamma_{RD}}{\Gamma_{SR}+\Gamma_{RD}\ +1}$$

For the second case diversity combining is used. The receiver node will get signal $Y_D[n]$ (Phase-I) and signal $\dot{Y}_{Ri}[n]$ (Phase-II) transmitted by the relay and source node respectively. The receiver will employ MRC technique for combining both of these signals. So the signal at the MRC part is given by:

$$Y_{MRC} = \frac{\sqrt{P_S}\,G_{SD}^*}{\sigma^2}(Y_D) + \frac{\sqrt{\frac{P_S P_R}{P_S|G_{SR}|^2+\sigma^2}} \quad G_{SR}^*G_{RD}^*}{\frac{P_R\,\sigma^2}{P_S|G_{SR}|^2+\sigma^2} \quad |G_{RD}|^2+\sigma^2}(\dot{Y}_{Ri}) \tag{4.11}$$

The signal-to-noise ratio after the combining of MRC is given by:

$$\Gamma_{AF}^{MRC} = \frac{P_S|G_{SD}|^2}{\sigma^2} + \frac{\frac{P_S|G_{SR}|^2}{\sigma^2}\cdot\frac{P_R|G_{RD}|^2}{\sigma^2}}{\frac{P_S|G_{SR}|^2}{\sigma^2}\cdot\frac{P_R|G_{RD}|^2}{\sigma^2}\ +1} \tag{4.12}$$

As, $$\Gamma_{SR} = \frac{P_S|G_{SR}|^2}{\sigma^2};\ \Gamma_{SD} = \frac{P_S|G_{SD}|^2}{\sigma^2};\ \Gamma_{RD} = \frac{P_R|G_{RD}|^2}{\sigma^2}$$

$$\Gamma_{AF}^{MRC} = \Gamma_{SD} + \frac{\Gamma_{SR}\Gamma_{RD}}{\Gamma_{SR}+\Gamma_{RD}\ +1}$$

4.4 Transmission Using Decode and Forward Protocol (DF)

In this section, decode-and-forward cooperative relaying with spatial multiplexing is being employed in network. The transmitter is equipped with a single antenna but the collection of these single antennas form a virtual antenna array when used cooperatively. The source transmits similar signal to both destination and involved relays. In this configuration the relay decodes the received signal and then forwards the decoded signal to the destination with its transmission power. The equations for signal received at the destination node are derived in the next section.

The same assumptions will be used for received signal expressions for Decode-and-Forward relaying protocol. The channel is assumed to be a Rayleigh fading channel and is normalized so that the fading coefficient matrix is complex Gaussian with zero-mean and varianceσ^2. Every communicating node in the network will obey rules of half duplex transmission which means it will either transmit or listen at any given instant. The knowledge of channel state information is not provided to the transmitter nodes but it is available at the receiver nodes. The multiple signals received by the receiver node will be combined using Maximal Ratio Combining (MRC) technique in order to maximize the signal-to-noise ratio (SNR). In this technique, weights will be assigned to the received signals and they will be added up to get the maximum signal-to-noise ratio received.

4.4.1 Transmission Model

For this scenario the network configuration is shown in the figure below. The network comprises of three nodes; a source node S, destination node D and a cooperating relay node R. Since we are interested in analyzing the transmission using relay node we consider the scenario where destination is not in the communication range of source node. So we will employ Decode-and-Forward relaying protocol. As it has been discussed in earlier chapters that cooperative relaying is performed in two phases in general.

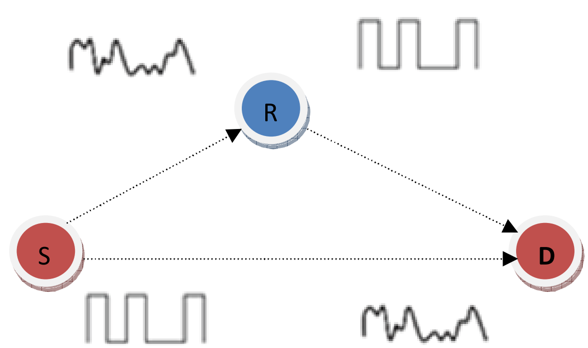

Figure 20 Transmission Using Decode-and-forward Configuration

In the first phase the source node S broadcasts the data X with its transmission power P_S to both relay and destination node. The channel gains for the source-relay and source-destination links are G_{SR} and G_{SD} respectively. The AWGN present at the destination and relay node will be n_D and n_R respectively. The equation of received signals in the phase-I at the relay and destination node will be expressed as Y_R and Y_D respectively.

$$Y_D[n] = \sqrt{P_S}\ \ G_{SD}.X[n] + n_D[n] \tag{4.13}$$

$$Y_{Ri}[n] = \sqrt{P_S}\ \ G_{SR}.X[n] + n_R[n] \tag{4.14}$$

In phase-II, the relay decodes the received signal Y_{Ri}. If the decoding process was successful, it will re-generate a message $\dot{X}[n]$ and then forwards it to the destination with its transmission power P_{Ri}.

G_{RD} is the channel gain for relay-destination link and n'_D is the noise at the receiver in phase-II. Now the signal received at the destination from the relay is:

$$\dot{Y}_{Ri}[n] = \sqrt{P_R}\ \ G_{RD}.\dot{X}[n] + n'_D[n] \tag{4.15}$$

$$\dot{Y}_{Ri}[n] = \sqrt{P_R}\ \ G_{RD}.X[n] + n'_D[n] \qquad [\text{As, } \dot{X}[n] = X[n]]$$

4.4.2 Reception Model

Since the cooperative relaying nodes are synchronized and send the data at the same time, the receiver node will get multiple copies of the message. If the destination node is far away from the source node the link quality of the source-destination is poor. Thus the signal received from this direct link is ignored at the receiver. On the contrary if the link is of high quality both the signals will be used for combining. These multiple signals will be combined using maximum-ratio-combiner (MRC). Therefore the reception transmission can be carried out in two ways i.e, *Using Spatial Diversity Combining* and *Not Using Spatial Diversity Combining*.

For the first case diversity combining is not used. The receiver node uses only the signal $\dot{Y}_{Ri}[n]$ which was transmitted by the relay node in phase-II for the purpose of detection. From the reference in (Hong, Huang & Kuo 2010:67-96), it is known this case is similar to a traditional multi-hop communication and the diversity gain offered by this case is not high enough. Even then this multi-hop communication system is efficient in case of constrained transmission power.

For the second case diversity combining is used. The receiver node will get signal $Y_D[n]$ (Phase-I) and signal $\dot{Y}_{Ri}[n]$ (Phase-II) transmitted by the relay and source node respectively. The receiver will employ MRC technique for combining both of these signals. So the signal at the MRC part is given by:

$$Y_{MRC} = \{\sqrt{P_S}\ G_{SD}^* . \sqrt{P_R}\ G_{RD}^*\} [Y_D[n] + \dot{Y}_{Ri}[n]] \quad (4.16)$$

$$Y_{MRC} = \{\ P_S\ |G_{SD}|^2 + P_R\ |G_{RD}|^2\} [X[n] + n_D^*[n]]$$

Where, $$n_D^*[n] = (\sqrt{P_S}\ G_{SD}^*)\ n_D[n] + (\sqrt{P_R}\ G_{RD}^*)\ n_D'[n]$$

$$Y_{MRC} = \{P_S\ |G_{SD}|^2 + P_R\ |G_{RD}|^2\}[X[n] + ((\sqrt{P_S} G_{SD}^*) n_D[n] + (\sqrt{P_R} G_{RD}^*) n_D'[n])]$$

The signal-to-noise ratio after the combining of MRC is given by:

$$\Gamma_{DF}^{MRC} = \frac{P_S |G_{SD}|^2}{\sigma^2} + \frac{P_R |G_{RD}|^2}{\sigma^2} \quad (4.17)$$

$$\Gamma_{DF}^{MRC} = \Gamma_{SD} + \Gamma_{RD}$$

4.5 Power Allocation Using Amplify and Forward

Cooperative relaying scheme uses random nodes in a wireless network to perform relaying functionalities for un-reliable communication links. Moreover, it offers advantages like redundancy against multi-path fading and higher spatial diversity gains. The most significant advantage is that using the same transmission power as that of a normal transmission it increases both signal-to-noise ratio (SNR) and network capacity.

As it has been discussed earlier that one of the most critical problem which hinders the performance of wireless network is the management of radio resources, specifically transmission power. An effective power allocation scheme must have the capability to increase the life time of network as well as increase the coverage of the network. There is a common understanding that for cooperative relaying systems, distribution of power equally among the involved nodes is the best possible solution, when it comes to the problem of power allocation. Whereas, practically the optimal power allocation scheme is the only one which can fully realize the potential of cooperative relaying systems.

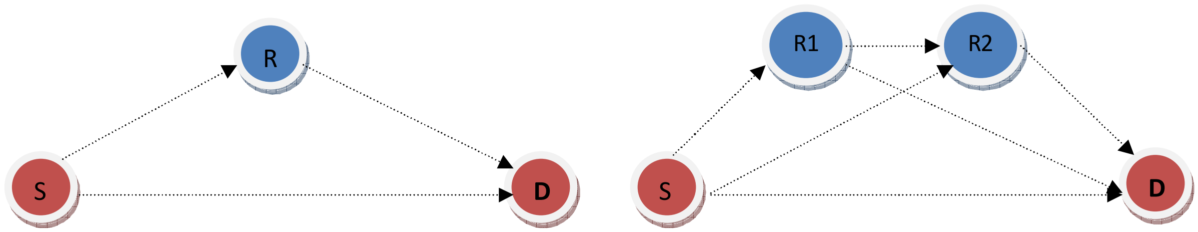

Figure 21 Simulation Configurations: Left 2-Node Network, Right 3-Node Network

In this thesis, a comprehensive framework for an optimal power allocation scheme has been discussed for two network configurations as shown in the above figure. In the later sections closed form expressions have been derived for the optimal transmission powers, first for the single relay node and then for the multiple relaying nodes scenario using Amplify and Forward relay protocol. An effort has been made to calculate the minimal transmission powers of the involved nodes using average-bit-error-rate as the performance criteria.

4.5.1 Performance Analysis for PA Algorithm (3-Hop Scenario)

The signal model in the next section will be designed with some assumptions. i.e. The channel is assumed to be a Rayleigh fading channel and is normalized so that the fading coefficient matrix is complex Gaussian with zero-mean and variance σ^2. Every communicating node in the network will obey rules of half duplex transmission which means it will either transmit or listen at any given instant. The knowledge of channel state information is not provided to the transmitter nodes but it is available at the receiver nodes.
The multiple signals received by the receiver node will be combined using Maximal Ratio Combining (MRC) technique in order to maximize the signal-to-noise ratio (SNR). In this technique, weights will be assigned to the received signals and they will be added up to get the maximum signal-to-noise ratio received. In the simulation the average-bit-error-rate has been analyzed keeping in mind the end-to-end transmission i.e. for source-to-destination transmission. Therefore power constraints are applied for the whole transmission instead of intermediate hops. Because if constraints have been applied for end-to-end transmission there is no point to apply them on individual links too, resulting in less complexity.

4.5.1-A Transmission Model

For this scenario the network configuration is shown in the figure below. The network comprises of four nodes; a source node *S*, destination node *D* and two cooperating relaying nodes *R1* and *R2*. Since we are interested in analyzing the transmission using relaying nodes we consider the scenario where destination is not in the communication range of source node. So we will employ Amplify-and-Forward relaying protocol. As it has been discussed in earlier chapters that cooperative relaying is performed in two phases in general.

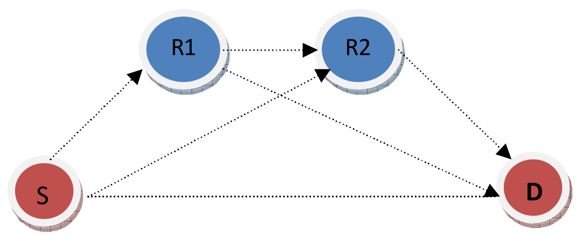

Figure 22 Power Allocation Algorithm involving 2-Relays (3-Hop Scenario)

In the first phase the source node *S* broadcasts the data *X* with its transmission power P_S to both relay and destination node, as shown in the next figure. The channel gains for the source-relay1 and from source- relay2 links are G_{SR1} and G_{SR2} respectively. The AWGN present at the relay 1 and relay 2 nodes will be n_{SR1} and n_{SR2} respectively. The equation of received signals in the phase-I at the relay 1 and relay 2 will be expressed as Y_{R1} and Y'_{R2} respectively.

$$Y_{R1}[n] = \sqrt{P_S}\; G_{SR1}.X[n] + n_{SR1}[n] \qquad (4.18)$$

$$Y'_{R2}[n] = \sqrt{P_S}\; G_{SR2}.X[n] + n_{SR2}[n] \qquad (4.19)$$

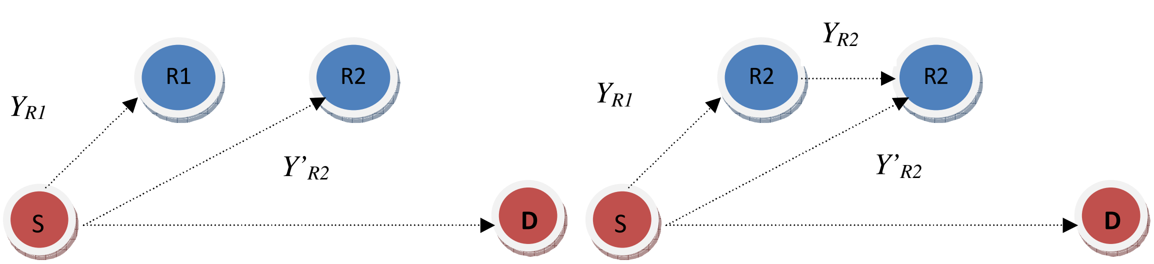

Figure 23 Signals received by the Relay Node1 and Relay Node2

After Phase-II, the relay2 node has received two signals Y'_{R2} and Y_{R2}, first one was in phase-I (broadcasting) and the second one was forwarded by relay1 with its amplification factor β_{R1} in phase-II. G_{R1R2} is the channel gain for relay1-relay2 link and n_{R1R2} is the noise at the relay node2 in phase-II. But since the link between source-relay2 is weak as compared to the link between relay1 and relay2 so the node relay2 discards the signal Y'_{R2} and the received signal Y_{R2} is defined as:

$$Y_{R2}[n] = \beta_{R1} \,.\, Y_{R1}[n] \,.\, G_{R1R2} + n_{R1R2}[n] \tag{4.20}$$

In phase-II, the relay2 amplifies the received signal Y_{R2} and then forwards it to the destination with its amplification gain β_{R2}. The destination node has two signals received from relay2 node and source node as shown in the figure. Now the signals received at the destination are given below:

$$Y_D[n] = (\sqrt{P_S}\,.\underbrace{G_{SD}.\, X[n] + n_{SD}}_{Z_{SD}}[n]) + (\beta_{R2} \,.\, Y_{R2}[n].\underbrace{G_{R2D} + n_{R2D}}_{Z_{R2}}[n]) \tag{4.21}$$

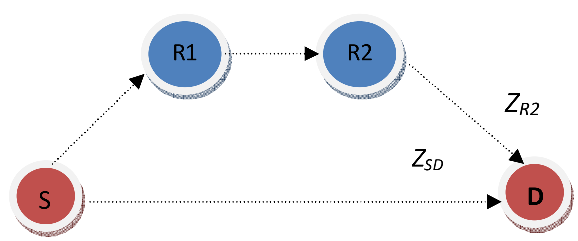

Figure 24 Signals received by the Destination Node (3-Hops)

Relay gains β_{R1} and β_{R2} are used to properly fine-tune the powers at the corresponding relays to reduce variations in the source-relay and relay–destination links. This is performed, while satisfying constrained transmission power. The relaying node's amplifier can provide a maximum gain defined by the following expressions:

Here, $$\beta_{R1} = \sqrt{\frac{P_{R1}}{P_S|G_{SR1}|^2 + N_0}}$$

and $$\beta_{R2} = \sqrt{\frac{P_{R2}}{P_{R1}|G_{R1R2}|^2 + N_0}}$$

4.5.1-B Reception Model

Maximal-Ratio-Combiner, provides the benefit of increasing the signal-to-noise ratio (SNR) at the output of the detector given that the noise terms at the input of the MRC are uncorrelated. As discussed earlier, amplify-and-forward protocol may induce some noise amplification but the MRC detector employed is quite competitive therefore with the help of its weights it can compensate effect of induced noise. For this network configuration of two cooperating relay nodes, we assume that the knowledge of the channel state information is available at the receiver end. Now the destination node will perform receiver diversity combining on the two signals it received. Therefore, the output of the MRC detector at the destination node will be:

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \alpha_1(\beta_{R2}.Y_{R2}[n].G_{R2D} + n_{R2D}[n]) \quad (4.22)$$

Substituting equation (4.20) into (4.22).

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \ldots \alpha_1(\beta_{R2}.(Y_{R1}[n].G_{R1R2} + n_{R1R2}[n]).G_{R2D} + n_{R2D}[n]) \quad (4.23)$$

Substituting equation (4.18) into (4.23).

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \ldots \alpha_1(\beta_{R2}.((\sqrt{P_S}\,G_{SR1}.X[n] + n_{SR1}[n]).G_{R1R2} + n_{R1R2}[n]).G_{R2D} + n_{R2D}[n]) \quad (4.24)$$

In the above equation, α_0 and α_1 are the weights of the maximal-ratio-combiner. These combining weight compensate for the effects of likely incorrect decisions and are therefore chosen accordingly.

Here, $$\alpha_0 = \frac{\sqrt{P_S}\,G_{SD}^{*}}{N_0}$$

and $$\alpha_1 = \frac{\sqrt{P_S}\,.\,\beta_{R1}.\,\beta_{R2}\,.\,G_{SR1}^{*}\,.\,G_{R1R2}^{*}\,.\,G_{R2D}^{*}}{N_0}$$

4.5.1-C Optimization Model

First the outage probability for this particular network configuration will be formulated, and then the next step will be to find the solution of the optimization problem for allocating power optimally between the source node and all other cooperating relay nodes.

The corresponding signal-noise-ratios (SNRs) at the source-destination link and the source-relay1-relay2-destination links are given by Γ_0 and Γ_1 respectively (Laneman & Wornell 2000).

$$\Gamma_0 = \frac{\sigma_{SD}{}^2 . P_S}{N_0}$$

In this configuration the multi-hop transmission can be viewed as a cascading single-hop transmission between the source and destination with single-hop transmission between any two communicating nodes. Therefore the source-destination path with cooperating relays is a summation of signal-noise-ratios at the individual links.

$$\Gamma_1 = \left(\frac{1}{\Gamma_{S1}} + \frac{1}{\Gamma_{R1R2}} + \frac{1}{\Gamma_{R2D}}\right)^{-1}$$

The total SNR Γ_T can be expressed in form defined below:

$$\Gamma_T = \Gamma_0 + \Gamma_1$$

$$\Gamma_T = \left[\frac{\sigma_{SD}{}^2 . P_S}{N_0}\right] + \left[\left(\frac{1}{\Gamma_{S1}} + \frac{1}{\Gamma_{R1R2}} + \frac{1}{\Gamma_{R2D}}\right)^{-1}\right]$$

The probability of bit error will be calculated using *Moment Generating Function (MGF)* approach. Since, it is a very helpful and simple tool for performance analysis of any modulation scheme in a fading scenario Also, used by (Fikadu, Elmusrati & Virrankoski 2012). In our case the modulation scheme is M-PSK. (Goldsmith 2005: 189).

$$P_e = \frac{1}{\pi} \int_0^{\left(\frac{N-1}{N}\right)\pi} \prod_{n=0}^{1} N_{\gamma_n} \left(\frac{g_{PSK}}{sin^2\theta}\right) d\theta \qquad (4.25)$$

The basic idea of this moment generating function approach for computing bit error probabilities in a fading scenario is to define the error probability for the particular modulation scheme as a exponential function of γ, as defined below.

$$N_{\gamma_n} = \int_0^{\infty} P_{\gamma_n}(\gamma) e^{s\gamma}\, d\gamma$$

Where, $g_{PSK} = sin^2\left(\frac{\pi}{N}\right)$. The average-bit-error-rate (ABER) over generalized independent I_l Rayleigh Fading Channel is given by the following expression (Simon & Alouini 2000:Table 3)

$$P_e = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \prod_{n=0}^{1} N_{\gamma_n}\ I_l(\gamma_l, g_{PSK}, \theta)\, d\theta \qquad (4.26)$$

As,

$$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) = \left(1 + \frac{g_{PSK}}{sin^2\theta}\gamma_n\right)^{-1}$$

$$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) = \left(1 + \frac{\gamma_n}{sin^2\theta}\right)^{-1}$$

Or,

$$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) \cong \left(\frac{\gamma_n}{sin^2\theta}\right)^{-1} \qquad \text{Since } (\gamma_n \gg 1)$$

Therefore,

$$P_e = \frac{3}{8}(\gamma_0.\gamma_1)^{-1} \qquad (4.27)$$

$$P_e = \frac{3}{8}\left[\left(\frac{\sigma_{SD}{}^2 . P_S}{N_0}\right).\left(\frac{\sigma_{SR1}{}^2 . P_S}{N_0} + \frac{\sigma_{R1R2}{}^2 . P_1}{N_0} + \frac{\sigma_{R2D}{}^2 . P_2}{N_0}\right)\right]^{-1} \qquad (4.28)$$

$$P_e = \frac{3}{8}\left[\frac{P_S{}^2 . \sigma^2{}_{SD} . \sigma^2{}_{SR1}}{N_0{}^2} + \frac{P_S . P_1 . \sigma^2{}_{SD} . \sigma^2{}_{R1R2}}{N_0{}^2} + \frac{P_S . P_2 . \sigma^2{}_{SD} . \sigma^2{}_{R2D}}{N_0{}^2}\right]^{-1} \qquad (4.29)$$

$$P_e = \frac{3N_0{}^2}{8}\left[\frac{1}{P_S . \sigma^2{}_{SD} . \sigma^2{}_{SR1}} + \frac{1}{P_S . P_1 . \sigma^2{}_{SD} . \sigma^2{}_{R1R2}} + \frac{1}{P_S . P_2 . \sigma^2{}_{SD} . \sigma^2{}_{R2D}}\right] \qquad (4.30)$$

Since the outage probability has been formulated for this configuration, an effort is made to minimize this outage probability of transmission power. This will be done keeping in mind the constraint of total transmission power. This optimization problem can be expressed as:

$$\text{Minimize} \quad P_e = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \prod_{n=0}^{2} N_{\gamma_n}\left(\frac{1}{sin^2\theta}\right) d\theta$$

$$\text{Subject to} \quad P_s + \sum_1^N P_R \leq P_T$$

Where, $P_T = P_S + P_1 + P_2$

Or, $\min_{P_S P_1 P_2} (P_e)$

Now as we have formulated the constrained optimization problem of this network configuration, we proceed with its solution. One of the most important methods to get a closed form expression of a constrained optimization problem is the *Lagrange Method*. The Lagrange function of this problem is defined as:

$$\text{J} = P_e + \lambda\,(P_s + \sum_1^2 P_R - P_T) \tag{4.31}$$

$$\text{J} = (\frac{1}{\pi}\int_0^{\frac{\pi}{2}} \prod_{n=0}^{2} N_{\gamma_n}\left(\frac{1}{sin^2\theta}\right) d\theta) + \lambda\,(P_S + P_1 + P_2 - P_T)$$

$$\text{J} = \frac{3{N_0}^2}{8}\left(\frac{1}{{P_S}^2\,\sigma^2{}_{SD}\;\sigma^2{}_{SR1}} + \frac{1}{P_S P_1\,\sigma^2{}_{SD}\;\sigma^2{}_{R1R2}} + \frac{1}{P_S P_2\,\sigma^2{}_{SD}\;\sigma^2{}_{R2D}}\right) + \lambda(P_S + P_1 + P_2 - P_T)$$

Now taking the partial derivatives of the Lagrange function J (P, λ), with respect to P_s, P_1, P2 and λ. Here , is the Lagrange multiplier. Afterwards these derivatives will be equated to zero, like defined below.

$$\frac{\partial \text{J}}{\partial P_S} = 0;\; \frac{\partial \text{J}}{\partial P_1} = 0;\; \frac{\partial \text{J}}{\partial P_2} = 0;\; \frac{\partial \text{J}}{\partial \lambda} = 0$$

$$\frac{\partial \text{J}}{\partial P_S} = \frac{3N_0^2}{8}\left[\frac{-2P_S.\,\sigma^2{}_{SD}\;.\,\sigma^2{}_{SR1}}{({P_S}^2.\,\sigma^2{}_{SD}\;.\,\sigma^2{}_{SR1})^2} - \frac{P_1.\,\sigma^2{}_{SD}\;.\,\sigma^2{}_{R1R2}}{(P_S.P_1.\,\sigma^2{}_{SD}\;.\,\sigma^2{}_{R1R2})^2} - \frac{P_2.\,\sigma^2{}_{SD}\;.\,\sigma^2{}_{R2D}}{(P_S.P_2.\,\sigma^2{}_{SD}\;.\,\sigma^2{}_{R2D})^2}\right] + \lambda = 0$$

$$\frac{\partial \text{J}}{\partial P_1} = \frac{3N_0^2}{8}\left[\frac{-P_S.\;\sigma^2{}_{SD}\;.\;\sigma^2{}_{R1R2}}{(P_S.P_1\;.\;\sigma^2{}_{SD}\;.\;\sigma^2{}_{R1R2})^2}\right] + \lambda = 0$$

$$\frac{\partial \text{J}}{\partial P_2} = \frac{3N_0^2}{8}\left[\frac{-P_S.\;\sigma^2{}_{SD}\;.\;\sigma^2{}_{R2D}}{(P_S.P_2\;.\;\sigma^2{}_{SD}\;.\;\sigma^2{}_{R2D})^2}\right] + \lambda = 0$$

$$\frac{\partial J}{\partial \lambda} = P_S + P_1 + P_2 - P_T = 0$$

After some algebraic manipulations the above equations are used to solve the value of P_S, P_1 and P_2 i.e. Power values of Source node, Relay 1 and Relay 2 respectively.

$$P_S = \begin{cases} \frac{A - 4B + \sqrt{A^2 + 8AB}}{4(A - B)} P_T \\ \frac{2}{3} P_T \end{cases}$$

Where, $A = (\sigma_{R2D} + \sigma_{R1R2})^2 . \sigma^2{}_{R1R2} . \sigma^2{}_{SR1}$ and $B = \sigma^2{}_{R2D} . \sigma^3{}_{R1R2}$

$$P_1 = \frac{\sigma_{2D}}{\sigma_{2D} + \sigma_{R1R2}} (P_T - P_S)$$

$$P_2 = P_T - P_1 - P_S$$

4.5.2 Performance Analysis for PA Algorithm (2-Hop Scenario)

The signal model in the next section will be designed with some assumptions. i.e. The channel is assumed to be a Rayleigh fading channel and is normalized so that the fading coefficient matrix is complex Gaussian with zero-mean and variance σ^2. Every communicating node in the network will obey rules of half duplex transmission which means it will either transmit or listen at any given instant.

The knowledge of channel state information is not provided to the transmitter nodes but it is available at the receiver nodes. The multiple signals received by the receiver node will be combined using Maximal Ratio Combining (MRC) technique in order to maximize the signal-to-noise ratio (SNR). In this technique, weights will be assigned to the received signals and they will be added up to get the maximum signal-to-noise ratio received. In the simulation the average-bit-error-rate has been analyzed keeping in mind the end-to-end transmission i.e. for source-to-destination transmission. Therefore power constraints are applied for the whole transmission instead of intermediate hops. Because if constraints have been applied for end-to-end transmission there is no point to apply them on individual links too, resulting in less complexity.

4.5.2-A Transmission Model

For this scenario the network configuration is shown in the figure below. The network comprises of three nodes; a source node *S*, destination node *D* and a cooperating relay node *R*. Since we are interested in analyzing the transmission using relay node we consider the scenario where destination is not in the communication range of source node. So we will employ Amplify-and-Forward relaying protocol. As it has been discussed in earlier chapters that cooperative relaying is performed in two phases in general.

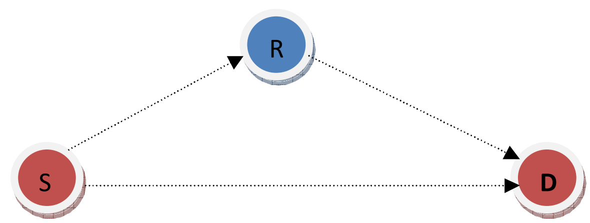

Figure 25 Power Allocation Algorithm involving 1-Relay (2-Hop Scenario)

In the first phase the source node *S* broadcasts the data *X* with its transmission power P_S to both relay and destination node, as shown in the next figure. The channel gains for the source-relay and from source- destination links are G_{SR} and G_{SD} respectively. The AWGN present at the relay and destination nodes will be n_{SR} and n_{SD} respectively. The equation of received signals in the phase-I at the relay and destination will be expressed as Y_R and Y_D respectively.

$$Y_R[n] = \sqrt{P_S}\; G_{SR}.X[n] + n_{SR}[n] \tag{4.32}$$

$$Y_D[n] = \sqrt{P_S}\; G_{SD}.X[n] + n_{SD}[n] \tag{4.33}$$

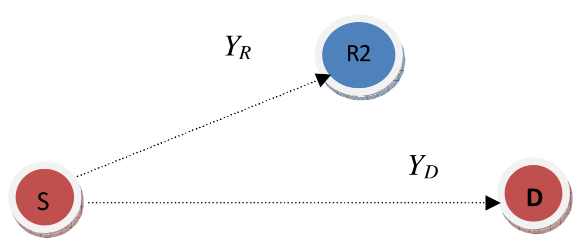

Figure 26 Signals received by the Relay and Destination

In phase-II, the relay amplifies the received signal Y_R and then forwards it to the destination with its amplifier gain β_R. Here, P_R is the transmission power of the relay node. G_{RD} is the channel gain for relay-destination link and n_{RD} is the noise at the receiver in phase-II. Now the signal received at the destination from the relay is:

$$Y^*_R[n] = \beta_R . Y_R[n] . G_{RD} + n_{RD}[n] \quad (4.34)$$

At the destination, the destination node has two signals received from relay node and source node as shown in the figure below. Now the signals received at the destination are given below:

$$Y^*_D[n] = (\underbrace{\sqrt{P_S} . G_{SD} . X[n] + n_{SD}[n]}_{Z_{SD}}) + (\underbrace{\beta_R . Y_R[n] . G_{RD} + n_{RD}[n]}_{Z_{RD}}) \quad (4.35)$$

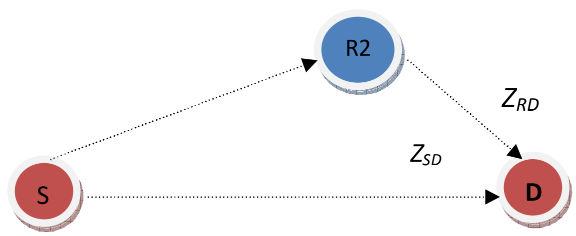

Figure 27 Signals received by the Destination Node (2-Hops)

Relay gain β_R is used to properly fine-tune the power at the relay to reduce variations in the relay–destination link. This is performed, while satisfying constrained transmission power. The relaying node's amplifier can provide a maximum gain defined by the following expressions:

Here,
$$\beta_R = \sqrt{\frac{P_R}{P_S|G_{SR}|^2 + N_0}}$$

4.5.2-B Reception Model

Maximal-Ratio-Combiner, provides the benefit of increasing the signal-to-noise ratio (SNR) at the output of the detector given that the noise terms at the input of the MRC are uncorrelated. As discussed earlier, amplify-and-forward protocol may induce some noise amplification but the MRC detector employed is quite competitive therefore with the help of its weights it can compensate effect of induced noise. For this network configuration of a single cooperating relay node, we assume that the knowledge of the channel state information is available at the receiver end. Now the destination node will perform receiver diversity combining on the two signals it received. Therefore, the output of the MRC detector at the destination node will be:

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \ldots$$
$$\alpha_1(\beta_R . Y_R[n] .\ G_{RD} + n_{RD}[n]) \quad (4.36)$$

Substituting equation (4.32) into (4.36).

$$Y_{MRC}[n] = \alpha_0(\sqrt{P_S}.G_{SD}.X[n] + n_{SD}[n]) + \ \ldots$$
$$\alpha_1(\beta_R . (\sqrt{P_S}\ G_{SR}.X[n] + n_{SR}[n]) .\ G_{RD} + n_{RD}[n]) \quad (4.37)$$

In the above equation, α_0 and α_1 are the weights of the maximal-ratio-combiner. These combining weight compensate for the effects of likely incorrect decisions and are therefore chosen accordingly.

Here, $$\alpha_0 = \frac{\sqrt{P_S}\, G_{SD}^*}{N_0}$$

and $$\alpha_1 = \frac{\sqrt{P_S}\ .\ \beta_R . G_{SR}^*\ .\ G_{RD}^*}{N_0}$$

4.5.2-C Optimization Model

First the outage probability for this particular network configuration will be formulated, and then the next step will be to find the solution of the optimization problem for allocating power optimally between the source node and all other cooperating relay nodes.

The corresponding signal-noise-ratios (SNRs) at the source-destination link and the source-relay-destination links are given by Γ_0 and Γ_1 respectively (Laneman & Wornell 2000).

$$\Gamma_0 = \frac{{\sigma_{SD}}^2 . P_S}{N_0}$$

In this configuration the multi-hop transmission can be viewed as a cascading single-hop transmission between the source and destination with single-hop transmission between any two communicating nodes. Therefore the source-destination path with cooperating relays is a summation of signal-noise-ratios at the individual links.

$$\Gamma_1 = (\frac{1}{\Gamma_{SR}} + \frac{1}{\Gamma_{RD}})^{-1}$$

The total SNR Γ_T can be expressed in form defined below:

$$\Gamma_T = \Gamma_0 + \Gamma_1$$

$$\Gamma_T = \left[\frac{\sigma_{SD}{}^2 . P_S}{N_0}\right] + \left[(\frac{1}{\Gamma_{SR}} + \frac{1}{\Gamma_{RD}})^{-1}\right]$$

The probability of bit error will be calculated using *Moment Generating Function (MGF)* approach. Since, it is a very helpful and simple tool for performance analysis of any modulation scheme in a fading scenario. Also, used by (Fikadu, Elmusrati & Virrankoski 2012). In our case the modulation scheme is M-PSK. (Goldsmith 2005: 189).

$$P_e = \frac{1}{\pi} \int_0^{(\frac{N-1}{N})\pi} \prod_{n=0}^{1} N_{\gamma_n} \left(\frac{g_{PSK}}{sin^2\theta}\right) d\theta \qquad (4.38)$$

The basic idea of this moment generating function approach for computing bit error probabilities in a fading scenario is to define the error probability for the particular modulation scheme as a exponential function of γ, as defined below.

$$N_{\gamma_n} = \int_0^{\infty} P_{\gamma_n}(\gamma) e^{s\gamma}\, d\gamma$$

Where, $g_{PSK} = sin^2\left(\frac{\pi}{N}\right)$. The average-bit-error-rate (ABER) over generalized independent I_l Rayleigh Fading Channel is given by the following expression (Simon & Alouini 2000:Table 3)

$$P_e = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \prod_{n=0}^{1} N_{\gamma_n}\ I_l(\gamma_l, g_{PSK}, \theta)\, d\theta \qquad (4.39)$$

As, $$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) = \left(1 + \frac{g_{PSK}}{sin^2\theta}\gamma_n\right)^{-1}$$

$$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) = \left(1 + \frac{\gamma_n}{sin^2\theta}\right)^{-1}$$

Or, $$N_{\gamma_n}\left(\frac{1}{sin\theta^2}\right) \cong \left(\frac{\gamma_n}{sin^2\theta}\right)^{-1}$$ Since $(\gamma_n \gg 1)$

Therefore, $$P_e = (\gamma_0 . \gamma_1)^{-1} \tag{4.40}$$

$$P_e = \left[\left(\frac{{\sigma_{SD}}^2 . P_S}{N_0}\right) . \left(\frac{{\sigma_{SR}}^2 . P_S}{N_0} + \frac{{\sigma_{RD}}^2 . P_R}{N_0}\right)\right]^{-1} \tag{4.41}$$

$$P_e = \left[\frac{{P_S}^2 . \sigma^2{}_{SD} . \sigma^2{}_{SR}}{{N_0}^2} + \frac{P_S . P_R . \sigma^2{}_{SD} . \sigma^2{}_{RD}}{{N_0}^2}\right]^{-1} \tag{4.42}$$

$$P_e = N_o^2\left[\frac{1}{P_S . \sigma^2{}_{SD} . \sigma^2{}_{SR}} + \frac{1}{P_S . P_R . \sigma^2{}_{SD} . \sigma^2{}_{RD}}\right] \tag{4.43}$$

Since the outage probability has been formulated for this configuration, an effort is made to minimize this outage probability of transmission power. This will be done keeping in mind the constraint of total transmission power. This optimization problem can be expressed as:

Minimize $$P_e = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{n=0}^{1} N_{\gamma_n}\left(\frac{1}{sin^2\theta}\right) d\theta$$

Subject to $P_s + P_R \leq P_T$

Now as we have formulated the constrained optimization problem of this network configuration, we proceed with its solution. One of the most important methods to get a closed form expression of a constrained optimization problem is the *Lagrange Metho*d. The Lagrange function of this problem is defined as:

$$J = P_e + \lambda (P_s + P_R - P_T) \tag{4.44}$$

$$J = \left(\frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{n=0}^{1} N_{\gamma_n}\left(\frac{1}{sin^2\theta}\right) d\theta\right) + \lambda (P_S + P_R - P_T)$$

$$J = N_0^2 \left(\frac{1}{P_S{}^2 \, \sigma^2{}_{SD} \; \sigma^2{}_{SR}} + \frac{1}{P_S P_R \, \sigma^2{}_{SD} \; \sigma^2{}_{RD}} \right) + \lambda (P_S + P_R - P_T)$$

Now taking the partial derivatives of the Lagrange function J (P, λ), with respect to P_s, P_1, P2 and λ. Here , is the Lagrange multiplier. Afterwards these derivatives will be equated to zero, like defined below.

$$\frac{\partial J}{\partial P_S} = 0; \; \frac{\partial J}{\partial P_R} = 0; \; \frac{\partial J}{\partial \lambda} = 0$$

$$\frac{\partial J}{\partial P_S} = N_0^2 \left[\frac{-2P_S . \sigma^2{}_{SD} \; . \sigma^2{}_{SR}}{(P_S{}^2 . \sigma^2{}_{SD} \; . \sigma^2{}_{SR})^2} - \frac{P_R . \sigma^2{}_{SD} \; . \sigma^2{}_{RD}}{(P_S . P_R . \sigma^2{}_{SD} \; . \sigma^2{}_{RD})^2} \right] + \lambda = 0$$

$$\frac{\partial J}{\partial P_R} = N_0^2 \left[- \frac{P_S . \sigma^2{}_{SD} \; . \sigma^2{}_{RD}}{(P_S . P_R . \sigma^2{}_{SD} \; . \sigma^2{}_{RD})^2} \right] + \lambda = 0$$

$$\frac{\partial J}{\partial \lambda} = P_S + P_R - P_T = 0$$

After some algebraic manipulations the above equations are used to solve the value of P_S and P_R i.e. Power values of Source node, Relay node respectively.

$$P_S = \frac{\sigma^2{}_{SR} + \sqrt{\sigma^2{}_{SR} + 8\sigma^2{}_{RD}}}{3\sigma^2{}_{SR} + \sqrt{\sigma^2{}_{SR} + 8\sigma^2{}_{RD}}} P_T$$

$$P_R = \frac{2\sigma_{SR}}{3\sigma^2{}_{SR} + \sqrt{\sigma^2{}_{SR} + 8\sigma^2{}_{RD}}} P_T$$

4.6 Summary

In this chapter it has been shown how cooperative transmission takes place with help of cooperative relaying nodes. The transmission process has been explained in detail with help of transmission and reception models. Moreover, there is explanation of how this process has been optimized with help of power allocation strategies. A detailed framework of power allocation strategy for Amplify-and-Forward protocol has been discussed with help of two scenarios: 2-Hop cooperative network model and 3-Hop cooperative network model. This mathematical background has been built for the Chapter 5 in which the simulation scenarios will be discussed based on these mathematical expressions derived for various stages of cooperative transmission.

5. Simulations & Results

5.1 Introduction

Cooperative relay transmission is indeed a powerful tool to achieve spatial diversity even when the node has just a single antenna instead of having multiple ones. This diversity gain can be accomplished using different relaying strategies, among them Amplify-and-Forward stands out because of its low complexity and higher diversity gains. As it has been discussed earlier that conventional relaying networks employ equal power allocation among involved communicating nodes which is not at all efficient (Sohaib & K.C 2011)(T.T, Nguyen & Tuan 2009). Therefore, an optimal power allocation scheme has been proposed in this thesis that offers salient features like better BER performance as well as increase in network life-time.

Moreover in context of wireless sensor networks where saving few dB(s) matters a lot, the performance of an optimal power allocation scheme has been simulated using amplify-and-forward as the relaying protocol. The simulation analysis contains the above mentioned relaying protocol employed in a sensor network along with power allocation, for various communication models. In the previous chapter, closed-form expressions for the optimal power allocation scheme were formulated with the sole aim of having higher received SNR. In this chapter, the numerical results of the formulated expressions have been explained through simulating BER curves to demonstrate the optimality and efficiency of proposed power allocation algorithm. The simulation results presented in the later section are based on the mathematical expressions derived earlier in chapter 4; therefore there will be only discussions about the simulation results in this chapter. The cooperative network simulation results have been analyzed into two phases.

In the first phase, a three node (*One Relay*) wireless network configuration has been simulated and the corresponding results have been presented. The BER performance curves have been presented for all three network scenarios i.e. *Direct Transmission*, *Transmission using Amplify-and-Forward Protocol* & *Transmission using Decode-and-Forward Protocol*. The purpose of this simulation analysis was to show first how these relaying protocols outperform a simple direct transmission in terms of efficiency. Then, showing the performance differences between these protocols under similar communication characteristics.

In the second phase, the simulation results have been presented for the proposed optimal power allocation algorithm for a cooperative network employing *Amplify-and-Forward* protocol. The results have been presented for different network scenarios i.e. First for a three node (*One Relay*) wireless network configuration and then for a four node (*Two Relays*) wireless network configuration. The scenarios are further divided into three cases based on channel quality between any two communicating nodes.

5.1 BER Performance of transmission Using Amplify and Forward Protocol (AF)

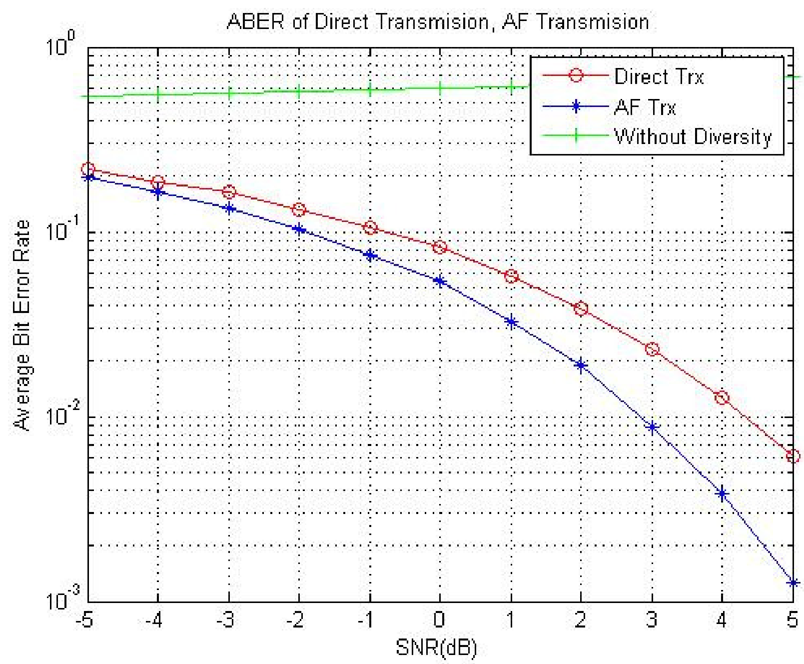

Figure 28 ABER Performance of Direct Transmission and AF Transmission

The simulation is carried out using the same assumptions which were used to derive the mathematical expressions in the previous chapter (*Section 4.3*). The above graph shows the result for a cooperative transmission carried out using Amplify-and-Forward (AF) relaying protocol between a source and destination node with help of a relaying node. The results of a direct transmission have been taken as a baseline performance, carried out between source and destination node with no involvements of any relay node. Then there are results of a cooperative communication scenario when no diversity is applied at the receiver's end. As it is evident from the results that if no *Virtual MIMO* is employed in a cooperative network, one cannot achieve required results, as it is one of the key techniques.

Without diversity the multiple streams being transmitted from cooperating relay nodes will offer no advantage. As discussed earlier that amplify-and-forward protocol is a simple relaying protocol that offers great performance and higher diversity gains as compared to other relaying protocols. The protocol uses simple method of amplifying instead of using complex digital processing in case of a decode-and-forward protocol which burdens the node having limited computational power. The results presented above also verify that by using relaying with amplify-and-forward protocol techniques gives much better BER performance than that achieved using a direct transmission. The results presented in this graph verify and validate the mathematical expressions and the assumptions formulated in the previous chapter.

5.2 BER Performance of transmission Using Decode and Forward Protocol (DF)

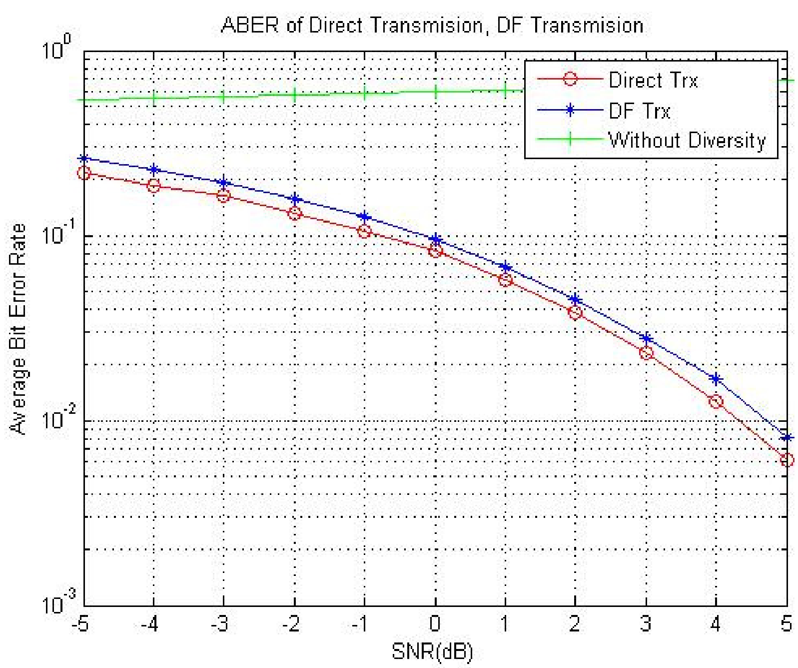

Figure 29 ABER Performance of Direct Transmission and DF Transmission

The simulation is carried out using the same assumptions which were used to derive the mathematical expressions in the previous chapter (*Section 4.4*).The above graph shows the result for a cooperative transmission carried out using Decode-and-Forward (DF) relaying protocol. The results of a direct transmission have been taken as a baseline performance, carried out between source and destination node with no involvements of any relay node.

Then, like the previous graph, there are results of a cooperative communication scenario when no diversity is applied at the receiver's end. And one can see it clearly that *No Diversity* scenario does not help the cause of this relaying protocol either and the system performance is below the acceptable level. As decode-and-forward protocol requires some digital processing at each intermediate hop so it affects the performance as well as the life span of an individual node, since the node has limited computational capacity. The performance of a decode-and-forward protocol greatly depends on the link quality between a source and relay node. If the link is weak, inaccurate decoding will be performed which in turn decreases the performance of the system. The remedy for this case will be to use some channel coding technique like Cyclic Redundancy Check (CRC) but that too hampers the performance as well as life-time of the communicating node. Based on these findings the optimal power allocation schemes have been analyzed only for Amplify-and-Forward protocol.

5.3 BER Performance of Power Allocation Algorithm for 2-Hop Scenario

The simulation is carried out using the same assumptions which were used to derive the mathematical expressions in the previous chapter (*Section 4.5.2*). In this section there will be numerous performance graphs showing the result of optimal power allocation strategy when employed in a cooperative transmission using Amplify-and-Forward (AF) relaying protocol. The transmission scenario (*2-Hop or Single Relay*) has been further categorized into 3 cases on the basis of channel quality between source-destination, source-relay and relay-destination links.

Case 1: $\boldsymbol{\sigma^2{}_{SD} = 1;\ \sigma^2{}_{SR} = 1;\ \sigma^2{}_{RD} = 1}$

This is the scenario in which the relay node lies in exactly in the center of source and destination node. In this case the link between source-destination, source-relay and relay-destination all have similar link qualities. Therefore the variance of the three links is taken to be 1. The ABER performance of the system is given below in Figure 30.

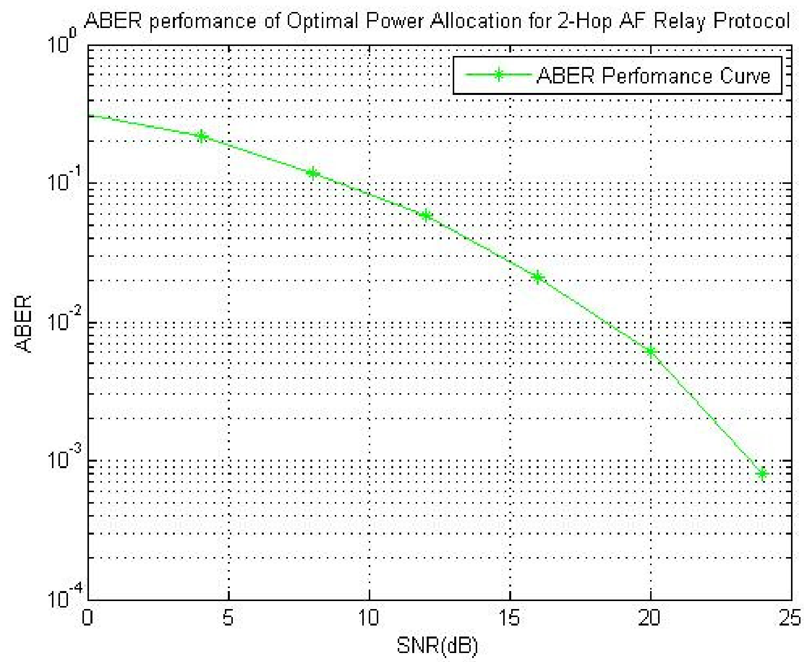

Figure 30 ABER performance 2-Hop AF Transmission (relay in middle)

For this scenario where the relay node lies exactly in the middle of source and destination node the optimal power allocation strategy assigns a power of 0.6667 to the source node and a power of 0.3333 to the relay node satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 31, shows the power distribution between the source and relay nodes.

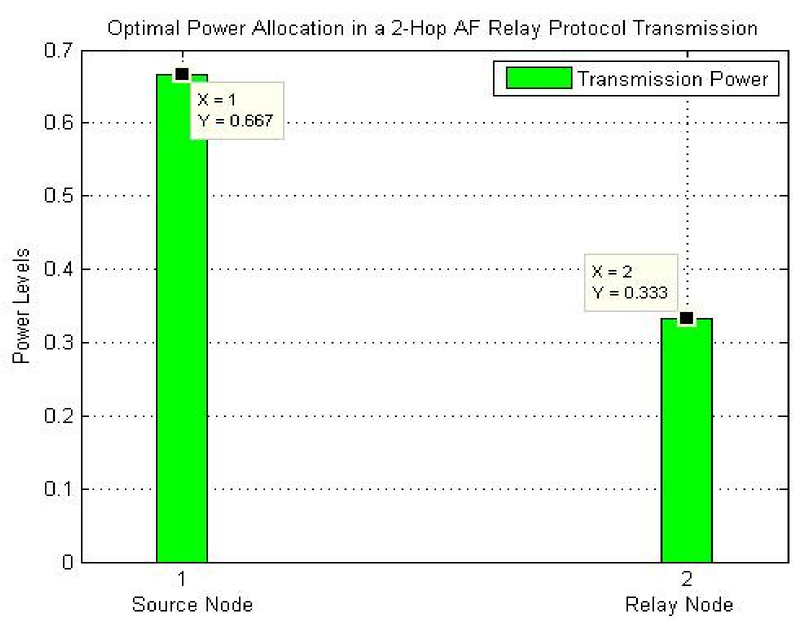

Figure 31 Optimal Power Allocation (relay in middle)

Case 2: $\sigma^2_{SD} = 1;\ \sigma^2_{SR} = 1;\ \sigma^2_{RD} = 10$

This is the scenario in which the relay node lies closer to the destination and far from source node. In this case the link between source-destination is weak and so is the link between source-relay. But the relay-destination link is strong compared to the other two. Therefore the variance of the three links has different values. The ABER performance of the system is given below in Figure 32.

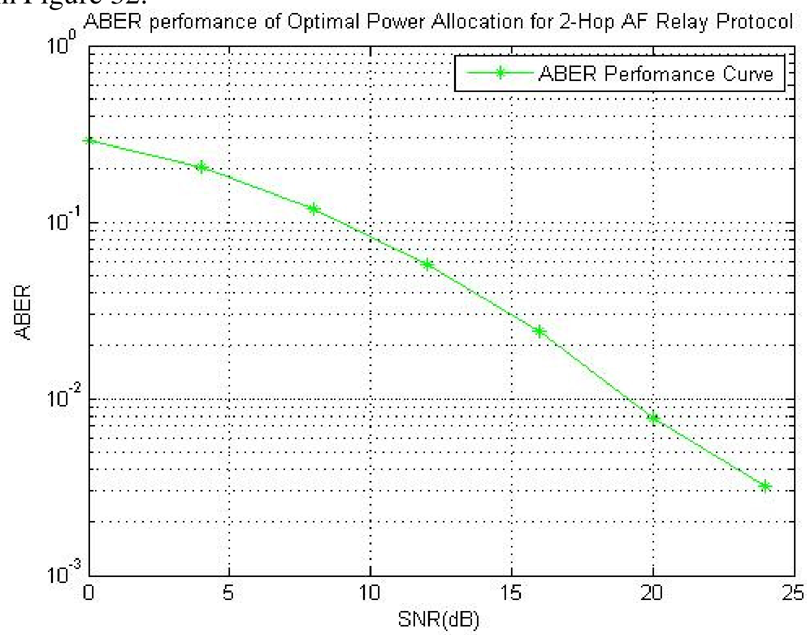

Figure 32 ABER performance 2-Hop AF Transmission (relay closer to destination)

For this scenario where the relay node lies closer to the destination node the optimal power allocation strategy assigns a power of 0.819 to the source node and a power of 0.181 to the relay node satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 33, shows the power distribution between the source and relay nodes.

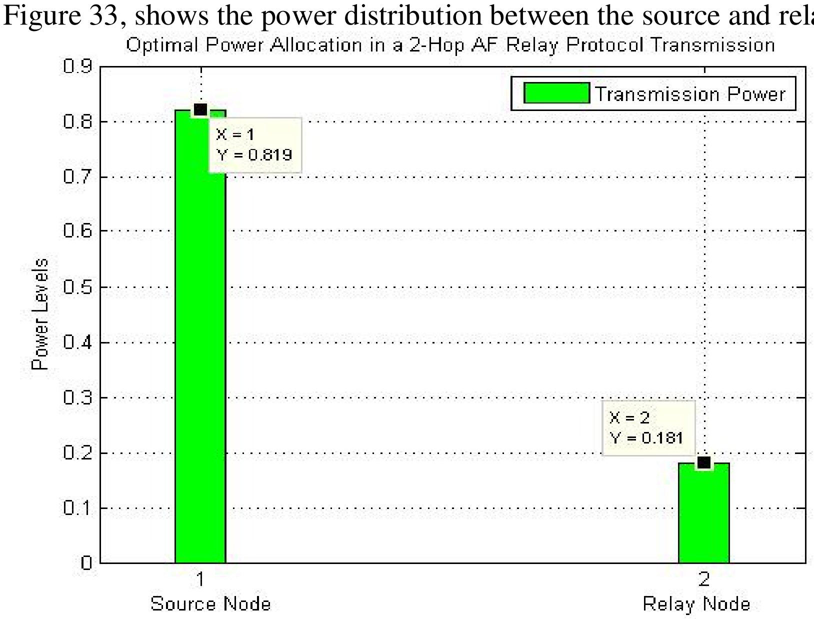

Figure 33 Optimal Power Allocation (relay closer to destination)

Case 3: $\sigma^2{}_{SD} = 10;\ \sigma^2{}_{SR} = 10;\ \sigma^2{}_{RD} = 1$

This is the scenario in which the relay node lies closer to the source and far from destination node. In this case the link between source-destination is strong and so is the link between source-relay. But the relay-destination link is weak compared to the other two. Therefore the variance of the three links has different values. The ABER performance of system is given in Figure 34.

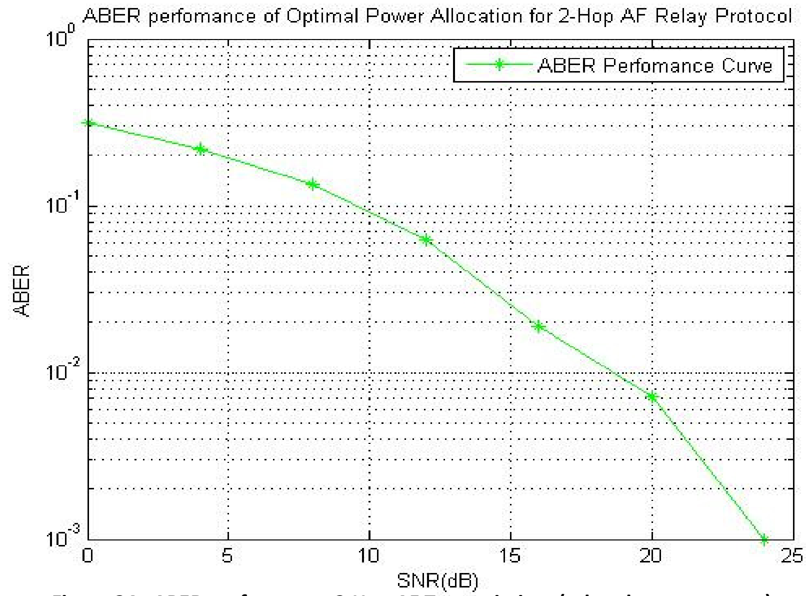

Figure 34 ABER performance 2-Hop AF Transmission (relay closer to source)

For this scenario where the relay node lies closer to the source node the optimal power allocation strategy assigns a power of 0.547 to the source node and a power of 0.453 to the relay node satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 35, shows the power distribution between the source and relay nodes.

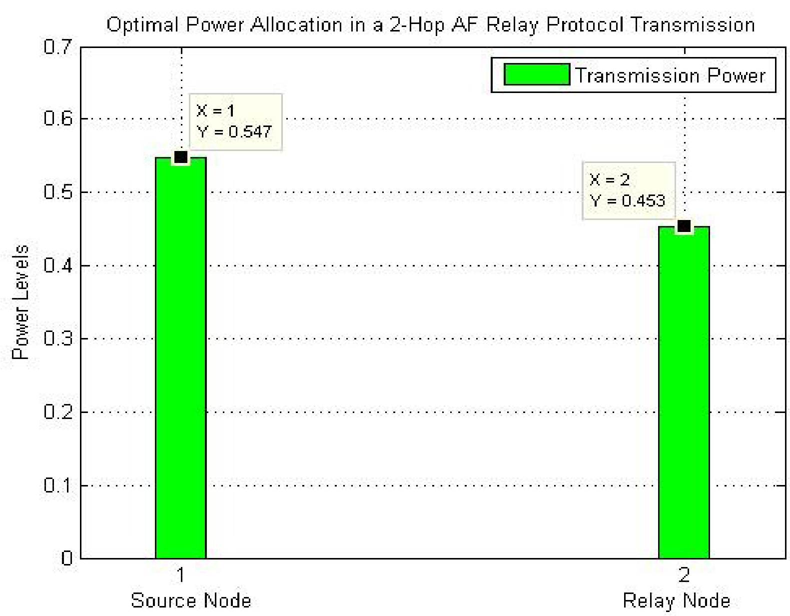

Figure 35 Optimal Power Allocation (relay closer to source)

In the end the results from all 3 cases discussed above are presented to analyze the overall performance of the proposed optimal power allocation framework, in Figure 36. As it is clearly visible that the ABER performance for each scenario is under an acceptable SNR range. The performance curves of all cases are almost similar in terms of ABER. This means that that overall optimal power allocation algortithm is mainting the ABER for every possible location of relay relative to source and destination node.

In the lower SNR range from 0-10(dBs), the perfomance is exactly the same for all three cases. For the SNR range from 10-20(dBs), the graphs for case 2: $({\sigma^2}_{SD} = 1;\ {\sigma^2}_{SR} = 1;\ {\sigma^2}_{RD} = 10)$ and case 3: $({\sigma^2}_{SD} = 10;\ {\sigma^2}_{SR} = 10;\ {\sigma^2}_{RD} = 1)$ converge while case 1: $({\sigma^2}_{SD} = 1;\ {\sigma^2}_{SR} = 1;\ {\sigma^2}_{RD} = 1)$ maintains its path. For the SNR range 20-30(dBs), the performance of case 2: $({\sigma^2}_{SD} = 1;\ {\sigma^2}_{SR} = 1;\ {\sigma^2}_{RD} = 10)$ is marginally better than the other two cases. The reason behind this improvement is that the optimal power allocation works better for situations where relay node is closer to the destination node. At higher SNR(s) the ABER performance is lower enough to offer a reliable communication between source and destination node irrespective of the relay location or relay-destination channel quality.

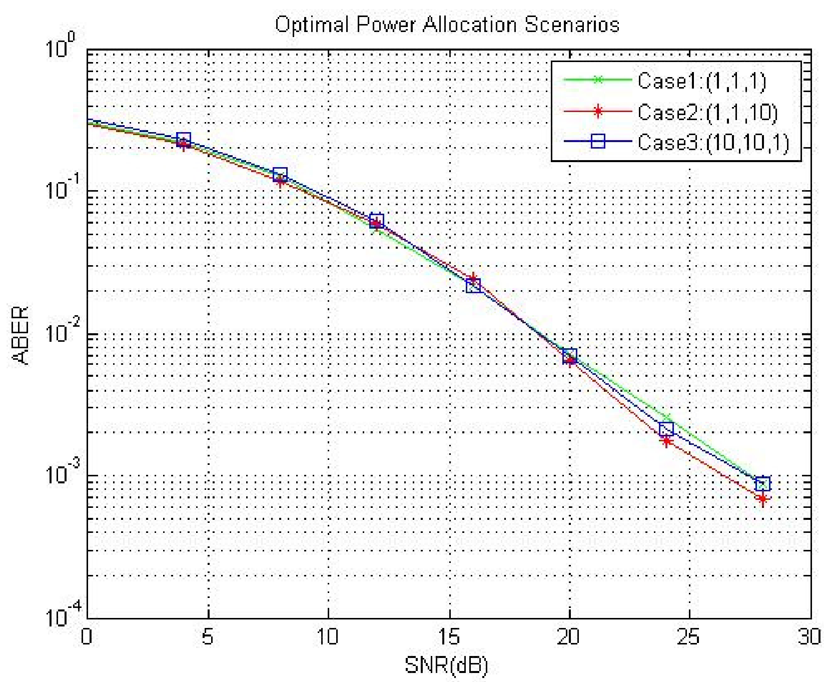

Figure 36 Optimal Power Allocation 3-Cases

The optimal power allocation algorithm allocates different values of transmission power for both source node (P_S) and relay node (P_R) depending on the channel qualities between any two communicating nodes. In Table 1, the values of transmission powers of the nodes are presented. The values are based on the formulae derived earlier in Chapter 4(*Section 4.5.2*):

$$P_S = \frac{\sigma^2{}_{SR} + \sqrt{\sigma^2{}_{SR} + 8\sigma^2{}_{RD}}}{3\sigma^2{}_{SR} + \sqrt{\sigma^2{}_{SR} + 8\sigma^2{}_{RD}}} P_T$$

$$P_R = \frac{2\sigma_{\ SR}}{3\sigma^2{}_{SR} + \sqrt{\sigma^2{}_{SR} + 8\sigma^2{}_{RD}}} P_T$$

Power/Variances	**Source Node(P_s)**	**Relay Node (P_R)**
($\sigma_{SD}, \sigma_{SR}, \sigma_{RD}$)=(1,1,1)	0.6667	0.3333
($\sigma_{SD}, \sigma_{SR}, \sigma_{RD}$)=(1,1,10)	0.8187	0.1813
($\sigma_{SD}, \sigma_{SR}, \sigma_{RD}$)=(10,10,1)	0.5472	0.4528

Table 1 Power Distribution for 2-Hop Cases

5.4 BER Performance of Power Allocation Algorithm for 3-Hop Scenario

The simulation is carried out using the same assumptions which were used to derive the mathematical expressions in the previous chapter (*Section 4.5.1*). In this section there will be numerous performance graphs showing the result of optimal power allocation strategy when employed in a cooperative transmission using Amplify-and-Forward (AF) relaying protocol. The transmission scenario (*3-Hop or Two Relays*) has been further categorized into 5 cases on the basis of channel quality between source-destination, source-relay1, relay1-relay2 and relay2-destination links.

Case 1: $\boldsymbol{\sigma^2{}_{SD} = 1;\ \sigma^2{}_{SR1} = 1;\ \sigma^2{}_{R1R2} = 1;\ \sigma^2{}_{R2D} = 10}$

This is the scenario in which the relay2 node lies closer to the destination and far from source node. In this case the link between source-destination is weak and so is the link between source-relay1. The link between relay1-relay2 is also weak. Therefore the link variance is equated to 1 for these three links. But the relay2-destination link is strong compared to the other three. Thus the variance of the four links has different values. The ABER performance of the system is given below in Figure 37.

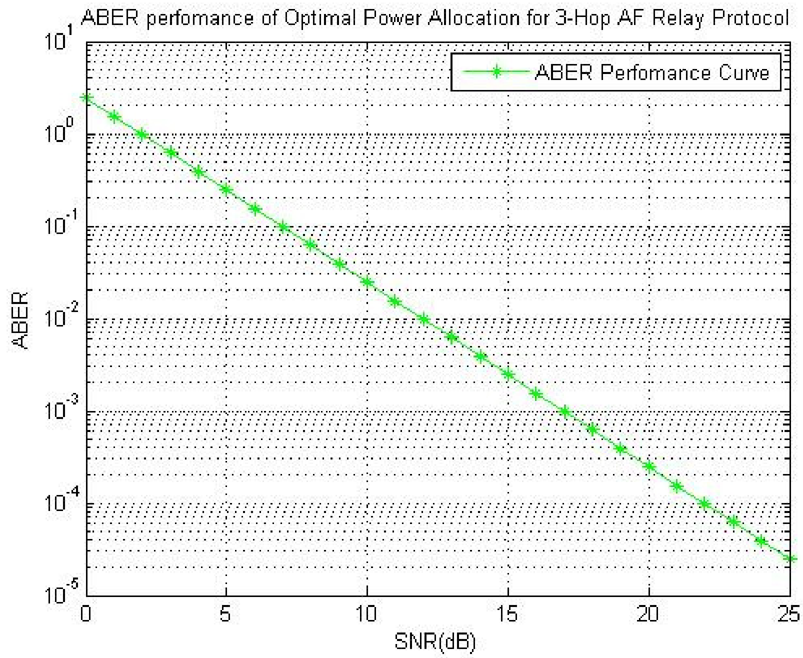

Figure 37 ABER performance 3-Hop AF Transmission (relay closer to destination)

For this scenario where the relay2 node lies closer to the destination node the optimal power allocation strategy assigns a power of 0.819 to the source node, a power of 0.278 to the relay1 and a power of 0.0986 to the relay2 node satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 38, shows the power distribution.

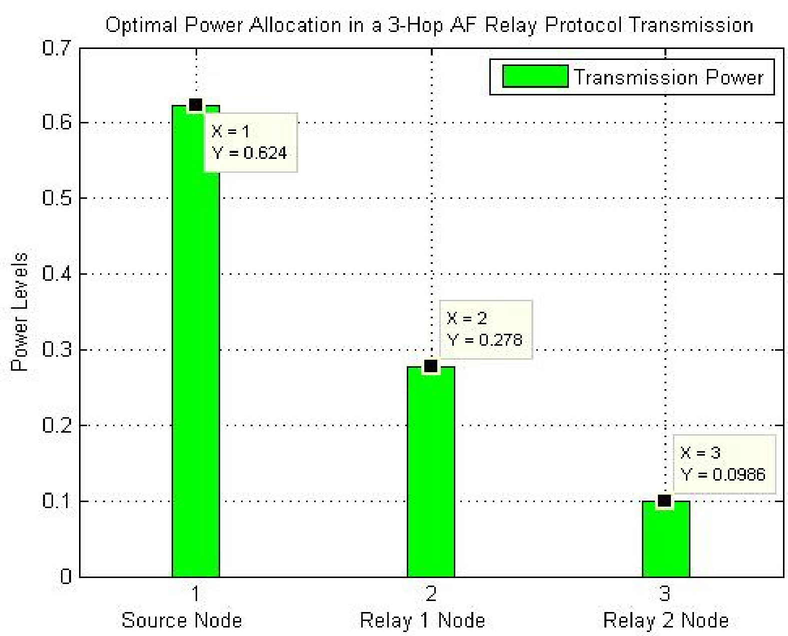

Figure 38 Optimal Power Allocation (relay closer to destination)

Case 2: $\sigma^2{}_{SD} = 10;\ \sigma^2{}_{SR1} = 10;\ \sigma^2{}_{R1R2} = 1;\ \sigma^2{}_{R2D} = 1$

This is the scenario in which one of the relay nodes (relay1) lies closer to the source and the other relay (relay2) is far from destination node. Moreover both relay1 and relay2 are at large distance from each other. In this case the link between source-destination is strong and so is the link between source-relay1 (both assigned value of 10). But the relay-destination link and the link between relay1-relay is is weak (both assigned value of 1) as compared to the other two links. Thus the variance of the four links has different values. The ABER performance of the system is given on the next page in Figure 39.

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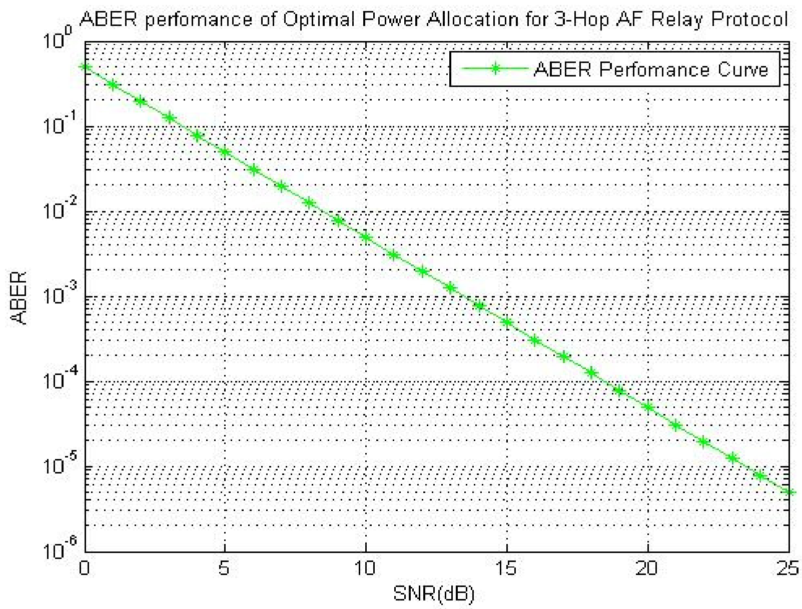

Figure 39 ABER performance 3-Hop AF Transmission (relay1 closer to source & relay2 far from destination)

This is the scenario in which one of the relay nodes (relay1) lies closer to the source and the other relay (relay2) is far from destination node, the optimal power allocation strategy assigns a power of 0.514 to the source node, a power of 0.243 to the relay1 and a power of 0.243 to the relay2 node satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 40, shows the power distribution.

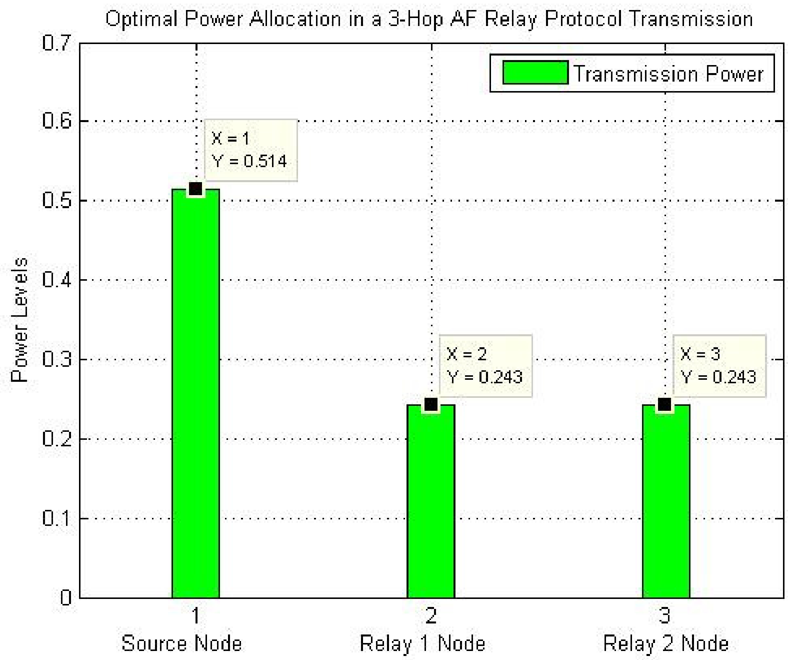

Figure 40 Optimal Power Allocation (relay1 closer to source & relay2 far from destination)

Case 3: $\boldsymbol{\sigma^2{}_{SD} = 1;\ \sigma^2{}_{SR1} = 10;\ \sigma^2{}_{R1R2} = 1;\ \sigma^2{}_{R2D} = 10}$

This is the scenario in which relay1 lies closer to the source and relay2 is closer to destination node. In this case the link between source-destination and relay1-relay2 is weak (both assigned value of 1). But the relay2-destination link and the link between source-relay1 is strong (both assigned value of 10) as compared to the other two links. The ABER performance of the system is given in Figure 41.

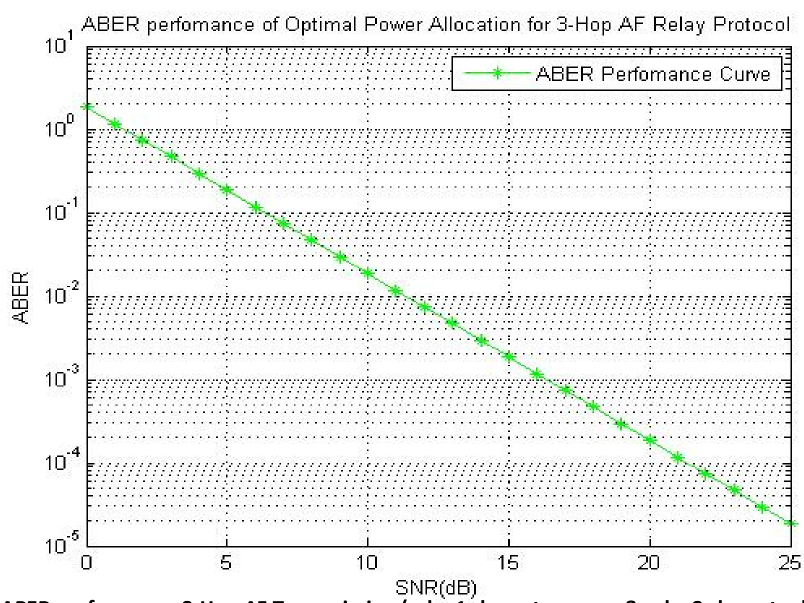

Figure 41 ABER performance 3-Hop AF Transmission (relay1 closer to source & relay2 closer to destination)

This is the scenario in which relay1 lies closer to the source and the relay2 is closer to destination node, the optimal power allocation strategy assigns a power of 0.529 to the source node, a power of 0.348 to the relay1 and a power of 0.123 to the relay2 node satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 42 shows power distributions.

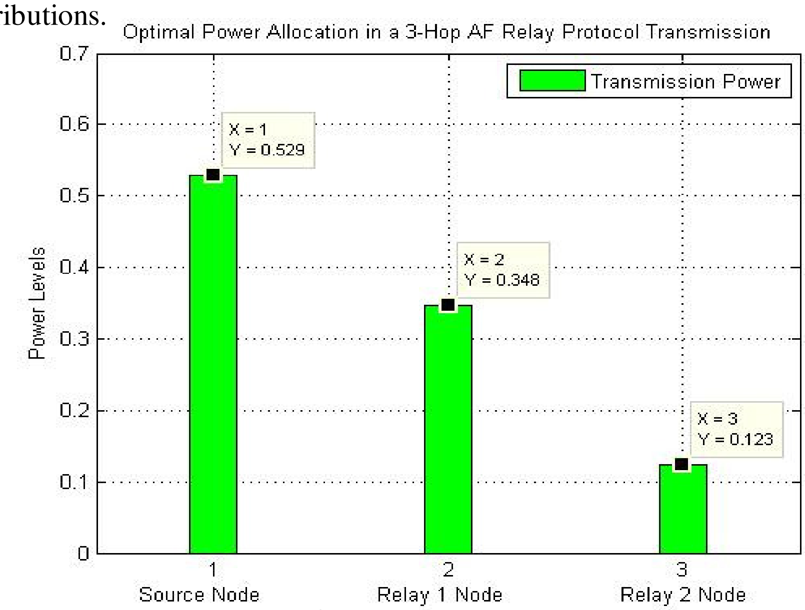

Figure 42 Optimal Power Allocation (relay1 closer to source & relay2 closer to destination)

Case 4: $\sigma^2{}_{SD} = 10;\ \sigma^2{}_{SR1} = 1;\ \sigma^2{}_{R1R2} = 10;\ \sigma^2{}_{R2D} = 10$

This is the scenario in which source-destination link is strong. The link between relay1-relay2 is also strong and so is the link between relay2-destination, as relay2 is closer to destination node. Therefore these three links are assigned a value of 10. But the source-relay1 link is weak (assigned value 1), since relay1 is far from source node. The ABER performance of the system is given in Figure 43.

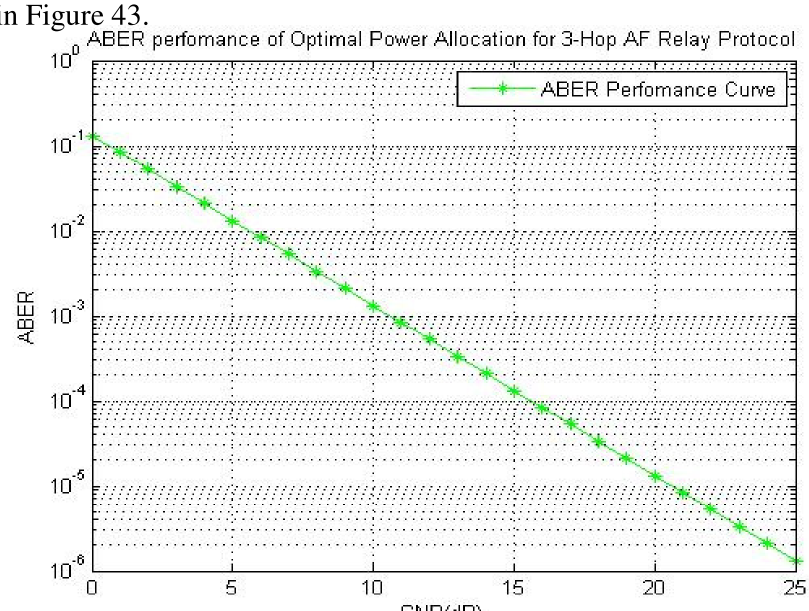

Figure 43 ABER performance 3-Hop AF Transmission (relay1 far from source & relay2 closer to destination)

In this case, the optimal power allocation strategy assigns a power of 0.719 to the source node, a power of 0.141 to the relay1 and a power of 0.141 to the relay2 node, satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 44 shows the power distributions.

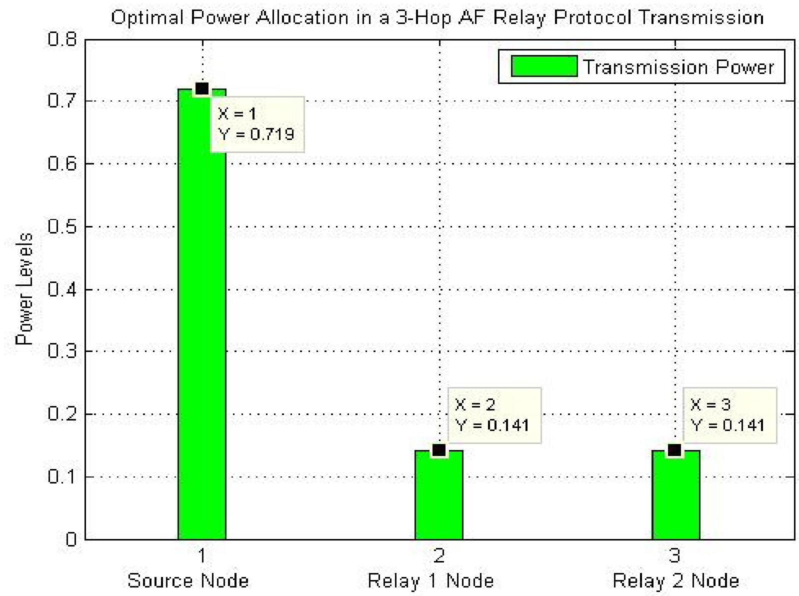

Figure 44 Optimal Power Allocation (relay1 far from source & relay2 closer to destination)

Case 5: $\sigma^2{}_{SD} = 1;\ \sigma^2{}_{SR1} = 10;\ \sigma^2{}_{R1R2} = 10;\ \sigma^2{}_{R2D} = 10$

This is the scenario in which the relay2 node lies closer to the destination and relay1 is closer to source. In this case the link between source-relay1 is strong and so is the link between relay1-relay2. The link between relay2-destination is also strong. Therefore the link variance is equated to 10 for these three links. But the source-destination link is weak compared to the other three. The ABER performance of the system is given below in Figure 45.

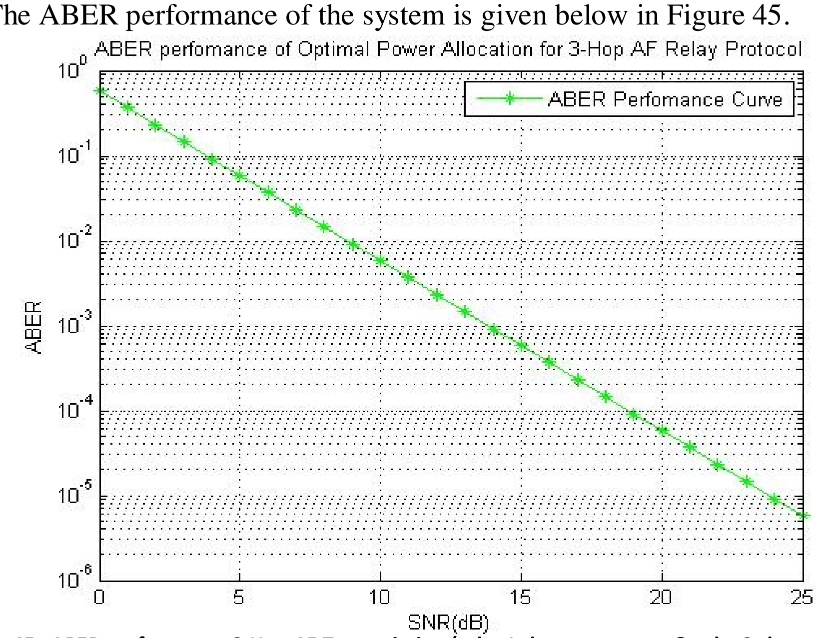

Figure 45 ABER performance 3-Hop AF Transmission (relay1 closer to source & relay2 closer to destination)

In this case, the optimal power allocation strategy assigns a power of 0.577 to the source node, a power of 0.211 to the relay1 and a power of 0.211 to the relay2 node, satisfying the total power constraint of 1, as defined in the derived mathematical expressions. Figure 46 shows the power distributions.

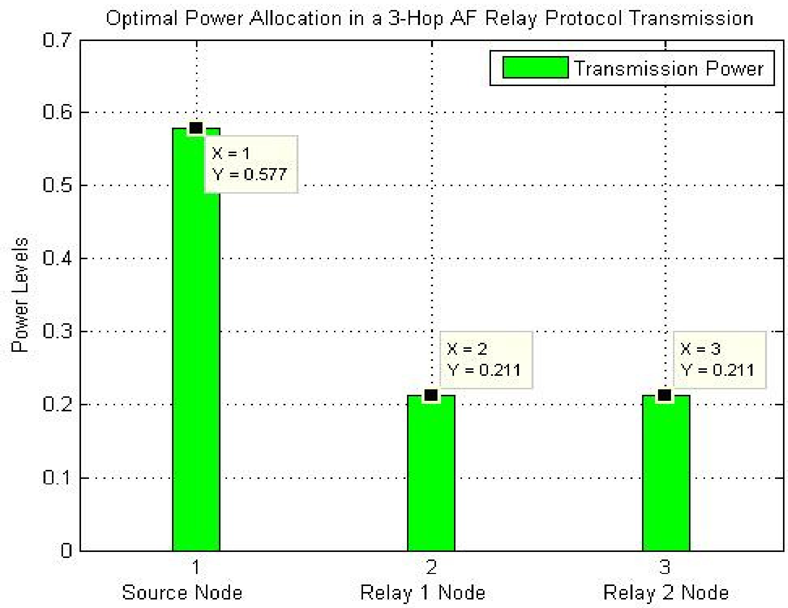

Figure 46 Optimal Power Allocation (relay1 closer to source & relay2 closer to destination)

In the end the results from all 5 cases discussed above are presented to analyze the overall performance of the proposed optimal power allocation framework, in Figure 47. As it is clearly visible that the ABER performance for each scenario is under an acceptable SNR range. The performance curves of all cases are going linearly with increase in higher SNR(s). This means that that overall optimal power allocation algortithm is mainting the ABER for every possible location of relay relative to source and destination node.

The ABER of the case 1: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) and case 5:($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 10$) is similar and is decreasing linearly for all the ranges of SNR(s). The reason behind this same performance is that fact that relay2 node is closer to the destination node. Therfore the quality of relay2-destination link is strong, resulting in a powerful signal at the destination node from relay2 node. Similarly, The ABER of the case 2: ($\sigma^2{}_{SD} = 1$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 10$; $\sigma^2{}_{R2D} = 10$) and case 4:($\sigma^2{}_{SD} = 10$; $\sigma^2{}_{SR1} = 10$; $\sigma^2{}_{R1R2} = 1$; $\sigma^2{}_{R2D} = 1$) is similar and is decreasing linearly for all the ranges of SNR(s). The reason is that for the case 2 the relay2-destination link is strong but the source-destination link is weak. On the other hand in case 4 the source-destination link is strong but the relay2-destination link is weak. Therefore the MRC gives equal results for both the cases at the destination node. But the best performance is of case 3: ($\sigma^2{}_{SD} = 10$; $\sigma^2{}_{SR1} = 1$; $\sigma^2{}_{R1R2} = 10$; $\sigma^2{}_{R2D} = 10$) which has the lowest ABER for any values of SNR when compared with the other cases. The reason is that the source-destination link is strong and so is the link between relay1-relay2 and relay2-destination. At the destination node the MRC will get strong signals from both relay2 and source node. Summing up these signal will surely reduce the ABER required at a given SNR.

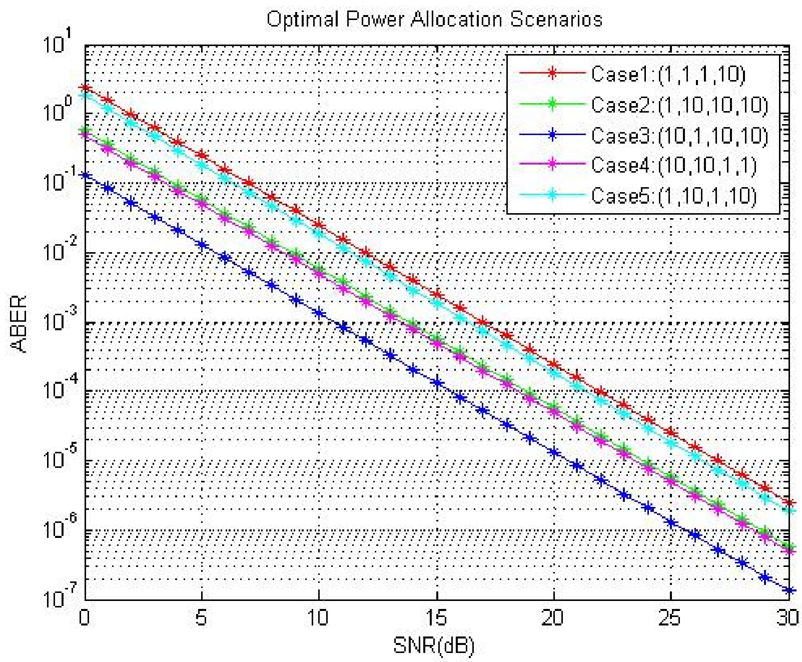

Figure 47 Optimal Power Allocation 5-Cases

The optimal power allocation algorithm allocates different values of transmission power for source node (P_S), relay1 node (P_1) and relay2 node (P_2), depending on the channel qualities between any two communicating nodes. In Table 2, the values of transmission powers of the nodes are presented. The values are based on the formulae derived earlier in Chapter 4(*Section 4.5.1*):

$$P_S = \begin{cases} \dfrac{A - 4B + \sqrt{A^2 + 8AB}}{4(A - B)} P_T \\ \dfrac{2}{3} P_T \end{cases}$$

Where, A=$(\sigma_{R2D} + \sigma_{R1R2})^2 . \sigma^2{}_{R1R2} . \sigma^2{}_{SR1}$ and B= $\sigma^2{}_{R2D} . \sigma^3{}_{R1R2}$

$$P_1 = \frac{\sigma_{2D}}{\sigma_{2D} + \sigma_{R1R2}}(P_T - P_S)$$

$$P_2 = P_T - P_1 - P_S$$

Power/Variances	**Source Node(P_s)**	**Relay Node (P_1)**	**Relay Node (P_2)**
($\sigma_{SD}, \sigma_{SR1}, \sigma_{R1R2}, \sigma_{R2D}$)=(1,1,1,10)	0.6237	0.2778	0.0986
($\sigma_{SD}, \sigma_{SR1}, \sigma_{R1R2}, \sigma_{R2D}$)=(1,10,10,10)	0.5774	0.2113	0.2113
($\sigma_{SD}, \sigma_{SR1}, \sigma_{R1R2}, \sigma_{R2D}$)=(10,1,10,10)	0.7187	0.1407	0.1407
($\sigma_{SD}, \sigma_{SR1}, \sigma_{R1R2}, \sigma_{R2D}$)=(10,10,1,1)	0.5144	0.2428	0.2428
($\sigma_{SD}, \sigma_{SR1}, \sigma_{R1R2}, \sigma_{R2D}$)=(1,10,1,10)	0.5288	0.3478	0.1234

Table 2 Power Distribution for 3-Hop Cases

6. Conclusions & Future Work

In the last chapter, there is a brief summary of the work presented in this thesis and then there is a discussion of some ideas that can be pursued in context of future work.

6.1 Conclusions

A Cooperative communication system enables the cooperating nodes in a sensor network to share their radio resources by employing a distributed transmission and processing operation. This technique is totally different from a traditional direct link communication system. The thesis starts with a qualitative analysis of the cooperative relaying schemes. With the help of some network configurations it was shown how these relaying strategies have radically modernized the wireless network design, making it more robust and flexible. Then it was discussed how these systems have evolved in the recent times and have made their way to future wireless standards like LTE-Advanced, IEEE 802.16j and IEEE 802.16m.

Later it was show that how this cooperative MIMO network enables the involved relays to jointly form a virtual antenna array and exploit traditional MIMO spatial diversity gains, resulting in enhanced system's performance. Afterwards, quantitative analysis was performed where various techniques like multi-hop, MIMO transmission and other techniques were discussed individually to build up a theoretical background of Cooperative networks. Then different phases of a Cooperative transmission were discussed in detail and then the role of power allocation was discussed. It was shown how power allocation is a significant design problem, for these energy-limited wireless sensor networks.

In the thesis a comprehensive analysis has been performed for cooperative relaying techniques. Both of the tested and well known techniques i.e., *Amplify-and-Forward* and *Decode-and-Forwar*d, were analyzed separately. The transmission and reception phases of both protocols were discussed with help of mathematical expressions. The received signal models were derived for both protocols giving a deep understanding as well as the comparison of these two relaying protocols. But the power allocation scheme was only discussed for the *Amplify-and-Forward* protocol, due to its less complex nature.

Closed form expressions using *Moment Generating Function* approach, of SNR of the received signal at the destination node were derived first for the three-node (*Two-Hop*) network and then for the four-node (*Three-Hop*) network. After that, ABER was calculated over Rayleigh fading channel. The optimal power allocation algorithm has been formulated with constraint of total transmission power so in order to solve this optimization problem Lagrange multipliers have been used. The analysis of the ABER performance of the optimal power allocation algorithm was based on QPSK modulation scheme.

The ABER performance analysis of the optimal power allocation using amplify-and-forward protocol spans from a basic three-node (*Two-Hop*) cooperative system to a more complex four-node (*Three-Hop*) cooperative system. The performance analysis was further extended by including the parameter of *Relay Location or Channel Variance.* Different scenarios were discussed based on the channel qualities between source-destination, source-relay, relay-relay and relay-destination links. The analysis shows that by using multiple relays lower average-bit-error rates can be achieved. When the relays are properly located and the corresponding channel qualities are good then lowest average-bit-error-rates can be achieved for any given value of SNR.

6.2 Future Work

A wireless sensor network comprises of several nodes acting as relays for facilitating communication between any two nodes at a given time. If the perfect knowledge of channel state information plus the residual energy information is known to the relay at each intermediate hop, the relays can intelligently decide whether it is feasible to forward the data it received from the previous node to the next node or not. This technique offers huge energy savings for these energy-limited networks like Ad-hoc Networks, Wireless Sensor Networks, and Cellular Networks etc. This technique is being referred as *Opportunistic Relaying* in the literature and a lot of work is being done in this direction. This technique is easily incorporated with the existing cooperative relaying techniques. One such example is (Mousavifar & Seyed 2013) in which opportunistic relaying is being used with amplify-and-forward protocol to analyze the lifetime of a relay network.

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