ABSTRACT

Wireless Communications is an ever evolving field and has been one of the rapidly growing technology sectors from a consumer, business, military and research perspective. With the explosive growth of wireless technologies, there is need to provide reliable, high bandwidth and high data rate services to meet the increasing consumer demand. Therefore, it is necessary to integrate enhanced technologies to the conventional wireless systems in order to improve these performance factors. Cooperative Communications is a promising technique addressing these performance issues beside it also provides extended coverage and mitigates multipath fading in a cost effective manner.

To date, Cooperative wireless systems exist in classical three node network to achieve diversity. The concept of multi-hop relayed Cooperative wireless system is proposed to further enhance the performance in terms of BER and extended coverage range of an overall system as compared to single hop cooperative wireless system. The advantages offered by multi-hop cooperative system are the outcome of the usage of multiple distributed antennas which leads to an overall better system performance by having independent uncorrelated channel paths and finally enables the system to make best use of the benefits of macro-diversity in annex to micro-diversity.

In this research, Turbo Codes with Maximum a-posteriori (MAP) decoding algorithm are integrated in multi-hop cooperative wireless system as Forward Error Correction (FEC) technique in order to combat the drastic effects of fading environment which improves the system performance in terms of BER. Use of such a powerful coding scheme leads to overall coding gain of the system. To make the system more robust, Hybrid Automatic Repeat re-Quest (HARQ) protocol is also incorporated in the system as retransmission scheme to rectify the errors that are detected at receiver end.

Finally integrate all three technologies, Multi-hop Cooperative system, Turbo Codes and HARQ together to enhance the system performance. The BER results of multi-hop cooperative system justify the usage of multiple relays in cooperative wireless systems in comparison to single-hop systems. In addition the proposed technique also provides cost effective solution to get diversity gains.

DEDICATION

All praise and thanks to almighty Allah, the most gracious and the most merciful, Master of the Day of Judgment. Guide us with courage and right path, path of those to whom, You have bestowed your blessings.

Dedicated to my parents
for their support and prayers;
to my siblings who have always been a source of motivation for me.

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All praise for Allah Almighty who brings me from the position when I knew nothing, who directed me to the right way during the dark phases of this life and for He, who brings me where I am today. I express my gratitude towards Him with humility and humbleness.

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LIST OF ACRONYMS

Acronym	Meaning
3G	Third-Generation
3GPP	Third Generation Partnership Project
4G	Fourth-Generation
AAF	Amplify And Forward
ACK	Positive Acknowledgement
ARP	Adaptive Relaying Protocol
ARQ	Automatic Repeat reQuest
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Bipolar Shift Keying
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CSI	Channel State Information
DAF	Decode And Forward
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FSK	Frequency Shift Keying
GBN	Go-Back-N
GSM	Global System for Mobile Communications
HARQ	Hybrid ARQ

Acronym	Meaning
IR	Incremental Redundancy
ISI	Inter-Symbol Interference
LLR	Log-Likelihood Ratio
LOS	Line of Sight
LTE	Long Term Evolution
MAP	Maximum a-Posteriori Probability
MIMO	Multiple Input Multiple Output
NACK	Negative Acknowledgement
PDF	Probability Density Function
QPSK	Quadrature Shift Keying
QoS	Quality of Service
RSC	Recursive Systematic Convolutional
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SOVA	Soft Output Viterbi Algorithm
SR	Selective Repeat
SRM	Switchable Relaying Mechanism
SW	Stop and Wait
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
VAA	Virtual Antenna Array
WiMax	Worldwide Interoperability of Microwave Access

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Chapter 1

INTRODUCTION

1.1 Background and Motivation

Wireless communications have seen remarkable technological growth during the past few years. With the advent of each new wireless technology, there comes significant improvement in terms of communication reliability, bandwidth usage, power consumption, data rates, network coverage range, hardware sizes, network connectivity and applications. The main objective behind all these developments is to facilitate the user to utilize the communication services for different applications within limited resources.

The concept of partial centralized controlling base station is gaining interest as it requires limited resources for deployment in order to provide highly reliable communication link to the users. Ad-hoc and wireless sensor networks are the perfect implementations where nodes assist other nodes in forwarding their signal to the terminus [1], [2]. Due to the broadcast nature of wireless channels, the signal of other nodes which are usually considered as interference, are taken into account and processed in an efficient manner, ended up in the performance gain of an overall system.

Realizing the importance of distributed communications via multiple antenna devices, precede the development of MIMO (Multi-Input Multiple-Output) technology. MIMO has been considered the promising technique that provides both spatial diversity as well as temporal diversity to effectively combat the channel fading elements for point-to-point communication links [3-5]. Multiple antennas at both transmitter and receiver terminals are deployed to achieve higher diversity degrees as this formation shapes itself into virtual antenna arrays (VAAs) with aim of providing uncorrelated independent channel paths. MIMO technology, no doubt brought improvement in the quality and capacity of the communication systems with the help of VAAs and also by enhanced signal processing techniques to combine the signals coming from multiple independent paths. However, due to the small size of wireless terminals, it is not cost effective way to incorporate multiple antennas on hardware. As it seems non feasible to implement MIMO technology on small wireless handsets, spatial-temporal diversities could be achieved by Cooperative Diversity technique [6-8].

Cooperative Wireless system utilizes the services of distributed antennas of other mobile devices creating VAAs to achieve all goals that are accomplished by conventional MIMO systems. For this reason, Cooperative wireless systems are also known as Cooperative MIMO, virtual MIMO or distributed MIMO [9]. Without the need of any additional hardware and power consumption at terminals, Cooperative wireless technology brings significant improvement in the performance of wireless communication systems. This concept is further enhanced to multi-hop Cooperative wireless systems to exploit the services of antennas of other multiple relays to achieve not only higher diversity level but also enhanced performance as compared to single-hop Cooperative systems. With the collaboration of other multiple relays, highly reliable communication is ensured in fading environment which ultimately improves the QoS constrained and other delay bounded data applications which make it perfect candidate technology for 4G wireless communications. To mention some, cooperative MIMO with fixed relays has already been incorporated in WiMAX standard of IEEE

802.16j. Meanwhile, testing of Cooperative technologies for their consolidation in 4G wireless technology, Long Term Evolution-Advanced (LTE-Advanced) is currently underway as Third Generation Partnership Project (3GPP) next venture.

Recently, there has been research limited to classical three node relay Cooperative systems in order to achieve diversity [10, 11]. Many transmission designs are also proposed for its practical implementation in the cellular networks. Moreover, parallel configured relays are being extensively used in past research to analyze the performance results. Besides that, no significant work has been done, where multiple relays are considered in a Cooperative paradigm to examine the results. In system model to be developed, multiple relays are serially placed where each relay receives the transmitted signal from the source and the previous relay. With the induction of number of relays in the multi-hop cooperative system, the complexity of the system however increased as well as the signaling overhead needed to cooperate for other nodes but on the other side, the advantages in terms of reliability, capacity, throughput, coverage range and group mobility clearly outweighs the disadvantages. The system model used in this project not only helps to improve the spatial diversity gain but also extends the coverage range of an overall system with minimum complexity and timing delays.

The error correcting capability of Turbo codes [12] gained attention among the research community and paved way to new horizons offering great deal of research in this specific area. Through iterative decoding procedure, Turbo codes have the capability to correct erroneous bits fulfilling its purpose to the possible error free communication between two wireless links. However, in case of worse channel conditions, the performance of turbo codes is also deteriorated, making its impact directly on the performance curve [13, 14]. To overcome this drawback, HARQ scheme is introduced in the system which is the combination of both FEC and ARQ schemes [15, 16]. When detected errors cannot be correct by FEC scheme, then HARQ protocol allows the receiver to make retransmission request. In cooperative systems, there is an ease to make retransmission request from some intermediate relay exist nearby the receiver, which responds the request in an efficient manner with minimum timing delays.

The induction of HARQ scheme in multi-hop cooperative system helps to improve the overall system performance by taking full advantage of the error rectification capability of turbo codes along with the retransmission nature of ARQ scheme and exploiting the diversity effect produced by the combination of multiple signals coming from different channel paths. All these technologies when integrated together provide cost effective solution with minimum complexity to meet the demand for highly reliable and high speed communication services for different application purposes.

1.2 Research Problem

Cooperative systems with classical three node relay structure with Turbo-coded HARQ mechanism provides reliable and cost effective wireless communication link between the users [35]. This approach proved to be a perfect contender versus all SISO and MIMO wireless technologies but that system was benefited by only the single intermediate relay even if some other intermediate relays are free and ready to cooperate at any time, thus squandering this opportunity to get high diversity. In this era of wireless technologies, there are numbers of wireless devices within certain vicinity that can effectively cooperate with each other towards the development of more robust system. So there is a need to make best use of all available resources and bring them into business in an efficient manner to achieve lower BER.

With the same classical three node cooperative network, it is very difficult to extend the coverage range of the system without degradation of system performance. Role of possible intermediate relays is again crucial as they can contribute to the extension of system without employment of additional hardware, just to achieve this goal. So both objectives can be achieved with the consideration of intermediate relays that already exist in the wireless environment.

Along with this, some powerful FEC scheme is needed to be in the system, capable of correcting errors when faded signal is received at the destination. In this context, Turbo codes are optimum choice because they are less prone to noise and fading channels. These codes can contribute a lot to keep BER fairly low in AWGN and quasi-static fading channels as they are more energy efficient [17]. However, in case of worse channel conditions, there is need for some retransmission request mechanism to provide error free communication. This need is fulfilled with the induction of ARQ scheme in the system.

1.3 Research Goals

Currently extensive research is in progress to evaluate the performance of Cooperative MIMO for its induction in 4G communication standard for cellular systems, Long Term Evolution-Advanced (LTE-Advanced). This research addresses the issues that were raised in previous section through proposal of employing multiple relay nodes in a certain environment for the purpose of cooperation. With the cooperation of such nodes, not only the BER performance is improved but also the coverage range of the system. Moreover, various other objectives could be achieved with this implementation but those issues are kept out of scope of our research.

Therefore, the main goal of this research is to incorporate multiple intermediate relays into the cooperative communication system potentially exploits the diversity effect in an efficient manner with minimum cost and power usage. With the essence of multi-hop cooperative system, HARQ scheme is implemented to keep BER curve as low as 10^{-5} at affordable range of SNR.

1.4 Thesis Outline

This thesis document is organized into seven chapters. Chapter 1 presents the nature of research work carried out under this project with full motivation and background. This chapter also addresses the problem statement and also presents its literature review. Research goals are also highlighted in this chapter. Chapter 2 explains fundamental concepts of digital communications and provides in-depth detail to readers about fading channels and their statistical models. Brief discussion on channel estimation and some detection techniques are also presented. With brief introduction of diversity in communications, the commonly used diversity techniques are also discussed. Chapter 3 gives theoretical introduction to cooperative communications, discuss its relaying algorithms and signal combining techniques. It also introduces the enhanced concept of multi-hop cooperative systems which is the core of our project. Chapter 4 explains FEC and ARQ schemes. Turbo coding and its different decoding procedures are presented. Retransmission mechanisms of ARQ are highlighted and finally discussion takes on HARQ strategy when both FEC and ARQ are merged. Chapter 5 builds up our system model for single-hop cooperative system. Flow procedure for HARQ scheme is presented and simulation parameters are defined. Performance graphs in terms of BER are carried out when Turbo-coded HARQ schemes are employed in the cooperative system and also compared with traditional cooperative schemes. Chapter 6 uses the model developed in fifth chapter to implement multi-hop cooperative system utilizing two relays. Implementation details and the performance results of our proposed scheme are carried out and compared with that of single-hop systems to validate our research work. Chapter 7 concludes the research work and also highlights some areas on which work can be done as future enhancement to this project.

Chapter 2

DIGITAL COMMUNICATION SYSTEMS, FADING CHANNELS AND DIVERSITY

2.1 Introduction

This chapter provides brief introduction to the fundamental concepts of digital communication systems, wireless fading channels and diversity techniques. The core stages involved in typical digital communication systems are discussed in detail. Then discussion takes on different types of wireless fading channels and their statistical models. Finally, the concept of diversity regarding to communications is presented and also some diversity techniques are discussed.

2.2 Digital Communication Systems

The evolution of digital communication systems has already attracted many communities living all around the world and still in process of achieving milestones, offering multiple advantages in contrast to analog communications. The basic digital communication system [18] is illustrated in Figure 2.1. Information source may be either an analog signal or a digital signal. The source encoder converts the input analog or digital signal into binary bits, c, after removing unnecessary redundant information from the source signal. The output of source encoder is supplied to channel encoder, which applies some forward error correction scheme on the binary signal. By introducing some parity bits into the binary sequence, the detrimental effects of noise and fading elements on the signal can be reduced when signal passes through the channel. Digital modulator takes input *v* from previous block and converts it into electrical waveform by translating its frequency to higher level making the signal capable enough to travel through the transmission medium. This translation of lower frequencies to higher frequencies is referred to as conversion of baseband signal into pass-band signal. Modulation can be performed by varying amplitude, frequency or phase of the carrier signal. Most commonly used digital modulation schemes are FSK (Frequency Shift Keying), BPSK (Bipolar Phase Shift Keying) and QPSK (Quadrature Phase Shift Keying). The modulated signal, *x(t)*, is then passed to channel for transmission.

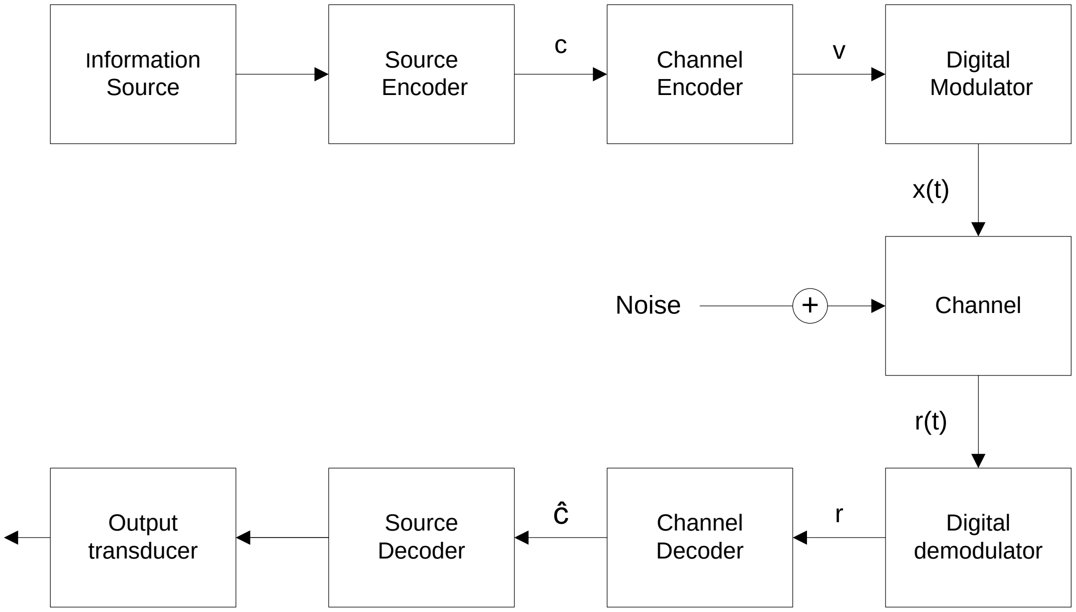

Figure 2.1: Block Diagram of Typical Digital Communication System

The role of channel is the successful transmission of source signal to its destination. Channel is categorized into wireless channel (atmosphere) and wired channel such as transmission wires or optical fiber cables. Signal is mainly corrupted by versatile channel conditions that act on the signal in form of noise and interference in wired physical medium and these elements are more prominent with multipath fading elements in wireless medium [6,7]. The most commonly used noise model in communication systems is AWGN [18].

When the signal, *r(t),* is received at the destination, the digital demodulator separates the high frequency carrier from the signal to convert it back to baseband signal, *r*, containing estimated data symbols. The channel decoder makes its attempt to recover the information sequence that was actually transmitted. Type of channel decoder is mainly identified by its counterpart used at the transmitter side to encode the information bits. Due to its error correcting capability, the errors in the information sequence can be corrected to certain level. The output of the channel decoder, ĉ, is passed to source decoder which reconstructs the actual signal. Our main focus will be on the wireless communication system which is mainly characterized by its wireless channel impairments such as fading; it will be discussed in detail in the next section.

2.3 Fading Channels

Fading occurs when multiple versions of the transmitted signal, experiencing variation in their amplitudes, attenuation delay and phases while coming from different paths are added up to give resultant signal at the receiver end. These multiple versions of the same signal are results of reflection, diffraction and scattering elements appear in the path of the signal. Multiple copies of the signal add up destructively, thus results in interference and it also attenuates the power of signal at the receiver; this phenomenon is referred to as multipath fading [18]. The speed of the mobile and signal transmission bandwidth have significant importance in fading. Some of the parameters having crucial role in the multipath fading are i.e. Doppler shift, Doppler spread, coherence bandwidth, and coherence time. Doppler Shift is the change in the frequency of transmitted signal due to the motion of mobile object. While, coherence bandwidth is the measure of frequency range over which the channel response remains invariant. Due to the effect of Doppler shift caused by the relative motion of mobile, the range of frequencies over which the received signal spectrum is non-zero and it is termed as Doppler spread. Coherence Time is the measure of time varying nature of divergence of channel frequencies in the time domain. It is the reciprocal of Doppler spread.

2.3.1 Types of Small-Scale Fading

Doppler spread and delay spread are two parameters that classify the type of small scale fading. Slow and fast fading comes under the domain of Doppler spread whereas the flat fading and frequency selective fading are put under the class of time delay spread. All types of fading are examined in detail below.

2.3.1.1 Slow and Fast Fading

Slow and fast fading addresses the affiliation between the channel's rate of change of time and the transmitted signal. The channel is considered as "fast fading" if the duration of symbol is greater than channel coherence time [19]. Coherence time is the time in which the impulse response of the channel remains same. In fast fading channels, the rate of change of channel is directly proportional to the motion of mobile. Considering T_0 as channel coherence time and T_s as duration of symbol, it can be written that $T_0 < T_s$. This type of fading is also termed as time-selective fading. Due to the variant character of fading channel, it is expected that it changes rapidly during the symbol duration, making its impact in baseband pulse shape distortion.

On the other side of the coin, the channel is considered as "slow fading" if the duration of symbol is lesser than the channel coherence time, $T_0 > T_s$. The channel response remains static during baseband signal transmission. Therefore, due to invariant nature of fading channel, it is expected that channel state remains unchanged during the symbol transmission time [19]. Such fading is also known as quasi-static fading channel [20] in which there is an independent change of fading coefficients from frame to frame.

2.3.1.2 Flat and Frequency-Selective Fading

In flat fading channels, the transmitted signal bandwidth is usually lesser than the bandwidth of channel. Flat fading channels are the major cause of deep fades that deteriorate the signal strength due to constant variations in the channel gain originated by multipath, which makes the recovery of the signal difficult [21]. In such conditions, additional transmitter power is required to keep the signal unharmed from such deep fades.

In contrast to flat fading channels, bandwidth of transmitted signal is greater than that of channel and channel's delay spread is at-least ten times greater than period of symbol transmission. Such channel is considered as frequency-selective fading channel [21]. Inter Symbol Interference (ISI) is the result of Frequency-Selective fading. Since each multipath component of signal needs to be modeled independently, the modeling of these fading channels is bit tougher than that of flat fading channels.

2.3.2 Statistical Models for Fading Channels

Different wireless fading channel models exist to describe the statistical nature of multipath fading. In this section, the most common models of Rayleigh, Rician and Nakagami fading will be presented.

2.3.2.1 Rayleigh Fading Channel

Rayleigh distribution is commonly applied to model those surroundings where there is no possibility of LOS path between the transmitter and receiver [22]. The phases of reflected components are random as they traverse different paths of different length; this is why a random variable is used to represent the instantaneous received power. The real and imaginary components of the channel response are added up to give an independent and zero-mean identically distributed Gaussian random process which follows the Rayleigh envelope. The probability density function (PDF) of Rayleigh distribution [23] is given by

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \qquad r \geq 0, \tag{2.1}$$

Where r represents random variable of Rayleigh distribution and σ^2 represents the variance of both zero mean iid Gaussian random variables.

2.3.2.2 Rician Fading Channel

If the resultant received signal consists of non-fading signal component following the line of sight propagation path and other reflected versions of the transmitted signal then fading distribution is said to be Rician [24]. These reflected waves are random independent multipath versions, superimposed on the direct LOS path component induce fading in resultant signal. The only difference between Rayleigh and Rician fading channels is the addition of direct line of sight path component in Rician distribution. If that component is discarded then Rician distribution becomes Rayleigh distribution. The PDF of Rician distribution [25] is given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{(r^2+A^2)}{2\sigma^2}} I_0\left(\frac{rA}{\sigma^2}\right) & r \geq 0, A \geq 0 \\ 0 & r < 0 \end{cases} \tag{2.2}$$

Where r is the random variable of Rician distribution and σ^2 represents the variance of two zero-mean identically distributed Gaussian random variables. A is the peak amplitude of LOS path component and $I_0(\cdot)$ is the first kind and zero order modified Bessel function [26]. K parameter also called Rician factor used to specify Rician distribution which is the ratio of power of LOS path component to the power of reflected multipath waves. It is given by

$$K = \frac{A^2}{2\sigma^2} \tag{2.3}$$

As A, amplitude of the dominant LOS path component approaches to zero; the Rician pdf shapes itself to Rayleigh pdf.

2.3.2.3 Nakagami Fading Channel

Fading channels that change rapidly over long distances are characterized as Nakagami fading channels. Both Rayleigh and Rician distributions can be elaborated through Nakagami distribution [27]. The fading channel characterization of Nakagami distribution produces results that are very much closer to Rayleigh and Rician distributions.

2.4 Channel Estimation

As the signal passes through wireless medium, it is contaminated due to the presence of various channel impairments and noise in an environment as discussed in previous section. On the reception of signal, the receiver makes an attempt to reverse the channel effects that has deteriorated the signal. Reconstruction of original signal is only possible when the receiver has correct estimates about the fading channel. Using these estimated channel coefficients, it processes to recover the original signal and finally delivers it to intended destination [28]. The characterization of the influence of physical channel on the transmitted signal is referred to as Channel Estimation process. And the process of recovery of original signal through the use of these channel coefficients is called Equalization. Numbers of channel estimation techniques are adopted in order to purify the received signal. The option of using specific technique is dependent on the channel conditions, bandwidth, intensity of fading and computational complexity etc.

In this thesis, a quasi-static Rayleigh fading channel is considered, which behaves constantly over a single data frame. So for each frame, channel realization is represented by value of single channel coefficient. Least-square criterion is used as channel estimation technique in which there is need to minimize the squared error between the estimated and detected signal using estimated channel coefficient $\hat{a}$. The procedure is given by

$$J = (y - \hat{a}\mathrm{x})(y - \hat{a}\mathrm{x})^* \tag{2.4}$$

To minimize this criterion, differentiating both sides with respect to $\hat{a}$ and setting left term to 0 to get the final term

$$\frac{dJ}{d\hat{a}} = -x(y - \hat{a}x)^* = -x(y^* - \hat{a}^* x^*) = 0 \tag{2.5}$$

$$\hat{a} = \frac{x^* y}{|x|^2} \tag{2.6}$$

So without the need of any knowledge about the channel, it is possible to apply channel estimation procedure of Least-square criterion the minimum computational complexity.

At the receiver end, there may be detectors used to detect the signal which include channel inversion, Minimum Mean Square Error (MMSE) and Maximum Likelihood (ML) methods.

2.4.1 Channel Inversion

The channel inversion technique is the simplest of all three to remove channel effect on the signal. This scheme is also called Zero-forcing technique in which received signal is simply divided by the estimated channel coefficient $\hat{a}$ given as

$$\hat{x} = \frac{1}{\hat{a}} y \tag{2.7}$$

$$= \frac{1}{\hat{a}}(ax + n) \qquad \text{as y= ax + n} \tag{2.8}$$

$$= \frac{a}{\hat{a}}x + \frac{n}{\hat{a}} \tag{2.9}$$

where x and y represents the transmitted signal and received signals respectively, n is zero-mean additive white Gaussian noise of the channel. This scheme has major drawback of amplifying noise at frequencies where channel response is almost zero as indicated by Eq. 2.9.

2.4.2 MMSE

MMSE is more balanced detection technique as compared to channel inversion method. It minimizes the mean square error between the expected and received signal to compute the estimator quality. Despite of producing good results, the computational complexity of the system is certainly increased. So there is a trade-off between the performance result and computational complexity. Mathematically, it is expressed as

$$\frac{dJ}{dG} = \frac{dE[(\hat{x}-x)(\hat{x}-x)^*]}{dG} \tag{2.10}$$

$$= \frac{dE[(G(ax+n)-x)(G(ax+n)-x)^*]}{dG} = 0 \tag{2.11}$$

Finally, it leads to

$$G = \frac{\hat{a}E[|x|^2]}{|a|^2E[|x|^2]+N_0} \tag{2.12}$$

$$= \frac{\hat{a}P}{|a|^2P+N_0} \tag{2.13}$$

where P represents the average symbol energy and N_0 is variance of noise.

2.5 Diversity

The performance of wireless communication system is severely degraded due to the drastic effects of multipath fading in wireless channels. However, different diversity techniques are applied to improve the quality of communication with marginal additional costs. The concept of diversity exploits the nature of independent signal paths which different copies of the signal experience during transmission. If one signal component faces deep fades, then there is less probability of facing the same situation by other signal component, usually a stronger one [4]. Taking advantage of that stronger signal component, a receiver can minimize the effects of small scale fading through signal combining techniques.

2.5.1 Diversity Techniques

Some diversity techniques are classified as spatial diversity, time diversity, frequency diversity and polarization diversity. These techniques are discussed below:-

2.5.1.1 Spatial Diversity

Employment of multiple antennas at both transmitter and receiver side, separated by little distance can contribute to improve the performance in multipath fading channel. This configuration however needs installation of multiple antennas that obviously increases the cost of the system. Moreover, some optimal signal combining methods are also required to combine and process the signals from each receiver antenna. But the degree of improvement using multiple antennas clearly outweighs these additional overheads. Spatial diversity is also referred as antenna diversity and it is classified into transmit diversity and receive diversity.

The diversity achieved by the employment of multiple antennas at transmitter side is called transmit diversity while the diversity achieved by the employment of multiple antennas at receiver side is called receive diversity.

2.5.1.2 Time Diversity

If signal is transmitted repeatedly with short span of time during which the response of the channel remains constant, the received signal is believed to have an independent fades. Using the concept of coherence time [21], different measures of channel varying response are taken into consideration depending on how much correlation between transmitted signals is needed. Thus time diversity can be realized by transmitting signal repeatedly separated by the time duration which is greater than the coherence time. Time diversity in combination with space diversity is widely used in GSM cellular systems where multiple antennas are installed at base station to receive signals with interleaving and error control coding scheme to make improvements possible.

2.5.1.3 Frequency Diversity

If signal is transmitted on different carriers separated by some frequency, the received signal undergoes independent fading. The concept of coherence bandwidth is used which is defined as the range of frequencies over which strong amplitude correlation is observed between two frequency components [21]. Thus frequency diversity can be achieved by transmitting signal over carriers whose frequencies are separated by a space that is greater than the coherence bandwidth.

2.5.1.4 Polarization Diversity

Diversity can also be achieved by using orthogonally polarized signals with independent fading nature. This technique is considered as polarization diversity. This technique is very useful where number of antennas can be placed together due to space limitations in urban areas. The number of reflections in a certain area badly affects the polarization diversity. Environments with LOS path use polarization diversity to make improvements in the system performance.

2.6 Summary

This chapter concludes with the aim of providing basic understanding of concepts related to digital communication systems, types and statistical models for fading channels and finally the diversity techniques. The importance of all these terms cannot be neglected regarding to any wireless communication technology. Using this chapter as the foundation for subsequent chapters, Cooperative diversity will be the theme of next chapter which is the core of this thesis.

Chapter 3

INTRODUCTION TO COOPERATIVE DIVERSITY

3.1 Introduction

The performance of any wireless communication system is challenged by the presence of attenuation and multipath fading in the environment which makes it difficult to provide highly reliable services to its consumers. To effectively mitigate these wireless channel impairments, there is need to devise some sort of diversity technique through which multiple independent clones of the same signal are transmitted over the channel and also to combine those uncorrelated signals that arrive at the receiver terminal in a constructive manner. Multiple-input and multiple-output systems (MIMO) and Cooperative systems are among the best competitors so far to make practical use of diversity concept.

The brief overview of MIMO systems is given in Section 3.2. Section 3.3, presents the concept of Cooperative diversity in detail which is followed by the discussion of Cooperative relaying protocols and signal combining techniques in Sections 3.4 and 3.5 respectively. The core of the thesis, multi-hop cooperative system is introduced in Section 3.6. System model of multi-hop cooperative systems is presented in Section 3.7. Finally the chapter is summarized in Section 3.8.

3.2 Overview of MIMO Systems

Multiple-input and multiple-output (MIMO) systems are widely acknowledged in wireless communications domain due to their potential to provide high diversity, increased capacity and improved data rates with its ability to suppress interference and multipath fading [5], [29-31]. MIMO is an advanced technology that needs multiple antennas to be installed at both transmitter and receiver of a communication link, aims to provide independent channel paths for signal transmission through this configuration. Due to independent channel gains of all paths, it is assumed that receiver can recover the signal correctly as long as there is at-least one strong channel path available in an environment. This configuration also requires the installed antennas at both sides to be separated by some appropriate distance, depends on the signal carrier frequency and scattering in vicinity of an antenna. The typical MIMO configuration is presented in Figure 3.1

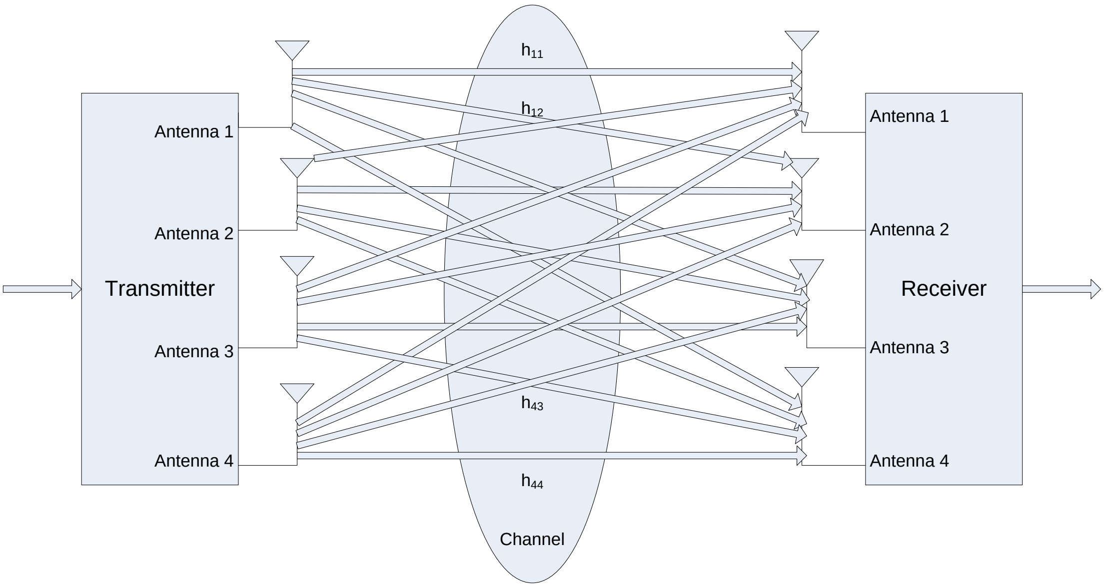

Figure 3.1: A MIMO System with Four Transmit and Receive Antennas

In general, both transmit and receive diversities can be realized in MIMO systems due to the fact that multiple antennas are used at both transmitter and receiver terminals satisfying the condition for transmit and receive diversities. Although diversity degree obtained by MIMO systems may be advantageous for special purpose applications but for commercial applications, due to the hardware limitations of most wireless devices, the implementation of multiple antennas may not be practical.

Moreover, if it is supposed to have multiple antennas on wireless devices then achievement of all MIMO advantages are not guaranteed due to the narrow separation distance between the antennas that results in highly correlated channel paths. To overcome the hindrance that limits the MIMO gains, new techniques must be sought out able to provide communication links beyond point-to-point communications. In multi-user scenario, it is possible to share the mobile antenna to cooperate with other mobiles without the need to employ multiple antennas on either side to reap same benefits that MIMO offers [6-8].

3.3 Cooperative Diversity

A Cooperative wireless system takes maximum advantage of intermediate relays located in between the source and destination to improve their quality of service. In a multi user environment, multiple distributed mobiles create Virtual Antenna Array (VAA) to cooperate with source and destination nodes by offering their services of using antennas to relay information signal as illustrated in Figure 3.2. Such distributed environment provides the opportunity to have independent fading paths between the source and destination as separation between the antennas is distant enough in contrast to MIMO systems. Thus, spatial diversity is achieved when signals coming from different paths are combined at the destination. This technique has potential to effectively mitigate the effects of not only small-scale fading but also large-scale fading as well.

The idea of classical relay network was first introduced by Van der Meulen, back in 1971 [11]. Relay channel properties regarding to information theory were studied by Cover and El Gamal [10]. Carleial used generalized feedback in multiple-access channels [32]. Sendonaris examines the performance of Cooperative diversity in multipath fading channels [33]. Recently, the Collaborative Hybrid ARQ schemes in single-hop cooperative network are studied by Kun Pang [34]. The concept of two user cooperative wireless network along with Turbo coded HARQ is presented by Haifa Fares [35].

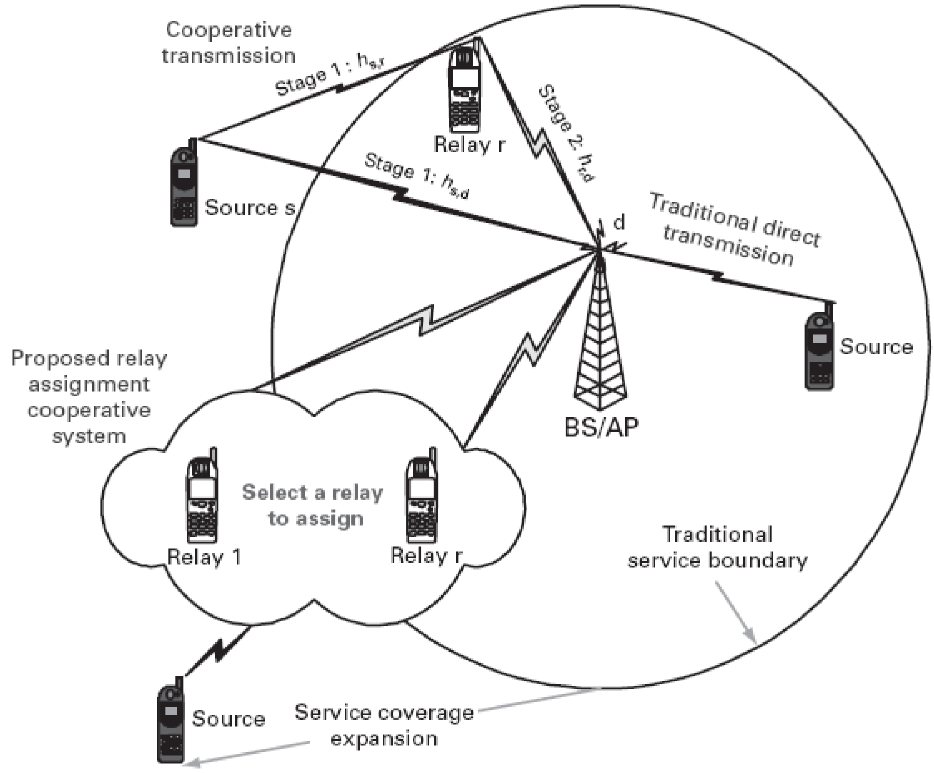

Figure 3.2: Illustration of Direct and Cooperative Transmission Techniques

A conventional cooperative system is represented by three terminals: source, relay and destination. The whole transmission takes two time instants. In the first instant, source broadcasts the signal which is received by the relay and destination. While in the next time instant, the relay node retransmits the processed version of the signal to the destination. Processing at the relay node depends on the nature of relaying protocol. Finally, when two different copies of the signal reach the destination, signal combining techniques can be applied to get resultant signal. Both relaying strategies and combining techniques are presented in Section 3.4 and 3.5

subsequently. The Figure 3.2 illustrates the environment where both direct and cooperative transmission takes place with some prospects of coverage extension too.

Two orthogonal phases are required to implement the cooperative network which could be accomplished through TDMA, FDMA or CDMA to avoid any interference between the phases. During the broadcast phase, the relay and destination receive the signal sent by the source denoted by $y_{sr}[n]$ and $y_{sd}[n]$ which can be represented as

$$y_{sr}[n] = \sqrt{P_{sr}} a_{sr} x[n] + n_{sr}[n], \quad n = 1, \dots N/2 \tag{3.1}$$

$$y_{sd}[n] = \sqrt{P_{sd}} a_{sd} x[n] + n_{sd}[n], \quad n = 1, \dots N/2 \tag{3.2}$$

where $x[n]$ is the signal sent by the source at time n, P_{sr} and P_{sd} are power of received signal at relay and destination, $a_{sr}$and $a_{sd}$are channel coefficients of source-relay link and source-destination link respectively, n_{sr} and n_{sd} represent the AWGN noise of each channel having zero mean and variance σ_n^2. During next phase, the processed version of signal $x_r[n]$, received by destination is given as

$$y_{rd}[n] = Q_{rd} a_{rd} x_r[n] + n_{rd}[n], \qquad n = \frac{N}{2} + 1, \dots N \tag{3.3}$$

where $x_r[n]$ is the signal forwarded by the relay and Q_r is the channel gain.

$$E(|x_r[n]|^2) \;\leq\; P_r \tag{3.4}$$

The relay is bounded to forward signal with transmit power limit P_r , expressed in Eq. 3.4. The three node cooperative model is illustrated in Figure 3.3.

3.4 Cooperative Relaying Protocols

Variety of relaying protocols exists to devise the method for processing of the signal at relay node. Relaying protocols are mainly categorized into fixed-relaying and adaptive relaying. Both categories will be discussed in upcoming subsections.

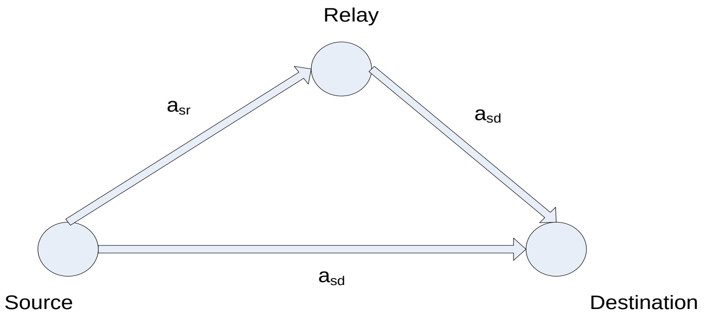

Figure 3.3: Illustration of Three Node Cooperative Model

3.4.1 Fixed Relaying Protocols

In fixed relaying, the resources are deterministically distributed among source and relay. Amplify And Forward (AAF) and Decode And Forward (DAF) use fixed relaying strategy that are commonly used in cooperative relaying networks. Ease in implementation is certainly an advantage of fixed relaying protocols but due to distribution of half of channel resources, this scheme has low bandwidth efficiency. It is more highlighted with the fact that when signal to noise ratio of channel becomes relatively high enough for error free communication between the source-destination link then transmissions from the relay would not be beneficial.

3.4.1.1 Amplify and Forward

Subjected to the power constraint of received signal sent by the source, the relay simply amplifies that signal and forwards it to destination. The signal forwarded by the relay is given by

$$x_r[n] = \mu y_{sr}[n] \tag{3.5}$$

where $y_{sr}[n]$ represents the received noisy version of the signal from the source, already expressed in Eq.(3.1). The relaying gain is denoted by μ. The relaying gain depends on multiple factors that include power of the transmitting signal, noise power spectral density and attenuation caused by fading. These factors can be calculated from Eqs. (3.1) and (3.4) as

$$\mu \leq \sqrt{\frac{P_r}{|a_{sr}|^2 P_{sr} + N_0}} \tag{3.6}$$

The amplifying process is believed to be linear transformation of the gain. Finally, the destination combine both received signals by applying some signal combining technique to maximize diversity effect. The general form of received signal is

$$y[n] = w_{sd} y_{sd}[n] + w_{rd} y_{rd}[n] \tag{3.7}$$

Expanding the R.H.S of Eq. 3.7

$$=w_{sd}\left[\sqrt{P_{sd}}a_{sd}x[n] + n_{sd}[n]\right] + w_{rd}\left\{Q_{rd}a_{rd}\mu\left[\sqrt{P_{sr}}a_{sr}x[n] + n_{sr}[n]\right] + n_{rd}[n]\right\} \tag{3.8}$$

where w_{sd} and w_{rd} are the combining weights that are associated with their respective incoming signals. These combining coefficients can be calculated depending on the type of signal combining technique used. The only drawback of this protocol is the amplification of noise that was accumulated in the signal during the first phase. The diversity level of two can be obtained through this protocol [36].

3.4.1.2 Decode and Forward

Upon the arrival of signal, the relay applies error detection /decoding procedure and then re-encodes the signal prior to forwarding it to final destination with power P_r.

$$x_r[n] = \sqrt{P_r}x[n] \tag{3.9}$$

The signal received at destination can be expressed as

$$y_{rd}[n] = Q_{rd}h_{rd}\sqrt{P_r}x[n] + n_{rd}[n] \tag{3.10}$$

This process corresponds to non-linear signal transformation at the relay. Like AAF protocol, DAF does not amplify the noise in the signal at the relay. However, in case of incorrect decoding at relay, the forwarded signal to the destination becomes meaningless, thus diversity of order one could only be achieved.

3.4.2 Adaptive Relaying Protocols

In fixed relaying protocols, the relays are confined to forward the signal to destination every time even if bits are detected in error or if there is an issue of noise amplification. Adaptive relaying protocols have proven to be an effective way to subjugate the above mentioned drawbacks of AAF and DAF protocols [8]. Both selection relaying and incremental relaying are considered as Adaptive relaying strategies.

3.4.2.1 Selection Relaying

Since the channel estimation provides fading coefficients of specific link, the terminals can use that knowledge and adapt their transmission accordingly. Taking A_{rs} as threshold measure, the relay decides whether to re-transmit the information signal or not. If the value of $|A_{rs}|^2$ is observed greater than certain threshold value then relay will forward the signal to its destination using any fixed relaying protocol otherwise it does not retransmits to avoid inefficient use of bandwidth.

3.4.2.2 Incremental Relaying

To avoid inefficient use of channel’s degrees of freedom, incremental relaying proposes a single feedback bit from destination node to acknowledge the success of direct transmission. For sufficiently high SNR between the source and destination, the success of direct transmission is almost guaranteed. In such case, the signal from relay doesn’t need to be transmitted. Or if relay receives negative acknowledgement from destination, it then transmits to take advantage of spatial diversity. The features of both incremental redundancy and Hybrid ARQ can be witnessed in incremental relaying as relay always waits for destination request to send the signal which corresponds to HARQ and achieves spatial diversity in case of transmission from relay node which makes it closer to incremental redundancy.

3.4.2.3 Switchable Relaying

This relaying protocol uses combination of both AAF and DAF protocols to relay the information signal. It also makes best use of available channel resources by applying CRC on the received signal broadcasted by the source. If CRC decoding is successful, the relay chooses DAF protocol otherwise it uses AAF protocol. This switching mechanism helps the system to avoid the drawbacks of both protocols that were encountered in fixed relaying schemes. One of most attractive feature of this protocol is ability of relay to adapt itself according to channel quality without any CSI required from destination. Moreover, this relaying protocol needs same processing at relay and destination as it was in fixed relaying scheme, thus not adding any complexity in terms of processing at relay or destination. This project also employs switchable relaying mechanism to achieve all above mentioned target goals.

3.5 Signal Combining Techniques

The systems incorporated diversity techniques need to define the mechanism for combination of multiple signals at the destination to exaggerate the received SNR. The most common combining techniques are Equal Ratio Combining (ERC), Fixed Ratio Combining (FRC), Signal to noise Ratio Combining (SNRC) and Maximum Ratio Combining (MRC). All these schemes are elaborated as:-

3.5.1 Equal Ratio Combining (ERC)

All the received signals are added up with equal ratio without any consideration of channel quality. So channel estimation is not required by this scheme, which make its implementation very simpler but offers low performance.

$$y_d[n] = \sum_{i=1}^{k} y_{i,d}[n] \qquad (3.11)$$

For single relay, this equation becomes

$$y_d[n] = y_{s,d}[n] + y_{r,d}[n] \qquad (3.12)$$

where $y_{s,d}[n]$ and $y_{r,d}[n]$ are the received signal components from both source and relay.

3.5.2 Fixed Ratio Combining (FRC)

In fixed ratio combining, the signals are combined with fixed gain not tend to change during the communication. The temporary changes in the channel quality are not taken into account but overall average quality of the link is given fixed weightage. The better the average quality, the higher the weightage will be given to that signal in combination process. The FRC scheme is expressed as

$$y_d[n] = \sum_{i=1}^{k} d_{i,d}.y_{i,d}[n] \qquad (3.13)$$

The incoming signal $y_{i,d}[n]$ is given the fixed weightage of $d_{i,d}$. In case of sigle relay, the equation simplifies to

$$y_d[n] = d_{s,d}.y_{s,d}[n] + d_{s,r,d}y_{r,d}[n] \qquad (3.14)$$

where $d_{s,d}$ and $d_{s,r,d}$ are fixed weights associated source-destination link and source-relay-destination link. As gains are fixed in accordance to average channel quality, this scheme performs better than ERC scheme.

3.5.3 Signal to Noise Ratio Combining (SNRC)

This scheme brings significant improvement in the performance by introducing the SNR estimation of each signal coming at the receiver. SNR is the one of the major characteristic of the signal through which quality of the signal can be determined. The greater the SNR value of signal, the stronger it is. For single relay system, it is represented by

$$y_d[n] = SNR_{s,d}.y_{s,d}[n] + SNR_{s,r,d}y_{r,d}[n] \qquad (3.15)$$

where $SNR_{s,d}$ and $SNR_{s,r,d}$ denotes the signal- to- noise of both direct link (source to destination) and indirect link (source- to-relay-to destination). This scheme needs some extra known pilot sequence to be sent along with the signal to estimate the SNR of the link. It certainly increases the complexity and requires more bandwidth but results out shown these additional overheads.

3.5.4 Maximum Ratio Combining (MRC)

Assuming the channel coefficients are known at the receiver, this scheme makes use of these channel coefficients to bring the certain improvements. It combines the each received signal with its corresponding conjugated channel coefficient. The mathematical form is given by

$$y_d[n] = \sum_{i=1}^{k} h_{i,d}^{*} . y_{i,d}[n] \tag{3.16}$$

For signal relay system, the above equation expands to

$$y_d[n] = h_{s,d}^{*} . y_{s,d}[n] + h_{r,d}^{*} y_{r,d}[n] \tag{3.17}$$

where $h_{s,d}^{*}$ and $h_{r,d}^{*}$ are the channel estimates of both source-destination and relay-destination links. Exact Channel State Information (CSI) is needed to be known at the receiver.

3.6 Multi-hop Cooperative Systems

Multi-hop cooperative systems exploit the presence of multiple intermediate nodes in certain vicinity in order to cooperate with each other to forward the signal to ultimate destination to achieve various objectives like high diversity degrees, higher data rates and coverage range extension. It promises performance enhancement by means of minimizing multipath fading and also provides ample opportunities to increase the capacity of system through spatial and frequency reuse. In multi-hop cooperative systems, several relays between the source and destination link are taken into account in order to expand the level of cooperation among the nodes. The deployment of general multi-hop cooperative scenario with emphasis on number of applications can be studied in [37].

The focus of recent research has already been deviated from classical single-hop systems to multi-hop relay systems to analyze the system performance. Some recent literature includes the work of Hasna and Alouini [38, 39] who used regenerative and non-regenerative relays in multi-hop systems to analyze the error performance and outage behavior over different fading channels. The performance bound of multi-hop system with blind relays over numerous fading channels is also studied in [40, 41]. The performance analysis of multi-hop diversity with multiple relays is carried out in [41]. These contributions are purely focused on multi-hop relaying without taking cooperative strategies into consideration. Moreover, these research contributions assumed multiple relays that used parallel relay configuration in cooperative environment [41]. No substantial work has been done regarding the incorporation of turbo codes with some retransmission mechanism in multi-hop cooperative systems.

3.7 Multi-hop Cooperative Systems: General System Model

In general, a multi-hop cooperative system has total N number of relays which can cooperate with source to forward its signal. The channel between any of two nodes is modeled as Rayleigh fading channel with AWGN having zero mean and variance N_0. Exploiting the broadcast nature of wireless medium, all relays in specific vicinity will overhear the transmission that is initiated by the source and aimed for destination. As there is an appropriate separation among the distributed intermediate relays, each wireless link between two relays experience independent fading coefficients. So highly uncorrelated channels are assumed over which relays can send information signal without interfering each other. The generalized system model is represented in Figure 3.4.

Once the signal is received by the relay, the relay applies same processing routine on the signal and then chooses the relaying protocol accordingly and forwards the processed version of signal to further nodes and destination. General cooperative scenarios can be considered where relay is allowed to receive the signal from all previous relays along with the source signal or it is kept bound to combine signals coming from source and only the previous relay. In both cases, signals are combined using maximum ratio combining method. The earlier scenario utilizes all independent signals that can have meaningful positive effects on the performance but requires the CSI to be estimated for all previous relays to use that information for signal combining which makes the system too complex to deploy it for large scale purpose. In contrast, the later scenario requires the channel estimates of source and only the previous relay in order to combine the signals which certainly make the practical implementation of the system very simpler as compared to earlier one.

The diversity order of the system having N relays is N+1. With the increase in number of relays for diversity gain, the bandwidth efficiency of the system will be reduced as source transmits the information using little fraction of total available degree of freedom of channel. The transmission of the same signal from multiple relays, leads to the inefficient use of the bandwidth of channel. So there is tradeoff between these two important performance factors, neither of which is compromised at the same time. Time diversity is another factor that should be taken into consideration. With N number of relays, it requires N+1 time slots for transmission of single frame.

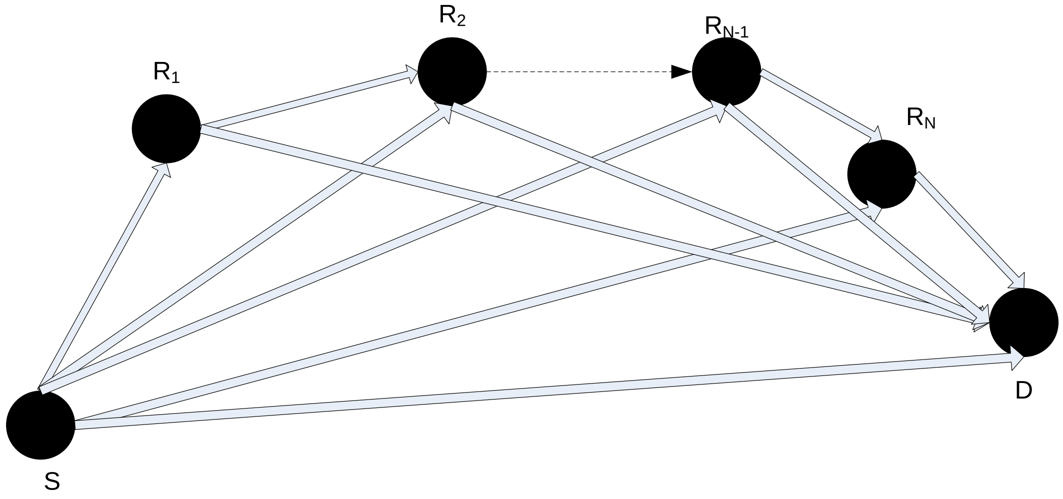

Figure 3.4: Illustration of General Multi-Hop Cooperative Model with N Relays

The employment of additional relays clearly adds timing delays in the reception of signal. So the cooperative system is bounded to utilize limited number of relays as to achieve spatial diversity gains as well as time diversity with efficient channel bandwidth usage. Power allocation for multiple relays is another important aspect to be considered in multi-hop cooperative systems. Usually, source use power P_s for transmission and this power is equally distributed among source-to-relay channels and relay-to-destination channels. In simple words, the power $P_s/2$ is assigned to source to broadcast the signal and the remaining power is uniformly distributed among the relay nodes.

3.8 Summary

This chapter purely focuses on the salient features of cooperative communications. The emulation of MIMO technology through cooperative network is elaborated and proved itself a promising technique for upcoming 4G wireless technology to use multiple distributed antennas. To get optimum performance, switchable relaying protocol is suggested with maximum ratio combining scheme. In the end, system model of multi-hop cooperative communications is presented with all its gains over single-hop systems. It also highlights the constraints and limitations that are required to be met to make the system more effective.

Chapter 4

HYBRID ARQ: TURBO CODES AND ARQ

4.1 Background

Shannon predicted the reduction of errors introduced by noisy channel upto certain level with the aid of any channel coding scheme as long as the data rate remains under the limit of channel capacity [42]. Shannon expressed the capacity of a band limited channel containing AWGN as

$$C = B\log_2(1 + SNR) \tag{4.1}$$

where capacity, C is expressed in bits/sec and B represents the bandwidth of the channel. The subsequent advancement in the error control coding theory is direct inspiration of Shannon's benchmark. Some significant developments include the design of convolutional codes [43] and its different decoding algorithms [44-47] that were proposed in order to reduce errors. This research was followed by the major breakthrough that introduces maximum likelihood (ML) detection algorithm for convolutional decoding [48]. C. Berrou, Glaviex and Thitimajashima introduced Turbo codes in 1993, capable of working within 1 dB of Shannon limit [49]. Since then, these codes are widely used as forward error correction (FEC) scheme in various communication systems. For error detection, Automatic Repeat Request (ARQ) protocol is used with few checksum bits that are annexed with information bits prior to transmission [13]. Receiver can simply identify the inclusion of errors with CRC check and requests for retransmission accordingly. The novel combination of channel coding scheme and automatic repeat request scheme is considered as Hybrid ARQ

(HARQ). So, turbo codes have been incorporated as FEC scheme and ARQ scheme as retransmission mechanism in multi-hop cooperative paradigm which proved to bring impressive improvement in the system performance.

In the upcoming sections, focus will be on these two error control schemes, Turbo codes and ARQ explicitly. In Section 4.2, the design and implementation of turbo codes will be discussed. Decoding algorithms used to decode turbo-coded data are put under the Section 4.3. Section 4.4 highlights the different ARQ retransmission protocols. Overview of HARQ scheme is presented in Section 4.5. At the end, Section 4.6 concludes the chapter.

4.2 Forward Error Correction- Turbo Codes

Turbo codes work on the basic principle of concatenating two convolutional encoders in parallel, separated by some random interleaver [12]. Same information bits are provided to both encoders but in distinct order which is achieved through interleaving process. The abstract of turbo encoder of rate 1/3 is depicted in Figure 4.1 [50]. A specific type, recursive systematic convolutional (RSC) encoder is used in the system. Each component encoder generates the systematic bit plus parity bit corresponding to each input bit. The output Y_0 is the systematic bit produced from first RSC encoder which is same as input bit whereas Y_1 is the parity bit generated by the same encoder. The output Y_2 is interleaved parity bit yielded by second RSC encoder, whereas the systematic bit of this encoder is not sent because it is just the interleaved version of input sequence. These three output bits $Y_{0,}Y_1$ and Y_2 are multiplexed to produce 1/3 rate turbo code.

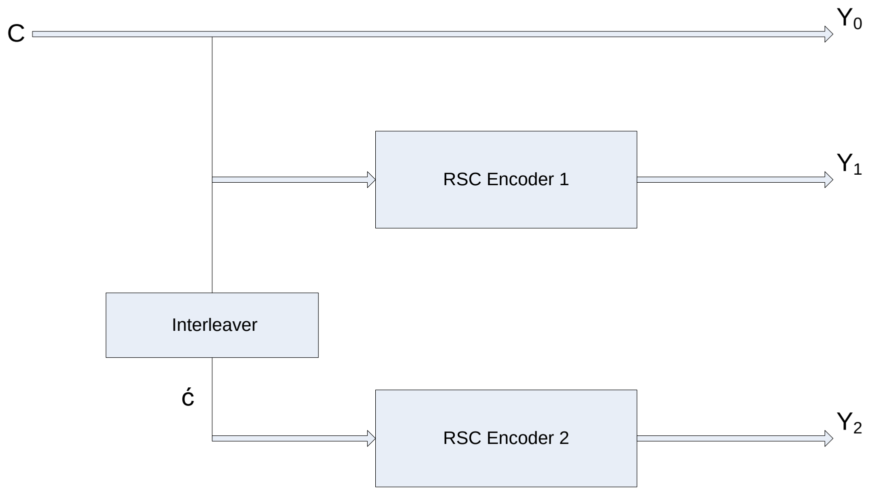

Figure 4.1: Block Diagram of 1/3 Rate Turbo Encoder

4.2.1 RSC encoder

As Figure 4.1 shows the RSC encoders are working in parallel structure with addition of interleaver in prefix to second component encoder. The interleaver tends to shuffle the bits randomly in order to make chances of producing highly uncorrelated parity bits from component encoders and it also plays a vital role in turbo code performance. Turbo codes must use RSC encoders to allow the parity bits from both encoders to evaluate the reliability of it taking systematic bit as a standard. The RSC encoder is usually designed by returning one of parity bits of the convolutional encoder to the input of the encoder and is shown in Figure 4.2 [48]. The generator matrix of RSC encoder is represented as G= [1, g_1/g_2] where 1 is the systematic output, g_1 is the output that is fed back to the input and g_2 is the output that is fed-forward.

Generator matrices [1 1 1 1] and [1 1 0 1] are used in RSC encoders, taken from Beneditto’s work [51]. The output sequence produced by the parallel combination of encoders is listed as $s_1p_1^1p_1^2\ s_2p_2^1p_2^2\ s_3p_3^1p_3^2 \ldots \ldots s_Np_N^1p_N^2$ where s and p symbols represent the occurrence of systematic and parity bits respectively. Bit number is symbolized by subscript and component RSC encoder is identified by the superscript.

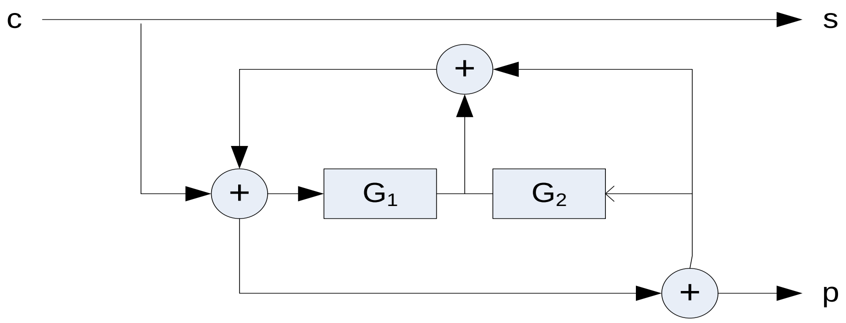

Figure 4.2: RSC Encoder of Rate 1/2

4.2.2 Purpose of Parallel Concatenation

The parallel concatenation produces codeword of rate 1/3, which is composed of systematic and parity bit from the first encoder and interleaved parity bit from the second encoder. The parity bits of both component encoders are usually uncorrelated. It is due to the fact that if one component encoder generates low weight output code then there remains a very rare chance of getting another low weight code from the second encoder. Due to un-correlation between both parity bits, the high weight output codeword is produced. In addition, Divide-and-conquer strategy is used for decoding. Two decoders are used, which exchange information to update their knowledge to produce soft output. That shared information is basically the interleaved output of decoder which is produced in result to iteration to keep information uncorrelated from other decoder’s output.

4.3 Turbo Decoding

A basic turbo decoder comprises of two component decoders which exchange the information with each other in an iterative fashion to estimate final decoded bits.

Decoder may be employing maximum a posterior probability (MAP) algorithm or soft output Viterbi algorithm (SOVA). Despite of using MAP algorithm in proposed system, brief overview of SOVA algorithm will also be presented.

4.3.1 Maximum A-Posteriori (MAP) Algorithm

Two component decoders are concatenated serially via an interleaving process just like the one represented in encoder design. The blue print of iterative MAP decoder is shown in Figure 4.3.

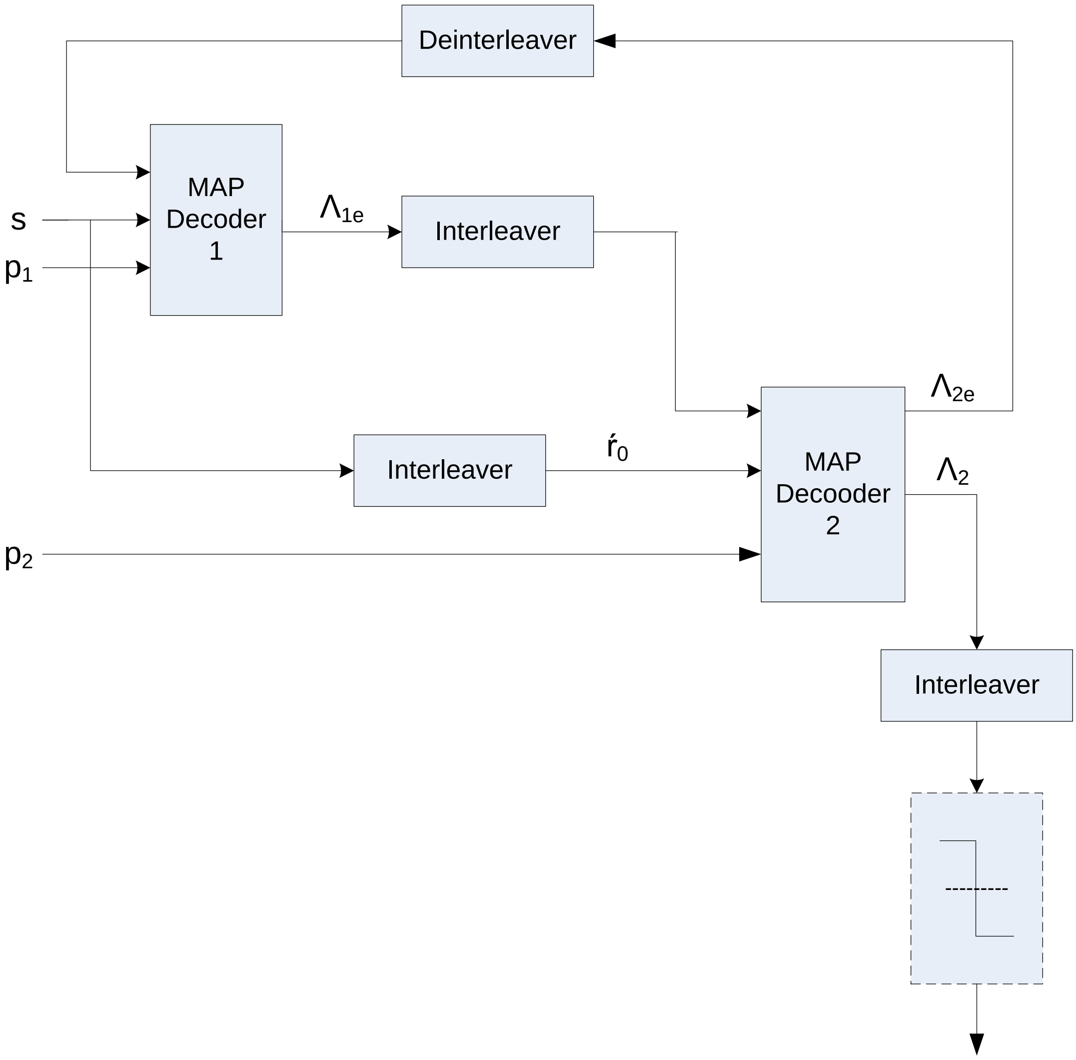

Figure 4.3: An Iterative Turbo Decoder Based on MAP Algorithm

The received information sequence is provided to iterative decoder, where first two received bits, systematic, *s* and parity, p_1 are taken by MAP decoder 1 and the other parity bit, p_2 will goes to its corresponding decoder. After the calculation of Log

Likelihood Ratio (LLR) based soft output by first decoder, it passes the interleaved version of that soft output to the second component decoder as it’s a-priori information. This a-priori information is represented as:-

$$L(u_k) = ln\frac{P(u_k=+1)}{P(u_k=-1)} \tag{4.1}$$

MAP Decoder 2 accepts LLR output, the interleaved systematic bit and its own parity bit to generate its own soft output which benefits first decoder to produce an improved soft output when output from second decoder is again used as feedback for first component. Through this exchange of information, the final estimate keeps on improving until the maximum number of iterations is reached. Finally component decoder 2 produces hard decision, which is already deviated from initial probability of 0.5 after series of information sharing. If hard output is positive then the bit is assumed as 1 otherwise it is regarded as bit 0.

The MAP decoder 1 produces LLR for rate 1/n code is given by

$$\Lambda_1(u_k) = log\frac{\sum_{u^+} \tilde{\alpha}_{k-1}(s').\tilde{\beta}_k(s).p_k^1(1).\exp\left(-\frac{\sum_{i=0}^{n-1}\left(r_{k,i}-x_{k,i}^1(s)\right)^2}{2\sigma^2}\right)}{\sum_{u^-} \tilde{\alpha}_{k-1}(s').\tilde{\beta}_k(s).p_k^1(0).\exp\left(-\frac{\sum_{i=0}^{n-1}\left(r_{k,i}-x_{k,i}^0(s)\right)^2}{2\sigma^2}\right)} \tag{4.2}$$

where $p_k^1(1)$ and $p_k^1(0)$ are a-priori probabilities assumed at first component MAP decoder for first iteration. In preceding iterations, the a-priori probability is taken from output of second decoder. The term α is the forward metric, β is the backward metric and γ is the transition metric. These metrics are calculated through MAP algorithm. The mathematical expression for α is

$$\propto_k(s) = P_r\{S_k = s, r_1^k\} \tag{4.3}$$

$$= \sum_{All\ states} P_r\{S_{k-1} = s', S_k = s, r_1^k\}$$

The Eq. 4.3 is reduced to

$$\sum_{s'=0}^{M_s-1} \propto_{k-1} (s'),\ \sum_{i\epsilon(0,1)} \gamma_t^i (s', s) \tag{4.4}$$

for t=1,2,3,4,……τ

Representing the $\beta_k(s)$ as

$$\beta_k(s) = P_r\{r_{k-1}^{\tau} | S_k = s\} \tag{4.5}$$

$$= \sum_{All\ states} P_r\{S_{k+1} = s', r_{k+1}^{\tau} |\ S_k = s\}$$

The Eq. 4.5 after some computations, shaped into

$$\sum_{s'=0}^{M_s-1} \beta_{k+1}(s'),\ \sum_{i\epsilon(0,1)} \gamma_{k+1}^i (s, s') \tag{4.6}$$

for k= τ-1,………3,2,1,0

The third term γ is represented as

$$\gamma_k^i(s', s) = P_r\{u_k = i, S_k = s\}, r_k\ | S_{k-1} = s' \tag{4.7}$$

$$= \frac{P_r\{r_k, u_k = i, S_k = s,\ S_{k-1} = s'\}}{P_r\{\ S_{k-1} = s'\}}$$

In its final form, Eq. 4.7 can be expanded as

$$\begin{cases} p_k(i)\exp(-\frac{\sum_{j=0}^{n-1}\left(r_{1,j}^i - x_{k,j}^i(l)\right)^2}{2\sigma^2})\ for\ (s, s') \in B_k^i \\ \qquad Otherwise \end{cases} \tag{4.8}$$

Rewriting Eq.4.2 as

$\Lambda_1(u_k)$

$$= \log\frac{p_k^1(1)}{p_k^1(0)} log \frac{\sum_{u^+} \tilde{\alpha}_{k-1}(s').\tilde{\beta}_k(s).\exp\left(-\frac{\left(\mathrm{r}_{\mathrm{t},0} - x_{k,0}^1\right)^2 \sum_{i=0}^{n-1}\left(r_{k,i} - x_{k,i}^1(s)\right)^2}{2\sigma^2}\right)}{\sum_{u^-} \tilde{\alpha}_{k-1}(s').\tilde{\beta}_k(s).\exp\left(-\frac{\left(\mathrm{r}_{\mathrm{t},0} - x_{k,0}^0\right)^2 \sum_{i=0}^{n-1}\left(r_{k,i} - x_{k,i}^0(s)\right)^2}{2\sigma^2}\right)}$$

(4.9)

The Eq.4.9 is further decomposed into

$$\Lambda_1(u_k) = \log\frac{p_k^1(1)}{p_k^1(0)} + \frac{2}{\sigma^2}\mathrm{r}_{\mathrm{t},0} + \Lambda_{1e}(u_k) \tag{4.10}$$

The first term in above equation is a-priori probability about initial guess in the first iteration whereas second term is relevant to systematic bit and channel information. Finally the third term is called a-posteriori value or extrinsic value which is computed and shared by each decoder iteratively trying to make a perfect decision on received bit status. This decomposed part $\Lambda_{1e}(u_k)$ of Eq.4.10 is given by

$$\Lambda_{1e}(u_k) = log \frac{\sum_{u^+} \tilde{\alpha}_{k-1}(s\prime).\tilde{\beta}_k(s).\exp\left(-\frac{\sum_{i=0}^{n-1}\left(r_{k,i}-x_{k,i}^{1}(s)\right)^2}{2\sigma^2} \right)}{\sum_{u^-} \tilde{\alpha}_{k-1}(s\prime).\tilde{\beta}_k(s).\exp\left(-\frac{\sum_{i=0}^{n-1}\left(r_{k,i}-x_{k,i}^{0}(s)\right)^2}{2\sigma^2} \right)} \tag{4.11}$$

In the last iteration, the sign of output generated by second MAP decoder decides the status of bit. If sign is positive, then bit is decoded as 1 and if negative sign appears with output then bit is decoded as 0.

4.3.1.1 Computational complexity

The computational complexity of the Turbo decoder using MAP algorithm [52] is carried out in Table 4.1

Table 4.1: Computational Complexity of MAP Algorithm Based Turbo Decoder

Operation	Maximum a-posteriori Algorithm
Maximization	2M-1
Addition	4M
Multiplication	10M
Total Operation	14M
Total # of Operations	30M-1

where M represents the total number of states that decoder have. Number of states will be 4, 8, and 16 for constraint length of 2, 3 and 4 respectively. Turbo encoder having constraint length of 3 is used, so having total 8 states. So for each single bit, there will be 30x8-1=239 total operations. If the data rate of transmission is known, then total number of operations needed for whole transmission can be calculated as *data rate* x *239.*

4.3.2 Soft Output Viterbi Algorithm (SOVA)

The SOVA algorithm is basically an extension of Viterbi Algorithm, prevail its drawbacks by producing soft output [53]. But in comparison to MAP decoders, SOVA's complexity and unmatched performance makes the MAP algorithm a perfect choice for turbo decoding. Soft output in form of LLR estimated by SOVA is represented as

$$\Lambda(u_k) = log\frac{P_r\{u_k=1|r_1^\tau\}}{P_r\{u_k=0|r_1^\tau\}} \tag{4.12}$$

Hard decision is taken by SOVA decoder by comparing $\Lambda(u_k)$ with a threshold value of zero.

$$u(k) = \begin{cases} 1 & if\ \Lambda(u_k) \geq 0 \\ 0 & otherwise \end{cases} \tag{4.13}$$

In the same way as VA selects the Maximum Likelihood path, SOVA also choose the path $\hat{x}$ having minimum metric $\mu_{r,min}$with the selection probability of this path

$$P_r(u|r_1^\tau) = P_r(x|r_1^\tau) \sim e^{-\mu_{r,min}} \tag{4.14}$$

Denoting μ_k^1 as minimum path metric for which u_k is 1 and μ_k^0 for which u_k is 0. LLR ratio of each binary symbol that was transmitted can be calculated considering these two cases. The time k at which ML estimate is 1, its complementary symbol μ_k^cat the same time instant will be 0. Therefore it can be written as $\mu_k^1 = \mu_{r,min}$ and $\mu_k^0 = \mu_k^c$. Similarly the time k at which ML estimate is 0, its complementary symbol at the same time instant will be 1. . Therefore it can be written as $\mu_k^1 = \mu_k^c$ and $\mu_k^0 = \mu_{r,min}$.

The LLR for both cases is expressed as

$$log\frac{P_r\{u_k=1|r_1^\tau\}}{P_r\{u_k=0|r_1^\tau\}} \sim log\frac{e^{-\mu_{k,c}}}{e^{-\mu_{r,min}}} = \mu_{r,min} - \mu_{k,c} = \mu_k^0 - \mu_k^1 \tag{4.15}$$

So, finally it can written as

$$\Lambda(u_k) \sim \mu_k^0 - \mu_k^1 \tag{4.16}$$

This final value of LLR is shared among both decoders iteratively for best possible estimate about the output bit.

4.4 Automatic Repeat Request (ARQ) Scheme

In the last section, error correcting scheme, turbo codes are discussed. This section is dedicated to error detection scheme, Automatic Repeat Request. Three basic ARQ protocols, Stop-and-wait (SW), Go-back-N (GBN) and Selective repeat (SR) will be discussed in the following sub-sections. The Figure 4.4 represents the working flow of all ARQ schemes

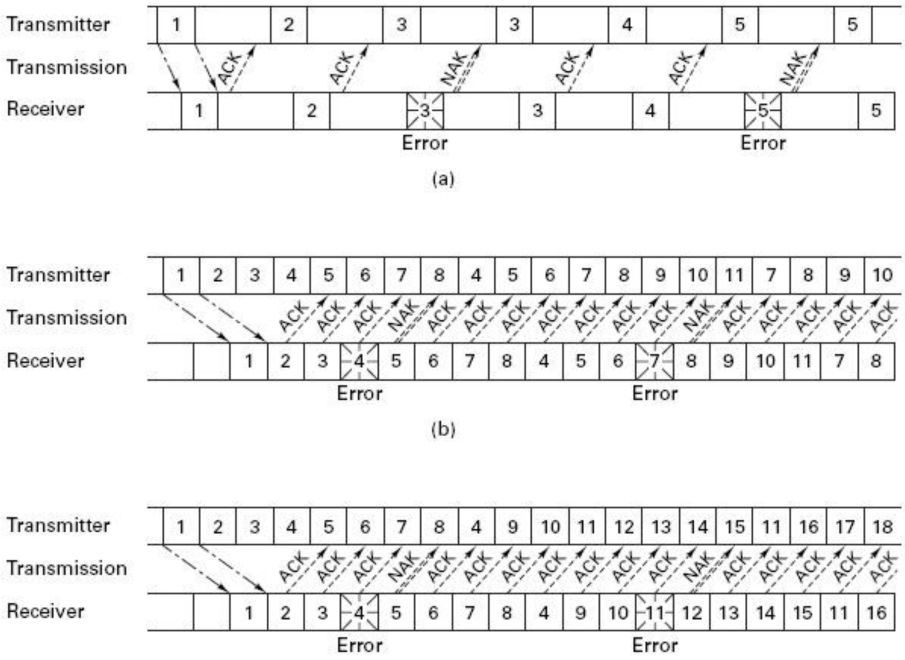

Figure 4.4: (a) Stop and Wait ARQ, (b) Go-Back-N ARQ, (c) Selective Repeat ARQ

4.4.1 Stop-and-wait (SW)

One of the simplest ARQ mechanisms is SW scheme. After the transmission of signal, the sender waits for an acknowledgement from the receiver side [13]. The

ACK affirms the validity of transmitted signal and allows the sender to send next data frame. In case of NAK, the sender holds its on-going transmission and fulfills the retransmission request made by the receiver until ACK is received. Sender keeps on retransmitting the signal unless it is correctly detected by the receiver. This procedure certainly escalates the timing delays in the transmission process which is sometimes unacceptable for military and other sensitive transmissions that need the continuous flow of information. Timing delays can be reduced up to some extent by putting maximum limit on retransmissions but it doesn’t guarantee the transmission reliability which makes it an inefficient scheme.

4.4.2 Go-back-N (GBN)

In this scheme, transmitter keeps sending the information code-words unless the first NAK is received from the receiver and also keeps those transmitted code-words in its buffer space to utilize them in case of NAK. As soon as it receives NAK, it halts further transmission and resends the codeword and the following N-1 code-words that were already transmitted regardless of the validity of N-1 code-words. Whenever the transmitter receives ACK, it resumes the transmission of fresh code-words. This scheme is somewhat more effective than SW but still have deficiencies of timing delays in the retransmission process.

4.4.3 Selective Repeat (SR)

The drawbacks of both SW and GBN ARQ schemes are nullified by selective repeat protocol. This scheme allows the transmitter to continuously send all the code-words and wait for ACK. At the receiver end, the buffer capacity is available for storage of all error free code-words preceding the unsuccessful transmission and asks transmitter to send only the erroneously detected codeword. As soon as the retransmission is authenticated through CRC, the receiver extracts its buffer and organizes the sequence of all code-words. This scheme is considered as the most efficient one as it does not waste already made transmissions in case of detection of incorrect codeword. It definitely increases the complexity of the system as it requires buffer storage and re-organization of data frames at the receiver end.

4.5 Hybrid ARQ (HARQ)

Despite various benefits offered by FEC and ARQ schemes, both FEC and ARQ have their own shortcomings which need to be addressed by introducing some mechanism that guarantees the reliability, efficiency and simplicity of the system. Such mechanism can be introduced by harmonizing FEC and ARQ schemes together which is referred to as Hybrid ARQ (HARQ) strategy [15, 54-55]. FEC scheme is simply embedded into ARQ system to give birth to HARQ. On one hand, FEC scheme contributes to reduce the frequent transmission errors through its error correcting capability, leading to less number of retransmissions. While on the other hand, ARQ scheme allows the destination to ask for retransmission in case of uncorrectable error pattern appears. Thus, the reliability of the system is achieved and better performance as well.

The HARQ scheme is further categorized into type-I HARQ, type II HARQ and type III HARQ with each one somehow differs from other. These schemes are presented in the following subsections.

4.5.1 Type-I HARQ

This scheme has the capability of both error detection and error correction, provided by fixed rate code in the system [13]. At first, receiver attempts to correct errors, if code-word is detected in error. If the identified errors are easily corrected through channel code, then purified message is passed to the receiver. Otherwise, it discards that code-word and asks sender to make retransmission attempt in order to get uncorrupted version of the same code-word. The sender carries on retransmissions until the signal is correctly decoded at receiver. Numbers of retransmissions are hugely dependent on the channel conditions because it has vital role in signal transmission process.

4.5.2 Type-II HARQ

The Type I HARQ strategy is perfectly suited for communication channels which constitute uniform noise and fading. In such scenario, it is possible to recover the actual bits with aid of error correcting codes, but system faces severe degradation when channel conditions are non-stationary. So the shortcomings of type I HARQ appeared openly. In perfect channel conditions, the error free communication even without an employing error-correcting code is fairly possible. In such case, incorporation of error-correcting code goes wasted. In noisy channel conditions, even the employment of error-correcting code is not enough, requires retransmissions which results in low throughput.

To address the above mentioned issues, type II HARQ strategy is proposed using the concept of adaptive HARQ. In perfect channel conditions, it just behaves like simple ARQ scheme with some aid of parity bits. However, in noisy channel conditions, the corrupted code-words are stored in the buffer and retransmission request is made. This retransmission is entertained by the sender with Incremental Redundancy codes to help the receiver in achieving error free decoded symbols in combination with already buffered codeword. With the employment of Rate Compatible Punctured Codes (RCPC) as IR codes, the low rate error correction is possible at lower SNR range [56].

4.5.3 Type-III HARQ

Type-II HARQ has the drawback of its dependency on incremental codes where these codes are badly tampered due to channel interference. To decode, it has to rely on both erroneous stored packets and incremental codes. Kallel introduced complementary punctured codes (CPC) as an extension to type-II HARQ [56]. Type-III HARQ has the capability of obtain the source code-words through only the previously received packet or by harmonize all previously stored packets just like it was done in type-II HARQ.

4.6 Summary

This chapter covers all major ingredients of different error control methods that are considered in this research work. With the essence of FEC scheme, the complete design and working of turbo codes is explained. All the factors that play vital role in turbo encoder design are studied in detail. For turbo decoding, two iterative decoding algorithms, MAP and SOVA are discussed. As MAP algorithm being part of this project, it is thoroughly studied in terms of mathematical relations. With the end of discussion on turbo codes, the most commonly used error control mechanism, ARQ scheme is presented. The three basic categories of ARQ scheme are briefly overviewed. Finally, the combination of FEC and ARQ, HARQ is introduced with brief discussion on all its three types and it is shown to be an effective transmission strategy.

Chapter 5

INTEGERATION OF TURBO-CODED HARQ IN SINGLE-HOP COOPERATIVE SYSTEM

5.1 Introduction

This chapter lays the foundation for multi-hop cooperative system by transmuting the theoretical concepts into run-time simulation of turbo-coded HARQ based cooperative system. This benchmark is accomplished with the development of SISO communication system and then its transformation into traditional three node cooperative system utilizing fixed relaying protocols. To make this system capable of mitigating path loss and fading elements, turbo codes are chosen as first choice to correct error patterns which appeared due to interference originated by path loss and fading. Moreover, the system performance is made even better with the usage of switchable relaying protocol instead of fixed relaying. HARQ scheme is used in conjunction with turbo codes and switchable relaying protocol to boost up the efficiency and reliability of the cooperative transmission. HARQ introduces retransmission mechanism through which retransmission requests are initiated from destination node in case of incorrect decoding results. Both source and relay node used to retransmit the data frame on an alternative turns to keep the retransmission load minimum. Finally the simulation results of traditional cooperative and turbo-coded HARQ based cooperative system are figured out, compared and analyzed in detail. Thus provides us the ideal groundwork to develop the targeted multi-hop cooperative system in next chapter.

5.2 System Model

The cooperative system assumed in this chapter is comprised of source, relay and destination node as illustrated back in chapter 3 in Figure 3.3. The channels between the source and destination, source and relay, and relay and destination are regarded as direct channel, intermediate channel and relay channel respectively. All channels are modelled as quasi-static Rayleigh fading channels where fading coefficients remain constant during the transmission of single frame, making the channel estimation possible at the destination node [58]. All three channels have independent fading coefficients. The system is considered as half-duplex model which requires two phases for transmission of single frame. Using TDD, orthogonal signals are transmitted by the source and relay [8]. The feedback channel is assumed as an error free channel over which destination acknowledges both source and relay about the decoding result of received signal.

First of all information signal is generated by the source in binary form, which is encoded by 1/3 rate turbo encoder. The output stream after channel coding denoted by **U**, is written as

$$\mathbf{U} = (u[1], \dots, u[n], \dots, u[l]), \tag{5.1}$$

where $u[n]$ represents the binary stream at time n after channel coding process and l represents the frame length. Appending CRC-32 bits, CRC coded sequence is denoted by **V** as

$$\mathbf{V} = (\mathbf{V}[1], \dots, \mathbf{V}[n], \dots, \mathbf{V}[l]), \tag{5.2}$$

where $\mathbf{V}[n] = (u[n], v[n])$ which contains the information and corresponding parity bits in $u[n]$ and CRC bits in $v[n]$. The binary information sequence is then mapped into Quadrature phase shift keying (QPSK) modulated symbols, denoted by X as

$$\mathbf{X} = (\mathbf{X}[1], \ldots, \mathbf{X}[n], \ldots, \mathbf{X}[l]), \tag{5.3}$$

The stream $\mathbf{X} \in \{-x-yj, -x+yj, x-yj, x+yj\}$; in which x and y represent the magnitude of the real and imaginary components of the mapped complex numbers in QPSK constellation. A root raised cosine pulse with roll-of-factor 0.22 is used for pulse shaping of modulated stream **X** which enjoys improved spectral properties rather than rectangular pulse shape. This baseband signal is then up-converted shifting its frequency band to pass-band for proper transmission of the signal through wireless medium. Finally the pass-band signal is transmitted through the Rayleigh channel. In the first transmission phase, the signal received by relay is given as

$$y_{sr}[n] = \sqrt{P_{sr}} a_{sr} x[n] + n_{sr}[n], \quad n = 1, \ldots N/2 \tag{5.4}$$

where P_{sr} denotes the power of received signal at relay and given by the relation $P_{sr} = P_s \,.\, (Q_{sr})^2$ containing P_s as transmit power of source and $(Q_{sr})^2$ as gain of intermediate channel elaborated by $Q_{sr} = \left(\frac{\lambda_c}{4\pi d_0}\right)\left(\frac{d_{sr}}{d_0}\right)^{-k/2}$ [21]. λ_c refers to the carrier wavelength, d_0 used as the reference distance, d_{sr} as the distance between source and relay and k is the path loss factor ranging from values 1 to 4. Upon the reception of signal at relay, it first validates the signal through CRC check in order to make its decision on relaying protocol. After applying appropriate relaying protocol, the relay transmits the signal with power P_r as

$$E(|x_r[n]|^2) \leq P_r \tag{5.5}$$

Finally both signal components arriving at destination node are given as

$$y_{sd}[n] = \sqrt{P_{sd}} a_{sd} x[n] + n_{sd}[n], \quad n = 1, \ldots N/2 \tag{5.6}$$

$$y_{rd}[n] = Q_{rd} a_{rd} x_r[n] + n_{rd}[n], \quad n = \frac{N}{2} + 1, \ldots N \tag{5.7}$$

where $x[n]$ and $x_r[n]$ are signals sent by the source and relay respectively. P_{sd} is the power of received signal at destination and can be calculated in the same way as it was for P_{sr} in Eq.5.4, $a_{sd}$and $a_{rd}$are channel coefficients of source-destination link and relay-destination link respectively, n_{sd} and n_{rd} represent the AWGN noise of each channel having zero mean and variance σ_n^2, Q_{rd} is the channel gain of relay-destination link.

The final step of combination of these two signals is done with MRC combining which simply multiplies the conjugate of channel coefficients of the specific link with its corresponding received signal component.

5.3 HARQ Scheme with Switchable Relaying Mechanism

The detailed implementation of Switchable Relaying along-with HARQ scheme is presented in this section. Switchable relaying mechanism gives relay privileges to switch its relaying protocol to AAF or DAF on basis of decoding result. It decodes the received signal by performing CRC test. The correct decoding result leads to the employment of DAF protocol otherwise the relay adopts AAF protocol. The implementation of switchable relaying gives several benefits over fixed relaying protocols. Firstly, the CSI information is not needed to be fed back from destination in order to estimate the channel quality. The CRC check and estimation of received signal SNR make this task simpler; assisting the relay terminal to adapt itself to the channel conditions accordingly by switching its relaying protocol. Secondly, the implementation of SRM does not increase the complexity of the system. It just needs to switch its relaying protocol between AAF and DAF and indicates the receiver about the relaying protocol it has been employed. On the receiver side, the same decoding procedure is required as it was required in fixed relaying protocol.

At destination node, it also examines the received signal through CRC check. After passing the CRC test, it then generates an acknowledgement signal ACK to both source and relay. In case of incorrect decoding result, it generates NACK for both nodes and asks one of them for retransmission.

5.3.1 Type-I HARQ with SRM

For the sake of simplicity, only Type-I HARQ is incorporated with switchable relaying mechanism in the cooperative system. The step by step procedure for whole transmission is detailed as:-

To initiate the transmission, the information signal is broadcasted by source to both relay and destination nodes. The source also keeps a copy of that signal in its buffer. At the relay node, it performs CRC decoding and adopts suitable relaying protocol based on the decoding result. It employs DAF protocol if CRC decoding validates the signal as correct. Otherwise it adopts AAF protocol. After making decision on relaying protocol, the relay forwards the signal satisfying the transmit power constraint.

The destination combines both signals coming from source and relay node with MRC combining method. It applies CRC check on resultant signal to guess the authenticity of received signal. If CRC check produces correct result, it accepts the frame and applies MAP iterative decoding procedure to recover the information bits and sends an ACK signal to both source and relay. As soon as source gets an ACK signal from destination node, the source broadcasts the next frame and then again waits for an acknowledgment signal.

If CRC check is not validated, it stores the erroneous frame in its buffer and initiates the retransmission request. Upon the reception of NACK signal, both source and relay checks the retransmission number if it is even or odd, in case of even number, the source extracts the same frame from its buffer and retransmits the frame. Otherwise, it stays idle so that relay makes retransmission attempt.

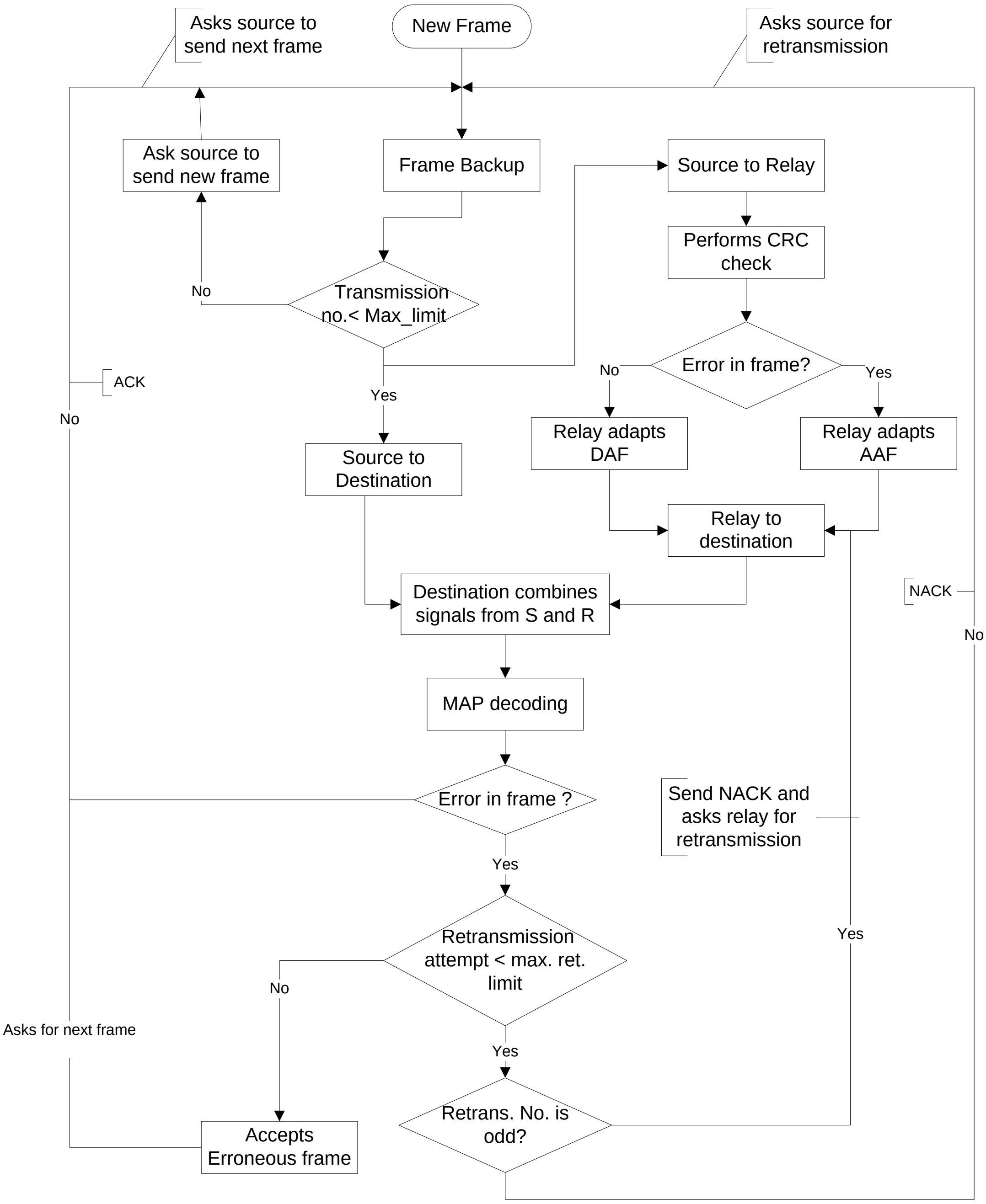

Figure 5.1: Flow Procedure for HARQ Scheme with Switchable Relaying

After the retransmission is made, the destination combines the previously received erroneous packet with freshly received version of the signal and checks the validity of resultant signal through CRC as mentioned earlier. However, the retransmission attempts are limited to maximum number of three. It is essential to put certain limit in order to avoid unacceptable delays during transmission. Source and relay are indicated through retransmission number so that they retransmit on their own turn. In this way, retransmission load remains minimum on each node as only one node has to retransmit at a time. Moreover, the flow procedure of whole transmission is also illustrated in Figure 5.1 containing all steps that occurred in the transmission process of single frame.

5.4 Simulation Results

In this section, simulation results of turbo-coded HARQ based single-hop cooperative system will be presented. To present the fair comparison of proposed single-hop cooperative model with other traditional schemes, the simplest SISO transmission system is developed and enhanced to traditional cooperative system utilizing fixed relaying protocols. Moreover, the performance of an un-coded cooperative system is also analyzed in addition to turbo-coded cooperative systems. All simulations are carried out under the quasi-static Rayleigh fading channel. The simulation parameters considered to extract performance results are summarized in Table 5.1.

In Figure 5.2, the BER curve of Turbo-coded SISO system is shown over SNR range of 0-20dB, assuming the same simulation parameters as presented in Table. 5.1. Due to the direct transmission, the intermediate and relay channels not need to be simulated. Figure 5.3, presents the performance comparison of un-coded CS, turbo-coded CS with AAF protocol and turbo-coded CS with DAF protocol. As the SNR of channel increases, both turbo-coded cooperative systems clearly outperform the un-coded cooperative system as coding gain is added to the system with the induction of turbo codes. At 10dB SNR, both coded cooperative systems achieve gain of 2-5dB in comparison to un-coded system.

Table 5.1: Simulation Parameters

Frame length	12 guard bits 32 training bits 1024 data and parity bits 32 CRC bits	1100 bits 550 symbols (QPSK)
Channel Encoder	Rate: Generator matrix: Interleaver:	1/3 rate turbo code [1 1 1 1] and [1 1 0 1] Random Interleaver
SNR range	Intermediate channel : Direct channel: Relay channel:	6dB, 12dB and 0-20dB 0-20dB 0-20dB
Type of channel	Data Channel: Feedback Channel:	Quasi-static Rayleigh Error free
Modulation	QPSK	
Turbo Decoder	Type: Number of Iterations :	Iterative MAP decoder 20
CRC Decoding	Type:	CRC-32
HARQ	Type :	Type I HARQ
	Retransmission limit:	3
No. of Frames No. of Trials	300 100	

The BER curve of turbo-coded HARQ based cooperative system in Figure 5.4 is compared with those of already presented in Figure 5.3. It shows tremendous

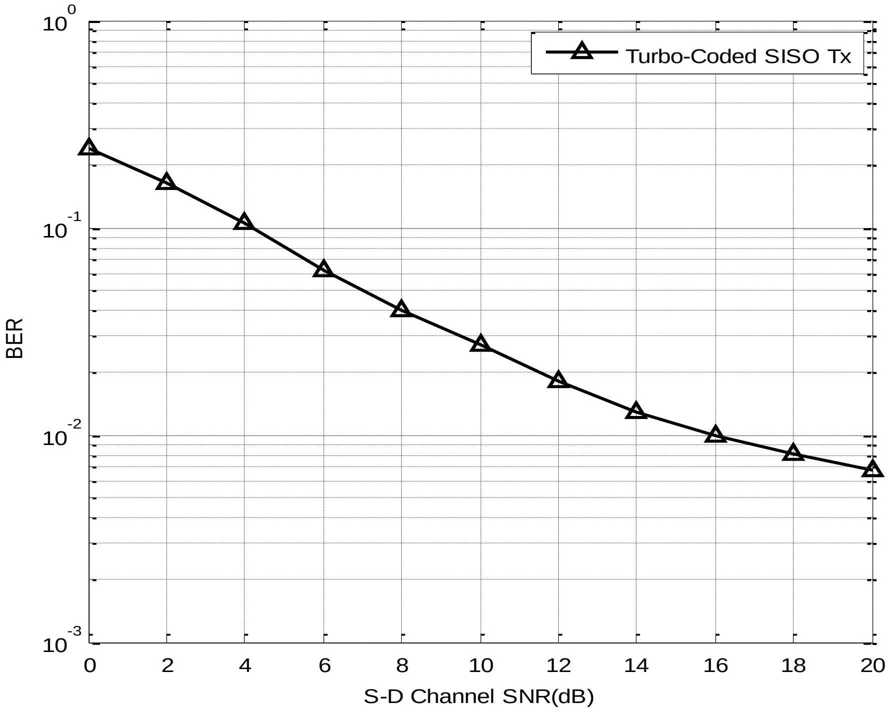

Figure 5.2: BER Curve of Turbo-Coded SISO Transmission

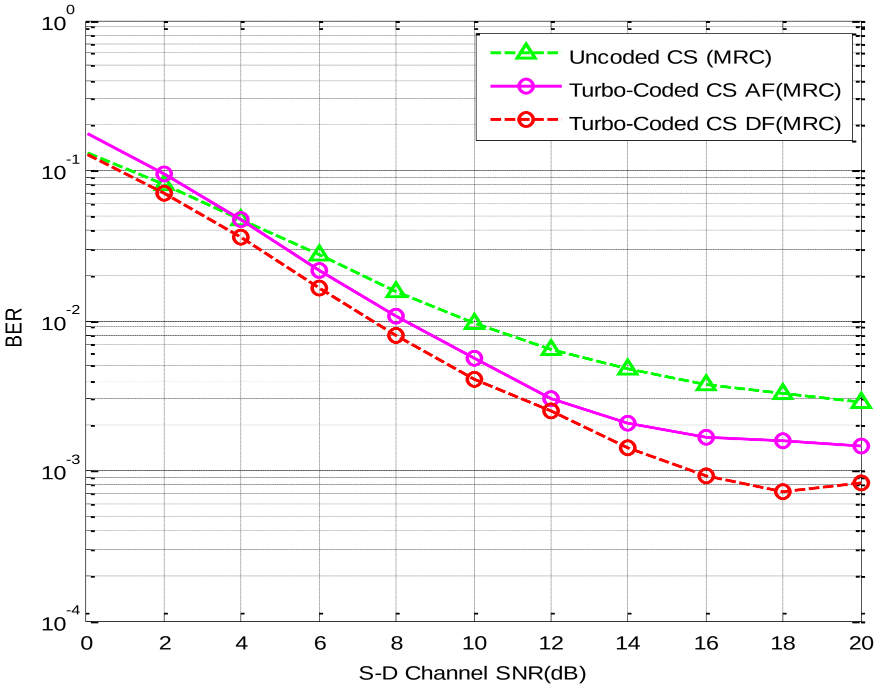

Figure 5.3: BER Comparison of Un-Coded and Turbo-Coded Cooperative System at Intermediate Channel SNR of 6dB

improvement as it achieves almost 4-6dB gain in comparison to Turbo-coded cooperative systems employing AAF and DAF protocols even at SNR 8dB of source-to-destination link, mainly due to the induction of retransmission mechanism provided by HARQ scheme. Moreover, the BER curve of reference scheme Two-Level ARQ Turbo-coded cooperation taken from research paper titled ‘Two-level HARQ for Turbo Coded Cooperation’ by H.Fares and C. Langlais [35] is also compared with simulated version of turbo-coded HARQ based cooperative system and it is observed that both performs nearly to each other.

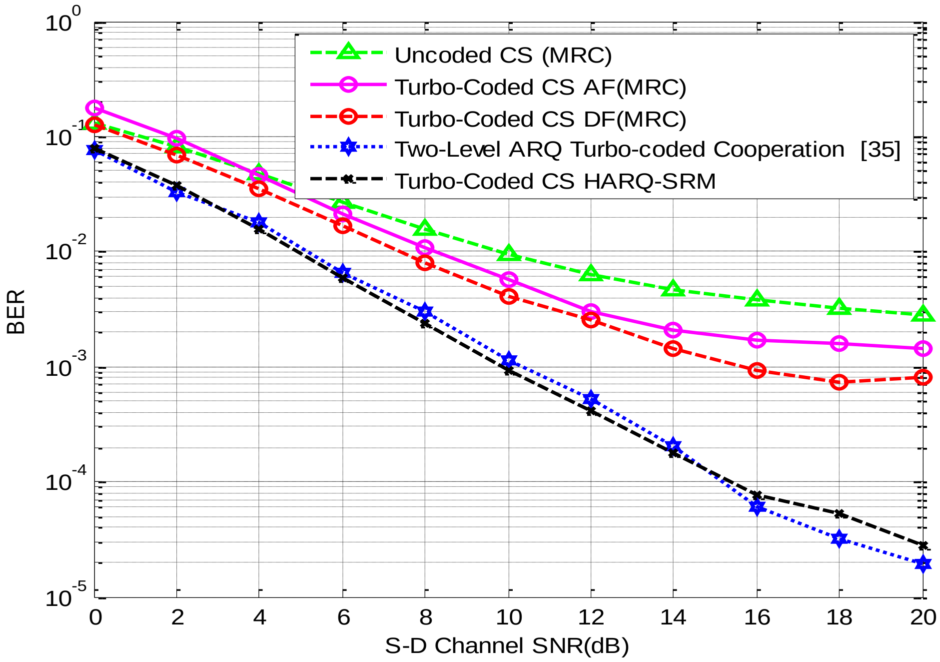

Figure 5.4: BER Comparison of Simulated Turbo-Coded HARQ-SRM with Traditional Cooperative Schemes at Intermediate Channel SNR of 6dB

Figure 5.5 shows the BER comparisons of same un-coded CS, turbo-coded CS (AAF) and turbo-coded CS (DAF) systems with intermediate channel SNR of 12dB. The superiority of coded cooperative systems over un-coded system is still prominent in the performance graph. However, the performance of the system utilizing DAF protocol is considered better with very little gain margin in comparison to system utilizing AAF protocol.

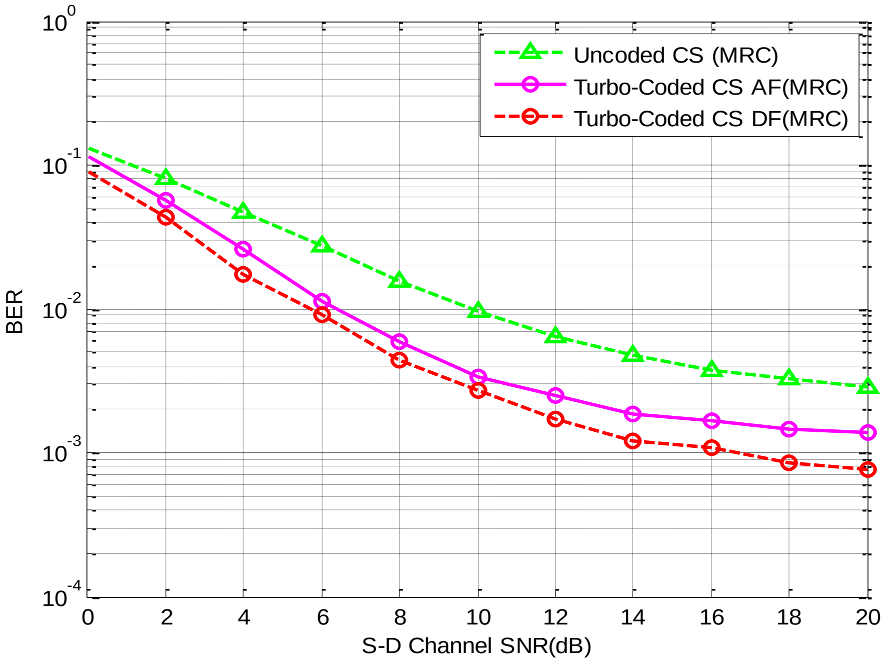

Figure 5.5: BER Comparison of Un-Coded and Turbo-Coded Cooperative System at Intermediate Channel SNR of 12dB

Figure 5.6 brings turbo-coded HARQ cooperative system into consideration for performance analysis at 12dB SNR of intermediate channel. The outcome of rise in intermediate channel SNR from 6dB to 12dB can be clearly observed in the figure which not only put traditional cooperative scheme far behind but also performs well than Two-level ARQ Turbo-coded cooperation [35] with marginal dB gain up till 16dB SNR of intermediate channel . However from that point, BER performances of both versions override each other. The main aim of comparison between reference scheme and simulated version is to show that simulated system is equivalent to system taken from research paper.

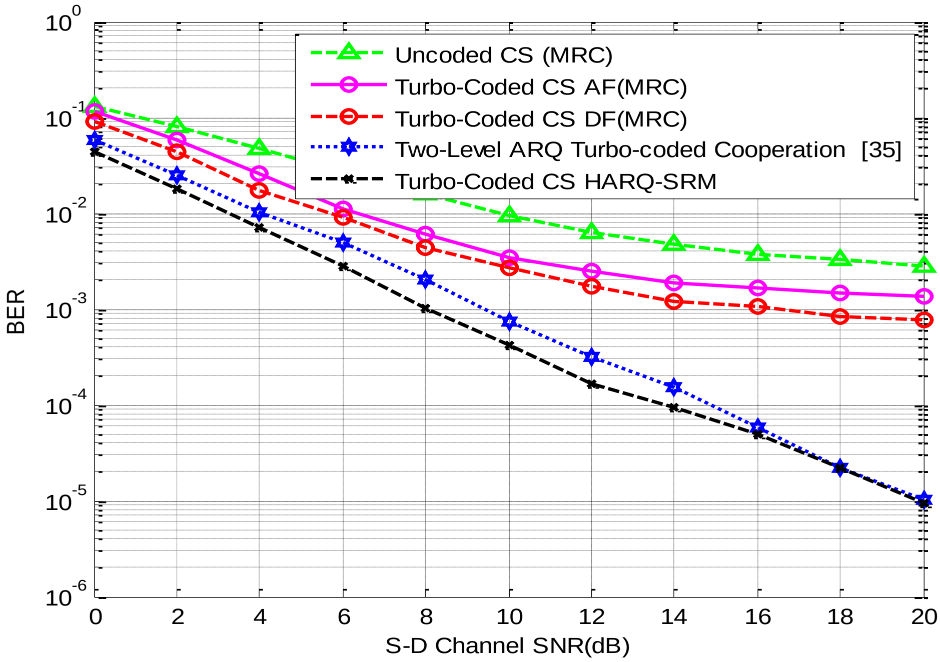

Figure 5.6: BER Comparison of Simulated Turbo-Coded HARQ-SRM with Traditional Cooperative Schemes at Intermediate Channel SNR of 12dB

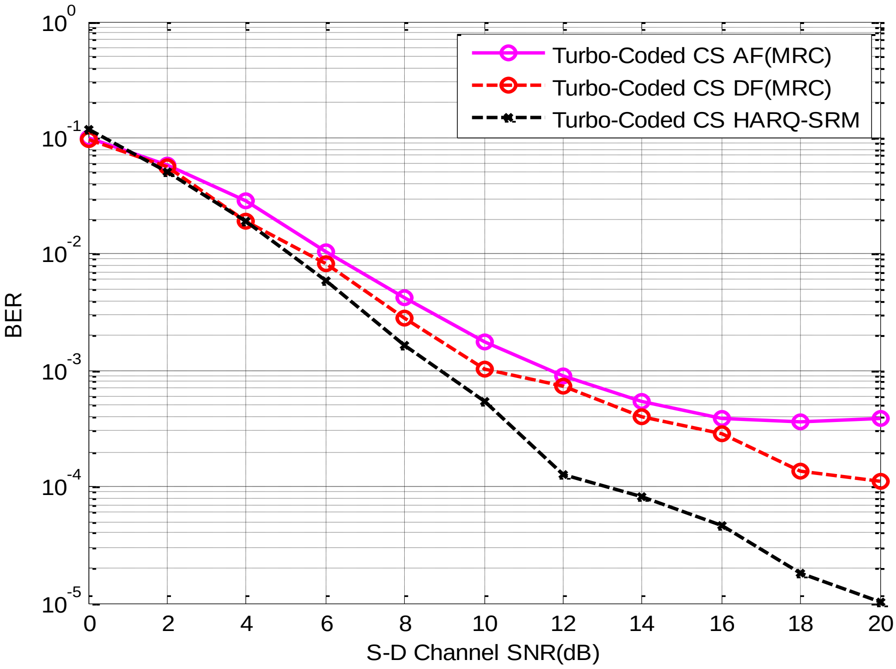

Figure 5.7: BER Comparison of Simulated Turbo-Coded HARQ-SRM with Traditional Cooperative Schemes at Intermediate Channel SNR Range of 0-20dB

In Figure 5.7, BER curves are compared, considering all three channels having SNR range that varies from 0 to 20dB. Hence, proves the consistency of simulation results that have been presented earlier in this section assuming different intermediate channel SNR values.

Figure 5.8 summarizes the main theme of this chapter by presenting fair comparison of turbo-coded HARQ based single-hop cooperative systems at intermediate channel SNR values of 6dB, 12dB and 0-20dB. It is observed that the results taken at SNR 12dB are superior to other curves till 11dB SNR of direct channel. Right from that point, BER curve carried out at 0-20dB intermediate channel SNR overtakes other curves and performs very near to curve taken at 12 dB intermediate channel's SNR. It proves the significance of intermediate channel SNR on the system performance. The impact of lower SNR values in 0-20dB range on the performance is noticeable for all three simulated cases.

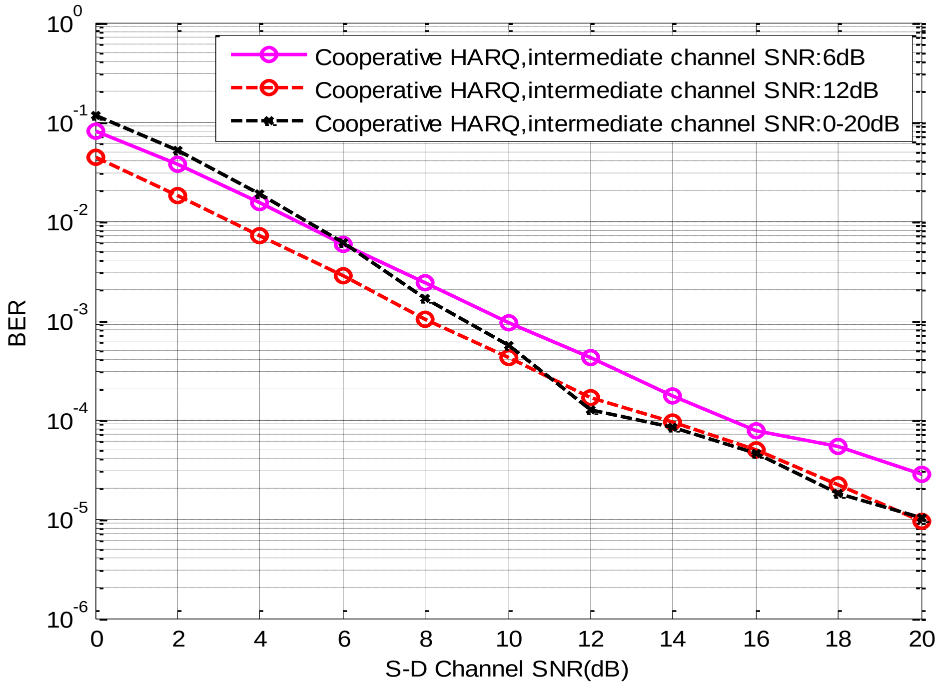

Figure 5.8: BER Comparison of Simulated Turbo-Coded HARQ-SRM at Intermediate Channel SNR of 6dB, 12dB and 0-20dB

5.5 Conclusion

This chapter focuses on the development of turbo-coded HARQ based single-hop cooperative wireless system. The system model and complete flow procedure for retransmission mechanism with switchable relaying is discussed in detail. Through simulation results it is shown that turbo-coded cooperative system employing fixed relaying protocols always perform better than SISO and un-coded cooperative systems. With the induction of retransmission strategy, the cooperative system achieves lower BER as compared to other cooperative scenarios over different SNR range. To conclude the chapter, three BER curves of established cooperative system are compared over different intermediate channel SNRs to judge the impact of given intermediate channel SNR on the system performance. Thus established cooperative system provides us the perfect platform to enhance this model to multi-hop cooperative system utilizing two intermediate relays.

Chapter 6

DEVELOPMENT OF TURBO-CODED HARQ BASED MULTI-HOP COOPERATIVE SYSTEM

6.1 Introduction

This chapter uses the foundation that has already been laid by the previous chapter in order to develop multi-hop cooperative system under the same simulation parameters. The existence of multiple relays between source and destination play a vital role to determine the system performance. In general, the more the relays cooperate with source and destination, the better the performance results are achieved due to diversity effect but at additional complexity and cost. With the employment of additional relays, robust algorithms for routing of information signals will be needed and channel estimates of each relay channel at destination node will be required, which adds complexity to the system. To conclude this research wyork, simulation results of proposed turbo-coded HARQ based multi-hop cooperative system model are presented and compared with those of turbo-coded HARQ based single-hop cooperative system. Just like the single-hop cooperative system, the multi-hop cooperative system is also empowered with switchable relaying mechanism to effectively combat the drawbacks of fixed relaying protocols. The performance comparison is done under different channel SNR values to validate the simulation results.

6.2 Proposed Two-Relay Cooperative System

In this project, a multi-hop system utilizing only two cooperative relays is considered. It is assumed that the second relay gets two editions of the same signal;

the first one from the source and the next one from the previous relay. The cooperative system model for two-relay system is depicted in Figure 6.1. Not bounded to only two relays, this system is scalable to number of intermediate relays that can actively cooperate to exploit the diversity effect. The relay nodes are spatially well separated to provide independent fading channel paths for signal transmission. While zero mean additive white Gaussian noise with variance N_0 is modeled in this system. In contrast to single relay system, the two relay system requires three time slots for transmission to take place. In the first phase, the source broadcasts the signal which is received by both intermediate relays and destination node given by following equations.

$$y_{sd}[n] = \sqrt{P_0} a_{sd} x[n] + n_{sd}[n] \tag{6.1}$$

$$y_{sr_i}[n] = \sqrt{P_0} a_{sr_i} x[n] + n_{sr_i}[n], \qquad 1 \leq i \leq N, \tag{6.2}$$

where P_0 is the source transmit power and $x[n]$ is the transmitted signal. In Eq.6.2, the variable i vary from 1 to N relays. In proposed model, i will be 2 as two relay nodes will be employed in between the source and destination nodes, given as

$$y_{sr_1}[n] = \sqrt{P_0} a_{sr_1} x[n] + n_{sr_1}[n], \tag{6.3}$$

$$y_{sr_2}[n] = \sqrt{P_0} a_{sr_2} x[n] + n_{sr_2}[n], \tag{6.4}$$

The channel coefficients of source-destination link and source-relay links are represented by a_{sd}, a_{sr_1}, and a_{sr_2} respectively. The terms n_{sd}, n_{sr_1}, and n_{sr_2} represents the AWGN of channels.

The relay R_1 applies decoding procedure through CRC just like it did in single-hop system. Depending on the result, it switches its relaying protocol to either AAF or DAF. After it transmits in the next phase, the second relay R_2 combine both signals coming from source and the previous relay and exploits diversity even before the signal reaches its ultimate destination which is given by

$$y_{r_2}[n] = \sqrt{P_0}a^*_{sr_2}x[n] + \sqrt{P_1}a^*_{r_1r_2}y_{sr_1}[n] + n_{sr_2}[n] + n_{r_1r_2}[n], \tag{6.5}$$

where $a^*_{sr_2}$and $a^*_{r_1r_2}$ are conjugates of source-relay2 and relay1-to-relay2 channel coefficients in order to perform MRC combining of both signals coming from source and previous relay.

Again CRC decoding procedure is applied at relay *R₂* for relay protocol selection, and forwards the processed signal to its ultimate destination where it combines all three versions of the same signal coming from source, relay R_1 and relay R_2 as where P_0,P_1,P_2 are the transmit powers of source, relay *1* and relay *2* respectively. Once again, the complete flow procedure for multi-hop system is elaborated in Figure 6.2.

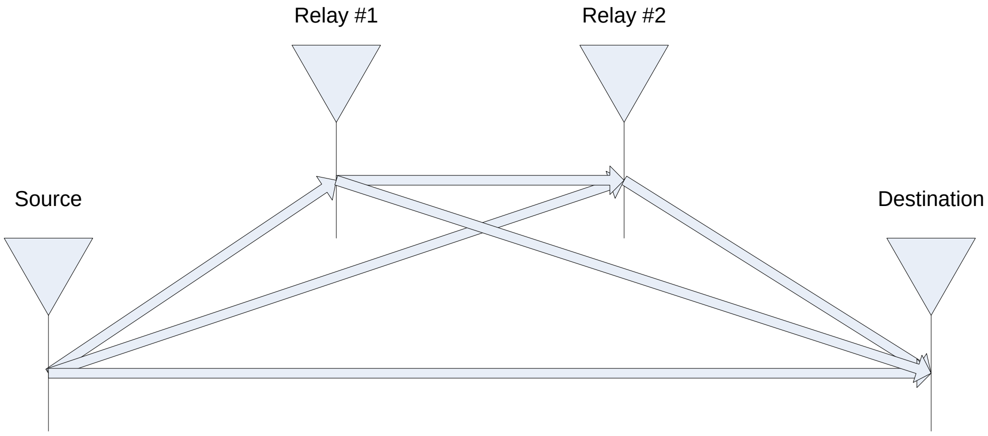

Figure 6.1: Multi-Hop Cooperative Communications Model with Two Relays

$$y_d[n] = \sqrt{P_0}a^*_{sd}x[n] + \sqrt{P_1}a^*_{r_1d}y_{sr_1}[n] + \sqrt{P_2}a^*_{r_2d}y_{r_2}[n] + \widetilde{N} \tag{6.6}$$

$a^*_{r_1d}$ and $a^*_{r_2d}$ are the respective channel coefficients of relay*1*-destination and relay*2*-destanation link. While $x[n]$ is signal transmitted by the source, $y_{sr_1}[n]$ by relay *1* and $y_{r_2}[n]$ by relay *2*. $\widetilde{N}$ is the resultant noise at the destination.

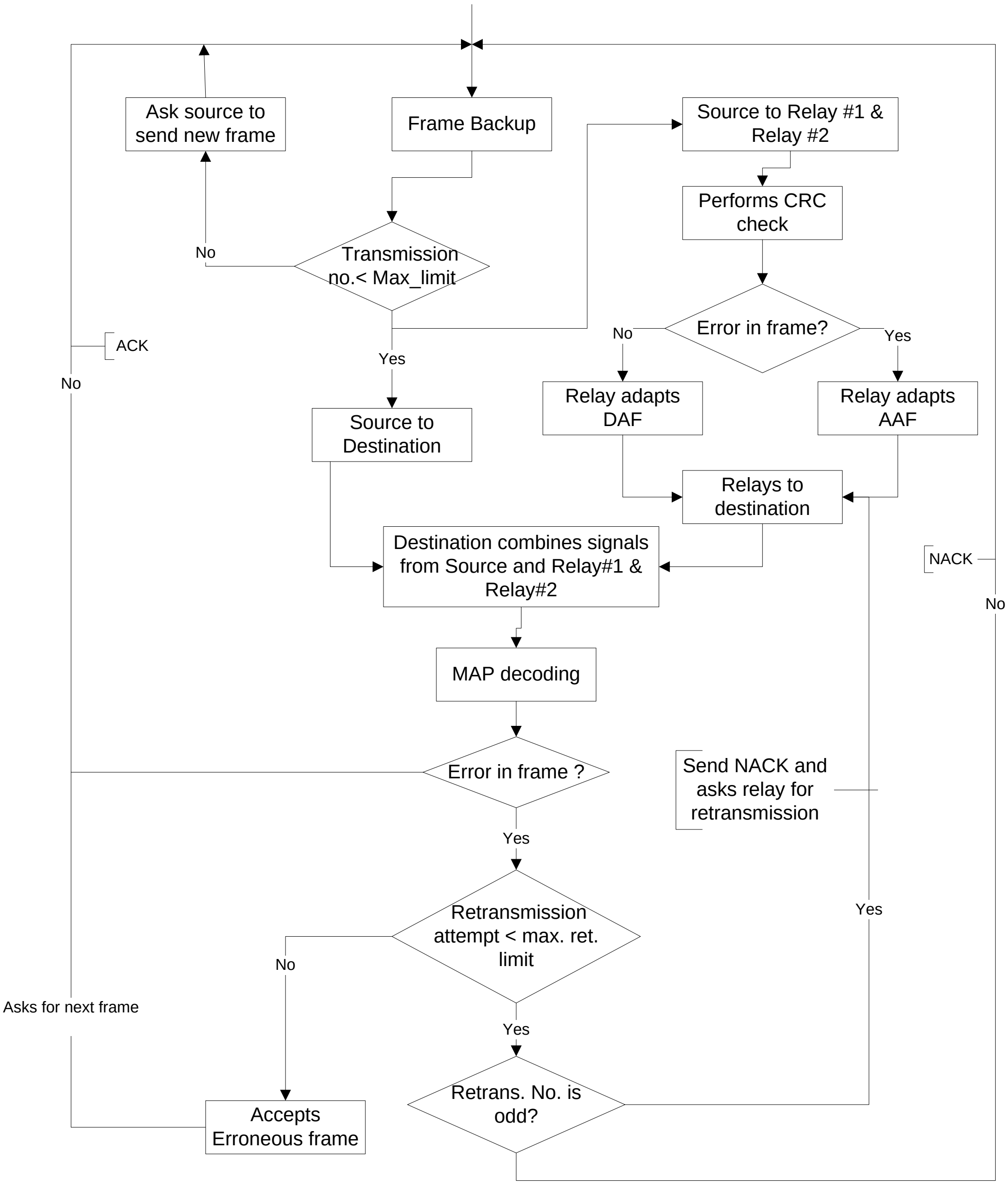

Figure 6.2: Flow Procedure for HARQ Scheme in Multi-Hop Scenario

These relays are distributed in an environment, so each channel between any of two nodes behaves independently, providing an opportunity to have highly uncorrelated signals at the receiver terminal. These uncorrelated signals when combined, contribute to obtain better resultant signal than individual signal in point-to-point communications. The simulation results of multi-hop cooperative system with dual relays are analyzed and compared with reference cooperative schemes in the next section.

6.3 Simulation Results

In this section, simulation results of turbo-coded HARQ based multi-hop cooperative system will be presented. BER performance curves are carried out by considering an additional relay in the single-hop cooperative system that has already been developed in the previous chapter. Thus, multi-hop cooperative environment is simulated under the same simulation parameters as it were assumed for simulation of single-hop cooperative system. However, this time an additional channel between two intermediate relays is introduced with the evolution of cooperative system from single relay to double relay. That particular channel is also termed as intermediate channel along-with other intermediate channel representing the link between source and relay1.

Figure 6.3 presents the comparison between the BER curves of Turbo-coded HARQ based multi-hop cooperative system and single-hop cooperative system at intermediate channel SNR of 6dB. Apart from 6dB direct channel SNR, the multi-hop BER curve seems to be better than single-hop BER curve for whole direct channel SNR range. At direct channel SNR of 8dB, it achieves almost 1dB SNR gain with respect to single-hop BER curve.

Another comparison of multi-hop and single-hop scheme is made at intermediate channel SNR of 12dB in Figure 6.4. The multi-hop system again performs slightly better than single-hop system at whole direct channel SNR range. At 8dB direct channel SNR, multi-hop system outperforms the single-hop system by almost 2dB

SNR and continues its course till the end. It purely justifies the use of multiple relays in the cooperative system tending to bring further improvements in the system.

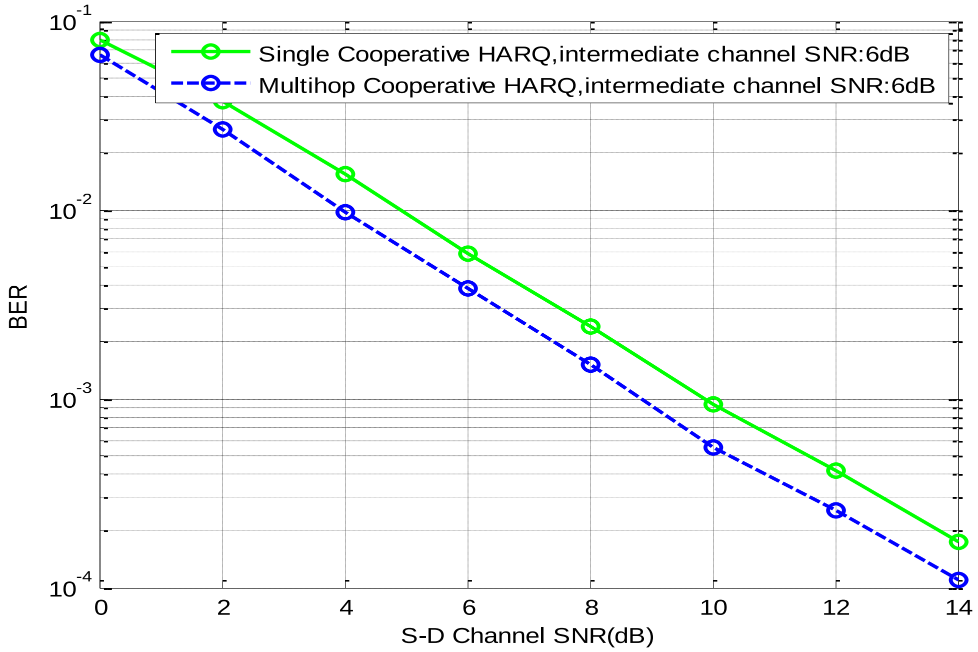

Figure 6.3: BER Comparison of Proposed Multi-Hop and Single-Hop Cooperative Systems at Intermediate Channel SNR of 6dB

The improvement in BER curve for multi-hop case in comparison to single-hop cooperative system is more evident in Figure 6.5 where both direct and intermediate channel SNR are varied from 0-14dB. For the whole course of SNR range, multi-hop system clearly outperforms the BER curve of single-hop cooperative system.

Finally Figure 6.6 summarizes whole discussion by presenting a fair comparison between turbo-coded HARQ based multi-hop cooperative system at different SNR values of intermediate channel. The BER curve taken at intermediate channel SNR of 6dB is relatively high in contrast to two other curves as it already has been experienced in single-hop performance curves. The influence of intermediate channel SNR on system performance is evident from simulation results.

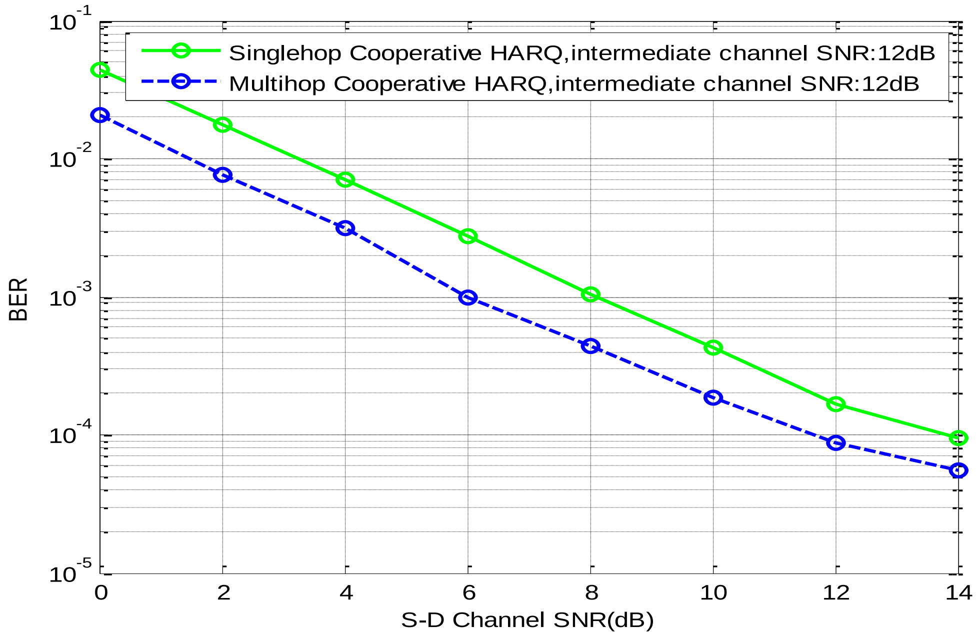

Figure 6.4: BER Comparison of Proposed Multi-Hop and Single-Hop Cooperative Systems at Intermediate Channel SNR of 12dB

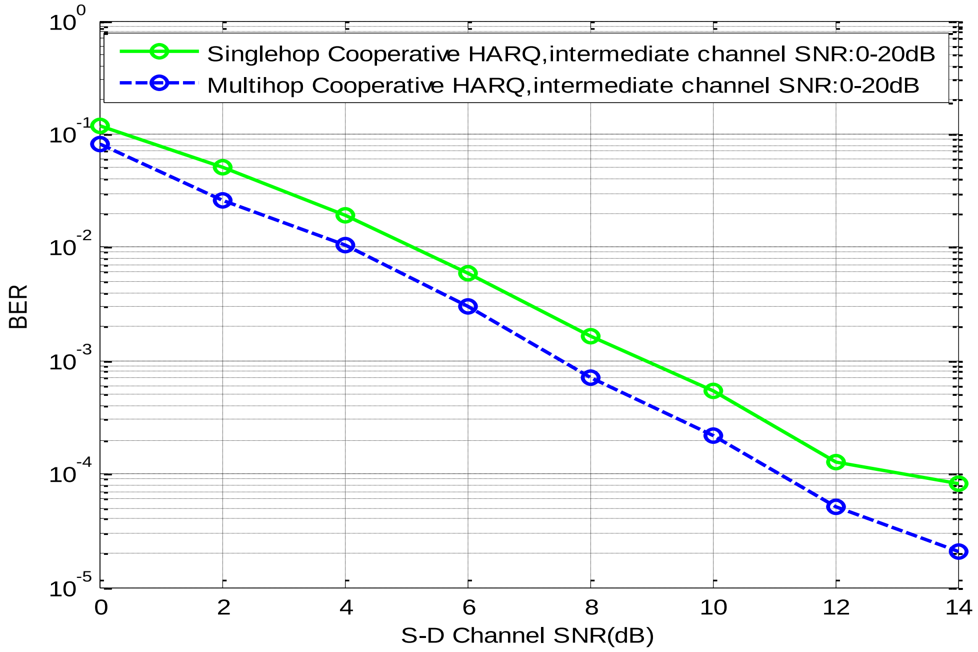

Figure 6.5: BER Comparison of Proposed Multi-Hop and Single-Hop Cooperative Systems at Intermediate Channel SNR Range of 0-20dB

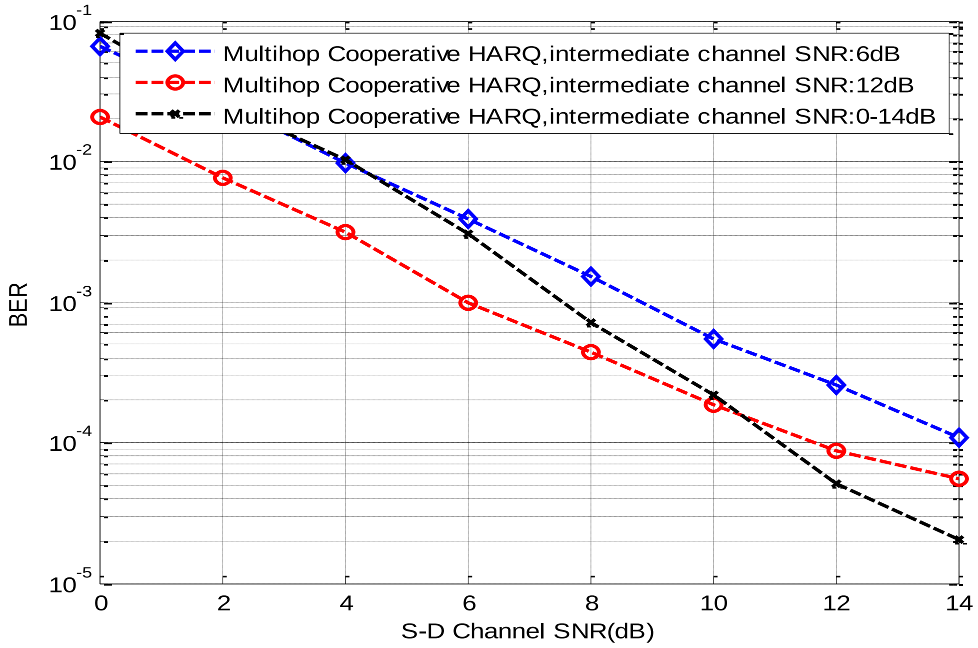

Figure 6.6: BER Comparison of Proposed Multi-Hop Cooperative Systems at Intermediate Channel SNR of 6dB, 12dB and 0-20dB

The case with intermediate channel SNR of 0-14dB crossovers the other two curves at 5dB and 10dB SNR of S-D channel justifies the impact of variation in intermediate channel SNR.

6.4 Summary

This chapter focuses on the performance evaluation of proposed scheme of turbo-coded HARQ based multi-hop cooperative system through matlab simulation. The performance curves are obtained for different intermediate channel SNR values and compared with the results of single-hop cooperative scheme which have already been achieved in the previous chapter. Both schemes are compared assuming same simulation parameters and it is shown that proposed model performs better than single-hop scheme in all SNR regions. Intermediate channel SNR value is kept changing to 6dB, 12dB and 0-20dB in order to validate the simulation results. These results purely justify the use of multiple relays in the cooperative system tending to bring improvements in the system performance.

Chapter 7

CONCLUSION AND FUTURE WORK

7.1 Summary of the Work

Unlike MIMO systems, Cooperative wireless systems utilize the existence of multiple wireless devices offering their antennas for signal processing without the need to employ those antennas on single wireless terminal. The main theme of this research work is to empower the cooperative wireless system by utilizing multiple relays that exist in some specific cooperative paradigm. The implementation of turbo codes and hybrid automatic repeat request scheme with an adaptive relaying protocol makes the cooperative system more vigorous to face all the odds that usually appear in wireless communication channels.

First three chapters provide the fundamental background of the research work. Chapter 1 provides the broad insight to research background, motivation, identifies the research problem and defines the targeted goals to be achieved at the completion of this project. Chapter 2 explains the fundamental concepts related to digital communication system, wireless fading channels, channel estimation, and different diversity techniques. Chapter 3 introduces the basic cooperative system model with various fixed and adaptive relaying protocols. It also explains the different signal combing techniques used in cooperative communications. Moreover, the generalized model of multi-hop cooperative system is also presented to conclude the chapter. Chapter 4 mainly focuses on error control schemes that include FEC, ARQ and HARQ mechanism. Under FEC scheme, the design and operation of turbo encoders is discussed in detail. For decoding, MAP iterative decoding algorithm is presented and decoding complexity of MAP algorithm is also discussed. ARQ schemes are introduced as retransmission strategy to add reliability to the system. Finally the discussion takes on proposed HARQ strategy which utilizes both error correction and retransmission mechanism in form of Turbo codes and ARQ scheme to boost up the system performance.

Chapter 5 integrates the FEC and ARQ technologies into single-hop cooperative communication system. The flow procedure for working of HARQ strategy in cooperative system is explained and illustrated through flow diagram. For performance analysis, the single-hop cooperative model is designed from scratch and simulated under various intermediate channel SNR values and then compared with the reference scheme to validate simulation results on single-hop level. The results are direct indication of prospects of making this single-hop system more reliable and efficient through development of multi-hop cooperative systems.

Chapter 6 proposes to enrich the cooperative wireless system developed in previous chapter by means of additional relays. The model for two relay system is presented and flow of signal transmission in multi-hop system is discussed in detail. With the aid of additional relay in the system, multi-hop cooperative system is shown to perform better than all other single-hop schemes in all SNR regions. The performance merit selected to compare the results is Bit Error Rate.

7.2 Conclusions

As the research problem outlined in first chapter, the use of multiple relays in cooperative system is justified by examining performance curves based on BER merit. The development of turbo-coded single relay cooperative system shows the superior

BER over un-coded cooperative systems. On the next level, the induction of retransmission scheme makes the single-hop system more robust, reliable and effective than traditional cooperative systems. The initial development of single-hop cooperative system makes the implementation of multi-hop cooperative system rather simpler and easier. Turbo-coded HARQ based multi-hop cooperative system aims to exploit the existence of multiple relays in a certain environment to achieve high diversity effect in comparison to single-hop cooperative system. The performance of proposed scheme is evaluated over different range of intermediate channel SNR which justifies the usage of multiple relays for betterment of cooperative systems with minimum computational complexity, cost, and timing delays. In addition to BER improvement, the proposed multi-hop cooperative system promises to improve the coverage range of the system. It is possible with the serial configuration of intermediate relays that is considered in proposed model.

7.3 Future Work

In this thesis, multi-hop cooperative system utilizing two relays is considered, but the general model of the system depicts that the system is scalable to number of relays. In practical scenario number of relays can be effectively utilized with turbo-coded HARQ scheme to make the system performance even better. Moreover, power allocation, path selection, puncturing patterns, need to be optimized to bring further improvements. It will be promising challenge that can be taken as future research. To provide higher throughput and lower code rate, incremental redundancy is supposed to be implemented with HARQ protocol. Though, it helps to achieve higher throughput but its decoding complexity grows as number of information bits grow and code rate gets low [60]. Luby [61] bypassed this drawback by coining the term rateless codes, which are better known as Luby Transform (LT) codes, which are quite different from puncturing patterns as used in incremental redundancy. These codes make use of an infinitely long stream to encode and transmit the source information. These codes make the system capable of recovering the actual information from unordered subsets of the code-stream. Therefore it would be a challenging task to investigate the performance of these codes in multi-hop cooperative communication system.

Partner assignment and management strategies have always been a hot research topic from the birth of cooperative systems. With some prior knowledge of user channels at the central base station, partners could be assigned to optimize the system performance.

BIBLIOGRAPHY

[1] S. Corson, J. Macker., "Mobile Ad-hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations", *IETF RFC2501*, 1999.

[2] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on Sensor Networks", *IEEE Communications Magazine*, vol. 40, Issue: 8, pp. 102-114, August 2002.

[3] P.F. Driessen and G. J. Foschini, "On the capacity for multiple input- multiple output wireless channels: a geometric interpretation", *IEEE Trans. Commun.*, vol.47, pp.173-176, Feb. 1999.

[4] V.Tarokh, N. Seshadri and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction", *IEEE Trans. Inf. Theory*, vol. 44, pp. 744-765, Mar. 1998.

[5] Q. H. Spencer, C. B. Peel, A. L. Swindlehurst and M. Haardt, "An introduction to the multi-user MIMO downlink", *IEEE Commun. Mag.*, pp. 60-67, Oct. 2004.

[6] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity, part I: system description", *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927-1938, Nov. 2003.

[7] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity, part II: implementation aspects and performance analysis", *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1939-1948, Nov. 2003.

[8] J. N. Laneman, D. N. C. Tse and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior", *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[9] Y. Fan and J. S. Thompson, "MIMO Configurations for Relay Channels: Theory and Practice", *IEEE Trans. Wireless Commun.*, vol. 6, no. 5, May 2007, pp. 1774–86.

[10] T. Cover and A. E. Gamal, "Capacity theorems for the relay channel", *IEEE Trans. Inf. Theory*, vol. IT-25, no. 5, pp. 572-584, Sep.1979.

[11] E. C. van der Meulen, "Three-terminal communication channels", *Adv. Appl. Prob.*, vol.3, pp.120-154, 1971.

[12] C. Berrou and A. Glavieux, "Near optimum error correcting coding and decoding: turbo-codes", *IEEE Commun. Mag.*, vol. 22, no. 12, pp. 5-17, Dec. 1984.

[13] S. Lin, D. J. Costello and M. Miller, “Automatic-Repeat-Request error control schemes*”, IEEE Commun. Mag.,* vol. 22, no. 12, pp. 5-17, Dec. 1984.

[14] H. El Gamal and A. R. Hammons, Jr., “Analyzing the turbo decoder using the Gaussian approximation”, *IEEE Trans. On Inf. Theory*, vol. 47, pp 671-686, Feb, 2001.

[15] S. Lin and P. Yu, “A hybrid ARQ scheme with parity retransmission for error control of satellite channels”, *IEEE Trans. Commun.*, vol. 7, no. COM-30, pp.1701-1719, Jul.1982.

[16] E. Y Rocher and R. L. Pickholtz, “An analysis of the effectiveness of hybrid transmission schemes”, *IEEE Trans. Commun.*, vol IBM J. Res. Dev., no. COM-30, pp. 426-433, Jul. 1970.

[17] S. Lin, D. J. Costello, “Error Control Coding Fundamentals and Applications 2nd ed.”, Upper Saddle River, New Jersey: *Prentice Hall*, 2004.

[18] J. G. Proakis, “Digital Communications 4th ed.”, New York, NY: *McGraw-Hill*, 2001.

[19] M. Simon and M. Alouini, *“*Digital Communication over Fading Channels A Unified Approach to Performance Analysis*”*, NewYork, NY: *John Wiley& Sons, INC.*, 2000.

[20] Rodrigues MRD, Chatzigeorgiou IA, Wassell IJ, Carrasco R., “On the Performance of Turbo Codes in Quasi-Static Fading Channels”, *In: IEEE International Symposium on Information Theory*.2005.

[21] Theodore S. Rappaport, “Wireless Communications: Principles and Practice 2nd Edition*”, Prentice Hall*, 2001.

[22] D. Chizhik, J. Ling, P. W. Wolniansky, R. A. Valenzuela, N. Costa and K. Huber, “Multiple-input-multiple-output measurements and modeling in Manhattan”, *IEEE J. Select. Areas Commun.*, vol. 21, pp. 321-331, Apr. 2003.

[23] J. G. Proakis, “Digital Communications 4th ed.”, New York, NY: *McGraw-Hill*, 2001.

[24] M. Miller, B. Vucetic and L. Berry, “Satellite Communications Mobile and Fixed Services”, Boston: *Kluwer Academic Publishers*, 1993.

[25] B. Sklar, “Digital Communications Fundamentals and Applications, 2nd ed.”, Upper Saddle River, NJ 07458: *Prentice Hall*, 2002.

[26] S. Schwartz and M. Schwartz, “Information, Transmission, Modulation and Noise, 2nd ed.” New York: *McGraw-Hill*, 1990.

[27] M. Nakagami, "The m distribution: a general formula of intensity distribution of rapid fading", in *Statistical Methods in Radio Wave Propagation*, W.G. Hoffman, ed., 1960, pp. 3–36.

[28] Valery Ramon, "Performance analysis of turbo equalization with channel estimation", PhD dissertation, University College London (UCL), 2007.

[29] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multiple antennas", *Bell Labs Technical Journal,* vol. 1, pp. 41-59, Autumn 1996.

[30] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas", *Wireless Personal Communications*, vol. 6, pp. 311-335, 1998.

[31] E. Telatar, "Capacity of multi-antenna Gaussian channels", *European Transactions on Telecommunications*, vol. 10, no. 6, Nov./Dec. 1999, pp. 585–595.

[32] *A. B. Carleial, "*Multiple-access channels with different generalized feedback signals*", IEEE Trans. Inform. Theory,* vol. IT-28, pp. 841-850, Nov. 1982.

[33] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing uplink capacity via user cooperation diversity", in *Proc. IEEE Int. Symp. Information Theory (ISIT)*, Cambridge, MA, Aug. 1998, p. 156.

[34] K. Pang, Y. Li, and B. Vucetic, "An improved hybrid ARQ scheme in cooperative wireless networks", *in IEEE Vehicular Technology Conf.*, Calgary, BC, Sep.2008, p 1-5.

[35] H. Fares, C. Langlais, A. Graell and M. Berbineau, "Two-level HARQ for turbo coded cooperation", in *IEEE Vehicular Technology Conf.*, Taipei, June 2010, pp. 1-5.

[36] J.N. Laneman, G.W. Wornell, and D.N.C. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks", *Proc. IEEE ISIT,* Washington, DC, June 2001, p.220.

[37] D. Soldani and S. Dixit, "Wireless Relays for Broadband Access", *IEEE Commun. Mag*., vol. 46, no. 3, Mar. 2008, pp. 58–66.

[38] M. O. Hasna, and M.-S. Alouini, "End-to-end performance of transmission systems with relays over Rayleigh fading channels", *IEEE Trans. Wireless Commun.*, vol. 2, no. 6, pp. 1126-1131, Nov.2003.

[39] M. O. Hasna, and M.-S. Alouini, "Outage probability of multi-hop transmission over Nakagami fading channels", *IEEE Commun. Letters*, vol. 7, no. 5, pp. 216-218, May.2003.

[40] G. K. Karagiannidis, "Performance bounds of multihop wireless communications with blind relays over generalized fading channels", *IEEE Trans. Wireless Commun.*, vol. 5, no. 3, pp. 498-503, March 2006.

[41] G. K. Karagiannidis, T. A. Tsiftsis,and R. K. Mallik, "Bounds for Multihop Relayed Communications in Nakagami-m Fading", *IEEE Trans. Commun*, vol. 54, no. 1, pp. 18-22, Jan. 2006.

[42] C. E. Shannon, "A mathematical theory of communication", *Bell Syst. Tech. J.*, vol. 27,pp. 379–423, Oct. 1948.

[43] P. Elias, "Coding for noisy channels", *IRE Convention Record*, pt.4,pp. 37.47, 1955.

[44] J. Wozencraft, "Sequential decoding for reliable communication", *IRE Natl. Conv. Rec.*, vol. 5, pt.2, pp. 11.25, 1957.

[45] J. Wozencraft and B. Reiffen, "Sequential Decoding", *Cambridge,MA,* USA: MIT Press, 1961.

[46] R. Fano, "A heuristic discussion of probabilistic coding", *IEEE Transactions on Information Theory*, vol. IT-9, pp. 64.74, April 1963.

[47] J. Massey, "Threshold Decoding". *Cambridge, MA,* USA: MIT Press, 1963.

[48] A.Viterbi, "Error bounds for convolutional codes and an asymptotically optimum decoding algorithm*", IEEE Transactions on Information Theory,* vol. IT-13, pp. 260.269, April 1967.

[49] Berrou C., Glavieux A., Thitimajshima P*, "*Near Shannon Limit Error-Correcting Coding and Decoding: Turbocodes (1)", *in IEEE Int. Conf. on Comm. ICC'93*, pp. 1064-1071, vol. 2, 23-26 May 1993.

[50] B. Vucetic and J. H. Yuan, "Turbo Codes: Principles and Applications", Boston: *Kluwer Academic Publishers*, 2000.

[51] S. Benedetto and G. Montorsi, "Design of Parallel Concatenated Convolutional Codes", published in *IEEE Transactions on Communications*, 1996.

[52] Hamid R. Sadjadpour, "Maximum *a posteriori* decoding algorithm for Turbo Codes", *in proceedings of SPIE,* Vol. 4045, 2000.

[53] J. Hagenaure and P. Hoeher, "A Viterbi algorithm with soft-decision outputs and its applications", in *Proc. Globecom'89,* Nov. 1989, pp. 1680–1686.

[54] R. Benice and A. Frey, Jr., "An analysis of retransmission systems", *IEEE Trans. Commun.,* no. CS-12, pp. 135–144, 1964.

[55] J. M.Wozencraft and M. Horstein, "Coding for two-way channels", *Res. Lab. Electron.MIT, Cambridge, MA,* vol. Tech. Rep. 383, Jan. 1961.

[56] J. Hagenauer, “Rate-compatible punctured convolutional codes (RCPC Codes) and their applications”, *IEEE Trans. Commun.*, vol. 36, no. 4, pp. 389–400, Apr. 1998.

[57] S. Kallel, “Complementary punctured convolutional codes and their applications”, *IEEE Trans. Commun.*, vol. 43, pp. 2005–2009, Jun. 1995.

[58] A. Stefanov and E. Erkip, “Cooperative coding for wireless networks”, *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1470-1476, Sep. 2004.

[59] I. Khalil, A.A. Khan and Zohaib-Ur-Rehman, “Turbo-Coded HARQ with Switchable Relaying Mechanism in Single Hop Cooperative Wireless System”, *FIT 2011*, pp.253-257, Dec. 2011.

[60] R. Palanki and J.S. Yedidia, “Rateless codes on noisy channels”, in Proc. *IEEE ISIT’04*, Jul. 2004, p. 37.

[61] M. Luby, “LT Codes”, in *Proc. IEEE STOC’02*, 2002, pp.271-280.