Performance Evaluation of Asynchronous Distributed Space Time Block Coded System for Cooperative Communication

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Submitted By

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CERTIFICATE

I, **Varsha Vimal** hereby certify that the thesis entitled "Performance Evaluation of Asynchronous Distributed Space Time Block Coded System for Cooperative Communication" which is being submitted by me to **Department of Electronics & Communication Engineering, Thapar Institute of Engineering and Technology, Patiala** in fulfillment of the requirements for the award of degree of "Doctor of Philosophy" is a record of bonafide research work carried out under the guidance and supervision of **Asso.Prof. (Dr.) Surbhi Sharma** and **Prof. (Dr.) Rajesh Khanna**. The matter presented in this thesis does not incorporate without acknowledgment any material previously published or written by any other person except where due reference is made in the text.

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This is to certify that the above statement made by the candidate is correct and true to the best of our knowledge and belief.

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Abstract

Cooperative communication has attracted much attention of the researchers for being one of the potential candidates for the 5G and future generations of wireless communications. It forms a virtual MIMO antenna array by utilizing a third terminal called relay which assists the direct communication. Benefits of multiple inputs multiple outputs (MIMO) designed specifically are reaped by the cooperative communication using spatially distributed antennas. The exorbitant cost of multiple antenna installation and system complexity are thus avoided in cooperative communications. There are added advantages of increased data rates, network capacity, reliability, network range, etc at the cost of system and computational complexity. The distributed space time block codes (DSTBC) is a scheme where the signals arriving from the relays are stacked as individual rows of STBC at the receiver. Due to the random spatial positioning and different times of transmission from the relays, the DSTBC system is prone to timing delays, thereby introducing asynchronicity to it. Thus cooperative communications are inherently asynchronous in nature. Several delay tolerant techniques which maintain diversity benefits in asynchronous cooperative communication have been presented in the existing literature.

The objectives formulated and achieved in this thesis are based upon an asynchronous DSTBC (ADSTBC) system which yields diversity and capacity gains in terms of Average Bit error Rate (ABER) and Ergodic capacity respectively, in delay prone environment. The ADSTBC system is designed using Optimized Asynchronous Linear Dispersion (OALD) matrices. The basic system model is improved by employing Optimal Relay Selection (ORS). Results show that the dual relay selection provides significant performance gains in terms of increased diversity and reduced complexity as compared to ADSTBC systems. Also from the results, it is concluded that as the number of candidate relays increase, the performance increase along with.

The error performance of the system improves significantly by concatenating it with powerful error correcting codes such as Low Density Parity Check (LDPC) codes in this work. The concatenated LDPC-ADSTBC system shows enhanced reliability in terms of Outage Probability and Pair wise Error Probability (PEP). The LDPC-ADSTBC system overrides the ADSTBC system in terms of power saving for a given value of performance index/value/criteria. The error performance of the proposed concatenated DSTBC system is compared against another time domain technique TR-STBC designed for asynchronous scenario. The results confirm the better results of the former against the latter. The performance of LDPC-ADSTBC system can further be increased by joint relay and transmit-receive antenna selection (RTRAS) as RTRAS-LDPC-ADSTBC system.

The ADSTBC as well as the concatenated LDPC-ADSTBC systems are analyzed in different fading scenarios such as Rayleigh and Rician. The simulated results show conformity with their analytical versions.

Keywords:

Average bit error rate, average post processed SNR, Distributed space time block codes (DSTBC), Ergodic Capacity, Linear dispersion (LD) codes, Low density parity check (LDPC) codes, Outage probability, Pair wise error probability, Relay Selection, Transmit-receive antenna selection

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(Varsha Vimal)

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List of Acronyms

5G	5th Generation wireless systems
ABER	Average Bit Error Rate
ADSTBC	Asynchronous Distributed Space Time Block Codes
AF	Amplify and Forward
AS	Antenna Selection
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CF	Compress and Forward
CSI	Channel State Information
DF	Decode and Forward
DSTC	Distributed Space-Time Coding
DSTBC	Distributed Space Time Block Code
DSTTC	Distributed Space Time Trellis Codes
D2D	Device to device
iid	Independent and Identically Distributed
IoTs	Internet of Things
LD	Linear dispersion
LDPC	Low Density Parity Check
LLR	Log Likelihood Ratio
LOS	Line Of Sight
LTE	Long Term Evolution
MATLAB	Matrix Laboratory
M2M	Machine to machine
MIMO	Multiple Input and Multiple Output
ML	Maximum Likelihood
mmW	Millimeter Wave
NOMA	Non Orthogonal Multiple Access

OFDM	Orthogonal Frequency Division Multiplexing
OSTBC	Orthogonal Space Time Block Coding
ORS	Optimal Relay Selection
PDF	Probability Density Function
PEP	Pairwise error probability
SNR	Signal-to-Noise-Ratio
STBC	Space Time Block coding
STC	Space Time Coding
STTC	Space Time Trellis Coding
TRAS	Transmit-Receive Antenna Selection
TWDP	Two Wave Diffuse Power
Tx	Transmitter
WiMAX	Worldwide interoperability for Microwave Access
WLAN	Wireless Local Area Networks

List of Symbols

$\mathbb{E}(\cdot)$	Expectation operator
${}_0F_1(;a;z)$	Confluent Hypergeometric function
$K\nu(\cdot)$	νth order modified Bessel function of the second kind
γth	SNR Threshold
ln(.)	Natural Logarithm
$N(\cdot,\cdot)$	Normal distribution
$V(\cdot)$	Variance operator
$\Gamma(\cdot)$	Gamma function
$Q(\cdot)$	Gaussian Q-function
$\mathbf{I}_N$	An N × N identity matrix
$\mathbf{O}_{MN}$	An M× N all zero matrix
$(\cdot)^H$	Hermitian transpose
$(\cdot)^\dagger$	Transpose
$(\cdot)^*$	Conjugate
$\otimes$	Kronecker product
$\mathrm{diag}(\mathbf{X}_1, \ldots, \mathbf{X}_R)$	block diagonal matrix with $\mathbf{X}_1, \ldots, \mathbf{X}_R$ on its diagonal
$\mathrm{Tr}(\mathbf{X})$	trace of $\mathbf{X}$
{}	Expectation
$\Re_k$	k^{th} relay
$\boldsymbol{A}_k$	Linear dispersion matrix for the k^{th} relay
δ_k	Delay experienced by signal sent by the k^{th} relay (integer multiples of symbol duration)
Pr(x)	Probability of occurrence of event x
$\max(\cdot)$	Maximum value
$\mathrm{argmin}(\cdot)$	The argument that minimizes the expression
$\mathrm{argmax}(\cdot)$	The argument that maximizes the expression

List of SCI publications

- Varsha Vimal Sood, Surbhi Sharma and Rajesh Khanna, "Performance Analysis of Joint Relay and Transmit–Receive Antenna Selection for Low Density Parity Check-Asynchronous Distributed Space Time Block Coded Cooperative Diversity System", Wireless Personal Communications, Vol. 92, No. 1, May 2018. **(Impact Factor: 1.2)**

- Varsha Vimal Sood, Surbhi Sharma and Rajesh Khanna, "Pairwise Error Probability Analysis of Low Density Parity Check Coded Asynchronous Distributed Space Time Block Codes", Electronika ir Electrotechnika , Vol.24, No.6, 2018**(Impact Factor: 1.7)**

- Varsha Vimal Sood, Surbhi Sharma and Rajesh Khanna, " Analysis of Asynchronous Distributed Space Time Block Coded System Based on Optimal Relay Selection ", Wireless Personal Communications, Feb 2019. **(Impact Factor: 1.2)**
  DOI : 10.1007/s11277-019-06126-2

Book Chapter: (Scoups indexed)

- Varsha Vimal Sood, Surbhi Sharma and Rajesh Khanna, Performance Evaluation of Cognitive Internet of Things in Asynchronous Distributed Space-Time Block Codesover Two-Wave Diffuse Power Fading Channel, Lecture Notes in Electrical Engineering, Vol. 478, Engineering Vibration, Communication and Information Processing, ICoEVCI 2018, India, Springer.

Chapter 1

Introduction to Cooperative Communications

1.1 Introduction

Wireless communication is developing with a great speed so as to cater to the ever growing demand for newer, faster and more reliable applications and services [1]. The Fifth generation of wireless communications (5G), promise a comfortable and smart living with reduced cost and complexity [2, 3]. The aim of 5G is to provide 100% connectivity and high data rates of the order of several gigabit-per-second (Gbps) to tens of billions of wireless devices by spending 90% lesser energy as compared that used by 4G. There is a need for high data rates along with ultra high reliability which calls for extensive research and innovations at the wireless system design. Multiple-Input Multiple-Output (MIMO) [4] is one such technique which yields spatial diversity and multiplexing due to the co-located multiple antennas at the transmitter and receiver. MIMO is a powerful technique for interference mitigation and reduction. MIMO was part of 3G and existing 4G wireless communications standards like IEEE 802.11n (Wi-Fi), IEEE 802.11ac (Wi-Fi), HSPA+ (3G), WiMAX (4G), and Long Term Evolution (4G),etc and holds potential in future the 5G as in Massive MIMO [5-7]. Hence for future wireless communications, MIMO antenna capabilities are must for associated wireless devices. In order to meet the requirements of next generation wireless communications the wireless networks are preferable to be equipped with MIMO antenna capabilities.

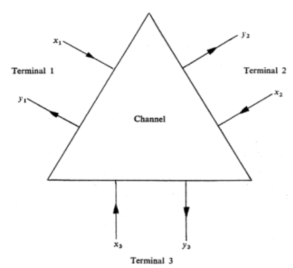
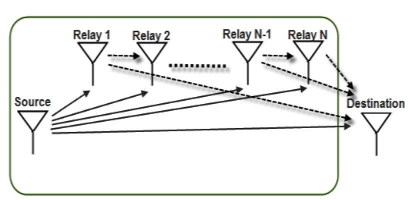
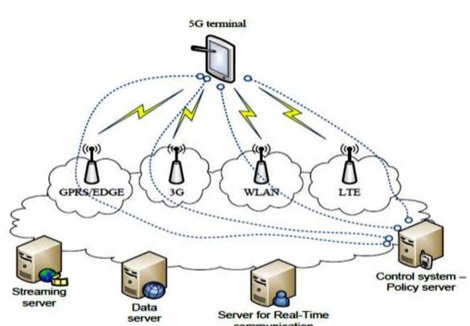
However, there are several scenarios where it is difficult to implement MIMO concept because of the size of the mobile devices, requirement on the distance between antennas, hardware complexity and cost. Also, with the high mobility of the user and evolving of concepts of Device-to-device (D-D) communication in Internet of things (IoT), it becomes difficult to install multiple antennas on the user device. One solution to these challenges is cooperative communication which implements the concept of MIMO in distributed manner. Cooperative communication is thus an alternative cost-effective technique to the MIMO systems where several single-antenna relay nodes share their antennas to achieve spatial diversity.

Cooperative Communication [10] is a technique where devices with single antenna share their antenna with other devices acting as nodes for efficient communication to reap the benefits of MIMO. The neighbouring nodes aid in relaying and range extension, create diversity and multiplexing gains in scenarios where MIMO system cannot be installed. Cooperative diversity has been extensively explored by the researchers which has led to the emergence of various cooperative transmission protocols to further increase the bandwidth efficiency and cooperative diversity. The evolution of cooperative communication is discussed next.

1.2 Evolution of cooperative communications

The journey of the cooperative communications can be sectioned on the basis of theoretical researches and applications [12] is shown in Table 1.1.

Table 1.1: Evolution of Cooperative Communications

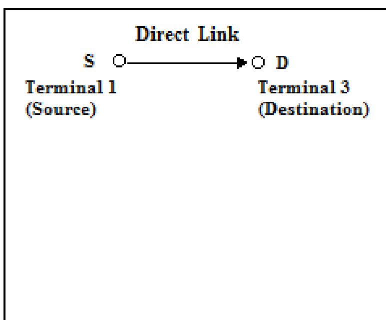
Evolution	System Model	Features
Theoretical foundations of cooperation (70's-80's)		▪ Introduction of relay channel in a three terminal network [9] in 1971. ▪ The subject got a major boost by the works done by [8]and[13].
Extensions to the theory (Late 90's-21st century)		▪ Driven by wireless ▪ Cooperative diversity ▪ Half-duplex/full-duplex ▪ Multiuser channels ▪ Cellular networks ▪ Large networks.
Applications in 5G (probably by 2020)		▪ Abundant DoF ▪ More spectrum (licensed+ unlicensed, mmWave) ▪ More antennas (massive MIMO) ▪ Full-duplex

From the above table it is clear that since the early studies in cooperative relaying, cooperative communication has come a long way through 4G LTE evolution to ad hoc networks, wireless sensor networks, vehicle to vehicle communications, under water communications, cognitive radios, etc [33-38]. Cooperative MIMO has been considered extensively in and hold potential in 5G and next generation wireless communications [7] such as IoT, non-orthogonal multiple access, mmWave technique etc[45-47].

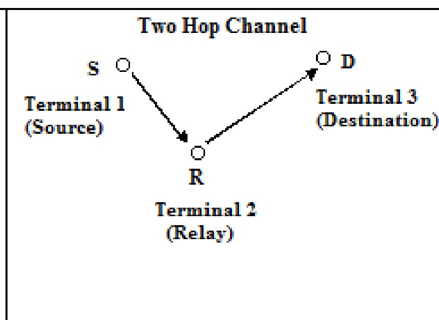
Thus, Cooperative communications is thus a promising technique for the present and future wireless applications given the fact that the cooperating nodes share their resources with each other, thereby leading to savings of overall network resources. Extension in the range of coverage area is another major advantage of the relay channel. For the cooperative systems, selecting an appropriate relay node is of prime importance which is discussed in the next section.

1.3 The Relay Channel

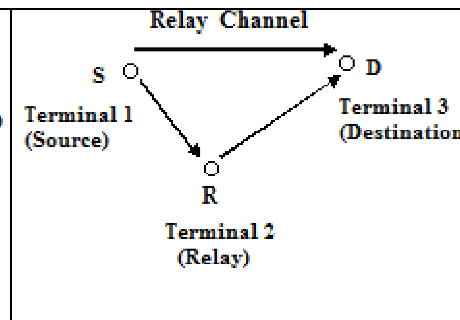
The concept of communication three terminal network, through a relay, first presented by van der Meulen [9] laying the foundation of the *relay channel*. The three-terminal network is the most basic model of the cooperative communication, in which Terminal 2 (relay) cooperates in transmitting the information of the Terminal 1 (source) aims to Terminal 3 (destination). The relay provides an auxiliary channel to assist the communication between the source and the destination by providing another path via itself, other than the direct channel as shown in Figure 1.1.



Direct Link



Two Hop Channel



Relay Channel

Figure 1.1: Direct link, two hop channel and relay channel

Cooperative communication becomes relevant when the source (S) to destination (D) link suffers is poor. It exploits the broadcast nature of a wireless transmission, where the k^{th} relay having good channel condition for $\Re_k$ – D link, re-transmits the over-heard messages to the destination. Cooperative communication thus, in its most basic implementation, helps a failed packet to reach the target destination, thereby improving the communication reliability. Figure 1.2 illustrates the basic block diagram of a cooperative communication system, where communication between S and D can be boosted by multiple relays or helper nodes, denoted by $\Re_1 \cdots \Re_R$. In a case with multiple helpers the destination node D combines multiple signals from all the helpers for detection. Cooperative transmission from the neighbouring relay nodes of an S - D pair enhances the throughput and transmission reliability of system. A basic cooperative system is studied in two phases.

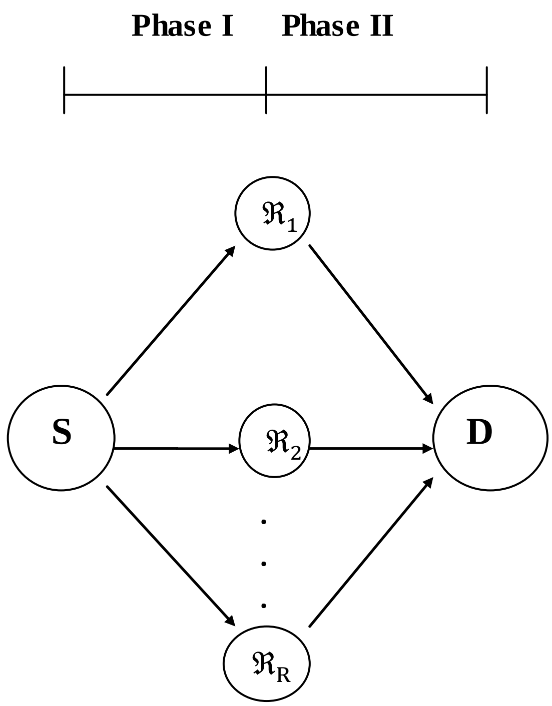


Figure 1.2: System structure for a two-phase cooperative Communications

In Phase I, the source broadcasts information to the relays and to the destination. In phase II, the relays forward the receive signal to the destination. In cooperative communications the users share the role of source and relaying nodes according to the needs of the system application. The ways in which the relays process the received signal and forwards them to the destination are known as cooperative communiaction protocols [14-15]. Various protocols have been introduced so far. The widely used relaying protocols used are summarized in the following section.

1.4 Cooperative Communication Protocols

The cooperative communication protocols are basically categorized as follows

- *Repetition based protocols* [11] -The repetition based relaying protocols process the incoming signals such that the information is repeated while re-transmitting to the destination. These techniques are simple to implement and yield full spatial diversity benefits, but come at a price of decreasing bandwidth efficiency since each relay requires its own sub-channel for repetition.
- *Space-time coded protocol* [22] - This is an efficient technique based upon space–time codes which improves the bandwidth efficiency of the algorithms by allowing all relays to transmit on the same sub-channel. The space time coded techniques yield full spatial diversity benefits without requiring feedback, at the price of added computational complexity.

The details of these two protocols are discussed in the next section.

1.4.1 Repetition based Protocols

The various repetition based protocols are classified in figure 1.3 below.

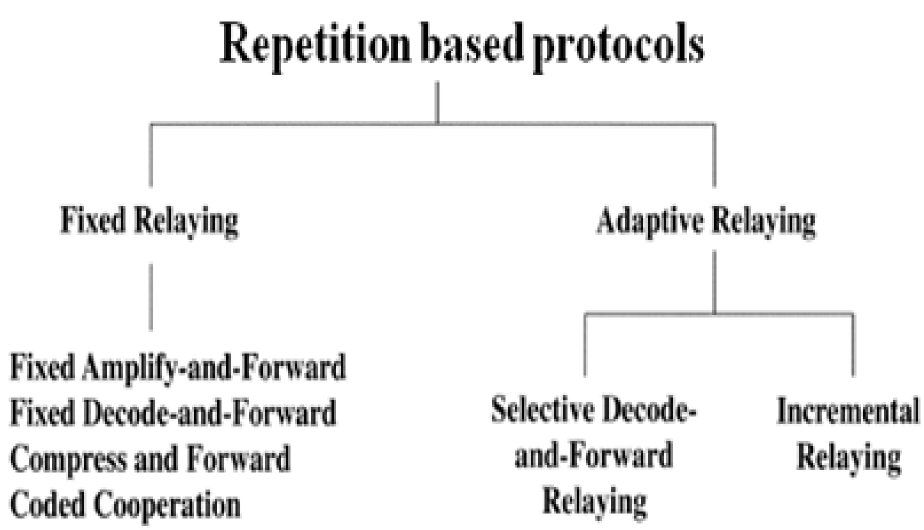


Figure 1.3: Repetition based protocols

1.4.1.1 Fixed Relaying

In fixed relaying schemes, the channel resources are divided in a fixed and pre-determined manner between the source and the relays.

(a) Amplify-And-Forward Relaying

Amplify-and-forward (AF) [11], as the name suggests, is a simple cooperative signaling where each user overhears signal affected by noise transmitted by its partner and then retransmits after amplification as shown in figure 1.4. The amplifying or the scaling factor is made inversely proportional to the received power so as to equalize channel fading effect between the source and the relay. Hence, it is also known as scale and forward relaying.

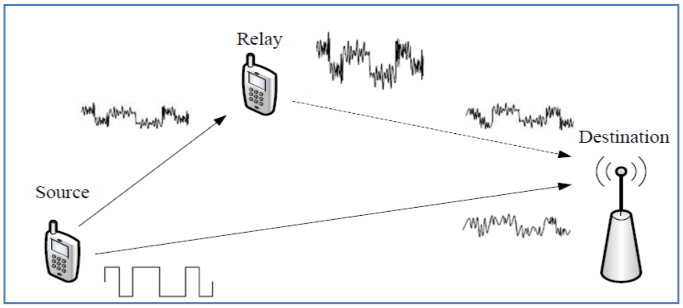


Figure 1.4: Amplify and forward relaying

(b) Decode-And-Forward Relaying

In decode-and-forward (DF) relaying protocol[11], the partner tries to decode the source transmission and then re-encodes the same before retransmitting as shown in figure 1.5. DF technique is optimal when the channel conditions between source and relay are excellent otherwise there are chances of propagating errors.

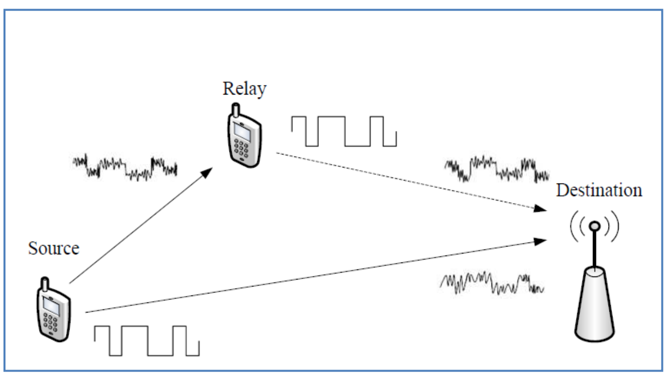


Figure 1.5: Decode and forward relaying

As in AF protocol, the partner provides a second data path in DF as well enriching diversity. Decode and forward relaying provides advantage of noise immunity.

(c) Compress-and-Forward

In Compress-and-Forward (CF) relaying, [14] the received signal at a relay is quantized and compressed using source coding and retransmitted to the destination. This protocol ensures security and capacity in the transmission link. In CF the requirement of decoding at the relay end, is omitted.

(d) Coded Cooperation

Coded cooperation [17] is a technique of harnessing the benefits of channel coding [65] in cooperative communication. Here, the first partition of the codeword or the information bits is transmitted to the partner relay and the destination in the first time slot. The second code partition or the parity bits of partner's code word are generated and sent by a user in the second time slot as shown in figure 1.6 For unsuccessful decoding of partner's second code partition, user transmits its parity bits.

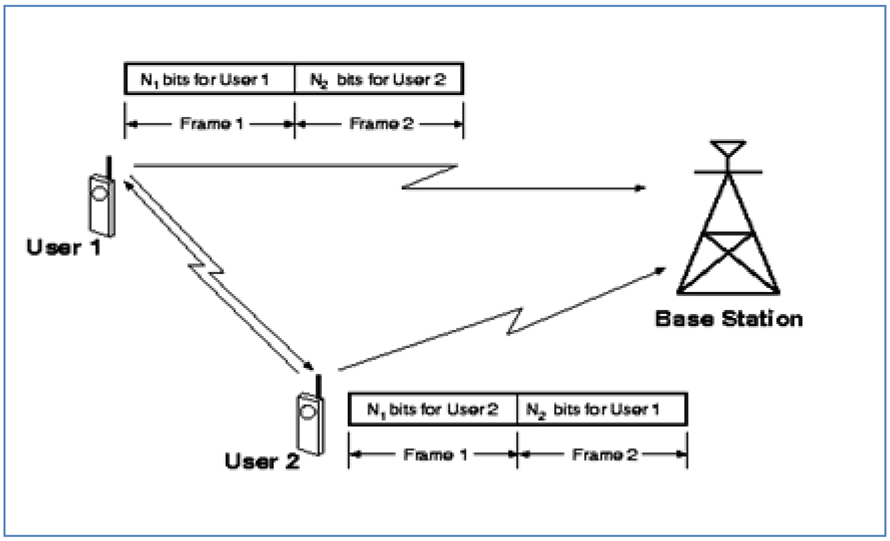


Figure 1.6: Coded Cooperation

Although complex, but coded cooperation is highly efficient since the code design is such that it avoids any sort of feedback. In the second frame of transmission, the users act independently without bothering whether their own first partition was correctly decoded or not.

1.4.1.2 Adaptive cooperation protocols

The fixed protocols have advantage of easy implementation, but they also have disadvantages which are low spectral efficiency and error propagation. There are adaptive cooperative protocols [11][19-20] that try to overcome the disadvantage of fixed protocols category and increase the overall performance. The main adaptive protocols, selective relaying and incremental relaying are discussed next.

(a) Selective Relaying

As the name suggests, in elective relaying technique, only those relays which satisfy certain threshold criteria are selected to retransmit the source message [19]. In case of fixed DF, if the channel between the source and the relay has severe fading then the nodes will detect incorrect symbols and retransmit these incorrect symbols to the destination,. Figure 1.7 shows the block diagram of a Selective Relaying protocol.

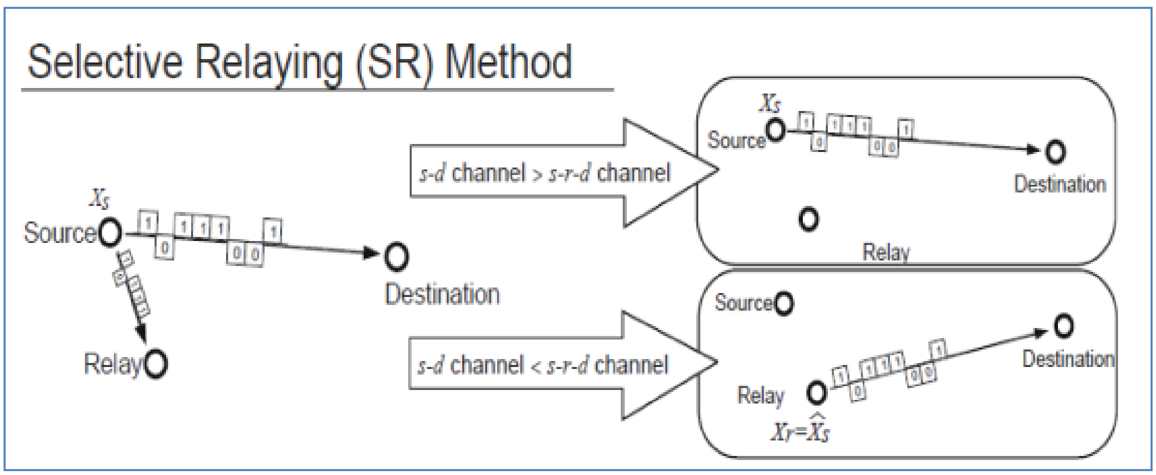


Figure 1.7: Selective Relaying

The error propagation problem is diminished in selective relaying by introducing a threshold value of SNR at the relay node such that if the SNR of the received signal at the relay exceeds the threshold only then the relay participates in the cooperation, otherwise the relay sits idle.

(b) Incremental relaying

In fixed protocol category, even if the destination correctly detects the transmitted symbols in phase 1, the channel resources, such, as the transmitting power, bandwidth etc are divided between the source and relay nodes thereby wasting the resources and reducing the overall data rate of the system. This issue can be overcome by providing feedback information from the destination to the relay nodes. This is called incremental relaying [11].

In this technique, the destination acknowledges the relays through feedback channel whether it receives the transmission of the source in phase 1 correctly. If yes, then the source utilizes the second time slot to transmit new frame, while the relay node is idle. If the source transmission fails in the first phase, any of the fixed relaying protocols may be opted by the relay to forward the source information received in the first phase, to the destination.

In repetition based protocols the information transmitted by the relays make use of separate sub channels, which is an inefficient utilization of the bandwidth .therefore space time coded protocols optimally utilize the bandwidth to improve overall spectral efficiency of the system.

1.4.2 Space Time Coded Cooperative Protocol

Space time coded (STC) system is one where the relays transmit on the same sub channel. In cooperative communications, it relies on the implementation of space time codes in distributed fashion among the relay nodes [21]. This is known as the Distributed Space Time Coded (DSTC) system [22]. The space time block codes (STBC) [23] when implemented in cooperative communications are named Distributed Space Time Block Coded (DSTBC) system[26] . Linear dispersion (LD) matrices [30] play a vital role in the design of STBC exhibiting diversity as well as capacity gains. The signals received from the source to the relays are linearly modulated by multiplying them with suitable LD matrices [31]. The DSTBC system yields the advantages of MIMO such as higher reliability, higher spectral efficiency and higher performance gain, in a distributive topology in cooperative communications [26-29]. The design of LD matrices takes into account several factors depending upon the desired results.

In this work, Optimized Asynchronous Linear Dispersion (OALD) matrices have been used to space time modulate the signals received at the relays. The linearly modulated signals from each participating relay arrive at the receiver as an individual row of the STBC thereby yielding spatial diversity.

1.5 Advantages of cooperation

- **Resource saving-** Given the fact that the cooperating nodes share their resources with each other, thereby leading to savings of overall network resources.

- **Range Extension**- The cooperative communication in its nascent stages was basically a relaying technique. The relays acted as repeaters thereby increasing the coverage area and also overcoming shadowing. Figure 1.1 shows a cellular cooperative system highlighting the role of the relay nodes (RNs).
- **Performance Gains**-The distributed nodes with single antennas cooperatively translate into a virtual MIMO. The pathloss gains, diversity and multiplexing gains can be achieved by cooperation. These performances can be traded off to lower transmission power requirements, depending on the needs of the application./ service
- **Distributed Infrastructure**-There are certain situations or scenarios where deployment of collocated antennas is not feasible such as in ad-hoc networks, or small size of the device, or may be due to cost constraints cooperative communications play a crucial role.
- **Cost effective-**For a given value of QoS cooperative relaying has proved to be more economical than traditional techniques.
- **Mobility-** Cooperative communications provide high performance gains in dynamic and mobile scenarios. Vehicle to vehicle communications demanding high reliability are catered through cooperation.

Along with the numerous advantages, cooperative communication has some challenges such as with extra relay traffic, there is requirement of complex schedulers and tight synchronisation increased overheads in terms of pilot signals, cost, etc. chances of interference and end to end latency also increases.

1.6 Asynchronous Cooperative Communication

Majority of existing literature [26-29] concerned with cooperative communications, consider an idealistic assumption that the signals from various relays arrive at the receiver without any delay i.e are synchronous in nature. However, due to the distributed locations of the cooperating nodes, the signals arriving at the destination are not synchronous. Hence cooperative communication is an inherently asynchronous system [52]. In the existing literature several delay tolerant techniques have been introduced which are categorised into three classes[55][57][62-66] as following:

1. Equalizers
2. Frequency domain approaches
3. Time domain approaches

These are such schemes which provide with diversity benefits despite the delays underlying the systems. These techniques are discussed in chapter 2.

The present work emphasizes on the time domain approach, which represent the techniques exploiting the 'time' dimension to combat the ill-effects of asynchronous communication. The new system proposed in this thesis is designed to meet the following requirements in asynchronous scenarios:

- Yielding capacity and diversity gains.
- Reduction of the system resources and the overall system complexity.
- Reduction of the error floor by channel coding

Keeping above defined challenges in our mind, the following objectives are formulated in this research work.

Objectives

1. To evaluate the performance of Distributed space time block codes in asynchronous cooperative MIMO system
2. To evaluate the performance of Channel coded distributed space time block codes in asynchronous cooperative MIMO system
3. To evaluate the performance of the proposed concatenated DSTBC scheme in Rayleigh and Rician fading channels.
4. To evaluate the performance of concatenated DSTBC in time reversal (TR) and Linear dispersive (LD) structures respectively.

1.7 Contributions of the Thesis

By meeting the requirements of the formulated objectives, the thesis contributes in general, the performance analysis of ADSTBC system. The performance of the system can be improved in terms of coding gain by concatenating with channel codes such as LDPC codes. The LDPC-ADSTBC system thus designed is compared with an LDPC concatenated TR-DSTBC system which is an existing time domain technique used in asynchronous environment. The system resources such as transmit power and complexity is reduced by optimal relays selection (ORS) and joint relay and transmit-receive antenna selection (RTRAS). The system is studied under different fading scenarios by using TWDP fading model whereby Rayleigh and Rician fading are special cases of the former. The main contributions of this thesis can be structured and summarized as follows

Contribution 1:

(a) Design of Optimized Asynchronous Linear Dispersion (OALD) matrices

(b) Performance evaluation and analysis of an Asynchronous Distributed Space Time Block coded (ADSTBC) system based on OALD matrices.

(c) Performance evaluation and analysis of an Optimal Relay Selection (ORS) based ADSTBC system

In this work, Optimized Asynchronous Linear Dispersion (OALD) matrices are designed which are optimized upon tight frame, equal power and rank-determinant criteria for asynchronous environment. The OALD matrices linearly modulate the incoming signal at the relays by simple multiplication. The product signal is made delay delay tolerant by introducing intentional delays and transmitted to the destination using suitable relaying protocol. The signals from different relays are stacked as rows of the Asynchronous Distributed Space Time Block coded (ADSTBC) system at the receiver. The ADSTBC system analyzed on the basis of average bit error rate (ABER) and Ergodic capacity.

The performance of the ADSTBC system improves significantly by optimal relay selection (ORS). ORS leads to power saving as well as increases efficiency, reliability and throughput. The improvement has been evaluated in terms of ABER, average post processing SNR and Ergodic capacity. The results obtained show that both the performance depends on the number of candidate relays.

Contribution 2:

(a) To evaluate the performance of Channel coded distributed space time block codes in asynchronous cooperative MIMO system

(b) To evaluate the performance of Channel coded distributed space time block codes in asynchronous cooperative MIMO system using joint relay and transmit-receive antenna selection (RTRAS)

The ADSTBC system yields diversity and capacity gain but lacks sufficient coding gain. Using channel codes such as Shannon limit approaching Low Density Parity Check (LDPC) codes [76] significant coding gain can be incorporated in the ADSTBC system. In this thesis, the ADSTBC system is concatenated with LDPC codes and thus is known as LDPC-ADSTBC system. Comparative analysis of LDPC concatenated LD based ADTBC and TR-DSTBC has been done and it is observed that LDPC-ADSTBC outperforms concatenated TR-DSTBC system in asynchronous scenarios. The performance of the LDPC-ADSTBC system is demonstrated using pair wise error probability (PEP) as the metric.

The performance of the LDPC concatenated ADSTBC system can further be increased by joint relay and transmit-receive antenna selection (RTRAS) in case of multiple antenna nodes. Upper and lower bounds on outage probability and PEP have been investigated. The performance of RTRAS-LDPC-ADSTBC system is a function of number of candidate relays and antennas.

Contribution 3:

(a) To evaluate the performance of the proposed DSTBC scheme in Rayleigh and Rician fading channels.

(b) To evaluate the performance of the proposed concatenated DSTBC scheme in Rayleigh and Rician fading channels.

The ADSTBC systems are analyzed in different fading scenarios adopting two wave diffuse power (TWDP) fading model. Rayleigh and Rician fading are special cases of TWDP fading channel. The severity of fading channels can be changed by varying the values of certain key parameters of the TWDP fading model. The LDPC-ADSTBC system has been evaluated in terms of PEP in Rayleigh and Rician fading environments.

1.8 Thesis organization

The structure of the thesis is listed as

Chapter I presents introduction to cooperative communication systems, relaying protocols, asynchronous cooperative communications and techniques to combat effects of asynchronous communication. It also presents motivation for research, aims, objectives and organization of the thesis.

Chapter II introduces existing research literature on cooperative communication, asynchronous/delay tolerant techniques, channel codes (LDPC), relay selection, transmit and receive antenna selection and TWDP fading channels.

Chapter III presents design and performance analysis of DSTBC in asynchronous environment. The system is analyzed both mathematically, using Mathematica and by Monte-Carlo simulations using MATLAB. The performance of the system is enhanced by using optimal relay selection (ORS).

Chapter IV deals with design and analysis of LDPC-ADSTBC system. This system provides significant coding gain to the ADSTBC system. This chapter also presents the results for LDPC concatenated ADSTBC and Time –Reversal-DSTBC (TR-DSTBC) systems. The performance of the LDPC-ADSTBC system is increased by adopting joint relay and transmit-receive antenna selection (RTRAS). The mathematical and simulated analyses of the proposed systems have been done.

Chapter V analyzes the Selective Decode and forward based ADSTBC and LDPC concatenated ADSTBC systems in different fading scenarios such as Rayleigh and Rician. Mathematical and simulation analysis of the system is presented.

Chapter VI presents the conclusion and the potential future scope of the research.

Chapter 2

Literature Survey

This chapter is sectioned into four parts. Sections 2.1 presents existing literature related to the cooperative communications, various protocols and applications of cooperative communications. Section 2.2 deals with the asynchronous cooperative communication, and various techniques to combat asynchronism in cooperative communications. Section 2.3 describes channel coding in cooperative communication to improve the performance of the system. Section 2.4 discusses various relay selection and transmit-receive antenna selection techniques in cooperative communication.

2.1 Introduction to Cooperative Communications

The advent of cooperative communications dates back to 1971 with the proposal of a three terminal communication channel by van der Mueulen [9]. Major boost to this field of study was given by authors in [8][13]. The technique of forwarding signals from the relays to the destination is known as relaying protocols. In [11] authors introduced the most popular fixed relaying schemes AF and DF relaying protocols as well as the adaptive incremental relaying. The authors in [14] have investigated the performance of an AF relaying-based MIMO STBC system with a two stage receiver over frequency-selective channels. The authors in [15] discuss the performance of fixed DF and CF relaying protocols. In [16], the authors proposes low complexity decoders for DF MIMO systems. In [17] the error performance of an DF based mobile-to-mobile (M2M) system over *N*-Nakagami fading environment is studied. Coded cooperation, which incorporates channel coding within itself, was introduced in [17]. In [18] the space-time and turbo based coded cooperation is investigated for their error performance. The fixed relaying techniques suffer from non- optimal usage of resources. Varshney et al. In [20] considers an adaptive protocol i.e. selective DF based MIMO-STBC cooperative system using single and multiple relays. Distributed space time coded (DSTC) relaying technique was first proposed by [21]. DSTCs achieve better spectral efficiency than their repetition based protocols by transmitting in the same sub-band but the price paid is higher complexity. STBCs have advantage of being simple and efficient [23-25] and are implemented in the cooperative case as distributed STBC (DSTBC) [26-29]. Linear dispersion (LD) codes are used for the design of DSTBCs because of their inherent simplicity, diversity and capacity gains [30-31]. Having proved a reliable candidate for 4G wireless communication, cooperative communications has secured its place in next generation wireless networks (NGWNs) such as in smart grid, ad-hoc networks, vehicular networks, cognitive radios, etc[32-37]. The potential areas of applications envisioned for the future wireless communications are Device to device and machine to Machine communication in Internet of Things (IoT)[40-44], Non-Orthogonal Multiple Access (NOMA)[46], mmWave and cmWave communications[48], Massive MIMO[50] etc.

2.2.1 Exisiting work on Cooperative communications, relaying protocols and its applications

Cooperative communication, which is viewed as a virtual Multiple-Input-Multiple-Output (MIMO) channel, provides diversity to increase robustness against channel impairments. Since the cooperative communication scheme depends on the relay nodes to forward the transmission, the manner in which the system resources are utilized in a particular relaying protocol becomes a determining factor to obtain optimal performance of the system. A brief overview of relaying protocols and cooperative communication is given below:

Nosratinia et al.in **[10]** introduce wireless cooperative communication as scheme to replicate the benefits of MIMO with single antenna mobiles by resource sharing. Various signalling schemes, design perspectives and their implications laid down in this work are seminal in character.

In **[11] J. N. Laneman et al.**proposed several cooperative protocols including fixed (AF and DF), selection relaying and incremental relaying schemes for single antenna terminals to achieve spatial diversity in cooperative system. The performance characterization is done with respect to outage probability in the high SNR regime. Results show that barring fixed DF, all the proposed protocols achieve full diversity.

Sendonaris et al. in **[13]** used a DF based CDMA framework to propose cooperative algorithms and study their achievable rate regions and outage probabilities. Results show that cooperation leads to capacity gains for users and the rates are less sensitive to channel variations and noise. The first part presents an analytical study that demonstrating a trade-off between capacity and cell coverage. The second part investigates the practical issues related to the implementation of cooperative communication.

In **[14] J. Gao et al.** have analyzed the performance of an AF -based MIMO-STBC with a novel two stage receiver, achieving full diversity order over frequency-selective channels Using the diversity-combining technique, space and multipath diversity can be achieved.

G. Kramer et al. in **[15]** propose decode and forward (DF) and compress and forward (CF) strategies. The DF technique is suitable when the relays are in proximity to the source and the CF scheme work wells in cases where relays are near the destination. Further, the paper shows that DF achieves the ergodic capacity as in many wireless channels, provided the relays are close to the source and availability of phase information is ensured.

Ankur Bansal et al. in **[16]** have derived an maximum likelihood (ML) and a suboptimal piecewise linear (PL) decoders. The proposed decoders are designed for the multi-antenna DF based cooperative MIMO systems utilizing OSTBCs for data transmission. The proposed system tries to achieve maximum diversity.

T. Hunter et al. in **[17]** have proposed coded cooperation, where a user, instead of repetition of the symbols transmitted by another user, sends the additional parity bits for its partner in accordance with a preset coding scheme. Bit and block error rate have been used for performance analysis showing significant improvement over non cooperation transmission.

In **[18] Janani et al.** have introduced space-time and turbo-based cooperation in coded cooperation thereby making the latter even more effective. Space-time cooperation achieves spatial and temporal diversity in fast fading whereas the turbo based cooperation leverages the two-code structure typical of coded cooperation for improved performance. Bounds on BER and BLER of the proposed schemes are developed.

In **[20] N. Varshney et al**. analyze single and multiple relay based selective DF MIMO STBC system in terms of PEP diversity order, and optimal power allocation. Optimal source relay power allocation is done by minimizing the end-to-end decoding error of the system. The authors extend the system from two-phase to multi-phase communication.

P.A. Anghel and M. Kaveh in **[22]** propose a DSTC system based on the Alamouti codes. The symbol error rate (SER) and optimum the power allocation for one and two non-regenerative relays are investigated in high SNR regime. The asymptotic SER shows that for the same information rate, the proposed system outperforms the AF cooperative and convolutional encoded systems by achieving 1.5 times the diversity gain.

In **[26] Y. Jing and B. Hassibi** have devised an STC is devised for multiple-antenna two-stage cooperative communications where the relays encode the incoming signals into a “distributed” LD code before transmitting them to the destination. The PEP behaves as (log P/P) min {T, R} in high SNR region which, except for the log P/P factor, is same as that of MIMO with R antennas. It is further shown that for a given power budget large number of relays, the optimal power allocation is to share equal halves of total power between the source and all relays together. At low and high SNR, the coding gain equals that of MIMO with R antennas.

In **[27] Pierluigi Salvo Rossi et al.** have proposed a packet-based Distributed Linear Block Codes (DLBC) for cooperative communications. The performance of the system is investigated in terms of BER and outage probability under the effects of the number of pilots, decoding and channel estimation errors.

In **[28] Shengbo Zhang et al.** have studied distributed linear dispersion based AF DSTBC wireless relay networks with varying number of. The upper and lower bounds of symbol (or codeword) error rate and diversity gain are derived. Power allocation, path loss and different coding matrices are other considerations for the system. Further, an OFDM-based space-time scheme for asynchronous environment is also studied.

In [**33] K.Yu. et al.** have developed methods for increasing the two-way transmission capacity of ad hoc networks. Mathematical expression for the transmission capacity of the given system has been derived, for efficient packet acknowledgement and channel feedback. Fixing transmission distance by adjusting two-way outage and rate requirements has been implemented. To maximize the transmission capacity, the concepts of guard zone and cooperative communication have been used.

In [**34] P. Wan et al.** have concluded that deployment of charging base stations in wireless rechargeable WSNs is an important factor which if optimized can significantly reduce the cost. In this work, the greedy algorithm and the location based behavior among the sensor nodes are used to present a new algorithm dealing with the plan of the charging base stations. The problems of combinatorial explosion and point coverage are taken care of by the proposed algorithm.

In [35] E. Ahmed and H. Gharavi discuss in detail the evolution and future prospects of cooperative vehicular networking (CVN). The various perspectives in designing CVN such as physical, MAC, routing schemes, link scheduling, power/resource allocation and security have been taken into account. The challenges imposed on CVNs are high-speed mobility, trade-offs among parameters, and node selection. The main design objectives are to improve performance of the system with respect to transmission reliability, throughput, and interference reduction incorporating cooperative communication among nodes of VN.

In **[40] M. A. Abd El-Gawad et al.** have highlighted the prospect of the terminal relays playing an important role in assisting the communication between base stations and cellular IoT devices. An autonomous sequence-based resource block assignment scheme has been designed for the IoT devices to work efficiently in the absence of CSI.

In **[42] A. Ghosh et al.** have suggested the concept of off loading to relax the IoT devices from the burden of transmitting large scale data to a remote site. In this scheme, a part of data is shifted from the primary channels and transported through opportunistic terminal-to-terminal (T2T) networks. Such a scheme is prone to data loss and delay. Hence, three novel prediction-based offloading schemes are suggested by the authors taking into account the mobility patterns and time-based contacts of nodes thereby predicting next data transfer opportunities. The performance analysis of the proposed schemes is done on account of delivery ratio, latency, and overhead.

In **[43] Weijun Xing et al.** investigate the possibility of using finite-field network codes by the relays for information transmission in D2D communication. The authors have proposed algorithms for the system outage probability derivation. They have and analyzed the trade-off between energy efficiency and spectral efficiency of the proposed system for 5G communication.

In [**44**] **J. W. Raymond et al.** have done implementation of cooperative communication in machine to machine (M2M) communication. The various challenges of the future wireless communications such as scheduling design, increasing message overheads, intra and inter network interferences, end-to-end latency, and redundancy have been considered. Relays and cluster based protocols are presented as solutions to the problems evoked in the work.

In **[46] Y. Zhou et al.** have introduced a dynamic DF based cooperative NOMA scheme. The performance analysis is done on the basis of outage probability; diversity order and the sum rate have for random and distance-based user pairing schemes.

W. Yue et al, in [**49]** perform diversity gain analysis of millimeter-wave (mmWave) massive MIMO systems using distributed antenna sub array design consisting of Kt and Kr sub arrays at the Tx and Rx respectively. It is assumed that all the sub channels have L propagation paths and Ns number of data streams. A diversity gain of $KrKtL - Ns + 1$ is achieved which is comparable to the diversity gain of $KrKt$ as in the case of MIMO systems. Making use of the proposed design the diversity gain in case of distributed topology may be made equal to that of the MIMO system and may outperform the latter.

In **[50] A. Minasian et al.** deals with a distributed massive MIMO (DM-MIMO) system where numerous distributed remote radio heads (RRHs), equipped with antennas reflect a massive MIMO within the coverage area providing uniform coverage and enabling macro-diversity. In order to achieve the maximum possible average rate in the downlink (DL) of a DM-MIMO system, the authors employ zero-forcing for the optimal RRH placement. An expression for the DL rate has been derived to formulate the optimal RRH placement. Two sub-optimal RRH placement schemes have been proposed for a homogeneous and non-homogeneous propagation environment respectively.

It is to be concluded that cooperative communications and its various advantages leads to its usage in myriad applications. It provides MIMO like spatial diversity in numerous scenarios like ad-hoc networks, WSNs, CVNs etc. The other advantages are deployment in distributive topology, reduced complexity and cost, range extension, efficient power utilization, high reliability, etc. The distributive topology of cooperative communications adds to it an asynchronous feature, which is discussed next.

2.2 Asynchronous Cooperative Communication

In the cooperative communication, the locations of the cooperating relaying nodes are randomly distributed. Also the times of transmission as well as the local oscillator associated with them are different. Hence the signals from different relays are arriving at different times at the receiver. Therefore, we can say that cooperative communications is basically asynchronous in nature [52]. Asynchronous relay transmissions in a communication system destroy the code structure designed specifically for optimal diversity gain and eventually diminishing the latter. For example in the case of DSTBC, these delay bound signals, which eventually are stacked as different rows of the DSTBC matrix, distort the rank of the said matrix [53, 54]. The diversity of the system which is dependent on the rank of the DSTBC matrix thus is low.

There are several approaches, presented in existing literature, used for obtaining optimal performance in asynchronous cooperative environment. The first is to make use of equalizers [55, 56] at the receivers which try to negate the harmful impact of the channel on the signals. This approach is not cost effective. Another approach is the frequency domain approach, where OFDM technique is used to combat the asynchronism [57-59]. Orthogonal frequency division modulation (OFDM) is the technique of converting a frequency selective channel into multiple flat fading channels. Here a cyclic prefix (CP) is appended to the signals at the source and removed at the destination. This technique entails complex IFFT and DFT computations at the source and the destination, respectively. The time domain approaches exploit the 'time' dimension of the system, hence the name [60-73]. These techniques are also known as delay-tolerant space time codes where the performance of the system becomes insensitive to delays among the received signals from each relay. The time domain techniques which combat the problems arising due to the asynchronism are discussed below.

- *Time reversal space time block codes* (TR-STBC)[62-64] – In this approach a block of B symbols are substituted for a symbol of the STBC codeword. To explore the orthogonality, the conjugation of symbol is obtained by transmitting the corresponding block in a time reversed order.
- *Distributed Threaded algebraic space time code* (TAST) [65] - This approach makes use of a suitable algebraic number for each layer. Different layers are hence laid in different algebraic space.
- *Linear asynchronous distributed space-time block codes* (LA-DSTBC) [66]- these codes employ a linear dispersive structure using sufficient guard intervals for combating the imperfect synchronization.

A brief overview of the work done on asynchronous cooperative communication is presented next.

S Wei et al. in **[52]** deal with the performance analysis of an ad hoc wireless network in asynchronous environment. Two delay diversity protocols and a novel joint DFE-MMSE equalizer were proposed in this work to attain diversity gains. Results show improvement over single hop schemes and those employing strict symbol synchronization. Outage probability has been considered for the performance analysis.

X. Guo and **X.-G. Xia** in **[54]** introduced the DSTC for synchronous cooperative systems to asynchronous relay communications. A novel set of DSTBCs able to achieve full spatial diversity in asynchronous cooperative networks has been proposed.

In **[55], R. Vahidnia et al.** take into account the ISI at the transceivers due to the asynchronous reception in a cooperative system. This ISI manifests into inter-block-interference (IBI) for block transmissions. Pre- channel block equalization along with relay beamforming weight vector are obtained at the transceivers so as to minimize the mean square error. The results of the pre-equalization are comparable to that of post equalization.

In **[56] Z. Liu et al.** have implemented an underwater decode-interleave-forward (UDIF) protocol for underwater acoustic system in asynchronous environment. A novel joint multi-branch combining and turbo equalization detector is presented in this paper. Without even having perfect CSI, the detector effectively performs the combining of signals due to the regular updation of combining coefficients based on the steady-state mean square error.

Z. Li and **X.G. Xia** in **[57]** propose an OFDM scheme for an asynchronous cooperative system achieving second-order diversity gain, where cyclic prefix (CP) at the source node and time-reversion and complex conjugation are implemented at the relay nodes. At the -has the fast symbol-wise ML decoding. It should be emphasized that the relay nodes only need to implement the time-reversion, sign changes, and/or the complex conjugation to the received signals at the relays relaxes the destination of the IDFT or DFT operations.

Z. Li et al. in **[58]** propose an OFDM based system for an asynchronous environment where a cyclic prefix (CP) is added to the source node, time reversion, complex conjugation done at the relays and removal of CP done at the destination to combat the frequency selective fading channels and the timing errors. The signals received at the destination having the orthogonal code structure on each subcarrier result in ML decoding and can achieves full spatial diversity in high SNR regime.

In **[59] C. Sexton et al.** explore the possibility of the use of multiple waveforms in 5G, where each service shall employ a waveform best suited for it. A device-to-device (D2D) communication is employed in a 5G machine type communication (MTC) scenario. The large number of machine-type D2D user equipment (DUE) renders synchronous communication infeasible. Hence, the asynchronous performances of all the candidate waveforms are considered with synchronous OFDM as the reference. It is concluded that the asynchronous D2D communication when employ FBMC/OQAM, the average achieved rate is greater than that of the synchronous OFDM.

In [60] S. Wang et al. have proposed Polynomial cancellation coded orthogonal frequency-division multiplexing (PCC-OFDM) and universal filtered multi-carrier (UFMC)to protect against intercarrier interference (ICI) in the 5G uplink . PCCOFDM and UFMC minimize the sidelobes of the OFDM signal. This paper also propose overlap and add UFMC (OA-UFMC) and a variant of UFMC using infinite impulse response prototype filter banks (IIR-UFMC) It relaxes the synchronization requirements in massive machine type communications (MTC). This paper provides closed-form expressions for time offsets interference, SINR, achievable rate and BER. UFMC improves the ICI and intersymbol interference (ISI) protection performance.

J. Wang et al. in **[61]** have based on the zero prefix and zero suffix ZPZS pre-coding structure, compatible both to single carrier transmission and OFDM, a block transmission algorithm, proposed for distributed space time codes in the asynchronous cooperative transmissions under frequency selective fading channels. Further, an improved QR decomposition-based recursive interference cancellation (QRD-RIC) detector is employed where the spatial and multipath diversities are acquired.

In **[62], Y. Liu et al.** propose a family of zero-padded time-reversal STC through analog network coding and ML decoding for an asynchronous two-way relay network. For two-relay scenarios, three code designs and for three-relay scenarios, one code design. Decoding complexity order, bit-error-rate performance and full diversity is analyzed for all four designs.

Mojtaba Rahmati and T.M.Duman in **[64]** proposed a new TR-STBC scheme for the asynchronous cooperative communications which achieves full diversity for flat fading channels. To combat the asynchronism, a smaller over head needs to be added in transmitting every pair of data blocks. Further, a sub-optimal detector is also proposed for the proposed TR-STBC technique . Results show that the proposed scheme achieves full diversity and high spectral efficiency.

Nan Wu et al. in **[66]** propose a family of CLDCs using linear dispersion structure which achieve full spatial diversity in asynchronous reception. To accommodate the dynamic topology of cooperative networks, guard intervals and block encoding/decoding techniques are employed. as well as to. A novel time-domain delay-tolerant ACLDC scheme is designed by exploiting the interference signals rather than discarding them to achieve higher throughput than conventional space–time codes based on orthogonal designs.

S Zhong et al. in **[67]** propose a novel family of DSTTC that achieves full cooperative and multipath diversities under asynchronous cooperative communications. Sufficient conditions are given to construct such family of DSTTC with the minimum memory order. Through the exhaustive computer search, optimal DSTTCs are found which give full diversity, coding gain, enhance transmission energy efficiency and reduce synchronization cost

Yi Liu et al. in **[68]** propose two DSTC schemes exploiting cross-talks between the relays. A partial distributed linear convolutive space time block code (DLC-STC) scheme is proposed to make use of the cross-talks instead of removing them. The authors also propose a a DLC-STC scheme without cross talks which uses signal from the loop channels.

In **[72] R. Cao, et al.** have designed an asynchronous relaying protocol using asynchronous amplify-and-forward relaying for underwater acoustic communication (UAC) channels. Also, precoded orthogonal frequency division multiplexing used to combat doubly selective fading in UAC. Performance of the proposed protocol has been done using the end-to-end signal-to- noise ratio, the average pair-wise error probability and the maximum collectable diversity.

In **[73] R. Rahimi and S. Shahbazpanahi**, have proposed an asynchronous cooperative communication system consisting of two transceivers and multiple multi-antenna relays. A beamforming matrix is multiplied to the signal vector received by the relays and then transmitted further. Selection of *symmetric* relay beamforming matrices and the transceivers' transmit powers is done such that the total consumed power is minimized while the data rates are increased. It is concluded in the paper that there exists an optimal number of antennas per relay which results in the lowest power consumption in the network.

This section shows that cooperative communications is inherently an asynchronous system and there are several techniques to mitigate its effect. From the three basic delay tolerant techniques, this work focuses on the Linear Dispersion codes based DSTBC system for the asynchronous scenarios.

2.3 Channel coding in cooperative communication

The next generation of wireless communications[74],[75] calls for high level of reliability. The cooperative communication system and its variants discussed in the previous section offer diversity as wells as capacity gains. Channel coding [77] is a technique of introducing coding gain to the system. In this work, the authors conclude that LDPC codes are the most suitable FEC codes for high performance Wi-Fi applications. LDPC codes have been selected in the 5G draft [78]. These are very powerful channel codes approaching Shannon limits. In [79] Quasi Cyclic LDPC (QC-LDPC) codes in particular have been accepted as the standard code for data transmission for 5G applications. [81] study the girth of Tanner (J; L) QC-LDPC design. [82] deals with maximizing the code rate of the bi-layer expurgated LDPC codes. In [83] two shaping techniques for obtaining LDPC lattices have been presented. Table 2.1 enlists the various wireless standards having LDPC codes as FEC

Table2.1 Wireless standards having LDPC codes as FEC

Year	2006	2009	2012	2012	2015	2016
Wireless Std.	IEEE 802.16e	IEEE 802.11n	IEEE 802.11ac	IEEE 802.11ad	WIA-FA	5G draft

The literature pertaining to the channel codes, particularly LDPC codes in cooperative communications has been discussed in the next section.

In [77] M. Zhan et al. propose four principles to select most suitable channel coding and its variants as demanded by high-performance wireless networks. Bit-error rate, packet error rate, and throughput are the performance metrics which are used to evaluate the system on the basis of increasing reliability and decreasing latency.

In [78] Uchoa and Lamare discuss the use of LDPC codes in future bandwidth-hungry Wi-Fi applications. Efficient and effective use of these codes demand reduction of encoding and decoding complexity, improved design and the decoding and high-performance decoding algorithms which have been discussed in this work. LDPC codes are suggested as the most potential solution for the future high bandwidth and high performance demanding Wi-Fi standards.

In **[80] H.Li et al.** propose an *algebra-assisted* method for constructing Quasi-cyclic LDPC (QC-LDPC) codes which are selected as standard codes for data transmission in the 5G wireless broadband data channel. Apart from reviewing the encoding mechanism and requirements, the *cycle analysis* for 5G LDPC codes are laid down. Based on the proposed metric known as *weighted average number of cycles* (WANC) and algebraic methods QC-LDPC codes are constructed that can support *multiple lifting sizes* or different information lengths and code rates.

In **[81] H.Xu, et al.** study the girth of Tanner (J; L) quasi-cyclic low-density parity-check (QC-LDPC) codes with finite code lengths so as to generalize the laws of the girth distributions. Girth is an important factor in the design of low LDPC codes where J and L is any two positive integers. The paper proposes an algorithm to determine the girth of Tanner (J; L) QC-LDPC codes. Using the exponent matrices of Tanner (J; L) QC-LDPC codes, column selection and/or masking methods are used for the construction of to construct LDPC codes.

In **[82] S. Mehrizi et al.** propose a bilayer-expurgated low density parity check (LDPC) codes in the relay channel. These codes are optimized for maximizing the code rate using a fast procedure. The code optimization also guarantees the convergence of the density evolution relations in upper and lower layer codes and lower complexity.

In [81] H. Khodaiemehr et al. employ the encoding and decoding of the LDPC lattices in a cooperative communication system. Hypercube and Voronoi shaping techniques are used to obtain LDPC lattice codes. Further, block Markov encoding is proposed for uni and bi-directional relay networks using these codes. The lower decoding complexity allows increasing the dimension of the lattice.

In this section we have studied channel coding in cooperative communications in various applications. From the literature we learn that LDPC codes are very powerful FEC and have been accepted for data transmission in 5G wireless applications. In this work we have concatenated the new ADSTBC system with LDPC for asynchronous cooperative communications which is very less explored.

2.4 Relay and Transmit-Receive Antenna Selection in cooperative communication

One of the major aim of the communication systems is to save resources without compromising with the performance. Optimal Relay and/ or antenna selection are techniques available in the literature [84-97] to enhance the performance of the system. The overhead incurred in the selection procedure is masked by the high performance gains obtained. In [85] dual relay selection method has been presented whereby reducing the BER of a DSTC system. [86] lays down a technique of selection in a multi-user dual-hop DF based cooperative communication system. [89] present an AF STBC system for asynchronous environment. Performance of the system is increased further by an outer convolutive coding. [90] proposes a relay selection scheme for dynamic D2D communication. In [91] and [92] the author relay selection methods for cooperative NOMA system. [93] deals with relay selection in an underwater acoustic sensor networks (UASNs). The authors in [94] propose two relay selection strategies for a DSTC based cooperative NOMA network. In [95] the authors present relay selection based on minimum path loss for Poisson point process (PPP) distributed relays. In [96] an adaptive multiple-relay selection scheme for Vehicular Delay Tolerant Networks is proposed. The performance of the cooperative system can be increased further in terms of increased spectral efficiency, power saving and reduced complexity by combining antenna selection [97] to relay selection [98]. In the literature there are several works dealing with joint relay and antenna selection for different applications [98-102].In [102] the secrecy performance of an energy harvesting technique using antenna selection and relay selection schemes has been presented. In [103], the authors have studied the performance of information and power transmission in shadowed Nakagami fading channels. [104] discusses energy harvesting of cooperative communication system in Rician fading channel. The following section deals with the available literature related to relay and antenna selection in cooperative communications.

S. Alabed in **[85]** present a bi-directional dual relay selection strategy with high reliability and very low decoding complexity for the wireless cooperative framework. Dual relay selection is performed by maximizing the BER performance of the system. Then bi-directional communications take place through the selected relay nodes that apply distributed orthogonal STC and/or network coding.

In **[86] K. Xiao et al.** propose an opportunistic relay selection in the multi-user dual-hop DF based cooperative networks with fixed power budget. The relay selection is done on the basis of the instantaneous signal-to-noise ratios over the relay links, the power load (PL) of the relays and the weight factor for ensuring fairness. The average channel capacity has been derived approximately.

Walid Qaja et al. in **[89]** discuss the interference cancellation creteria in AF based single bit closed-loop extended orthogonal space-time block coding (CL EO-STBC) system. The system implements dual relay selection, each having two antennas, out of N_R available. Outer convolutive coding is used to improve performance. A near-optimum detection scheme is used at the destination which effectively eliminates the interference components induced by asynchronism.

In**[90], P. K. Mishra et al**. propose a D2D communication using relay selection in a dynamic environment, provided the system has more than one relay. The communicating devices exchange neighbor tables and find common relay for continuing the information transmission after reaching the maximum distance threshold. This selection scheme is based SNR, SINR, residual battery power, buffer space, and reliability.

In **[91] P. K. Mishra et al.** investigate the joint user and relay selection algorithm for AF based cooperative NOMA networks. An optimal selection criterion is proposed at the user-relay pairs to improve the outage performance of system. Further, the closed-form analytical expressions on the outage probability, as well as the asymptotic expressions for large transmission power have been derived.

In **[93] X. Li et al.** have proposed a model of multi-user relay selection under a multiuser multi-armed bandit (MU-MAB) framework for underwater acoustic sensor networks (UASNs) which exempts the receiver of perfect CSI. The authors propose a novel DSMU-MAB algorithm for relay selection and a DSMU-rMAB, a derivative of DSMU-MAB for achieving a high quality transmission and avoiding collisions.

In **[94] J. Zhao et al.** propose two relay selection strategies, namely: *two-stage dual relay selection with fixed power allocation* (DRS-FPA) and *two-stage dual relay selection with dynamic power allocation* (DRS-DPA) for the DSTC based multi-relay cooperative NOMA network. Lower and upper bounds on the outage probability and the exact outage probability have been derived for the DRS-FPA and the DRS-DPA, respectively. The proposed two-stage DRS achieve better outage performance, spectral efficiency and full diversity gain than the existing single relay selection schemes without sacrificing, but can also.

In **[95] K. Belbase et al.** study the effect of deployment of DF relays, distributed as a 2-D homogeneous Poisson point process (PPP) in contrast to the fixed point locations of the source and the destination, to improve the coverage probability, rate coverage and spectral efficiency of a millimeter wave network. A set of 2-D inhomogeneous PPP is obtained from the randomly distributed decoding relays having SNR greater than the minimum SNR threshold. From this set, a relay is selected that has minimum path loss to the receiver.

In **[96] S. H. Ahmed et al.** propose an adaptive multiple-relay selection scheme for Vehicular Delay Tolerant Networks.. To cover the long highways, a Roadside Unit (RSU) is enabled to select one relay vehicle to carry on unhindered communications for the which is unable to receive signals from the corresponding RSU.

In **[102] N. Nguyen et al.** investigate the secrecy performance of a time-switching-based radio frequency energy harvesting technique using antenna selection and relay selection schemes. Specifically, two relay selection schemes based on the partial and full knowledge of channel state information and two antenna selection schemes for harvesting energy at source and relays are proposed enhance the security of the system and to achieve full secrecy diversity order.

This section highlighted the significance of relay and antenna selection in cooperative communication. The system performance increases manifolds by such selection schemes. The system complexity reduces and hence the system resources as well as cost of implementation. Motivated by this fact, we have implemented relay selection in chapter 3 and joint relay and antenna selection scheme on LDPC-ADSTBC system in chapter 4.

Chapter 3

Performance Evaluation and Analysis of Asynchronous Distributed Space Time Block Coded system

The contribution of this chapter is the design of and analysis of Asynchronous Distributed Space Time Block Coded (ADSTBC) system designed using Linear Dispersion (LD) matrices optimized for asynchronous environment. The performance analysis of the proposed system has been done using Average Bit Error Rate (ABER) and the Ergodic capacity. It is shown that the performance of the system improves with Optimal Relay Selection (ORS). As the number of candidate relays for optimal selection is increased, performance will improve further.

3.1 Introduction

Cooperative communication [10] in recent years has put its foot firm and forward in the wireless communications. Catering to the huge demands due to its capability of providing diversity and capacity gains, it has found its way in the state of art technologies like LTE and 5G [5-7]. The geographically distributed relay nodes are able to achieve cooperative diversity by creating a distributed space time block coded system (DSTBC) [26]. The benefits of diversity gains in a distributed topology come with a price of added complexity. The existing literature assumes cooperative communication in synchronous environment whereas the latter is basically asynchronous in nature. The distributed nature of a cooperative communication system leads to timing offsets among the geographically distributed nodes [52] which degrade the system performance thereby losing the diversity benefits. The existing literature presents that optimal performance is achieved even in the asynchronous scenarios using equalizers, frequency domain (OFDM) and time domain techniques [55-66]. Delay tolerant codes are time domain techniques which yield diversity gain in delay prone or asynchronous environment.

This chapter presents the design and performance analysis of a delay tolerant Distributed Space-Time Block Coded (DSTBC) system in asynchronous environment. The Asynchronous DSTBC (ADSTBC) system is designed using an Optimized Asynchronous Linear Dispersion (OALD) matrix. The performance as well as the resource saving of the proposed ADSTBC system can further be increased by relay selection [84]. Hence, an Optimal Relay Selection (ORS) technique has been employed in the work. The analytical expressions for the proposed ADSTBC and ORS-ADSTBC systems has been derived and simulated. The contributions of this chapter are listed below:

- Optimized Asynchronous Linear Dispersion (OALD) matrices have been designed by optimizing the linear dispersion (LD) matrices [30] with constraints such as tight frame, equal power and rank-determinant criteria in asynchronous scenario.
- An Asynchronous DSTBC (ADSTBC) system has been designed using the OALD matrix.
- Optimal Relay Selection (ORS) technique based ADSTBC (ORS-ADSTBC) system has been designed by maximizing the end to end instantaneous SNR.
- Probability density functions (PDF) for the ADSTBC and ORS-ADSTBC systems have been derived to analyze the system performance.
- Based upon the PDFs, closed form expressions for average bit error rate and ergodic capacity have been derived for the proposed systems.

The system model for the ADSTBC and ORS-ADSTBC systems have been discussed in the following sections.

3.2 Framework for Asynchronous Distributed Space Time Block Coded (ADSTBC) System

We study the ADSTBC system considering $R+2$ nodes, where the transmitter, receiver and each of the R relay nodes are designed for single antenna system. The proposed system is analyzed in two phases as shown in figure 3.1.

Phase 1: Broadcasting phase

In the first phase, the information bits, b_N are BPSK modulated as $\boldsymbol{s} = [s_1 \dots\dots\dots.. s_N]^\dagger$ in the codebook $\{\boldsymbol{s}_1 \cdots\cdots\cdots \boldsymbol{s}_L\}$ where $s_N = 2b_N$- 1. The average power used at the transmitter for any transmission is assumed to be P_1. The transmitter broadcasts N symbols, $\sqrt{P_1}\, s_1, \dots.., \sqrt{P_1}\, s_N$ to each relay. The signal received at k^{th} relay has the effect of both the fading $h_{k,1}$ as well as the noise $\boldsymbol{n}_k$. The fading coefficients and the noise are circularly symmetric Gaussian distributed with mean 0 and variance 1(C$\mathcal{N}$(0,1)).

Phase 2: Cooperative Phase

In the second phase, the signal received at the k^{th} relay is given as:

$$\boldsymbol{r}_k = \sqrt{P_1}\, h_{k,1}\boldsymbol{s} + \boldsymbol{n}_k \tag{3.1}$$

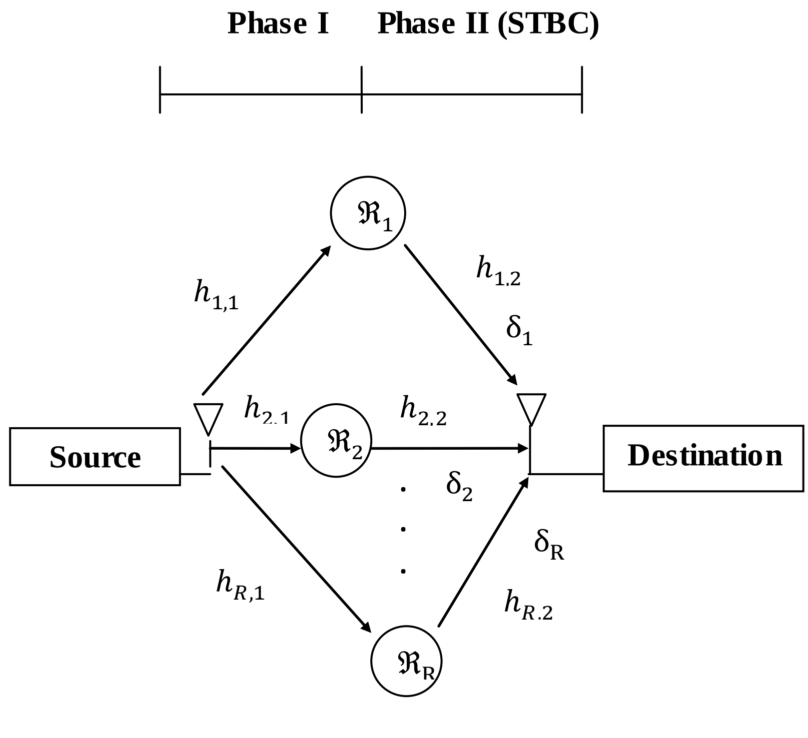


Figure 3.1: Block diagram of ADSTBC system

The k^{th} relay linearly modulates the received signal $\boldsymbol{r}_k$ by combining it with an Optimized Asynchronous Linear Dispersion (OALD) matrix $\boldsymbol{A}_k$ to form $\boldsymbol{x}_k$. Further, Amplify and Forward (AF) protocol is used for relaying the signal to the destination which scales the signal with a factor $\sqrt{\frac{1}{P_1+1}}$. The signal transmitted by the k^{th} relay is given as

$$\boldsymbol{x}_k = \sqrt{\frac{P_2}{P_1+1}}\boldsymbol{A}_k\boldsymbol{r}_k \tag{3.2}$$

Where P_2 is the average power used at the k^{th} relay for transmission, $\boldsymbol{A}_k = \begin{bmatrix} a_{k,11} & \cdots & a_{k,1N} \\ & & \vdots \\ a_{k,T1} & \cdots & a_{k,TN} \end{bmatrix}$ for $k=1 \ldots\ldots\ldots R$. N and T are the coherence interval for phase 1 and 2 respectively, during which the fading coefficients remain constant for N and T transmissions. The dispersion matrix $\boldsymbol{A}_k$ distributes the N symbols among T channel uses. The OALD matrix used in this work is represented using the theory of unitary matrices [31] and optimized for tight frame, equal power, rank and determinant criteria in the asynchronous scenario. The design of OALD matrix has been discussed in **Appendix-A**.

In a cooperative communication system, there are timing offsets at the receiver due to the random spatial positioning of the relay nodes. These delays cause overall performance degradation of the system. The relays and receiver are assumed to have full knowledge of the delay profile and the OALD matrices $\boldsymbol{A}_k$. The signal, $\boldsymbol{y}(t)$, with delayed symbols received at the destination at any given time t, is

$$\boldsymbol{y}(t) = \sum_{k=1}^{R} \boldsymbol{x}(t-\delta_k)\, h_{k,2} + \boldsymbol{v}(t) \tag{3.3}$$

Substituting (3.1) and (3.2) in (3.3)

$$\boldsymbol{y}(t) = \sum_{k=1}^{R} \sqrt{\frac{P_2}{P_1+1}}\, \boldsymbol{A}_k \left(\sqrt{P_1} h_{k,1}\, \boldsymbol{s}(t-\delta_k) + \boldsymbol{n}_k\right) h_{k,2} + \boldsymbol{v}(t) \tag{3.4}$$

where $h_{k,2}$ is the path gain between the k^{th} relay node and the destination, $\boldsymbol{v}(t)$ is the additive white Gaussian noise with variance N_0. δ_k is the delay observed for the kth relay at the receiver, relative to the first relay**.** The delay introduced in the system distorts the arrangement of the DSTBC matrix formed at the destination thereby causing loss of the diversity gain. Hence in case of asynchronous DSTBC system, delay tolerant codes are designed where each relay pads extra zeros, equivalent to a delay of $(\delta_{max} - \delta_k)$, to the total T symbol periods to make the system delay tolerant [69]. Therefore the signal received from all relays after $(T + \delta_{max})$ symbol durations is given as

$$\boldsymbol{y} = \sum_{k=1}^{R} \sqrt{\frac{P_1 P_2}{P_1+1}} \left(\widehat{\boldsymbol{h}} \boldsymbol{D}(\delta_k) \boldsymbol{A}_k \boldsymbol{s}\right) + \boldsymbol{w} \tag{3.5}$$

Where, $\widehat{\boldsymbol{h}} = h_k \otimes \boldsymbol{I}_\Delta$ **,** $h_k = h_{k,1} h_{k,2}$, $\otimes$ denotes the kronecker product and $\boldsymbol{I}_\Delta$ is an identity matrix of size $T_\delta \times T_\delta$, $T_\delta = T + \delta_{max}$. δ_{max} denotes the maximum delay incurred and is denoted by, $\delta_{max} \triangleq max\ \{\delta_1 \ \ldots.. \delta_R\}$. The receiver is synchronized to the first relay i.e. $\delta_1 = 0$. The delay matrix is given as $\boldsymbol{D}(\delta_k) = \begin{bmatrix} \boldsymbol{O}_{\delta_k \times T} \\ \boldsymbol{I}_T \\ \boldsymbol{O}_{(\delta_{max}-\delta_k)\times T} \end{bmatrix}$, **O** denote a zero matrix and

$$\boldsymbol{w} = \sqrt{\frac{P_2}{P_1+1}} \sum_{k=1}^{R} \boldsymbol{D}(\delta_k) h_{k,2} \boldsymbol{A}_k \boldsymbol{n}_k + \boldsymbol{v}$$

Equation (3.5) is rewritten by vertically stacking the matrices as

$$\overline{\boldsymbol{y}} = \sqrt{\frac{P_1 P_2}{P_1+1}}\, \widetilde{\boldsymbol{H}} \boldsymbol{D}(\Omega)\, \overline{\boldsymbol{\chi}} \overline{\boldsymbol{s}} + \overline{\boldsymbol{w}}$$

$$= \sqrt{\frac{P_1 P_2}{P_1+1}}\widetilde{\boldsymbol{H}}\boldsymbol{D}(\Omega)\boldsymbol{S} + \overline{\boldsymbol{w}} \quad (3.6)$$

where, $\widetilde{\boldsymbol{H}} = \boldsymbol{H} \otimes \boldsymbol{I}_{\Omega}, \boldsymbol{H} = [h_1 \ldots\ldots h_R], \boldsymbol{D}(\Omega) = diag\left(\boldsymbol{D}(\delta_1), \boldsymbol{D}(\delta_2), \ldots, \boldsymbol{D}(\delta_R)\right)$,

$\overline{\boldsymbol{\chi}} = \begin{bmatrix} \boldsymbol{A}_1 & & \\ & \ddots & \\ & & \boldsymbol{A}_R \end{bmatrix}, \overline{\boldsymbol{s}} = \begin{bmatrix} \boldsymbol{s} \\ . \\ . \\ \boldsymbol{s} \end{bmatrix}$, where $\boldsymbol{s}$ is stacked R number of times and $\boldsymbol{S} = \begin{bmatrix} (\boldsymbol{A}_1\boldsymbol{s})^{\dagger} \\ . \\ . \\ . \\ (\boldsymbol{A}_R\boldsymbol{s})^{\dagger} \end{bmatrix}$.

3.3 Analytical expressions of ADSTBC system

To derive the analytical expression of the given system with respect to SNR (γ) let, $\Re_k$, denotes the k^{th} relay with instantaneous end-to-end SNR (γ_k). The cumulative distribution function (CDF) of the instantaneous end-to-end SNR of each S - $\Re_k$ - D link is, computed with respect to the CDFs of the S - $\Re_k$ and $\Re_k$ - D links .

$$F(\gamma_k) = 1 - (1 - F(\gamma_{S-\Re_k}))(1 - F(\gamma_{\Re_k - D})) \quad (3.7)$$

It is assumed that the CDF between S - $\Re_k$ and $\Re_k$ - D links experience Rayleigh fading having $F\left(\gamma_{S-\Re_k}\right) = 1 - e^{-\frac{\gamma_{1,k}}{(\bar{\gamma})}}, F\left(\gamma_{\Re_k - D}\right) = 1 - e^{-\frac{\gamma_{2,k}}{(\bar{\gamma})}}$, $\bar{\gamma}$ is the average SNR of all the links. Assuming $\gamma_{1,k} = \gamma_{2,k} = \gamma_k$, (3.7) is rewritten as

$$F(\gamma_k) = 1 - e^{-\frac{2\gamma_k}{(\bar{\gamma})}} \quad (3.8)$$

Differentiating (3.8) with respect to γ_k, we obtain the PDF of the end to end instantaneous SNR as

$$f(\gamma_k) = \frac{2e^{-\frac{2\gamma_k}{(\bar{\gamma})}}}{\bar{\gamma}} \quad (3.9)$$

Assuming that the proposed system has two relays, the joint PDF of the two independent links (k = x, y) contributing in ADSTBC is given as:

$$f(x, y) = f(x)f(y) \quad (3.10)$$

$$f(x, y) = \frac{4}{\bar{\gamma}^2} e^{\left(-\frac{2x}{\bar{\gamma}}\right)} e^{\left(-\frac{2y}{\bar{\gamma}}\right)} \quad (3.11)$$

To analyze the medium and high SNR regimes, it is important to have simple closed form bounds, therefore the upper and lower bounds on received total SNR γ_d are considered as

$$\gamma_{low} \leq \gamma_d < \gamma_{upper} \tag{3.12}$$

Where $\gamma_{low} = \frac{1}{2}\sum_k^R \gamma_k$ and $\gamma_{upper} = \sum_k^R \gamma_k$ [105].

Therefore, to find the joint PDF at the receiver side, let z ≤x+y, be the upper bound on the joint CDF (F(z)) of the proposed system is given as in [105]

$$\mathrm{F(z)} = \int_0^{\frac{z}{2}} \int_y^{z-y} f(x,y)\,\mathrm{dx\,dy} \tag{3.13}$$

Putting the values of $f(x,y)$ from (3.11)

$$\mathrm{F(z)} = \int_0^{\frac{z}{2}} \int_y^{z-y} \frac{4}{\bar{\gamma}^2} e^{\left(-\frac{2x}{\bar{\gamma}}\right)} e^{\left(-\frac{2y}{\bar{\gamma}}\right)}\,\mathrm{dx\,dy}$$

$$= \frac{1}{2} - \frac{e^{-\frac{2z}{\bar{\gamma}}}(\bar{\gamma}+2z)}{2\bar{\gamma}} \tag{3.14}$$

Differentiating the above, we obtain the joint PDF of the ADSTBC system given below

$$f(z) = -\frac{e^{-\frac{2z}{\bar{\gamma}}}}{\bar{\gamma}} + \frac{e^{-\frac{2z}{\bar{\gamma}}}(\bar{\gamma}+2z)}{\bar{\gamma}^2} \tag{3.15}$$

In asynchronous system, apart from the fading, a delay incurs the major factor that affects the system performance. The delay of each resolvable path from the relay to the destination is assumed to be uniformly distributed on ($\delta_{min}, \delta_{max}$), and is mutually independent, where, δ_{max} is the maximum delay incurred by the system and δ_{min} is the minimum delay. Assuming the signals from the two relays arrive at the destination via two resolvable paths, the PDF of the delay profile is given [106] as

$$\frac{1}{(\delta_{max}-\delta_{min})^2} \tag{3.16}$$

The final joint PDF of the ADSTBC system is given as

$$f(z) = \frac{1}{(\delta_{max}-\delta_{min})^2}\left(-\frac{e^{-\frac{2z}{\bar{\gamma}}}}{\bar{\gamma}} + \frac{e^{-\frac{2z}{\bar{\gamma}}}(\bar{\gamma}+2z)}{\bar{\gamma}^2}\right) \tag{3.17}$$

The final joint PDF has been used to analyze the various performance metrics of the given system.

(a) Average Bit Error Rate (ABER)

The bit error rate (BER) is defined as the error probability of a detection scheme. BER is a very important measure to examine the reliability of the wireless communication system. The average bit error rate (ABER) is obtained by averaging the received error conditioned on the fading channel ($P_e(z)$), w.r.t. the PDF of the system.

$$P_e = \int_0^\infty P_e(z) f(z) dz \tag{3.18}$$

An approximate expression for the conditional error is given by [107] as $P_e(z) = \frac{1}{6}e^{-z} + \frac{1}{2}e^{\frac{-4z}{3}}$ for BPSK modulation. Putting the value of $f(z)$ from (3.17) in (3.18), we obtain

$$\begin{aligned} \mathrm{P_e} &= \int_0^\infty \frac{1}{(\delta_{max}-\delta_{min})^2}\left(\frac{1}{6}e^{-z} + \frac{1}{2}e^{\frac{-4z}{3}}\right)\left(\frac{e^{-\frac{2z}{\bar{\gamma}}}}{\bar{\gamma}} + \frac{e^{-\frac{2z}{\bar{\gamma}}}(\bar{\gamma}+2z)}{\bar{\gamma}^2}\right) dz \\ &= \frac{1}{3(\delta_{max}-\delta_{min})^2}\left(\frac{1}{(2+\bar{\gamma})^2} + \frac{27}{4(3+2\bar{\gamma})^2}\right) \end{aligned} \tag{3.19}$$

From the (3.19), it is observed that probability of error depends on

- *Delay*: It is system specific and therefore cannot be directly controlled.
- *Average SNR*: Depends on the average transmitted power of a system and is a vital resource which must be used optimally and increasing the same is not a good option.

Hence, in order to relax the burden on the transmitted power, we have to further optimize the proposed system model.

(b) Ergodic Capacity

Ergodic capacity is the average capacity obtained by assuming the source information is transmitted at a constant rate over many independent channel realizations. The ergodic capacity of ADSTBC system is given as

$$C_{erg} = E_{H,\Omega}\{C_{sys}\} \tag{3.20}$$

Where, $\mathbb{E}_{H,\Omega}$ refers to expectation with respect to different channel realizations and delay profile. C_{sys} is the Capacity of the given system, given by the Shannon capacity formula[106], $C_{sys} = log2(1+SNR)$. For the proposed ADSTBC system

$$C_{sys} = \left\{\frac{1}{2}log_2(1+z)\right\} \tag{3.21}$$

Where z is the total SNR of the system. We have employed the PDF obtained in (3.17) for averaging the capacity of the system to obtain the ergodic capacity. The ergodic capacity is approximated using the Taylor series expansion of the logarithmic function [38] as

$$C_{erg} \approx log_2(1+\mathbb{E}\{z\}) - \frac{log_2 e*(var\{z\})}{2*(1+\mathbb{E}\{z\})^2} \tag{3.22}$$

Where, $var\{z\} = \mathbb{E}^2\{z\} - (\mathbb{E}\{z\})^2$ and $\mathbb{E}^2\{z\} = \frac{3d^2}{4\delta^2}$. Using Mathematica, the Ergodic capacity is given as

$$C_{erg} = \frac{2MeijerG(\{\{-2\},\{-1\}\},\{\{-2,-2,0\},\{\}\},\frac{2}{\bar{\gamma}})}{\bar{\gamma}^2(\delta_{max}-\delta_{min})^2 ln2}, Re[\bar{\gamma}] > 0 \quad (3.23)$$

ln is the natural logarithm

As we compare the (3.19) and (3.23), both parameters ABER and C_{erg} depends on the delay difference and transmitted power. The delay is always system specific, whereas the power is constrained. Hence, to improve the system performance, we have improvised the proposed system model using optimal relay selection discussed in the following section.

3.4 Optimal Relay Selection based ADSTBC (ORS-ADSTBC) System

In a cooperative communication system, since the relay nodes are positioned at randomly distributed locations, there are chances that some relays may cause deep fades at the receiver. The transmitted power of the system has to be increased to get optimal performance which puts a constraint on the system resources.

Relay selection been used in this work to increase the system performance and saving of the resources. The relay selection technique is based upon selecting a set of optimum relays$(\acute{R})$ out of total R relays, which satisfy certain desired criteria. In this work, instantaneous end to end SNR at the receiver from all the relays is maximized to create an Optimal Relay Selection based Asynchronous Distributed Space Time Block Coded (ORS-ADSTBC) system. For optimal relay selection, arrange the instantaneous end-to-end SNR (γ_k) of each S - $\Re_k$ - D link γ_k in ascending order as ... $\gamma_{sel2} \leq \gamma_{sel1}$. In this work, $\acute{R} = 2$, i.e. two best relays are selected. The first best and second best selected relays' ($\Re_{sel1}, \Re_{sel2}$) instantaneous end-to-end SNRs are given as

$$\gamma_{sel1} = max_k\{\gamma_k\} \text{ and } \gamma_{sel2} = max_{k-1}\{\gamma_{k-1}\} \quad (3.24)$$

where, $\gamma_k = min(\gamma_{S-\Re_k}, \gamma_{\Re_k-D})$, where $\gamma_{S-\Re_k} = \frac{P\,|h_{k,1}|^2}{N_o}, \gamma_{\Re_k-D} = \frac{P\,|h_{k,2}|^2}{N_o}$, assuming $P_1 = P_2 = P$. The joint PDF of the selected relays using order statistics [108] and (3.8) and (3.9) is given as

$$f(\gamma_{se1l}, \gamma_{sel2}) = R(R-1)F(\gamma_{sel2})^{R-2} f(\gamma_{sel1}) f(\gamma_{sel2})$$

$$= R(R-1)\left(1 - e^{-\frac{2\gamma_{se12}}{(\bar{\gamma})}}\right)^{R-2} \left(\frac{2e^{-\frac{2\gamma_{se1l}}{(\bar{\gamma})}}}{\bar{\gamma}}\right)\left(\frac{2e^{-\frac{2\gamma_{se12}}{(\bar{\gamma})}}}{\bar{\gamma}}\right) \quad (3.25)$$

3.5 Performance analysis of ORS-ADSTBC system

Considering the delay profile to be independent of the system, the overall PDF of the ORS-ADSTBC system is the product of the PDF of the delay profile (Ω) given in (3.16) and the relay selected system PDF given in (3.25). Thus

$$f(\gamma_{se1l},\gamma_{sel2},\Omega)=\frac{4R\,(R-1)}{(\delta_{max}-\delta_{min})^2\,\bar{\gamma}^2}\,[1-e^{\left(-\frac{2\gamma_{sel2}}{\bar{\gamma}}\right)}\,]^{R-2}\,e^{\left(-\frac{2\gamma_{sel1}+2\gamma_{sel2}}{\bar{\gamma}^2}\right)} \tag{3.26}$$

Let $\gamma_{sel1}=x$ and γ_{sel2}=y. The PDF given in (3.26) is approximated using [107] and written as

$$f(x,y,\Omega)=\frac{2^R R(R-1)}{(\delta_{max}-\delta_{min})^2}\left(\frac{y^{R-2}}{\bar{\gamma}^R}\right)\,e^{\left(-\frac{2x+2y}{\bar{\gamma}^2}\right)} \tag{3.27}$$

The upper bound of on the joint CDF is given as

$$F(z)=\int_0^{\frac{z}{2}}\int_y^{z-y}\frac{2^R R(R-1)}{(\delta_{max}-\delta_{min})^2}\left(\frac{y^{R-2}}{\bar{\gamma}^R}\right)\,e^{\left(-\frac{2x+2y}{\bar{\gamma}^2}\right)}\,dxdy$$

$$=\frac{2^{-R}\bar{\gamma}(R-1)R}{(\delta_{max}-\delta_{min})^2}\left(\frac{2^R e^{-\frac{2z}{\bar{\gamma}}}\left(\frac{z}{\bar{\gamma}}\right)^R}{z-Rz}+\frac{2\Gamma(R-1)}{\bar{\gamma}}-\frac{2\Gamma\left(-1+R,\frac{2z}{\bar{\gamma}}\right)}{\bar{\gamma}}\right) \tag{3.28}$$

The joint PDF is obtained by differentiating (3.27) w.r.t. z as

$$f(z)=\frac{2^{-R}\bar{\gamma}(R-1)R}{(\delta_{max}-\delta_{min})^2}\left(\left(\frac{2^R e^{-\frac{2z}{\bar{\gamma}}}\left(\frac{z}{\bar{\gamma}}\right)^{R-2}}{\bar{\gamma}^2}\right)-\left(\frac{2^R e^{-\frac{2z}{\bar{\gamma}}}(1-R)\left(\frac{z}{\bar{\gamma}}\right)^R}{(z-Rz)^2}\right)\right.$$
$$\left.+\left(\frac{2^R e^{-\frac{2z}{\bar{\gamma}}}R\left(\frac{z}{\bar{\gamma}}\right)^{R-1}}{\bar{\gamma}(z-Rz)}\right)-\left(\frac{2^{R+1}e^{-\frac{2z}{\bar{\gamma}}}\left(\frac{z}{\bar{\gamma}}\right)^R}{\bar{\gamma}(z-Rz)}\right)\right) \tag{3.29}$$

Using the joint PDF given in (3.29), we analyze the system performance in terms of Average post processing SNR, Average Bit Error Rate (ABER) and Ergodic capacity. The following section discusses the derivation of the analytical expressions of these performance metrics.

(a) Average Post Processing SNR

Signal to noise ratio (SNR) is a very important performance measure in the digital communication system. It serves as an effective indicator of the overall fidelity of the system and is defined as the power ratio of a signal to the noise, as $\gamma = \frac{P_s}{N_o}$, γ denotes the instantaneous SNR, Ps is the signal power and N_o is the noise power. The average post processing SNR is the mean of the total instantaneous SNR at the destination obtained from the two best selected relays.

$$\mathbb{E}\{z\} = \int_0^{\infty} z\, f(z) dz = \frac{2^{-R}(\frac{1}{\bar{\gamma}})^R \bar{\gamma}^{1+R} R\Gamma(1+R)}{(\delta_{max} - \delta_{min})^2} \quad (3.30)$$

(b) Average Bit Error Rate (ABER)

The conditional bit error rate or ABER for M-ary modulation is given as [108]

$$P_e = A \times erfc\left(\sqrt{B(z)}\right) \quad (3.31)$$

Where, A and B are constants, erfc is the complementary error function, $erfc(\cdot) = 1 - erf(\cdot)$[110, 8.250.4]. By changing the values of A and B conditional bit error for different modulation techniques is found. For further analysis, we consider the case of BPSK for simplicity for which A=2 and B=1. Using a tight approximation for $erfc(\sqrt{z})$ as in (3.19) the conditional BER is given as

$$P_e = 2erfc(\sqrt{z}) = \frac{1}{6} e^{-z} + \frac{1}{2} e^{-\frac{4z}{3}} \quad (3.32)$$

Using (3.32), The ABER can thus be obtained as

$$\overline{P_e} = \int_0^{\infty} P_e\, f(z) dz$$

$$\overline{P_e} = \frac{R(R-1)}{(\delta_{max} - \delta_{min})^2} \int_0^{\infty} \left(\frac{1}{6} e^{-z} + \frac{1}{2} e^{-\frac{4z}{3}}\right) \left(2^{-R}\bar{\gamma} \left(\frac{2^R e^{-\frac{2z}{\bar{\gamma}}} \left(\frac{z}{\bar{\gamma}}\right)^{R-2}}{\bar{\gamma}^2} \right) - \left(\frac{2^R e^{-\frac{2z}{\bar{\gamma}}} (1-R) \left(\frac{z}{\bar{\gamma}}\right)^{R}}{(z - Rz)^2} \right) \right.$$
$$\left. + \left(\frac{2^R e^{-\frac{2z}{\bar{\gamma}}} R \left(\frac{z}{\bar{\gamma}}\right)^{R-1}}{\bar{\gamma}(z - Rz)} \right) - \left(\frac{2^{R+1} e^{-\frac{2z}{\bar{\gamma}}} \left(\frac{z}{\bar{\gamma}}\right)^{R}}{\bar{\gamma}(z - Rz)} \right) \right) dz \quad (3.33)$$

After solving (3.33), the closed form expression for ABER is given as

$$\overline{P}_e = \frac{\left(\frac{1}{\overline{\gamma}}\right)^R \left(3^{1+R}\left(4+\frac{6}{\overline{\gamma}}\right)^{-R} + \left(\frac{2+\overline{\gamma}}{\overline{\gamma}}\right)^{-R}\right)\Gamma(1+R)}{3(\delta_{max}-\delta_{min})^2} \quad (3.34)$$

(c) Ergodic Capacity

The ergodic capacity, C_{erg} of a system is defined as the average system capacity over all the realizations of the fading channel expressed as follows

$$C_{erg} = \mathbb{E}\{C_{sys}\} \quad (3.35)$$

The ergodic capacity is approximated using the Taylor series expansion of the logarithmic function as in (3.22)

$$C_{erg} \approx log_2(1+\mathbb{E}\{z\}) - \frac{log_2 e * (var\{z\})}{2*(1+\mathbb{E}\{z\})^2} \quad (3.36)$$

where, $var\{z\} = \mathbb{E}^2\{z\} - (\mathbb{E}\{z\})^2$ and $\mathbb{E}^2\{z\} = \int_0^\infty z^2 f(z)dz = \frac{2^{-R-1}\left(\frac{1}{\overline{\gamma}}\right)^R \overline{\gamma}^{2+R} R\Gamma(2+R)}{(\delta_{max}-\delta_{min})^2}$

Solving (3.36), we obtain the closed form expression for the ergodic capacity of the ORS-ADSTBC system as

$$C_{erg} \approx \frac{\frac{\left(\frac{1}{\overline{\gamma}}\right)^R \overline{\gamma}^{2+R} R\left(2\left(\frac{1}{\overline{\gamma}}\right)^R \overline{\gamma}^R R\Gamma(1+R)^2 - 2^R(\delta_{max}-\delta_{min})^2\Gamma(2+R)\right)}{2\left(2^R(\delta_{max}-\delta_{min})^2 + \left(\frac{1}{\overline{\gamma}}\right)^R \overline{\gamma}^{1+R} R\Gamma(1+R)\right)^2} + 2ln\left(1+\frac{2^{-R}\left(\frac{1}{\overline{\gamma}}\right)^R \overline{\gamma}^{1+R} R\Gamma(1+R)}{(\delta_{max}-\delta_{min})^2}\right)}{2ln(2)} \quad (3.37)$$

where, ln is the natural logarithm.

As from the expressions, (3.30),(3.34) and (3.37), it is clear that the performance of the ORS-ADSTBC system also depends on the delay factor, average SNR and the number of selected relays. It will be verified in the Results and Discussions section (Table 3.2) that significant power saving is obtained by relay selection as compared to ADSTBC system.

3.6 Results and Discussions

The results of the simulations have been obtained for the ADSTBC system for a transmitter-receiver pair and R relays, each equipped with single antenna. A frame consisting of N=2, BPSK modulated bits are broadcast to the relays. We further assume that in phase 1 transmission, there is no error at the relays i.e. the information received at the relays is the same as what the source terminal had sent. The relays also do not decode the message. The results have been obtained using Monte Carlo simulation from 1000 independent iterations of each frame, for each value of SNR varying from 0 to 20 dB. For both systems(ADSTBC and ORS-ADSTBC), the channel is assumed to be quasi-static flat fading subjected to maximum time delay of δ_{max} symbol durations w.r.t. the OALD coded symbol vector transmitted from the relays to the destination. The system parameters considered for Monte-Carlo simulation are enlisted in table 3.1.

Table 3.1: Parameters for Monte-Carlo simulation of ADSTBC and ORS-ADSTBC system

S.No.	Parameters	Values
1.	Number of bits	1000
2.	Number of iterations	10^6
3.	Maximum delay	2 symbol periods
4.	Minimum delay	0 symbol periods
5.	SNR considered	1-20 dB
6.	Number of candidate relays(in case of ORS)	4,5,6
7.	Number of selected relays(in case of ORS)	2
8.	Number of antennas per relay	1
9.	Modulation technique	BPSK
10.	Detector	ML detector

The analytical results have been verified by the simulation results.The results of the simulations have been obtained for the ORS-ADSTBC system for a transmitter-receiver pair and R relays, each equipped with single antenna. The performance is evaluated with respect to the average post processing SNR, average bit error rate and the ergodic capacity (C_{erg}) for binary phase shift keyed (BPSK) information symbol. The channel information is perfectly known to the receiver where as the relays are aware of the maximum delay incurred by the system as well as the indices of the best relays via a feedback channel from the destination to the relays.

Figure 3.2 depicts the ABER of the ADSTBC system with varying relays. It is observed from the figure that for ABER of 10^{-3}, as the number of relays increase from 2 to 3 to 4, there is a gain of 5 dB and 8dB respectively. The diversity gain thus obtained leads to enhanced error performance with reduced power requirements.

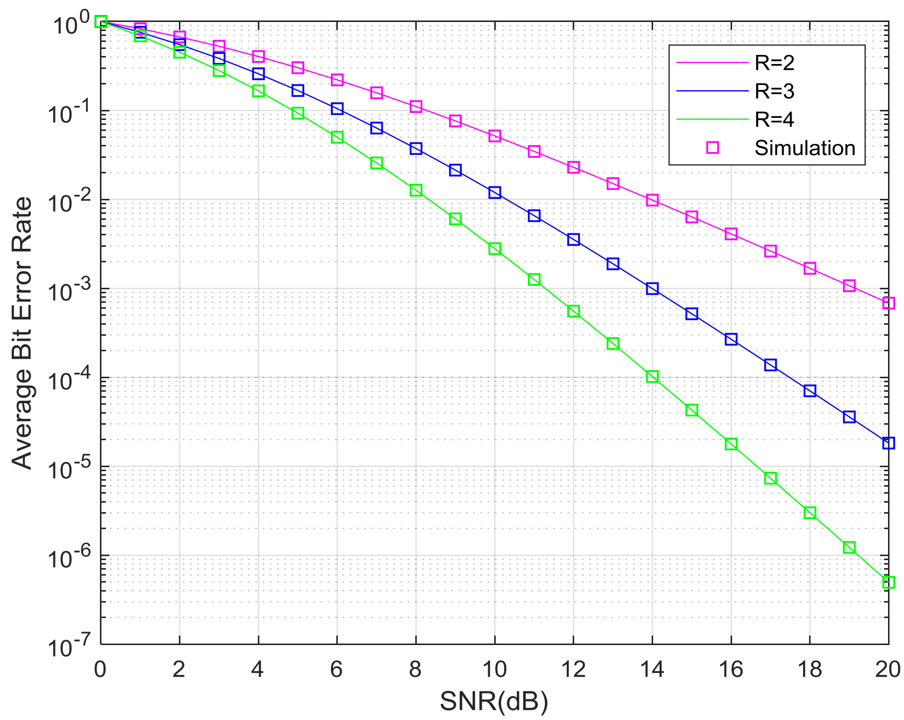


Figure 3.2: ABER of the ADSTBC system with varying number of relays

Figure 3.3 shows the result for the Ergodic capacity while increasing the number of relays and number of symbols transmitted.

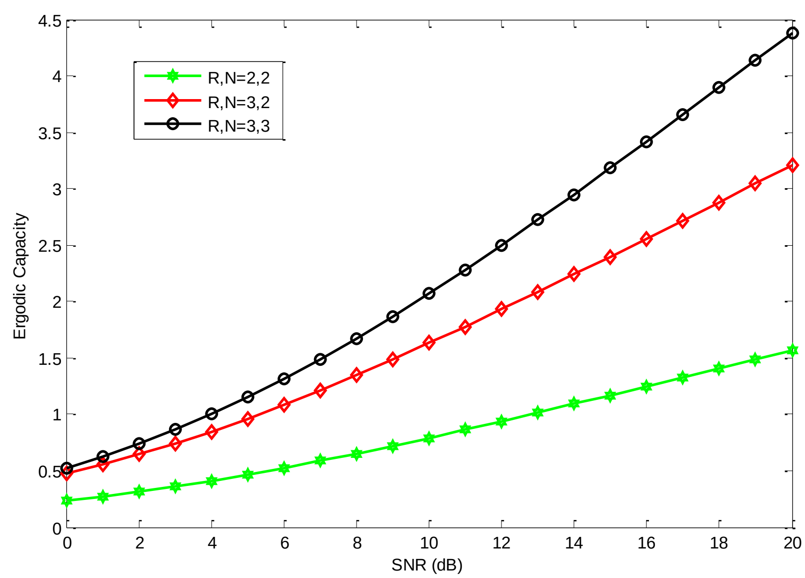


Figure 3.3: Ergodic capacity of ADSTBC for different values of R and N

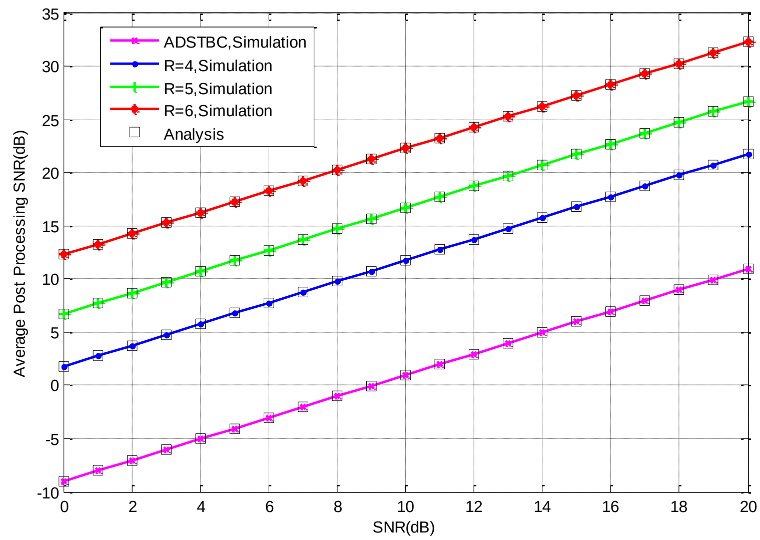


Figure 3.4: Average Post processing SNR of ADSTBC (R=2) and ORS- ADSTBC system

It is observed from figure 3.4 that at SNR of 10dB at the transmitter, the average post processing SNR is 12 dB for ORS-ADSTBC system versus 2 dB that of the ADSTBC system. Further, it is verified from the results that the average post processing SNR gain increases by 5dB and 8.5dB as the candidate relays for selection are increased from four to five and six respectively. The increased SNR gain leads to improved system performance for a given value of transmitted power.

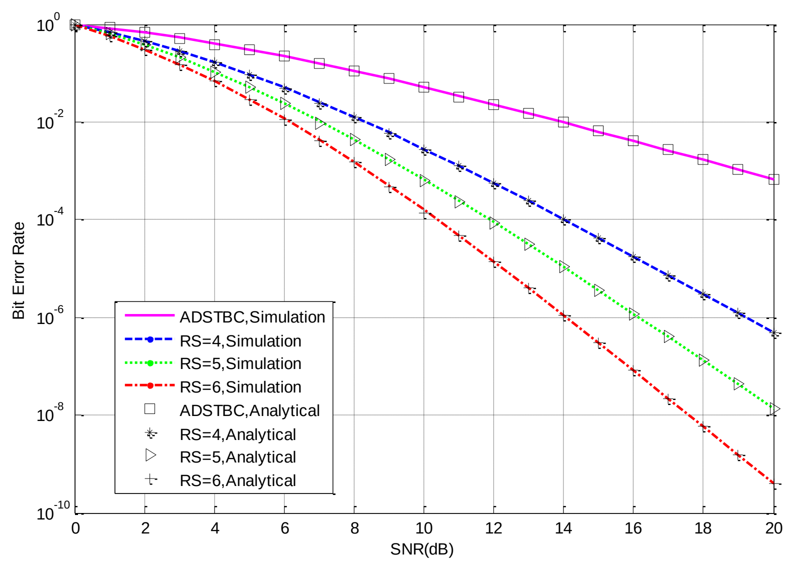


Figure 3.5: ABER of ADSTBC(R=2) and ORS ADSTBC

Figure 3.5 demonstrates the average bit error rate of the ADSTBC and ORS-ADSTBC sytems. For a ABER of 10^{-3}, the ORS-ADSTBC system having four candidates relays for selection shows a remarkable performance of 8dB over the ADSTBC system. The power saving increases further by 1.5dB and 2dB as the number of candidate relays increases to five and six respcetively. If we further increase the number of candidate relays from 4 to 5 or 6 the gain will increase further.

In figure 3.6, the ergodic capacity of the ORS-ADSTBC system is compared with the ADSTBC system. For SNR 10dB, the ADSTBC system has a capacity of 0.395 bits/s/Hz. For the ORS-ADSTBC,R=4 system for same value of input SNR, the capacity is 3.57 bits/s/Hz. Upon increasing the number of relays to 5 and 6, the ergodic capacity improves by 2.5 and 4.4 bits/s/Hz respectively. By increasing the number of candidate relays from 4 to 5 to 6, there is further improvement in the capacity.

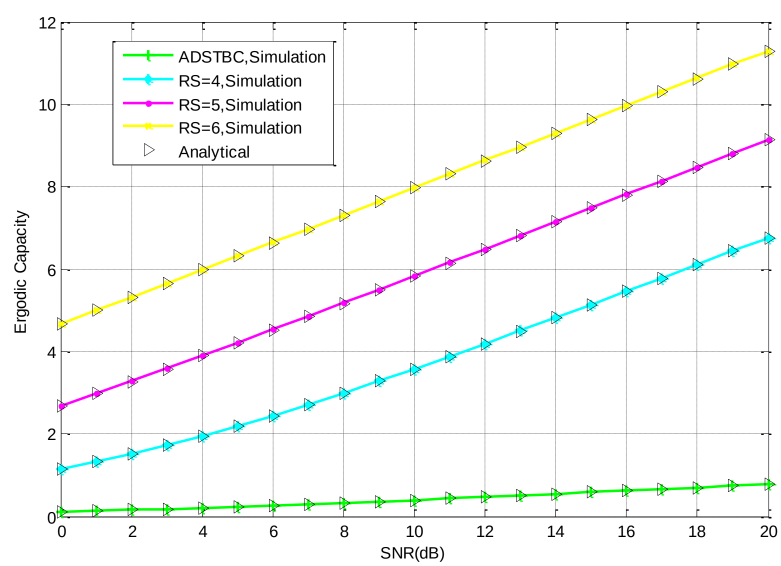


Figure 3.6: Ergodic capacity of ADSTBC(R=2) and ORS-ADSTBC system for R=4, 5, 6

Table 3.2 depicts the comparison of performance of ORS-ADSTBC with ADSTBC with respect to the performance metrics viz. average post processing SNR, ABER and ergodic capacity. It is observed that there is considerable improvement in error performance of ORS-ADSTBC as compared to the ADSTBC system. The average post processing SNR gain of 10 dB is obtained for SNR=10dB. At ABER of 10^{-3}, a gain of 8 dB in SNR is obtained in ORS-ADSTBC, R=4 over ADSTBC. For the ergodic capacity, there is an improvement of 3.18 bits/s/Hz when compared to ADSTBC. The performance improves when the candidate relays for relay selection are increased. It is observed from the table 3.2 that as the number of candidate relays are increased from four to five there is a further gain of 5dB, 1.5 dB and more than 80 % for average post processing SNR, ABER and ergodic capacity respectively. The analytical results are validated by the Monte-Carlo simulation results and show closed conformity with each other. Hence it is concluded that the performance improves considerably by relay selection in asynchronous cooperative communication systems.

Table 3.2 Comparison of ORS-ADSTBC with ADSTBC system

Proposed System (different values of R)	**Average Post Processing SNR (SNR=10dB) gain over ADSTBC**	**Average Bit Error Rate(ABER) of 10^{-3} gain over ADSTBC**	**Ergodic Capacity gain over ADSTBC for SNR= 10dB (in bits/s/Hz)**
ORS-ADSTBC,R=4	10 dB	8 dB	3.18
ORS-ADSTBC, R=5	15 dB	9.5 dB	5.68
ORS-ADSTBC, R=6	18.5 dB	11.5 dB	7.58

3.7 Conclusion

In this work, we have analyzed the performance of the proposed ADSTBC system in terms of ABER and Ergodic capacity. The performance of the proposed system is improved by optimal selection of relays, thereby reducing the system complexity. Analysis of optimal relay selection based asynchronous distributed space time block coded (ORS-ADSTBC) system has been done with respect to the performance metrics viz. average post processing SNR, average bit error rate and the ergodic capacity. The two best relay selection based proposed system is compared with an ADSTBC system in a Rayleigh fading environment. It is concluded that in spite of the un-intentional delay experienced in the asynchronous environment, the proposed delay tolerant ORS-ADSTBC system offers improvement over ADSTBC. Further it is verified that the performance of the proposed system improves by increasing the number of candidate relays. The simulation and analytical results verify the performance of the proposed system over the ADSTBC system

Chapter 4

Performance Analysis of Low Density Parity Check coded –Asynchronous Distributed Space Time Block Codes

This chapter investigates the performance of Low Density Parity Check (LDPC) concatenated ADSTBC system by incorporating joint Relay and Transmit-Receive Antenna pair Selection (RTRAS). The error performance of the system is evaluated using metrics viz. Pair wise error probability and Outage probability. Results corroborate that the system performance is a function of number of candidate relays, transmit and receive antennas

4.1 Introduction

Channel coding is a means to provide coding gain by adding redundant parity bits to the transmitted STBC which lowers the transmission power requirements and increases the reliability thereby eliminating the need for retransmission in many cases. Low Density Parity Check (LDPC) codes are highly efficient linear error-correcting codes [76]. LDPC codes are characterized by very sparse parity-check matrices yielding efficient decoding, hence, low error floors. The parallelizable decoder structure makes them suitable for high-speed applications. LDPC codes have been adopted for data channels for the 5G wireless communications [77, 78].

In this chapter, the scheme proposed in chapter 3 is extended to the channel coded scenario having variable number of receive antennas at the destination. Although the ADSTBC system enjoy low complexity, these codes have low coding gain. Therefore to achieve significant coding gain, the ADSTBC system is concatenated with channel codes, known as LDPC-ADSTBC system. The cooperative scenario is basically an asynchronous system where delay constraints and deep fades may make one or many links unsuitable for further relaying. In such cases relay and/or antenna selection is an optimum solution.

In this work, a selection based technique is used to choose the best two relays using order statistics provided that there are more than two relays. Apart from relay selection, assuming the source, relays and the destination to have multiple antennas, best antenna at each such node is selected for transmission and/or reception of signals. The Relay and Tx-Rx Antenna Selection

(RTRAS) has been done jointly to improve the overall system performance of RTRAS-LDPC-ADSTBC system.. The contributions of this chapter are listed below:

- Design of a joint Relay and Transmit-Receive Antenna Selection based (RTRAS-LDPC-ADSTBC) system.
- Error performance analysis of the proposed systems has been done in terms of pair wise error probability (PEP) and Outage probability.

The system models for the LDPC-ADSTBC and RTRAS-LDPC-ADSTBC systems have been discussed in the following sections.

4.2 System model for the LDPC-ADSTBC system

In this work, a Low Density Parity Check codes based Asynchronous Distributed Space Time Block Coded (LDPC-ADSTBC) system has been proposed constituting of 'R+2' nodes, as shown in figure .1

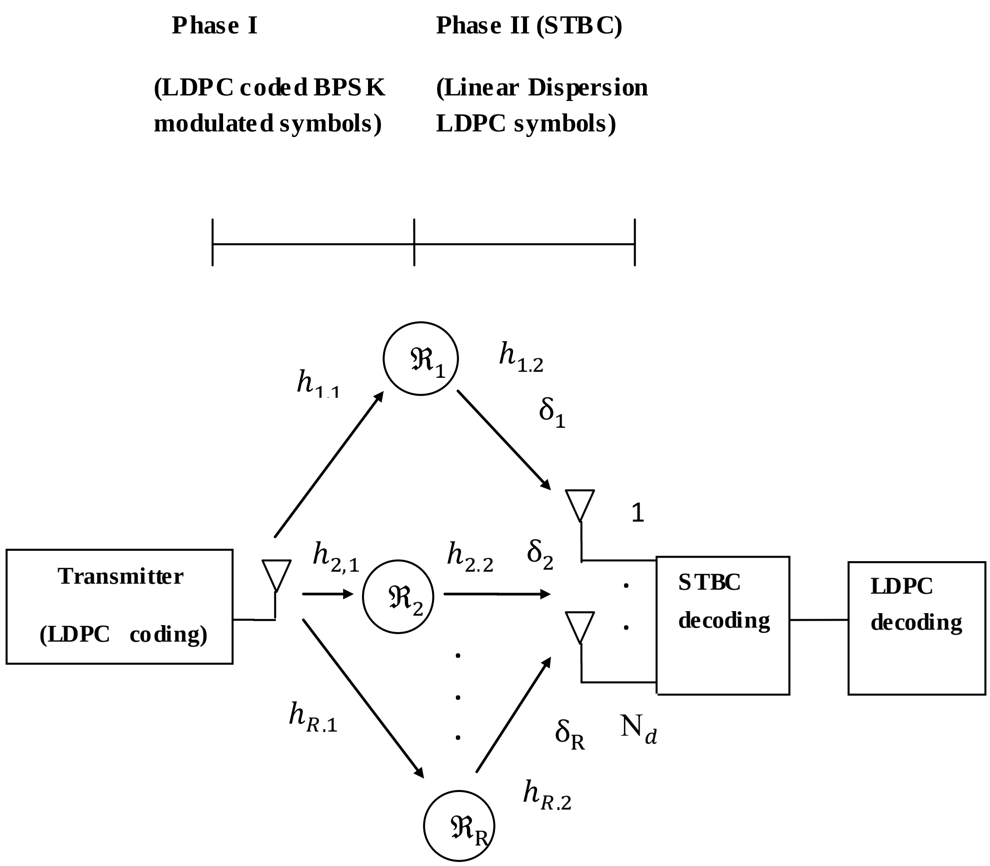


Figure 4.1: Block diagram of LDPC-ADSTBC system

It is assumed that the transmitter and each of the R relay nodes have single antenna whereas the receiver may employ variable number of antennas (N_d). An $(\widetilde{\mathcal{M}}, \tilde{J})$ LDPC code having code rate 1/2 is employed here, where $\widetilde{\mathcal{M}}$ refers to the length of the information vector and $\tilde{J}$ is the length of the LDPC codeword. The LDPC coded information bits, $b_{\tilde{J}}$ are BPSK modulated as $\boldsymbol{s} = [s_1 \dots \dots \dots .. s_J]^\dagger$ in the codebook $\{\boldsymbol{s}_1 \cdots \cdots \cdots \boldsymbol{s}_L\}$, where $2s_{\tilde{J}} = 2b_{\tilde{J}}$- $1(j \in 1 \dots J)$. The received signal $\boldsymbol{y}$ at the receiver with N_d antennas is given as

$$\boldsymbol{y} = \sum_{k=1}^{R} \sum_{n=1}^{N_d} h_{k,2,n} \sqrt{\frac{P_2}{P_1 + 1}} \boldsymbol{D}(\delta_k) \boldsymbol{A}_k \left(\sqrt{P_1}\, h_{k,1}\, \boldsymbol{s} + \boldsymbol{n}_k\right) + \boldsymbol{v}$$

$$= \sqrt{\frac{P_2 P_1}{P_1 + 1}} \widehat{\boldsymbol{H}} \boldsymbol{D}(\Omega) \boldsymbol{S} + \boldsymbol{V} \qquad (4.1)$$

Where, $\widehat{\boldsymbol{H}} = \boldsymbol{H} \otimes \boldsymbol{I}$. In this chapter number of antennas at the receiver is N_d, so $\boldsymbol{H}$ representing the overall channel gain from the source to the destination is given as

$$\boldsymbol{H} = \begin{bmatrix} h_{1,1} h_{1,2,1} \dots \dots \dots h_{R,1} h_{R,2,1} \\ . \quad . \\ . \quad . \\ h_{1,1} h_{1,2,N_d} \dots \dots h_{R,1} h_{R,2,N_d} \end{bmatrix} \quad \text{and} \quad \boldsymbol{V} = \sqrt{\frac{P_2}{P_1 + 1}} \sum_{k=1}^{R} \sum_{n=1}^{N_d} h_{k,2,n} \boldsymbol{D}(\delta_k) \boldsymbol{A}_k\, \boldsymbol{n}_k + \boldsymbol{v} \quad .$$

Manipulating equation (4.1) for the vertical stacking of the columns of **y** as done in gives the following equivalent matrix

$$\overline{\boldsymbol{y}} = \sqrt{\frac{P_1 P_2 T}{P_1 + 1}} \overline{\boldsymbol{H}}\, \boldsymbol{D}(\Omega)\, \overline{\boldsymbol{\chi}} \overline{\boldsymbol{s}} + \overline{\boldsymbol{V}}$$

$$= \sqrt{\frac{P_1 P_2 T}{P_1 + 1}} \overline{\boldsymbol{H}} \overline{\boldsymbol{S}} + \overline{\boldsymbol{V}} \qquad (4.2)$$

The symbols pertaining to equation (4.1) and (4.2) have same notation as used in (3.5) and (3.6) of chapter 3. The transmitted symbols are detected using a Maximum Likelihood (ML) Decoder as:

$$\hat{\overline{\boldsymbol{s}}} = arg\ \ min_{s_k} \left\| \overline{\boldsymbol{y}} - \sqrt{\frac{P_1 P_2 T}{P_1 + 1}} \overline{\boldsymbol{H}}\ \overline{\boldsymbol{S}} \right\|^2 = arg\ \ min_{s_k} \left\| \overline{\boldsymbol{y}} - \sqrt{\frac{P_1 P_2 T}{P_1 + 1}} \overline{\boldsymbol{H}}\ \boldsymbol{D}(\Omega)\, \overline{\boldsymbol{\chi}} \overline{\boldsymbol{s}} \right\|^2 \qquad (4.3)$$

The output of the ML decoder is given to the LDPC decoder which outputs the estimated information vector.

LDPC Decoding

LDPC decoding calls for determining the log-likelihood ratio (LLR):

$$L(\boldsymbol{s}_i) \triangleq log \frac{Pr\ (s_i=0|\hat{\boldsymbol{s}})}{Pr\ (s_i=1|\hat{\boldsymbol{s}})} \tag{4.4}$$

Let, the posterior LLR be computed as:

$$L(\boldsymbol{\phi}_i) = L(\boldsymbol{s}_i) + \ updated\ information \tag{4.5}$$

The details of computation of posterior LLR and the updated information based upon the message passing algorithm (MPA) are omitted here owing to the complexity involved. Further, a hard decision is made based on the posterior LLR in every iteration:

$$\widehat{s_i} = \begin{cases} 1 & if\ L(\phi_i) < 0 \\ 0 & else \end{cases} \tag{4.6}$$

The iterative decoding algorithm continues till all the parity check equations are satisfied by the hard decisions or when the number of iteration reach a pre-set value, whichever occurs earlier. The output is analyzed for various parameters such as capacity, diversity, etc. The ADSTBC system is LDPC coded which enhances the error performance of the system. In this chapter we analyse the LDPC-ADSTBC system using the Pair wise Error Probability (PEP). PEP holds significance in space-time systems as the reliability of the codeword is desired criteria.

4.3 Performance Analysis of the LDPC-ADSTBC System

Pair wise Error Probability

We begin by deriving the PEP for LDPC-ADSTBC with two relays (i.e. R=2). Let $\{\boldsymbol{S} = \boldsymbol{S}_\alpha\}$ denote the LDPC-ADSTBC codeword set, each $\boldsymbol{S}_\alpha \leq \mathbb{C}^{R\times T}$, $1 \leq k \leq |\mathbb{C}|$ and $|\mathbb{C}|$ denotes the cardinality of the codeword set $\mathbb{C}$. Let $P_{\alpha\beta}$ be the probability of mistaking a delayed codeword $\overline{\boldsymbol{S}}_\alpha$ by $\overline{\boldsymbol{S}}_\beta$, where $\overline{\boldsymbol{S}}_\alpha$ and $\overline{\boldsymbol{S}}_\beta$ are elements in the ADSTBC set conditioned on the fading channel matrix $\boldsymbol{H}$ and the delay profile Ω is given as

$$P(\boldsymbol{S}_\alpha \rightarrow \boldsymbol{S}_\beta / \boldsymbol{H}, \Omega) = Q\left(\sqrt{\frac{\frac{P_1 P_2}{(P_1+1)} \left\| \boldsymbol{H}\,(\overline{S}_\alpha - \overline{S}_\beta) \right\|_F^2}{2(noise\ variance)}}\right) \tag{4.7}$$

where the noise variance = $\left[\frac{P_2}{P_1+1}\sum_{k=1}^{R}\left|h_{k,2}\right|^2 + 1\right] I_T$. The eigen value decomposition of the delayed codeword difference matrix $\boldsymbol{M}_{\alpha\beta} = (\overline{\boldsymbol{S}}_\alpha - \overline{\boldsymbol{S}}_\beta)$ be given as

$$\boldsymbol{M}_{\alpha\beta} = \boldsymbol{U}\boldsymbol{N}_{\alpha\beta}\boldsymbol{V}^H \tag{4.8}$$

Where $\boldsymbol{M}_{\alpha\beta}$ contains the eigen values $\lambda_{\alpha,1}, \lambda_{\alpha,2}$ of the codeword difference matrix. $\boldsymbol{U}\boldsymbol{U}^H = \boldsymbol{V}\,\boldsymbol{V}^H$ and represent Identity matrix. Simplifying the frobenious norm

$$\begin{aligned}
&\left\|\widehat{\boldsymbol{H}}\,(\overline{\boldsymbol{S}}_\alpha - \overline{\boldsymbol{S}}_\beta)\,\right\|^2_F \\
&= \mathrm{Tr}\left\{\,\widehat{\mathbf{H}}\,(\overline{\mathbf{S}}_\alpha - \overline{\mathbf{S}}_\beta)\;\;(\overline{\mathbf{S}}_\alpha - \overline{\mathbf{S}}_\beta)^{\mathrm{H}}\widehat{\mathbf{H}}^{\mathrm{H}}\right\} \\
&= \mathrm{Tr}\left\{\,\widehat{\mathbf{H}}\;\mathbf{U}\mathbf{N}_{\alpha\beta}\mathbf{V}^{\mathrm{H}}\mathbf{V}\mathbf{N}_{\alpha\beta}{}^{\mathrm{H}}\mathbf{U}^{\mathrm{H}}\;\widehat{\mathbf{H}}^{\mathrm{H}}\right\} \\
&= Tr\left\{\boldsymbol{N}_{\alpha\beta}{}^2\widetilde{\boldsymbol{H}}\widetilde{\boldsymbol{H}}^H\right\} \\
&= \sum_{k=1}^{R}\lambda_{\alpha,k}\;\sum_{\tilde{k}=1}^{R}\left|\tilde{h}_{\;\tilde{k},k}\right|^2
\end{aligned} \tag{4.9}$$

$\boldsymbol{N}_{\alpha\beta}{}^2 = \begin{bmatrix}\lambda_{\alpha,1} & 0 & 0\\ 0 & \lambda_{\alpha,2} & 0\\ 0 & 0\;\ldots & \lambda_{\alpha,R}\end{bmatrix}$ contains the eigen values $\lambda_{\alpha,1}$, $\lambda_{\alpha,2}$ of the codeword difference matrix. The coefficient $\tilde{h}_{\;\tilde{k},k}$ is the $(\tilde{k},\;k)^{th}$ entry of the matrix $\widetilde{\boldsymbol{H}} = \widehat{\boldsymbol{H}}\boldsymbol{U}$ for $1 \le \tilde{k}\,,\;k \le R$. Therefore, the above expression for the PEP conditioned on $\widetilde{\boldsymbol{H}}$ is simplified by substituting (4.9) for $\left\|\widehat{\boldsymbol{H}}(\,\overline{\boldsymbol{S}}_\alpha - \overline{\boldsymbol{S}}_\beta)\,\right\|^2_F$ in (4.7), thus PEP is given as

$$P\left(\frac{\overline{\boldsymbol{S}}_\alpha \rightarrow \overline{\boldsymbol{S}}_\beta}{\boldsymbol{H},\Omega}\right) = Q\left(\sqrt{\frac{\frac{P_1P_2}{(P_1+1)}\sum_{k=1}^{R}\lambda_{\alpha,k}\;\sum_{\tilde{k}=1}^{R}\left|\tilde{h}_{\;\tilde{k},k}\right|^2}{2\left(\left[\frac{P_2}{P_1+1}\sum_{k=1}^{R}\left|h_{k,2}\right|^2+1\right]\;I_T\right)}}\right) \tag{4.10}$$

The average PEP is obtained by taking the expectation of the above PEP over $\boldsymbol{H}$. The unconditional PEP over $\mathbf{H}$ is given by

$$P\left(\frac{\overline{\boldsymbol{S}}_\alpha \;\rightarrow\; \overline{\boldsymbol{S}}_\beta}{\Omega}\right) = E_{\boldsymbol{H}}\left\{Q\left(\sqrt{\frac{\frac{P_1P_2\sum_{k=1}^{R}\lambda_{\alpha,k}\;\sum_{\tilde{k}=1}^{R}\left|\tilde{h}_{\;\tilde{k},k}\right|^2}{(P_1+1)}}{2\left(\frac{P_2}{P_1+1}\sum_{k=1}^{R}\left|h_{k,2}\right|^2\;+1\right)}}\right)\right\}$$

$$= Q\left(\sqrt{\frac{\frac{P_1P_2\sum_{k=1}^{R}\lambda_{\alpha,k}\;\sum_{\tilde{k}=1}^{R}\left|\tilde{h}_{\;\tilde{k},k}\right|^2}{(P_1+1)}}{2\left(\frac{P_2}{P_1+1}R+1\right)}}\right) \tag{4.11}$$

As given in [26], the expectation over all $|h_{k,2}|^2$ is approximated by its mean, 'R' which is the number of relays. Let μ denote the average power gain of the coefficients, $\tilde{h}_{\tilde{k},k}$ of the Rayleigh distributed effective channel matrix $\tilde{\boldsymbol{H}}$**.** Rewriting the above equation using Craig's bound

$$P\left(\frac{\bar{\boldsymbol{S}}_\alpha \to \bar{\boldsymbol{S}}_\beta}{\Omega}\right) \leq \frac{1}{2}\int_0^{\pi/2} e^{\frac{-(P_1 P_2 \mu \sum_{k=1}^{R} \lambda_{\alpha,k})}{4(1+P_1+RP_2)\sin^2\theta}} d\theta \qquad (4.12)$$

Further the unconditional average PEP with respect to all delay profiles is given as

$$E_\Omega\left(P\left(\frac{\bar{\boldsymbol{S}}_\alpha \to \bar{\boldsymbol{S}}_\beta}{\Omega}\right)\right) = \Psi\left(\Pi_{k=1}^{R}(1 + \frac{(P_1P_2\mu\lambda_{\alpha,k})}{4(1+P_1+RP_2\ )\sin^2\theta})\right) \qquad (4.13)$$

Where, $\Psi(\eta(\theta)) = \frac{1}{2}\int_0^{\pi//2} \frac{1}{\eta(\theta)} d\theta$ [20] .The total PEP for decoding at the destination is upper bounded using the union bound which is the sum of the PEPs over all codewords $\boldsymbol{S}_\alpha \in \mathsf{C}$ is given as

$$P(\ \bar{\boldsymbol{S}}_\alpha \to \bar{\boldsymbol{S}}_\beta) \leq \sum_{\alpha=1}^{|\mathsf{C}|} \Psi(\Pi_{k=1}^{R}(1 + \frac{(P_1P_2\mu\lambda_{\alpha,k})}{4(1+P_1+RP_2\ )\sin^2\theta})) \qquad (4.14)$$

For high SNR the total PEP is approximated as

$$P(\ \bar{\boldsymbol{S}}_\alpha \to \bar{\boldsymbol{S}}_\beta) \leq \sum_{\alpha=1}^{|\mathsf{C}|} \Psi(\Pi_{k=1}^{R} \frac{(P_1P_2\mu\lambda_{\alpha,k})}{4(1+P_1+RP_2\ )\sin^2\theta})$$

0r, $$P(\ \bar{\boldsymbol{S}}_\alpha \to \bar{\boldsymbol{S}}_\beta) \leq \sum_{\alpha=1}^{|\mathsf{C}|} \Psi\left(\Pi_{k=1}^{r}\lambda_{\alpha,k}\left(\frac{(P_1P_2\mu)}{4(1+P_1+RP_2\ )\sin^2\theta}\right)^{-r}\right) \qquad (4.15)$$

where r is the rank of codeword difference matrix $\boldsymbol{M}_{\alpha\beta}$ and equals R for all delay profiles in case of full diversity ADSTBC. The result is extended to multiple antennas receiver with number of antennas equal to N_d and achieving full diversity is given as follows

$$P(\ \bar{\boldsymbol{S}}_\alpha \to \bar{\boldsymbol{S}}_\beta) \leq \sum_{\alpha=1}^{|S|} \Psi\left(\left(\frac{(P_1P_2\mu)}{4(1+P_1+RP_2\ )}\right)^{N_d} \Pi_{k=1}^{R}\left(\lambda_{\alpha,k}\right)^{RN_d}\right) \qquad (4.16)$$

4.4 Results and Discussions of ADSTBC system

The analytical results have been obtained for the LDPC-ADSTBC system for single transmitter-receiver pair and R relays. We assume that the source and relays are equipped with single antenna each whereas the receiver has variable number of antennas, N_d. The number of symbols transmitted in one frame is 'N'. In this work, an irregular LDPC with column weight 3 has been employed. Monte- Carlo simulations using MATLAB validate the analytical results obtained using Mathematica. A frame consisting of LDPC coded bits is sent from the LDPC encoder with all the bits with random values 0 and 1 which has further been BPSK modulated and broadcast to the relays. The results have been obtained from 1000 independent iterations of each frame, for each value of SNR varying from 0 to 20 dB.

Figure 4.2 shows the plot of error performance of the synchronous DSTBC, ADSTBC and LDPC-ADSTBC with varying N_d at the receiver. It is observed that, at PEP of 10^{-3} for single antenna, the synchronous DSTBC requires an SNR of 19.25 dB, the ADSTBC requires 16.25 dB whereas LDPC coded the ADSTBC requires 14.75 dB.

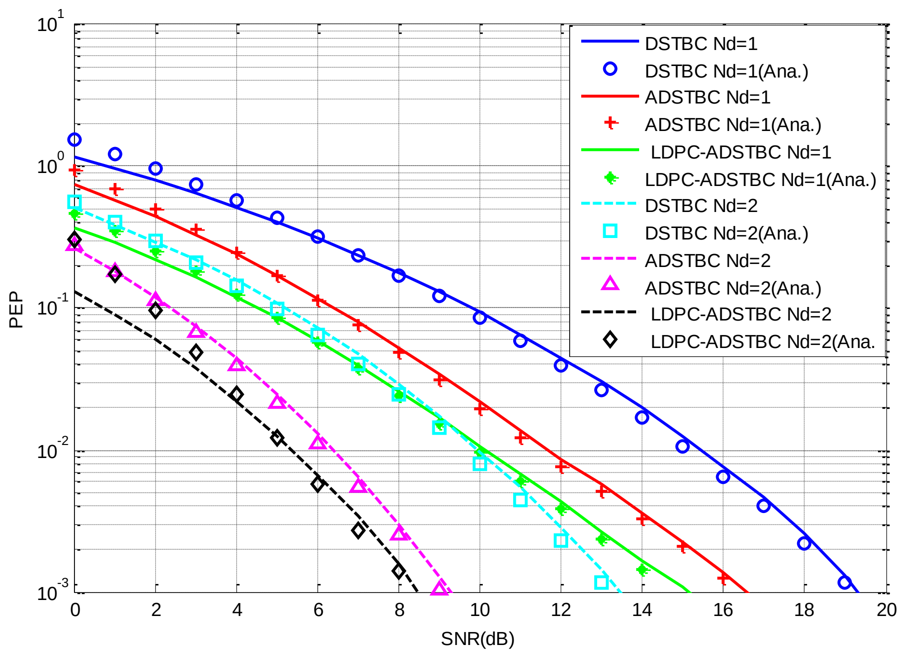


Figure 4.2: Error performance of different systems by varying number of antennas (N_d) at the receiver

The comparison among the given schemes has been tabulated in Table 4.1. The results show an improvement of 1.5 dB in SNR for PEP of 10^{-3} for the case of LDPC coded asynchronous DSTBC system (LDPC-ADSTBC) over asynchronous DSTBC system and 4.5 dB over synchronous DSTBC.

Table 4.1. SNR (dB) required for different transmission schemes for *N*=*R*=2 and varing N_d at PEP of 10^{-3}

Scheme	SNR(in dB) required at PEP of 10^{-3}	
	N_d=1	N_d =2
DSTBC	19.25	13
ADSTBC	16.25	9
LDPC-ADSTBC	14.75	8.25

When, N_d is increased from a single antenna to 2, we observe an increase in diversity as well as coding gain. At a given PEP for two antennas, SNR required LDPC-ADSTBC shows an gain of 1.25 dB in over ADSTBC system and approximately 4.5 dB over synchronous DSTBC. Figure 4.3 shows the PEP of the LDPC-ADSTBC with delay of two and one symbol period at the two relay nodes with number of modulated symbols=2 and 3 and N_d =1 and 2.

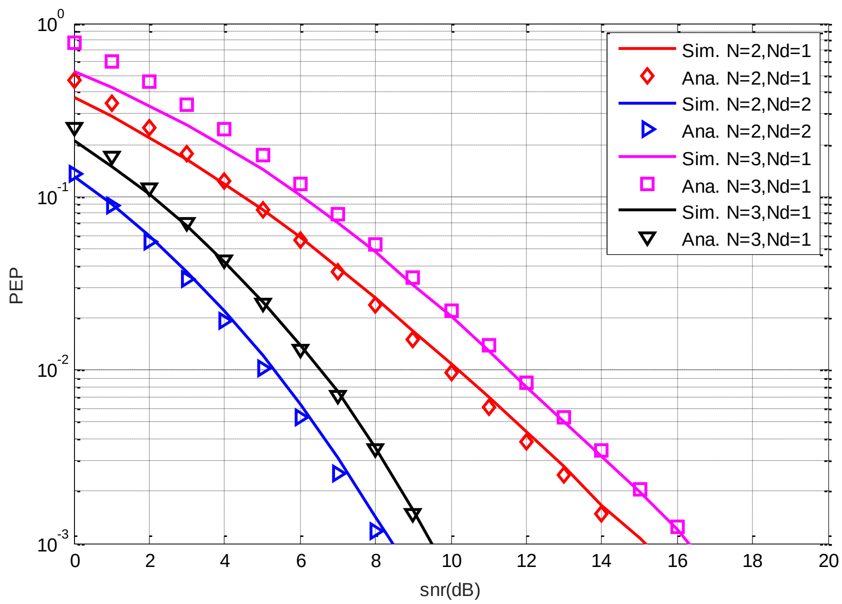


Figure 4.3:Error performance of the LDPC-ADSTBC with varying number of symbols (*N*)

From Table 4.2, it is observed that, for the given PEP, LDPC-ADSTBC with *N*=2, N_d =1 requires an SNR of 14.75 dB whereas the LDPC-ADSTBC *N*=2, N_d =2 requires an SNR of 8.5 dB . When we increase the number of modulated symbols from 2 to 3, the transmission rate increases thereby leading to a fall in diversity. However the SNR required for *N*=3, in case of

LDPC-ADSTBC N=3, N_d =1 is approximately 17 dB whereas in the LDPC-ADSTBC N=3, N_d =2 case an SNR of 9.5 dB is required.

Table 4.2. SNR (dB) required for LDPC-ADSTBC for varying N and N_d and fixed R at PEP of 10^{-3}

No. of modulated symbols (N) with R=2	SNR (in dB) required at PEP of 10^{-3}	
	N_d =1	N_d =2
N=2	14.75	8.5
N=3	17	9.5

From Figure 4.4, it is observed that there is significant improvement in error performance of the LDPC-ADSTBC with 3 relays(R) and 2 antennas at the receiver and the asynchronous LDPC-DSTBC with 2 relays and 1 antenna at the receiver.

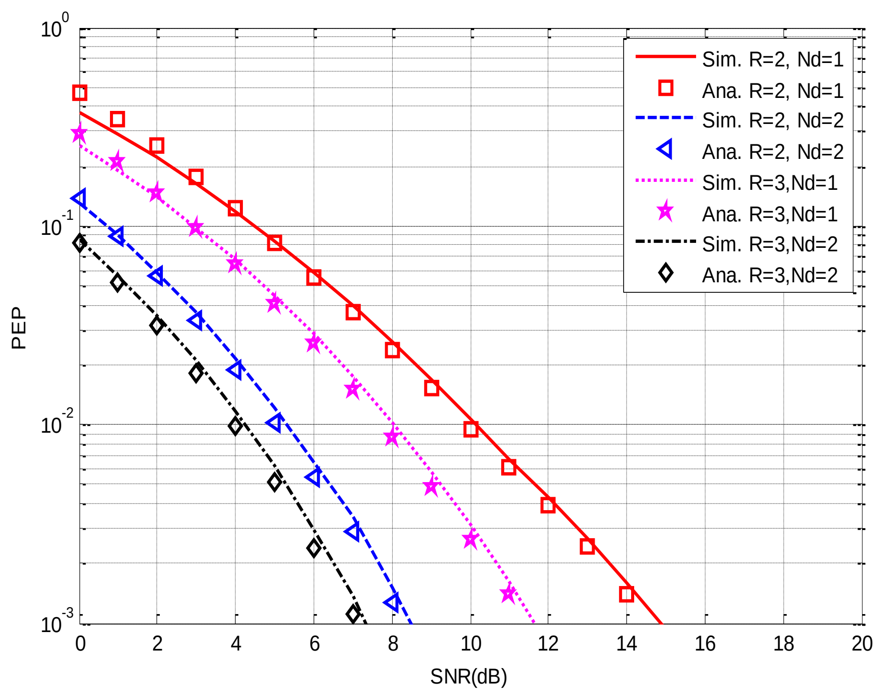


Figure 4.4: Error performance of the LDPC-ADSTBC with varying number of relays (R)

In Table 4.3, it is evident that, for the given PEP and N_d =1, the SNR required by LDPC-ADSTBC at R =2 and 3 are 14.75 dB and 11.5 dB respectively, whereas with N_d=2, the required SNR decreases by 6.25 and 4.5 respectively. The performance of the LDPC-ADSTBC system approximates the results of [20] ,which is the case of PEP of synchronous scenario, even in the asynchronous environment.

Table 4.3. SNR (dB) required for LDPC-ADSTBC for varying R and N_d and fixed N at PEP of 10^{-3}

No. of relays (R) with N=2	SNR(in dB) required at PEP of 10^{-3}	
	N_d =1	N_d =2
R=2	14.75	8.5
R=3	11.5	7

4.5 Comparison between LDPC concatenated ADSTBC and TRSTBC systems

The significance of the proposed work is highlighted only when it is compared to other contemporary techniques designed for similar scenarios. As discussed in chapter 1, there are different types of time domain approaches to combat the ill-effects of the asynchronous nature of cooperative communications. Out of these, DSTBC systems in time reversal (TR) and Linear dispersive (LD) structures find mention in this work. Time-reversal (TR) also known as phase conjugation in frequency domain is a simple method of preparing a message such that it appears at a particular time at a particular location in space and nowhere else. In TR, a signal is pre filtered such that it focuses in space and time at an intended receiver. This is achieved by using a time reversed complex conjugate of the channel impulse response at the receiver as a transmitter pre filter. TR-STBC protects the Alamouti's scheme by transmitting blocks instead of symbols in the time domain.

In this work, we compare our proposed ADSTBC and LDPC-ADSTBC system with a zero padded time reversal system [63] and its channel coded version, in terms of error performance. Figure 4.5 shows the ABER results of proposed systems viz. ADSTBC and LDPC-ADSTBC. The results have been compared with a TR based cooperative system and LDPC coded TR system for asynchronous system.

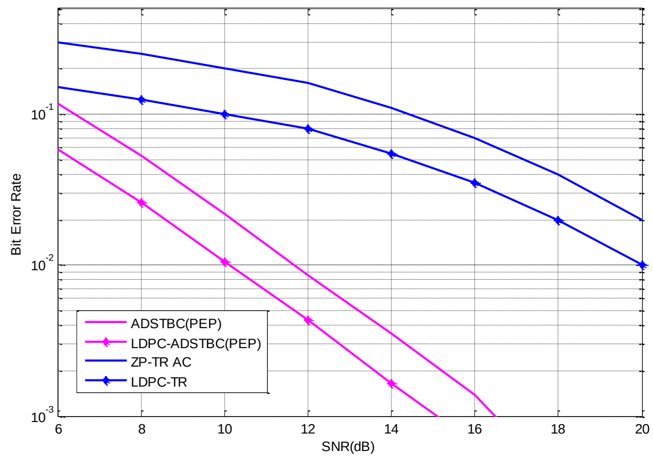


Figure 4.5: Comparison of ABER results of LDPC coded ADSTBC and TR system

From the figure 4.5, we observe that the ADSTBC system outperforms the TR system, with and without channel coding. The LDPC-ADSTBC system shows a gain of approximately 10 dB over the LDPC concatenated TR-STBC system. The performance of the LDPC-ADSTBC system is improved further in terms of reliability and reduced complexity by joint selection of best antennas and best transmit receive antenna pairs considering the system containing multiple antennas. The improvised system is discussed in the next section.

4.6 System Model for RTRAS-LDPC-ADSTBC System

In the previous section we studied the design and analysis of LDPC-ADSTBC system. The system shows improvement in terms of the ADSTBC system discussed in chapter 3. The performance of the system is increased further by antenna selection namely the Joint Relay and Transmit-Receive Antenna Selection (RTRAS) in this section.

The Joint Relay and Transmit-Receive Antenna Selection for Low Density Parity Check - Asynchronous Distributed Space Time Block Coded (RTRAS-LDPC-ADSTBC) system is shown in figure 4.6 which consists of a source transmitter, R relays and a destination, each having N_s, N_r and N_d antennas respectively.

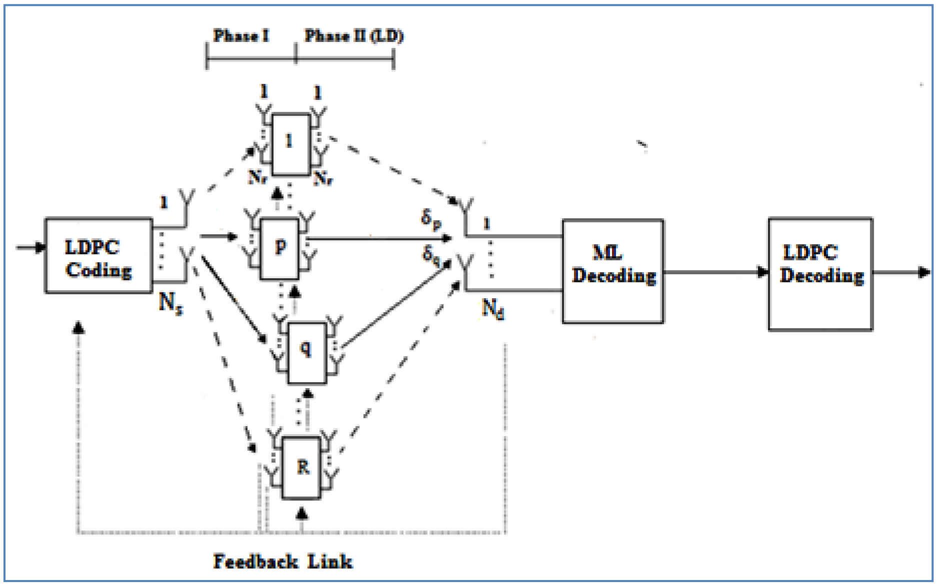


Figure 4.6: Block diagram of RTRAS-LDPC-ADSTBC system

The cooperative communication exploiting amplify and forward (AF) protocol, is analyzed in two phases as discussed in section 4.2.

Phase I: Let the source information $\boldsymbol{s}$ be the signal broadcasted using power P_1. The signal transmitted by the i^{th} antenna of the source to the j^{th} antenna of the k^{th} relay where, $k \in (1 \dots R)$, and is received as

$$\boldsymbol{r}_k^{ij} = \sqrt{P_1} h_{k,1}^{ij} \boldsymbol{s} + \boldsymbol{n}_k \tag{4.17}$$

where, $\boldsymbol{r}_k^{ij} = [r_k^{ij,1} \dots r_k^{ij,N}]^{\dagger}$, $\boldsymbol{n}_k$ represents noise at the k^{th} relay and is assumed to be AWGN with mean zero and variance σ_o. $h_{k,1}^{ij}$ represents fading between the i^{th} transmitting and the j^{th} receive antenna of the source and the k^{th} relay, respectively.

$$h_{k,1}^{ij} \in \boldsymbol{h}_{k,1} = \begin{bmatrix} h_{k,1}^{11} & \cdots & \cdots \\ \vdots & \ddots & \vdots \\ \vdots & \cdots & h_{k,1}^{N_s\ N_r} \end{bmatrix} \tag{4.18}$$

The fading coefficients are Gaussian distributed random variables with mean 0 and variance 1.

Phase II: The STBC symbols are transmitted, by the m^{th} antenna of k^{th} relay to l^{th} antenna of the destination with average power $P_2 = \frac{\acute{P} - P_1}{R}$, where $\acute{P}$ is the total power. The destination has full information of the fading gains and respective delays from the relays. The coherence interval is N and T for phase I and II respectively. The signal transmitted by the k^{th} relay is given by

$$\boldsymbol{x}_k^{ml} = \sqrt{P_2}\mu_k h_{k,2}^{ml}\boldsymbol{A}_k\boldsymbol{r}_k^{ij} \quad (4.19)$$

where, $\mu_k = \sqrt{\frac{1}{P_1\left|h_{k,1}^{ij}\right|^2+\sigma_o}}$ is the amplification factor at the k^{th} relay , σ_o being the noise power at the k^{th} relay. $h_{k,2}^{ml} \in \boldsymbol{h}_{k,2} = \begin{bmatrix} h_{k,2}^{ml} & \cdots & \cdots \\ \vdots & \ddots & \vdots \\ \vdots & \cdots & h_{k,2}^{N_r\ N_d} \end{bmatrix}$ represent the channel coefficient between by the m^{th} antenna of the k^{th} relay and the l^{th} antenna of the destination. $\boldsymbol{A}_k$ is the OALD matrix of size $(T \times N)$, for the k^{th} relay, which distributes the N symbols among T channel uses. The signal received at the destination is made delay tolerant by introduction of intentional delay at the k^{th} relay. The AF signal received at the destination from the source via k^{th} relay is given as

$$\begin{aligned}\boldsymbol{y}_k &= \boldsymbol{D}(\delta_k)\boldsymbol{x}_k^{ml} + \boldsymbol{n}_d \\ &= \sqrt{P_2}\mu_k h_{k,2}^{ml}\boldsymbol{D}(\delta_k)\boldsymbol{A}_k\boldsymbol{r}_k^{ij} + \boldsymbol{n}_d \quad (4.20)\end{aligned}$$

Where, $\boldsymbol{n}_d$ is the AWGN at the destination being added to the signal from the k^{th} relay. All the other symbols hold their meaning same as in (3.5). Substituting $\boldsymbol{r}_k^{ij}$ in equation (4.20), we obtain the following expression for the received signal at the destination

$$\begin{aligned}\boldsymbol{y}_k &= \sqrt{P_1P_2}\mu_k h_{k,1}^{ij}h_{k,2}^{ml}\boldsymbol{D}(\delta_k)\boldsymbol{A}_k\boldsymbol{s} + \sqrt{P_2}\mu_k h_{k,2}^{ml}\boldsymbol{D}(\delta_k)\boldsymbol{A}_k\boldsymbol{n}_k + \boldsymbol{n}_d^l \\ &= \sqrt{P_1P_2}\mu_k h_{k,1}^{ij}h_{k,2}^{ml}\boldsymbol{D}(\delta_k)\boldsymbol{A}_k\boldsymbol{s} + \boldsymbol{w}_k \quad (4.21)\end{aligned}$$

where, $\boldsymbol{n}_d^l$ is the noise present at the l^{th} antenna of the destination $\boldsymbol{w}_k = \sqrt{P_2}\mu_k h_{k,2}^{ml}\boldsymbol{D}(\delta_k)\boldsymbol{A}_k\boldsymbol{n}_k + \boldsymbol{n}_d^l$ is the total equivalent noise at the destination with respect to the k^{th} relay .

4.6.1 Joint Relay and Transmit-receive antenna pair selection for RTRAS-LDPC-ADSTBC system

For the given system model, a joint selection technique is used to select the best two relays using order statistics provided that there are more than two relays. Apart from relay selection, assuming the source, relays and the destination to have multiple antennas, best antenna at each such node is selected for transmission and/or reception of signals. The relay and antenna selection is done jointly. Prior to transmission of the information, the best transmitting, receiving and receiving-transmitting antennas of the source, destination and selected relays respectively are chosen by maximizing the end to end SNR γ_k. The bold lines in figure 4.5 denote the selected paths.

Using relay and transmit-receive antenna selection(RTRAS), LDPC coded information broadcast from the source is being padded with suitable delay, multiplied with suitable OALD matrices, amplified and relayed by the best two relays via their respective best transmit-receive antenna pairs thereby forming distributed space time block codes at the destination in the asynchronous environment (RTRAS-LDPC-ADSTBC).

The indices of the best relay$(\acute{k})$, the best transmit-receive antenna pair between the source and the selected relay$(\acute{i},\acute{j})$, best transmit-receive antenna pair between the selected relay and the destination $(\acute{m},\acute{l})$ are computed as follows [97] :

$$\{\acute{k},(\acute{i},\acute{j}),(\acute{m},\acute{l})\} = \underset{\substack{1\le k\le R \\ 1\le i\le N_S, 1\le j,m\le N_r, 1\le l\le N_D}}{argmax}\left(\gamma_k^{ij,ml}\right) \tag{4.26}$$

Where,$\gamma_k^{ij,ml}$ is the instantaneous end-to-end SNR through the k^{th} relay obtained using RTRAS. $\acute{k} = \{p,q\}$, $p \neq q$

$$(\acute{i},\acute{j}),(\acute{k},\acute{l}) = \begin{cases} (I,J),(M,L) for\ \acute{k} = p \\ (\dot{I},\dot{J}),(\dot{M},\dot{L})\ for\ \acute{k} = q, q \neq p \end{cases} \tag{4.27}$$

Here, p and q represent the best and second best relay respectively. (I,J) is the best transmit-receive antenna pair between the source and p, whereas (M,L) is the best transmit-receive antenna pair between p and the destination. Similarly, $(\dot{I},\dot{J}),(\dot{M},\dot{L})$ are the best transmit-receive antenna pair of the 'source - q' and 'q- destination', respectively. The total received SNR at the destination i.e. γ_d is bounded as in (3.12) and given as

$$\gamma_{ub} = \gamma_p + \gamma_q \ge \gamma_d \ge \frac{1}{2}(\gamma_p + \gamma_q) = \gamma_{lb} \tag{4.28}$$

Where, γ_{lb} and γ_{ub} are the lower and upper bounds on the total end-to end instantaneous SNR.

4.6.2 CDF and PDF of the instantaneous SNR of RTRAS-LDPC-ADSTBC system

The CDF and the PDF of the best transmit-receive antenna pair between the source and k^{th} relay are defined by order statistics [108] and given as follows

$$F_{\gamma_{h_{k,1}^{ij}}}(\gamma_k) = \left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,1}}}}\right)^{N_S\ N_r} \tag{4.29}$$

$$f_{\gamma_{h_{k,1}^{ij}}}(\gamma_k) = \frac{N_S\ N_r e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,1}}}}\left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,1}}}}\right)^{N_S\ N_r - 1}}{\bar{\gamma}_{h_{k,1}}} \tag{4.30}$$

Similarly, the CDF and PDF of the best transmit-receive antenna pair between the k^{th} relay and the destination is given as

$$F_{\gamma_{h_{k,2}^{ml}}}(\gamma_k) = \left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,2}}}}\right)^{N_r\ N_D} \tag{4.31}$$

$$f_{\gamma_{h_{k,2}^{ml}}}(\gamma_k) = \frac{N_r\ N_D\, e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,2}}}}\left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,2}}}}\right)^{N_r\ N_D - 1}}{\bar{\gamma}_{h_{k,2}}} \tag{4.32}$$

where, $\bar{\gamma}_{h_{k,1}} = E\{\gamma_{h_{k,1}^{ij}}\}$ and $\bar{\gamma}_{h_{k,2}} = E\{\gamma_{h_{k,2}^{ml}}\}$.

Since the source to relay and relay to destination links are independent, the CDF for end to end SNR is computed exploiting its relationship with outage probability as given in [105]. CDF of end to end SNR(γ_k) via the k^{th} relay = outage probability of γ at γ_k is given as

$$F_\gamma(\gamma_k) = 1 - Pr\left(\gamma_{h_{k,1}^{ij}} > \gamma_k\right) Pr\left(\gamma_{h_{k,2}^{ml}} > \gamma_k\right)$$

$$= 1 - \left[1 - Pr\left(\gamma_{h_{k,1}^{ij}} \le \gamma_k\right)\right]\left[1 - Pr\left(\gamma_{h_{k,2}^{ml}} \le \gamma_k\right)\right] \tag{4.33}$$

Since, $Pr\left(\gamma_{h_{k,1}^{ij}} \le \gamma_k\right) = F_{\gamma_{h_{k,1}^{ij}}}$ and $Pr\left(\gamma_{h_{k,2}^{ml}} \le \gamma_k\right) = F_{\gamma_{h_{k,2}^{ml}}}$, therefore the above equation is written using the values of CDFs from (4.29) and (4.31) in the (3.7), as

$$F_\gamma(\gamma_k) = 1 - \left(1 - \left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,1}}}}\right)^{N_S\ N_r}\right)\left(1 - \left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_{h_{k,2}}}}\right)^{N_r\ N_D}\right) \tag{4.34}$$

Considering $\bar{\gamma}_{h_{k,1}} = \bar{\gamma}_{h_{k,2}} = \bar{\gamma}_k$, (4.34) is re-written as

$$F_\gamma(\gamma_k) = \left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\right)^{N_S\ N_r} + \left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\right)^{N_r\ N_D} - \left(1 - e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\right)^{N_S\ N_r + N_r\ N_D} \tag{4.35}$$

We differentiate the above CDF with respect to γ_k to obtain the end to end PDF through the k^{th} relay as

$$f_\gamma(\gamma_k) = \frac{N_S\ N_r e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\left(1-e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\right)^{N_S\ N_r-1}\left(1-\left(1-e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\right)^{N_r\ N_D}\right)+N_r\ N_D e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\left(1-e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\right)^{N_r\ N_D-1}\left(1-\left(1-e^{-\frac{\gamma_k}{\bar{\gamma}_k}}\right)^{N_S\ N_r}\right)}{\bar{\gamma}_k} \quad (4.36)$$

The selection of the two best relays is not mutually independent events. Therefore we apply Order Statistics to compute the joint PDF of the two best selected relays

$$f_\gamma(\gamma_p, \gamma_q) = R(R-1)[F_\gamma(\gamma_q)]^{R-2} f_\gamma(\gamma_p) f_\gamma(\gamma_q) \quad (4.37)$$

Taking into account the PDF of the delay profile (Ω) given in (3.16), (4.35), (4.36) and (4.37), the overall PDF of the RTRAS-ADSTBC system is given as

$$f_{(\gamma,\Omega)}(\gamma_p, \gamma_q, \delta_k) = \frac{R(R-1)}{(\delta_{max}-\delta_{min})^2}\left(\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_S\ N_r} + \left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_r\ N_D} - \left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_S\ N_r + N_r\ N_D}\right)^{R-2}$$

$$\left(\frac{N_S\ N_r e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_S\ N_r-1}\left(1-\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_r\ N_D}\right)+N_r\ N_D e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_r\ N_D-1}\left(1-\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_S\ N_r}\right)}{\bar{\gamma}_k}\right)$$

$$\left(\frac{N_S\ N_r e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_S\ N_r-1}\left(1-\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_r\ N_D}\right)+N_r\ N_D e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_r\ N_D-1}\left(1-\left(1-e^{-\frac{\gamma_q}{\bar{\gamma}_k}}\right)^{N_S\ N_r}\right)}{\bar{\gamma}_k}\right) \quad (4.38)$$

The upper bound on CDF is given as

$$F_{\gamma_{up}}(z) = \int_0^{\frac{z}{2}} \int_{\gamma_q}^{z-\gamma_q} f_{(\gamma,\Omega)}(\gamma_p, \gamma_q, \delta_k) d\gamma_p\, d\gamma_q \quad (4.39)$$

Where, $z = \gamma^p + \gamma^q$. Similarly, the lower bound on the CDF is computed as

$$F_{\gamma_{lb}}(z) = \int_0^{z} \int_{\gamma_q}^{2z-\gamma_q} f_{(\gamma,\delta)}(\gamma_p, \gamma_q, \delta_k) d\gamma_p\, d\gamma_q \quad (4.40)$$

Using the derived bounds on the CDF, we have plotted the results for upper and lower bounds on PEP and Outage Probability in the results section.

4.7 Performance Analysis of RTRAS-LDPC-ADSTBC System

(a) Outage Probability

Outage probability is another measure that is widely used in wireless channels for the evaluation of the performance of wireless communication systems. The probability that the total instantaneous SNR at the destination being less than a given threshold γ_{th} is defined as the outage probability (P_{out}).

$$P_{out}^{RTRAS} = Pr(z \leq \gamma_{th}) \tag{4.41}$$

The outage probability can directly be obtained from the CDF of the total instantaneous SNR at the destination as:

$$P_{out}^{RTRAS} = F_{\gamma}(\gamma_{th}) \tag{4.42}$$

$$P_{out}^{ub} = \int_{0}^{\frac{\gamma_{th}}{2}} \int_{q}^{\gamma_{th}-q} f_{(\gamma,\delta)}\left(\gamma_p, \gamma_q, \delta_k\right) d\gamma_p \, d\gamma_q \tag{4.43}$$

$$P_{out}^{lb} = \int_{0}^{\gamma_{th}} \int_{q}^{2\gamma_{th}-q} f_{(\gamma,\delta)}\left(\gamma_p, \gamma_q, \delta_k\right) d\gamma_p \, d\gamma_q \tag{4.44}$$

(b) Pairwise Error Probability

Let $P_{\alpha\beta}$ be the probability of mistaking $\boldsymbol{S}_{\alpha}$ by $\boldsymbol{S}_{\beta}$ **,** where $\boldsymbol{S}_{\alpha}$ and $\boldsymbol{S}_{\beta}$ are codewords in the RTRAS-LDPC-ADSTBC code set conditioned on the fading channel matrix $\boldsymbol{H}$ and the delay profile $\Omega$is given as:

$$P_{\alpha\beta} = P(\boldsymbol{S}_{\alpha} \rightarrow \boldsymbol{S}_{\beta} / \boldsymbol{H}, \Omega) = Q\left(\sqrt{\frac{\frac{P_1 P_2}{(P_1+\sigma_o)} \left\| \boldsymbol{H} \, (\boldsymbol{S}_{\alpha} - \boldsymbol{S}_{\beta}) \right\|_F^2}{2(noise\ variance)}}\right) \tag{4.45}$$

where the equivalent noise variance is given by $\frac{P_2}{P_1+\sigma_o} + \sigma_o$, σ_o is the noise power at the relay and destination.

$$P(\boldsymbol{S}_{\alpha} \rightarrow \boldsymbol{S}_{\beta} / \boldsymbol{H}, \Omega) = Q\left(\sqrt{\frac{\frac{P_1 P_2 \, \boldsymbol{H} \, (\boldsymbol{S}_{\alpha} - \boldsymbol{S}_{\beta}) \, (\boldsymbol{S}_{\alpha} - \boldsymbol{S}_{\beta})^H \boldsymbol{H}^H}{(P_1+\sigma_o)}}{2(\frac{P_2}{P_1+\sigma_o} + \sigma_o)}}\right) \tag{4.46}$$

By using the Craig's bound, where $Q(x) = \frac{1}{\pi} \int_0^{\pi/2} e^{\frac{-x^2}{2 sin^2 \theta}} d\theta$ on P_{kl} **:**

$$P(\boldsymbol{S}_{\alpha} \rightarrow \boldsymbol{S}_{\beta} / \boldsymbol{H}, \Omega) \leq \frac{1}{\pi} \int_0^{\pi/2} e^{\frac{-(P_1 P_2 \, \boldsymbol{H} \, (\boldsymbol{S}_{\alpha} - \boldsymbol{S}_{\beta}) \, (\boldsymbol{S}_{\alpha} - \boldsymbol{S}_{\beta})^H \boldsymbol{H}^H)}{4(P_1+P_2) sin^2 \theta}} d\theta \tag{4.47}$$

Simplifying (4.49) using the Eigen value decomposition of the codeword difference matrix $M_{\alpha\beta} = (\boldsymbol{S}_\alpha - \boldsymbol{S}_\beta) = \boldsymbol{\zeta}(\Omega) N_\beta \xi^H(\Omega)$, $\boldsymbol{\zeta}^H(\Omega)\, \boldsymbol{\zeta}(\Omega) = \xi^H(\Omega)\, \xi(\Omega)$ =Identity matrix

$$\boldsymbol{H}\,(\boldsymbol{S}_\alpha - \boldsymbol{S}_\beta)\,(\boldsymbol{S}_\alpha - \boldsymbol{S}_\beta)^H \boldsymbol{H}^H = \sum_{k=1}^{2} \lambda_{\beta,k} \sum_{\tilde{k}=1}^{2} \left|\tilde{h}_{\tilde{k},k}\right|^2 \tag{4.48}$$

Where, $\lambda_{\beta,k}$ are the eigen values of the codeword difference matrix $\boldsymbol{M}_{\alpha\beta}$ and $\tilde{h}_{\tilde{k},k}$ are the elements of the equivalent matrix $\widetilde{\boldsymbol{H}} = \boldsymbol{H}\boldsymbol{\zeta}(\Omega)$. Substituting (4.48) in (4.47),

$$P(\boldsymbol{S}_\alpha - \boldsymbol{S}_\beta / \boldsymbol{H}, \Omega) \leq \frac{1}{\pi} \int_0^{\pi/2} e^{\frac{-P_1 P_2 \sum_{k=1}^{2} \lambda_{\beta,k} \sum_{\tilde{l}=1}^{2} \left|\tilde{h}_{\tilde{k},k}\right|^2}{4(P_1+P_2)\sin^2\theta}} d\theta \tag{4.49}$$

Since,

$$\frac{P_1 P_2 \sum_{\tilde{k}=1}^{2} \left|\tilde{h}_{\tilde{k},k}\right|^2}{(P_1+P_2)} = \gamma^p + \gamma^q = z \tag{4.50}$$

The bounds on the average PEP is obtained using as:

$$P(\boldsymbol{S}_\alpha - \boldsymbol{S}_\beta) \leq \frac{1}{\pi} \int_0^{\infty} \int_0^{\pi/2} e^{\frac{-\sum_{k=1}^{2} \lambda_{\beta,k} z}{4\sin^2\theta}} F_{\gamma_{lb}}(z)\, d\theta\, dz$$

$$\text{Or, } P_{kl}(ub) \leq \frac{1}{\pi} \int_0^{\infty} \prod_{k=1}^{2} \int_0^{\pi/2} e^{\frac{-\lambda_{\beta,k} z}{4\sin^2\theta}} F_{\gamma_{lb}}(z)\, d\theta\, dz \tag{4.51}$$

$$P_{kl}(lb) \geq \frac{1}{\pi} \int_0^{\infty} \prod_{k=1}^{2} \int_0^{\pi/2} e^{\frac{-\boldsymbol{\lambda}_{\boldsymbol{\beta},\boldsymbol{k}} \boldsymbol{z}}{4\sin^2\theta}} F_{\gamma_{ub}}(z)\, d\theta\, dz \tag{4.52}$$

Owing to the complexity involved in simplifying the power series involved in the joint PDF, numeric values of upper and lower bounds on the outage probability(P_{out}) and the pair-wise error probability is computed .

4.8 Results and Discussion of RTRAS-LDPC-ADSTBC System

In this section we provide the analytical results which are verified by the simulation results. Figure 4.6 depicts the PEP of the ORS-LDPC-ADSTBC system.

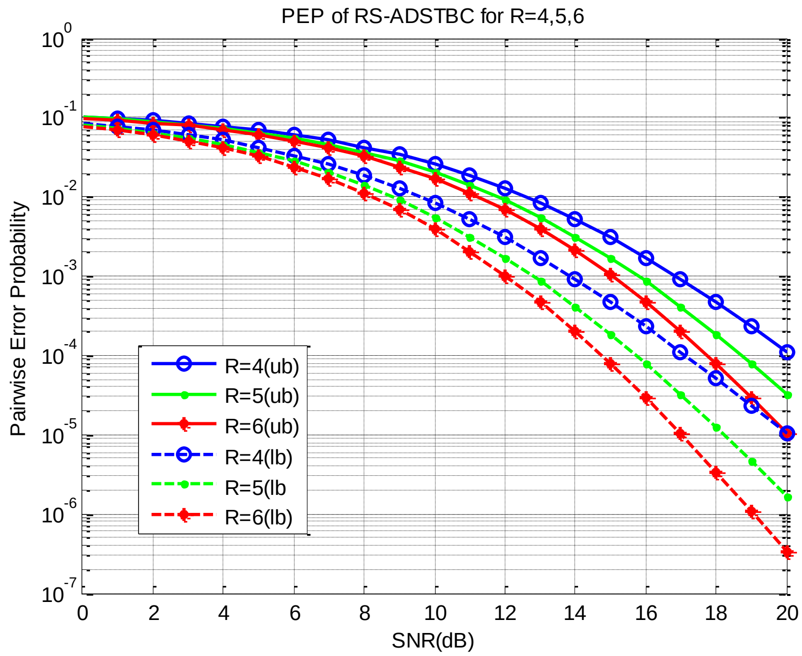


Figure 4.7: PEP bounds of ORS-LDPC-ADSTBC without TRAS

In figure Fig. 4.7, we observe an increase in the diversity gain by increasing number of candidate relays suitable for selection. Considering the lower bound on the PEP, there is a gain of over 1dB and 2.4 dB at PEP of 10^{-4} respectively as number of candidate relays are increased from four to five to six.

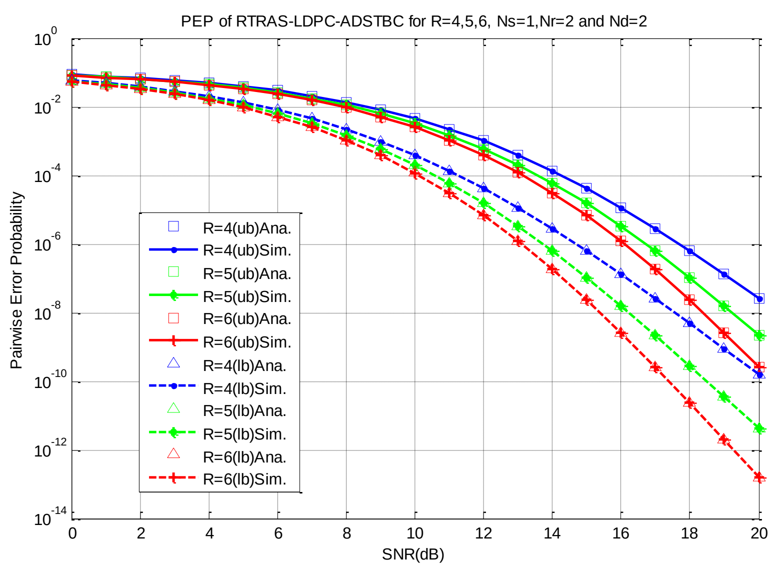


Figure 4.8: PEP bounds of RTRAS-LDPC-ADSTBC for $N_s = 1, N_r = 2, N_d = 2$ and varying R

In figure 4.8, we study the effect of joint relay transmit-receive antenna selection (RTRAS) on the LDPC-ADSTBC system. It is observed that TRAS further improves the performance of the relay selection based system. The analytical results are supported by the simulation results. For PEP of 10^{-4}, there is a gain of 6dB in the lower bound of the system for four candidate relays, assuming $N_s = 1, N_r = 2$ and $N_d = 2$, for the RTRAS-LDPC-ADSTBC system compared to the RS-LDPC-ADSTBC system. The performance increases with increasing the size of the set of relays(R) for selection. In this work, we have considered R=4, 5, 6 respectively. At low SNR values, the improvement in error performance is not as significant as at higher SNR values. As we increase the number of candidate antennas for TRAS, there is further increase in the error performance.

In figure 4.9, by increasing N_s from one to two, without changing N_r and N_d, i.e. $N_r = 2$ and $N_d = 2$, there is observed a gain of approximately 2dB in the lower bound for PEP of 10^{-5} for R=4. As we increase the number of relays to 6, there is a power saving of 3dB. The analytical and simulated results are compared in figure 4.8 for RTRAS-LDPC-ADSTBC for R=4, 5, 6, $N_s = 2, N_\mathrm{r} = 2$ and $N_d = 2$.

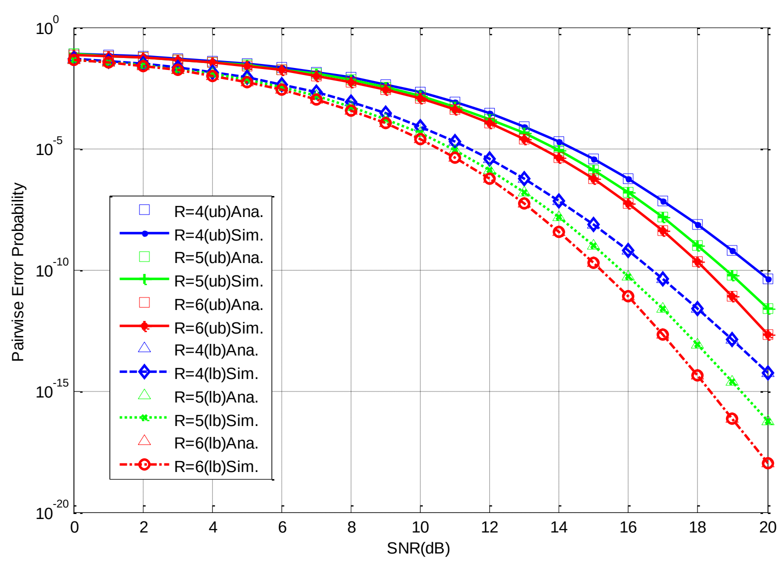


Figure 4.9: PEP bounds of RTRAS-LDPC-ADSTBC for $N_s = 2,\ N_\mathrm{r} = 2,\ N_d = 2$ and varying R

In figure 4.10, we study the performance of the ORS-LDPC-ADSTBC system with respect to the outage probability. For the evaluation, γ_{th}=3.

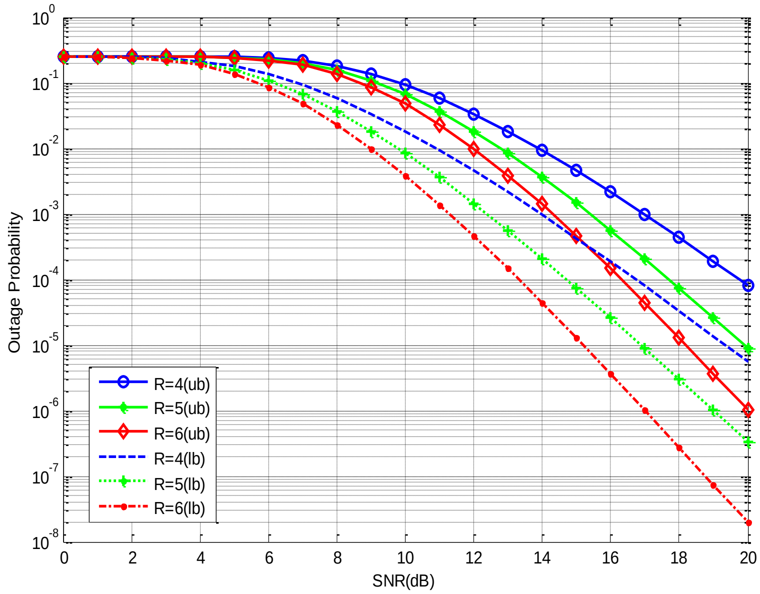


Figure 4.10: Outage Probability bounds of ORS-LDPC-ADSTBC without TRAS

We compare the simulated P_{out} results with the derived lower and upper bounds on it. As in PEP, the outage probability also shows significant performance gain with relay selection. As we increase R, there is observed marked improvement in the performance. For P_{out} 10^{-4}, there is a saving of approximately 3.3 dB if we increase R from 4 to 6. For the upper bounds, a gain of approximately 4dB is obtained for the same situation.

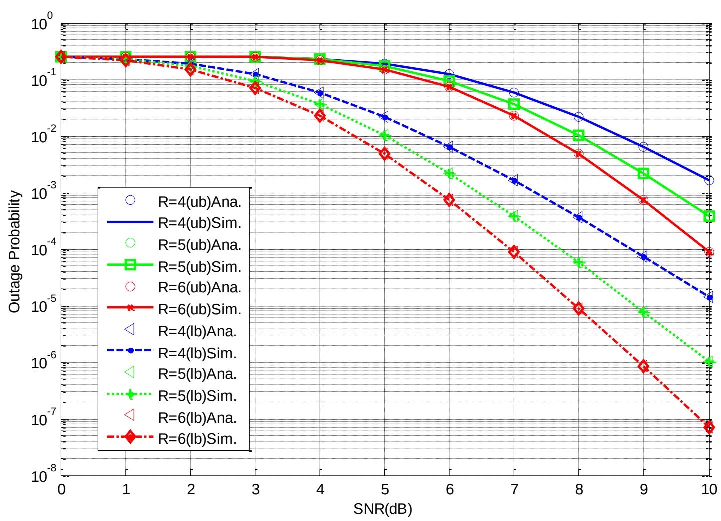


Figure 4.11: Outage Probability bounds of RTRAS-LDPC-ADSTBC for $N_s = 1, N_r = 2, N_d = 2$ and varying R

In figures 4.11 and 4.12, we observe the advantage of RTRAS over plain relay selection with respect to the outage probability. Although relay selection offers significant performance gain which is bettered by increasing R or the freedom of degree, application of TRAS over it leads to higher performance gains. This is justified by figure 4.11, which shows the lower and upper bounds of RTRAS-LDPC-ADSTBC for R=4, 5, 6, $N_s = 1, N_{\mathrm{r}} = 2$ and $N_d = 2$. For P_{out} 10^{-4}, considering the lower bound, a gain of approximately 8dB is obtained for R=4 in the RTRAS system over the RS system. This gain is further increased by increasing N_s , N_r , N_d. In figure 4.12, we observe that by increasing N_s from 1 to 2, increased power saving by more than 2.5 dB is obtained over that obtained in figure 4.11.

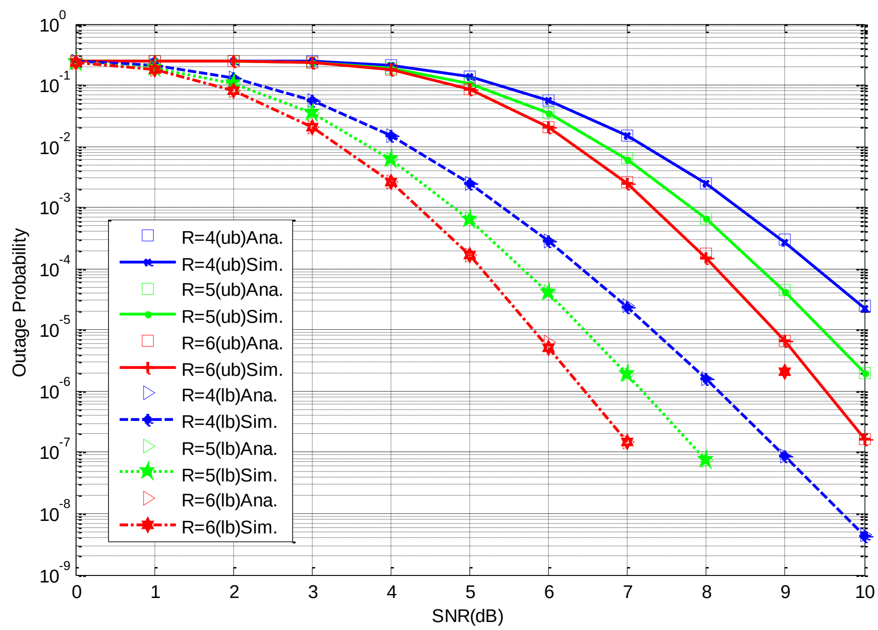


Figure 4.12: Outage Probability bounds of RTRAS-LDPC-ADSTBC $N_s = 2, N_{\mathrm{r}} = 2$, $N_d = 2$ and varying R

Table 4.4 depicts the performance of the ORS as well as joint RTRAS based LDPC-ADSTBC system. It is observed from the table that RTRAS provides gain over ORS. Further by increasing the number of relays and antennas lead to better performance in terms of improved PEP and P_{out}.

Table 4.4: Performance comparison of ORS-LDPC-ADSTBC and RTRAS-LDPC-ADSTBC

System / Parameters	Bound	ORS-LDPC-ADSTBC $N_s = N_r =, N_d = 1$, **SNR**(dB)			RTRAS-LDPC-ADSTBC $N_s = 1, N_r = N_d = 2$, **SNR**(dB)		
		No. of Relays(*R*)					
		R=4	*R*=5	*R*=6	*R*=4	*R*=5	*R*=6
Pairwise Error Probability (10^{-4})	lb	17	16	14.6	11	10.5	10
	ub	20	19	18	14	13.5	13
Outage Probability (10^{-4})	lb	16.6	14.6	13.3	8.8	7.7	7
	ub	20	18	16.3	11.8	10.8	10

4.9 Comparison of LDPC and Turbo coded asynchronous cooperative systems

The 3GPP study report [74] lays down the requirements of next generation access technologies which include high throughput, low latency, strong error correction capability and low implementation complexity. During the study phase of 5G standardization, many coding schemes including 4G's were evaluated based on the aforementioned requirements, such as the Turbo, LDPC and Polar codes. Erstwhile, for the implementation of 3G and 4G wireless technology, Turbo codes were used for channel coding. Hence it becomes a realistic step to do a qualitative and quantitative comparison between the proposed LDPC-coded system with a turbo coded system for asynchronous cooperative communication system present in literature. In this section the error performance of the a Turbo coded multiple relay aided Loosely synchronous Cooperative Differential Space Time Spreading (LS CDSTS) [75] system has been compared against the RTRAS LDPC ADSTBC system.

4.9.1 Block diagram of the Loosely synchronous Cooperative Differential Space Time Spreading (LS CDSTS) system

In the broadcast phase the source message is differentially-encoded by using Recursive Systematic Convolutional (RSC) code, interleaver , a recursive Unity-Rate Coder (URC) and the DPSK mapper block. Further, the DPSK-modulated symbols are spread using a source-specific direct sequence spreading code.

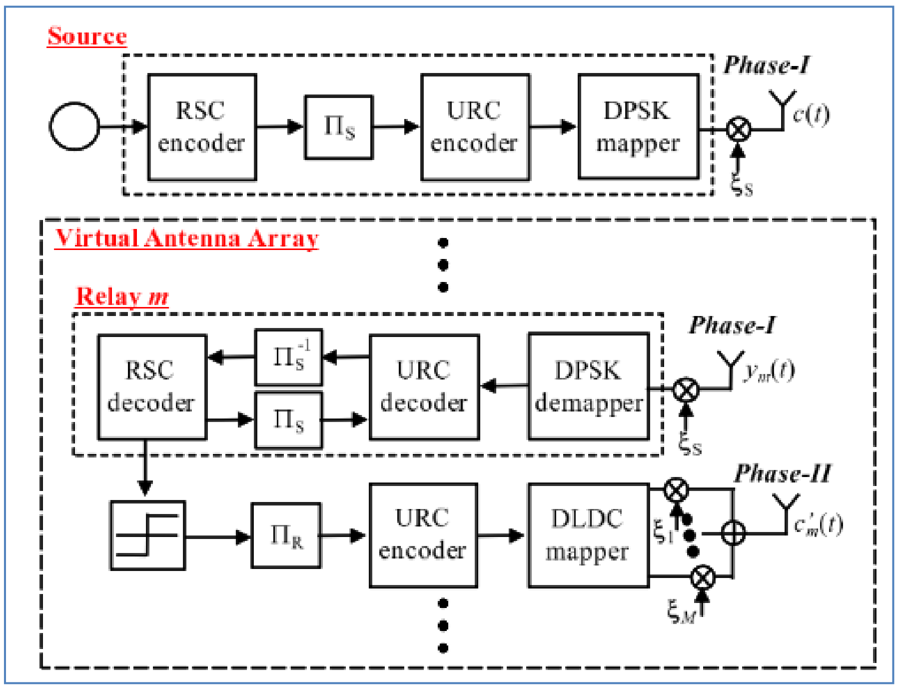


Figure: 4.13 Schematic of Source and relay nodes of CDSTS system [74]

In the cooperative phase-II, the received signals at the receiver are dispread and decoded, making use of inner and outer decoder as shown in figure 4.14.

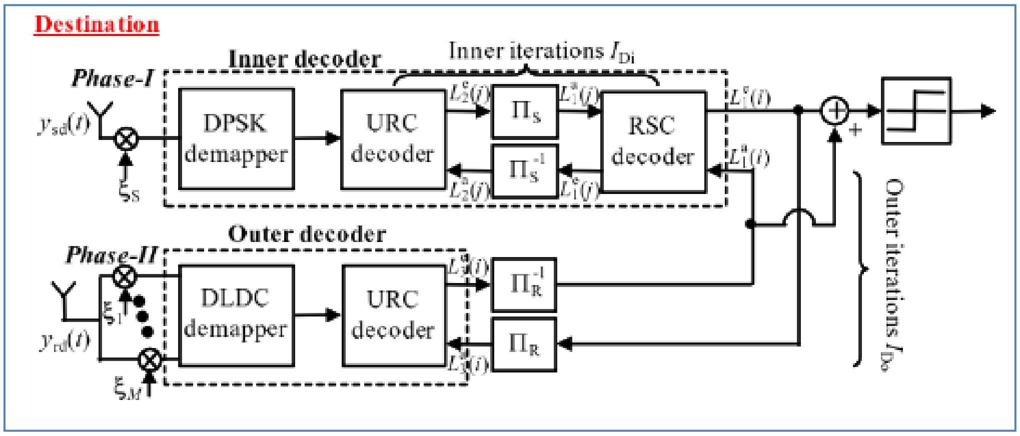


Figure 4.14: The Three stage iterative detector at the destination [74]

4.9.2 Error performance comparison of LS CDSTS and the RTRAS LDPC ADSTBC systems

It can be observed from figure 4.15 that the LDPC coded system shows higher reliability over the Turbo aided system. At the SNR of 10 dB, the LS CDSTS system shows an error of 2.5×10^{-4} whereas the RTRAS LDPC ADSTBC system has an error of approximately 10^{-4}. The error performance is further improved by increasing number of source antennas from one to two. The error thereby reduces to 2.5×10^{-5}.

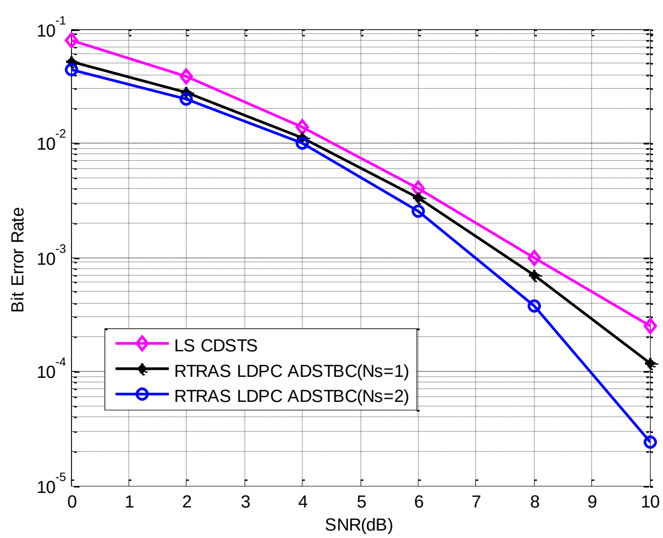


Figure 4.15: Comparison of Turbo and LDPC coded system in asynchronous cooperative scenario

Table 4.5: Error Performance of RTRAS LDPC-ADSTBC and LS CDSTS systems

SNR (dB)required for BER 10^{-3}		
LS CDSTS	**RTRAS-LDPC-ADSTBC**	
	$\boldsymbol{N_s = 1, N_r = N_d = 2}$	$\boldsymbol{N_s = N_r = N_d = 2}$
8	7	7.6

From table 4.5, it can be observed that the proposed RTRAS LDPC ADSTBC system outperforms the turbo coded LSCDSTS system by an SNR gain of 0.4 dB. If the number of source antennas in proposed system is increased from one to two, the gain is of 1dB.

4.10 Conclusions

In this chapter, we have analyzed the error performance of LDPC codes concatenated with ADSTBC system. The PEP of the system under study is analyzed using Craig's bounds. Analytical results verify the performance of the LDPC-ADSTBC system. We obtain an SNR gain of over 5 dB with LDPC-ADSTBC as compared to synchronous DSTBC system. Performance further improves by increasing number of relays. It is concluded that LDPC-ADSTBC codes perform better than their synchronous counterpart. In this work, we have compared the proposed LDPC-ADSTBC system with an LDPC concatenated TR-STBC system. Results show that former outperforms the latter. We have also derived the bounds on the CDF and PDF of the RTRAS-LDPC-ADSTBC system. We have analyzed the performance of the system in terms of pair-wise error probability (PEP) as well as the outage probability (P_{out}). The analytical and the simulation results confirm that by increasing the number of candidate relays and antennas at the source, relays and the destination, the performance of the system improves considerably. Results corroborate that RTRAS provides increased performance gain over ORS.

Chapter 5

Performance Analysis of ADSTBC and LDPC-ADSTBC systems using Selective Decode and Forward relaying in Different Fading channels

In the present chapter, the Amplify and forward based ADSTBC and LDPC-ADSTBC system models studied in Rayleigh fading environment, presented in chapter 3and 4 respectively, have been extended in Rician fading channel. The above mentioned systems show versatility not only in terms of fading scenarios, but also in the methods of relaying. A non-regenerative relaying protocol, Selective Decode and Forward relaying has been used in the present system design. The performance analysis has been done using average bit error rate (ABER) for the ADSTBC system and pair wise error probability (PEP) for the LDPC concatenated ADSTBC system.

5.1 Introduction

As discussed earlier, cooperative communication systems play a very significant role in providing a reliable and high rate wireless communication. With the emerging of several 5G technologies such as device-to-device communication in IoT or vehicle to vehicle communication, there are cases of line of sight (LoS) and non- line of sight (NLoS) scenarios. The existing literature presents cooperative systems in different channels[109-112] Two-wave with diffuse power (TWDP) fading is used to model LoS (Rician fading), Rayleigh fading and severe fading environment [112]. The distributed random locations of the relaying nodes and differing times of transmission from them makes cooperative communication an asynchronous system [52]. The present work analyses the performance of a selective decode and forward (DF) [20] based asynchronous distributed space time block coded (ADSTBC) system in TWDP fading channel.

Contributions of this chapter are as follows:

- Analysis of the selective DF based ADSTBC system on the basis of ABER in Rayleigh and Rician fading channels.
- Analysis of selective DF based LDPC-ADSTBC system on the basis of PEP in Rayleigh and Rician fading channels.

5.2 System Model of Selective DF based ADSTBC system

The Selective DF based ADSTBC system consisting of a transmitter, a receiver and 'R' relays. The information signal is broadcasted to the relaying nodes. The cooperative communication process is realized using the Selective decode and forward (DF) protocol. In Selective DF, only '$\acute{R}$' nodes out of 'R' nodes participate in the relaying phase which have successfully decoded the information and have received signal to noise ratio (SNR) greater than a threshold. The codeword $\boldsymbol{s}$ is decoded as vector $\boldsymbol{r}_k$ by the k^{th} relay. This decoded symbol vector is linearly modulated using dispersion matrix $\boldsymbol{A}_k$, re-encoded and transmitted with average power P_2as $\boldsymbol{x}_k$, is given below

$$\boldsymbol{x}_k = \sqrt{P_2}\boldsymbol{A}_k\boldsymbol{r}_k \tag{5.1}$$

In order to make the system, depicted in figure 3.1, delay tolerant, the received signal at the destination becomes:

$$\boldsymbol{y} = \sum_{k=1}^{\acute{R}} \sqrt{P_2}\left(\widehat{\boldsymbol{H}}\boldsymbol{D}(\delta_k)\boldsymbol{A}_k\boldsymbol{r}_k\right) + \boldsymbol{w} \tag{5.3}$$

where, $\widehat{\boldsymbol{H}} = \boldsymbol{h} \otimes \boldsymbol{I}_{\Delta}$, $\boldsymbol{I}_{\Delta}$=Identity matrix of size(T+ maximum delay), $\otimes$ denotes the kronecker product, $\boldsymbol{h} = [h_{1,2} \ldots\ldots h_{\acute{R},2}]$, g_k is TWDP fading coefficient from k^{th} relay to destination, $\boldsymbol{D}(\delta_k) =$ delay matrix$= \begin{bmatrix} \boldsymbol{O}_{\delta_k \times T} \\ \boldsymbol{I}_T \\ \boldsymbol{O}_{(\delta_{max}-\delta_k)\times T} \end{bmatrix}$, $\mathbf{O}$ denote a zero matrix. δ_k is the delay observed for the k^{th} relay at the receiver relative to the first relay and $\boldsymbol{w}$ is the additive white Gaussian noise with variance N_0.

Two Wave Diffuse Power (TWDP) channel

In this work, the Two Wave Diffuse Power (TWDP) channel has been used to realize different fading channels such as Rician and Rayleigh. Owing to the non availability of the exact closed form expression, an approximate probability density function for the instantaneous SNR of the TWDP channel is given as [113]

$$f_{\gamma}(\gamma_k) = \frac{\kappa}{2\bar{\gamma}} \sum_{\varsigma=1}^{Z} \sum_{\upsilon=0}^{1} a_{\varsigma} e^{-P_{2\varsigma-\upsilon} - \frac{\kappa * \gamma_k}{\bar{\gamma}}} I_0\left(2\sqrt{\Gamma_{\varsigma,\upsilon}}\right) \tag{5.4}$$

where, $\kappa = K + 1$, K here denotes the total specular power to the diffuse power, $\bar{\gamma}$ is the average SNR of all relay to destination links.

$$P_{2\varsigma} = (\kappa - 1)\big(1 + \alpha_\varsigma\big),\ P_{2\varsigma-1} = (\kappa - 1)\big(1 - \alpha_\varsigma\big), \tag{5.5}$$

where $\alpha_\varsigma = \Delta cos\,(\frac{\pi(\varsigma-1)}{2Z-1})$ and Δ is the relative strength the specular components. Z defines the order of the TWDP fading. a_ρ are constant coefficients related with the fading and first five values are tabulated in [112]. I_0 is the modified zeroth order Bessel function of the first kind and $\Gamma_{\varsigma,\upsilon} = \frac{P_{2\varsigma-\upsilon}\gamma\kappa}{2\bar{\gamma}}$.The joint PDF of $\acute{R}$ statistically independent relay nodes which have successfully decoded the information and have received SNR greater than a threshold, is given as

$$f_\gamma(\gamma_1, \gamma_2 .. \gamma_\nu) = \prod_{\nu=1}^{\acute{R}} f_\gamma(\gamma_\nu), \quad \nu = 1, \dots, \acute{R} \tag{5.6}$$

In this work we assume that the value of $\acute{R}$=2. Let $\gamma_1 = x$ and $\gamma_2 = y$. The joint PDF of the instantaneous SNR from the two relaying nodes through the TWDP channel is expressed as the product of their respective marginal PDFs, owing to statistical independence between them

$$f_\gamma(x, y) = f_\gamma(x) f_\gamma(y)$$

$$= \left(\frac{\kappa}{2\bar{\gamma}} \sum_{\rho=1}^{Z} \sum_{\iota=0}^{1} a_\rho\, e^{-P_{2\rho-\iota} - \frac{\kappa * x}{\bar{\gamma}}} I_0\big(2\sqrt{X_{\rho,\iota}}\big)\right) \left(\frac{\kappa}{2\bar{\gamma}} \sum_{\eta=1}^{Z} \sum_{\omega=0}^{1} a_{\eta s} e^{-P_{2\eta-\omega} - \frac{\kappa * y}{\bar{\gamma}}} I_0\big(2\sqrt{Y_{\eta,\omega}}\big)\right) \tag{5.7}$$

The joint PDF in (5.7) is approximated using [108 eqn(9.6.47)] as

$$f_\gamma(x, y) = \frac{1}{4\bar{\gamma}^2} \kappa^2 \left(\sum_{\rho=1}^{Z} \sum_{\iota=0}^{1} a_\rho\, e^{-P_{2\rho-\iota} - \frac{\kappa * x}{\bar{\gamma}}}\, {}_0F_1(;1; 0.25 * \left(2\sqrt{X_{\rho,\iota}}\right)^2) \right) \left(\sum_{\eta=1}^{Z} \sum_{\omega=0}^{1} a_\eta e^{-P_{2\eta-\omega} - \frac{\kappa * y}{\bar{\gamma}}}\, {}_0F_1(;1; 0.25 * \left(2\sqrt{Y_{\eta,\omega}}\right)^2) \right) \tag{5.8}$$

Where ${}_0F_1(;a;z)$ is the Confluent Hypergeometric function. An approximate result for the above PDF may be obtained by expanding the Confluent Hypergeometric function to its first two values. We proceed with the mathematical analysis with respect to the upper bound on the CDF and PDF.

5.2.1 CDF of the total instantaneous SNR

Assuming, $z \leq x+y$, is the total instantaneous SNR at the destination, the upper bound on the CDF may be obtained as follows

$$F_{\gamma_{ub}}(z) = \int_0^{\frac{z}{2}} \int_y^{z-y} f_{x,y}(x, y)\, dx dy$$

$$= \int_0^{\frac{z}{2}} \int_y^{z-y} \left(\frac{\kappa}{2\bar{\gamma}} \sum_{\rho=1}^{Z} \sum_{\iota=0}^{1} a_\rho e^{-P_{2\rho-\iota} - \frac{\kappa * x}{\bar{\gamma}}} I_0\left(2\sqrt{X_{\rho,\iota}}\right) \right) \left(\frac{\kappa}{2\bar{\gamma}} \sum_{\eta=1}^{Z} \sum_{\omega=0}^{1} a_\eta e^{-P_{2\eta-\omega} - \frac{\kappa * y}{\bar{\gamma}}} I_0\left(2\sqrt{Y_{\eta,\omega}}\right) \right) dx dy$$

$$= \frac{1}{4\bar{\gamma}^4} \sum_{\rho=1}^{Z} \sum_{\eta=1}^{Z} \sum_{\iota=0}^{1} \sum_{\omega=0}^{1} \frac{1}{24} e^{-\frac{z\kappa + \bar{\gamma} P_{2\rho-\iota} + \bar{\gamma} P_{2\eta-\omega}}{\bar{\gamma}}} \bar{\gamma} a_\rho a_\eta (3\bar{\gamma}(4\bar{\gamma}((-1 + e^{\frac{z\kappa}{\bar{\Upsilon}}})\bar{\gamma} - z\kappa) + (6(-1 + e^{\frac{z\kappa}{\bar{\Upsilon}}})\bar{\gamma}^2 - 6\bar{\gamma} z\kappa - 3z^2\kappa^2) P_{2\eta-\omega}) + P_{2\rho-\iota}(3\bar{\gamma}(2(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^2 - 2\bar{\gamma} z\kappa - z^2\kappa^2) + 2(6(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^3 - 6\bar{\gamma}^2 z\kappa - 3\bar{\gamma} z^2\kappa^2 - z^3\kappa^3) P_{2\eta-\omega}))$$

(5.9)

We obtain the joint PDF by differentiating (5.9) with respect to z as

$$f(z) = \sum_{\rho=1}^{Z} \sum_{\eta=1}^{Z} \sum_{\iota=0}^{1} \sum_{\omega=0}^{1} \frac{1}{96\acute{\Upsilon}^4} (e^{-\frac{z\kappa + \bar{\gamma} P_{2\rho-\iota} + \bar{\gamma} P_{2\eta-\omega}}{\bar{\gamma}}} \bar{\gamma} a_\rho a_\eta (3\bar{\gamma}(4\bar{\gamma}(-\kappa + e^{\frac{z\kappa}{\bar{\Upsilon}}}\kappa) + (-6\bar{\gamma}\kappa + 6e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}\kappa - 6z\kappa^2) P_{2\eta-\omega}) + P_{2\rho-\iota}(3\bar{\gamma}(-2\bar{\gamma}\kappa + 2e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}\kappa - 2z\kappa^2) + 2(-6\bar{\gamma}^2\kappa + 6e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}^2\kappa - 6\bar{\gamma} z\kappa^2 - 3z^2\kappa^3) P_{2\eta-\omega})) - e^{-\frac{z\kappa + \bar{\gamma} P_{2\rho-\iota} + \bar{\gamma} P_{2\eta-\omega}}{\bar{\gamma}}} \bar{\gamma} a_\rho a_\eta (3\bar{\gamma}(4\bar{\gamma}((-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma} - z\kappa) + (6(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^2 - 6\bar{\gamma} z\kappa - 3z^2\kappa^2) P_{2\eta-\omega}) + P_{2\rho-\iota}(3\bar{\gamma}(2(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^2 - 2\bar{\gamma} z\kappa - z^2\kappa^2) + 2(6(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^3 - 6\bar{\gamma}^2 z\kappa - 3\bar{\gamma} z^2\kappa^2 - z^3\kappa^3) P_{2\eta-\omega}))) \quad (5.10)$$

The overall PDF of the Selective DF based ADSTBC system takes into account the PDF of the delay profile (3.16) and is given as

$$f_{sys}(z) = \frac{1}{(\delta_{max} - \delta_{min})^2} \sum_{\rho=1}^{Z} \sum_{\eta=1}^{Z} \sum_{\iota=0}^{1} \sum_{\omega=0}^{1} \frac{1}{96\acute{\Upsilon}^4} (e^{-\frac{z\kappa + \bar{\gamma} P_{2\rho-\iota} + \bar{\gamma} P_{2\eta-\omega}}{\bar{\gamma}}} \bar{\gamma} a_\rho a_\eta (3\bar{\gamma}(4\bar{\gamma}(-\kappa + e^{\frac{z\kappa}{\bar{\Upsilon}}}\kappa) + (-6\bar{\gamma}\kappa + 6e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}\kappa - 6z\kappa^2) P_{2\eta-\omega}) + P_{2\rho-\iota}(3\bar{\gamma}(-2\bar{\gamma}\kappa + 2e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}\kappa - 2z\kappa^2) + 2(-6\bar{\gamma}^2\kappa + 6e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}^2\kappa - 6\bar{\gamma} z\kappa^2 - 3z^2\kappa^3) P_{2\eta-\omega})) - e^{-\frac{z\kappa + \bar{\gamma} P_{2\rho-\iota} + \bar{\gamma} P_{2\eta-\omega}}{\bar{\gamma}}} \bar{\gamma} a_\rho a_\eta (3\bar{\gamma}(4\bar{\gamma}((-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma} - z\kappa) + (6(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^2 - 6\bar{\gamma} z\kappa - 3z^2\kappa^2) P_{2\eta-\omega}) + P_{2\rho-\iota}(3\bar{\gamma}(2(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^2 - 2\bar{\gamma} z\kappa - z^2\kappa^2) + 2(6(-1 + e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^3 - 6\bar{\gamma}^2 z\kappa - 3\bar{\gamma} z^2\kappa^2 - z^3\kappa^3) P_{2\eta-\omega}))) \quad (5.11)$$

Using the derived PDF, we analyze the Selective DF based ADSTBC system on the basis of ABER in the following section.

5.2.2 Average bit error rate (ABER) of ADSTBC system in different fading channels

The average bit error rate (ABER) is obtained by averaging the received error conditioned of the system with respect to the PDF of the system.

$$P_e = \int_0^\infty P_e(z) f_{sys}(z) dz \quad (5.12)$$

$P_e(z)$ is the system error conditioned on the fading channel. An approximate expression for the conditional error is given in (3.19) as $P_e(z) = \frac{1}{6}e^{-z} + \frac{1}{2}e^{\frac{-4z}{3}}$ for BPSK modulation.

$$P_e = \int_0^\infty \left(\frac{1}{6}e^{-z} + \frac{1}{2}e^{\frac{-4z}{3}}\right) \frac{1}{(\delta_{max}-\delta_{min})^2} \sum_{\rho=1}^{Z}\sum_{\eta=1}^{Z}\sum_{\iota=0}^{1}\sum_{\omega=0}^{1} \frac{1}{96\acute{Y}^4} (e^{-\frac{z\kappa+\bar{\gamma}P_{2\rho-\iota}+\bar{\gamma}P_{2\eta-\omega}}{\bar{\gamma}}} \bar{\gamma} a_\rho a_\eta (3\bar{\gamma}(4\bar{\gamma}(-\kappa + e^{\frac{z\kappa}{\acute{Y}}}\kappa) + (-6\bar{\gamma}\kappa + 6e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}\kappa - 6z\kappa^2)P_{2\eta-\omega}) + P_{2\rho-\iota}(3\bar{\gamma}(-2\bar{\gamma}\kappa + 2e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}\kappa - 2z\kappa^2) + 2(-6\bar{\gamma}^2\kappa + 6e^{\frac{z\kappa}{\bar{\gamma}}}\bar{\gamma}^2\kappa - 6\bar{\gamma}z\kappa^2 - 3z^2\kappa^3)P_{2\eta-\omega})) - e^{-\frac{z\kappa+\bar{\gamma}P_{2\rho-\iota}+\bar{\gamma}P_{2\eta-\omega}}{\bar{\gamma}}} \bar{\gamma} a_\rho a_\eta (3\bar{\gamma}(4\bar{\gamma}((-1+e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma} - z\kappa) + (6(-1+e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^2 - 6\bar{\gamma}z\kappa - 3z^2\kappa^2)P_{2\eta-\omega}) + P_{2\rho-\iota}(3\bar{\gamma}(2(-1+e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^2 - 2\bar{\gamma}z\kappa - z^2\kappa^2) + 2(6(-1+e^{\frac{z\kappa}{\bar{\gamma}}})\bar{\gamma}^3 - 6\bar{\gamma}^2 z\kappa - 3\bar{\gamma}z^2\kappa^2 - z^3\kappa^3)P_{2\eta-\omega}))) dz$$

$$= \frac{1}{96\bar{\gamma}^4(\delta_{max}-\delta_{min})^2} \sum_{\rho=1}^{Z}\sum_{\eta=1}^{Z}\sum_{\iota=0}^{1}\sum_{\omega=0}^{1} e^{-P_{2\rho-\iota}-P_{2\eta-\omega}} \kappa^2 a_\rho a_\eta \left(2\bar{\gamma}^4\left(\frac{1}{(\bar{\gamma}+\kappa)^2} + \frac{27}{(4\bar{\gamma}+3\kappa)^2}\right) + \left(\frac{3\bar{\gamma}^4\kappa}{(\bar{\gamma}+\kappa)^3} + \frac{9\bar{\gamma}\kappa}{\left(\frac{4}{3}+\frac{\kappa}{\bar{\gamma}}\right)^3}\right)P_{2\eta-\omega} + \kappa P_{2\rho-\iota}\left(\bar{\gamma}^4\left(\frac{1}{(\bar{\gamma}+\kappa)^3} + \frac{81}{(4\bar{\gamma}+3\kappa)^3}\right) + \left(\frac{2\bar{\gamma}^4\kappa}{(\bar{\gamma}+\kappa)^4} + \frac{6\kappa}{\left(\frac{4}{3}+\frac{\kappa}{\bar{\gamma}}\right)^4}\right)P_{2\eta-\omega}\right)\right) \quad (5.13)$$

This is the closed form equation for the ABER of the system.

5.3 Results of ADSTBC system in Rayleigh and Rician fading channels

The new derived closed form expressions are validated by Monte-Carlo simulations. The ABER derived in (5.13), has been plotted in figure 5.1. At the source the information bits with random values 0 and 1 has been BPSK modulated and broadcast to the relays. The results have been obtained from 1000 independent iterations of each frame, for each value of SNR varying from 0 to 20 dB. TWDP fading is used to model the channels. It is assumed that the receiver has full channel and delay information from the relay nodes to the destination. The performance curves are plotted for TWDP fading channels for different values of K and Δ. The Rayleigh and Rician fading channels are special cases of TWDP fading. By decreasing the value of K= 0, one approaches scenario closer to Rayleigh, whereas Rician fading is modeled by reducing the value of Δ to zero and K>0. ABER curves for the above mentioned fading channels have been plotted along with other cases of TWDP fading.

In figure 5.1 we, plot the ABER curves for K=1 and differing values of Δ with respect to the Rayleigh case obtained by putting K=0. It is observed that as we decrease the value of Δ i.e.move closer to the Rician type , the ABER reduces. By decreasing Δ from 0.8 to 0.5, we observe a gain of 0.5 dB for 10dB average SNR for ABER of 10^{-4}. We observe that for Δ=1 i.e. the TWDP case is depicting the worst case scenario.

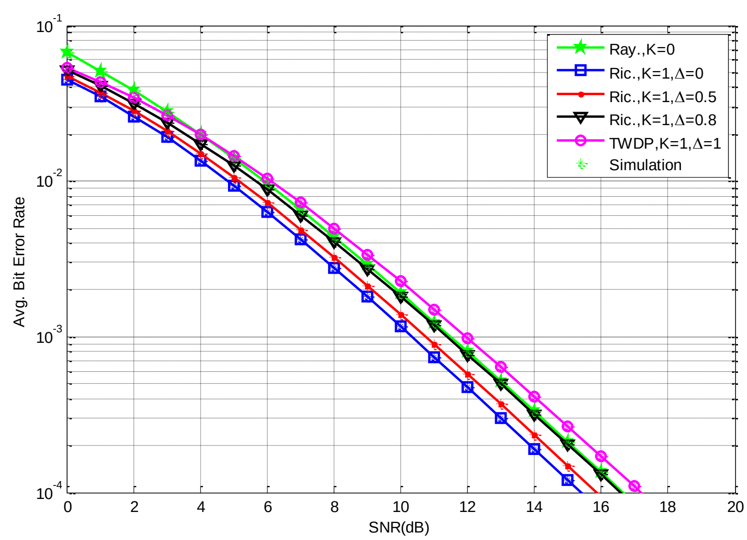


Figure 5. 1: ABER for ADSTBC system for K=1 and different values of Δ

In figure 5.2 ABER results for K=3 and different values of Δ is plotted. We observe from the figure that as we decrease the values of Δ from 1 to 0, the performance improves.

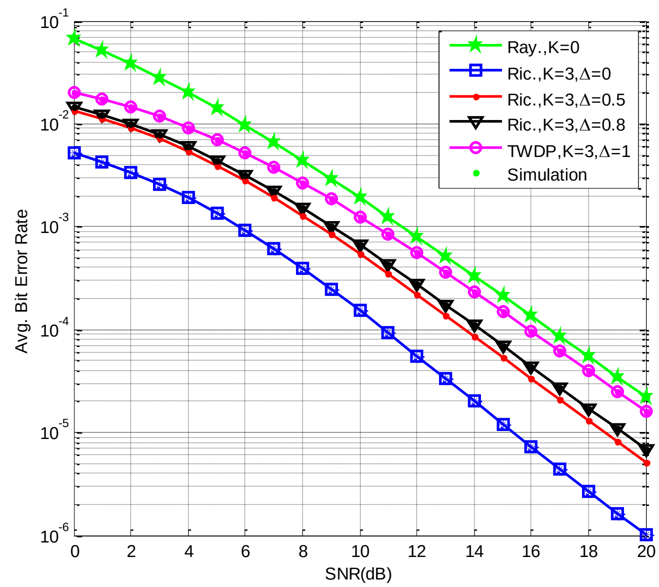


Figure 5.2: ABER for ADSTBC based system for K=3 and different values of Δ

Comparing figure 5.1 and 5.2 we observe that this improvement becomes more pronounced when K increases from 1 (figure 5.1) to 3(figure 5.2). Figure 5.3 illustrates the ABER results for K=5 and various values of Δ. We see that the performance improves while decreasing Δ.

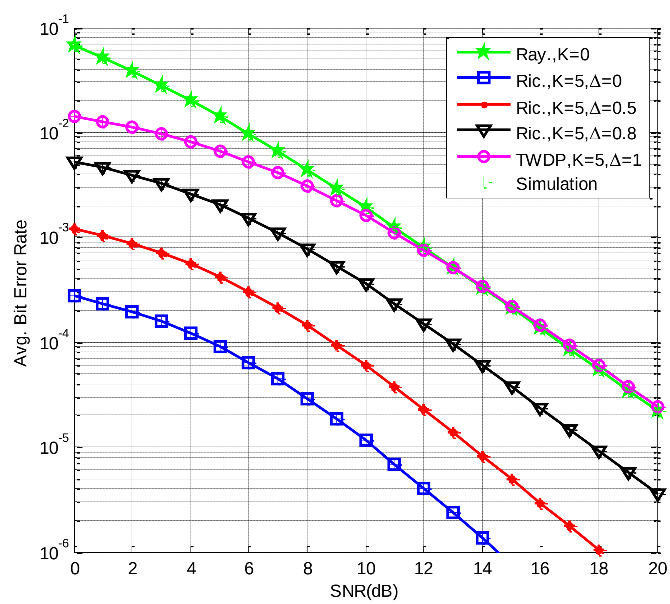


Figure 5.3: ABER for ADSTBC system for K=5 and different values of Δ

Also a comparative analysis of figures 5.1, 5.2, and 5.3 make clear that as K increases the improvement in the performance is registered in the form of coding gain. We also observe that for K=5, for SNR below 13 dB, TWDP fading shows better results as compared to the Rayleigh fading. Table 5.1 tabulates the values of ABER for different values of K and Δ. For an ABER of 10^{-4}, deterioration of approximately 3 dB to 5 dB is observed as we move from Rician fading with K=3, Δ=0, to K=3, Δ=0.5 to TWDP fading with K =3, Δ =1. The system improves in case of Rician fading as K increases, whereas we can observe deterioration in performance for the TWDP cases while increasing K.

Table 5.1 Performance of ADSTBC system in terms of ABER for Rayleigh and Rician fading channels

Channel / **Metric**	**Rayleigh**	**Rician**								
	K =0	K=1			K=3			K=5		
	Δ =0	Δ=0	Δ=0.5	Δ=1	Δ=0	Δ=0.5	Δ=1	Δ=0	Δ=0.5	Δ=1
ABER for 10^{-4}	16.8	15.4	15.8	17.2	11	14	16	5	9	16.9

5.4 LDPC concatenated ADSTBC system in different fading channels

In this work Low Density Parity Check codes based Asynchronous Distributed Space Time Block Coded (LDPC-ADSTBC) system has been presented where the source information is LDPC coded and then broadcasted to the relays. The relays employ Selective DF to forward the incoming signal to the destination. It is assumed that the source to relay link suffers no error and relays are selected on the basis of an SNR threshold. In this work, $\acute{R}$ refers to the number of relays selected for relaying, out of the total R relays. It is assumed that the receiver may have N_d antennas as contrast to the single antenna source and relay nodes. The signal received at the destination are detected using a Maximum Likelihood (ML) Decoder and given as

$$\hat{\boldsymbol{s}} = arg\ \ min_{\boldsymbol{s}_k} \left\| \bar{\boldsymbol{y}} - \sqrt{P_2}\bar{\boldsymbol{H}}\ \bar{\boldsymbol{C}} \right\|^2 = arg\ \ min_{\boldsymbol{s}_k} \left\| \bar{\boldsymbol{y}} - \sqrt{P_2}\bar{\boldsymbol{H}}\ \boldsymbol{D}(\Delta)\,\bar{\boldsymbol{\chi}}\bar{\boldsymbol{s}} \right\|^2 \qquad (5.14)$$

The output of the ML decoder is given to the LDPC decoder which outputs the estimated information vector.

5.5 Performance Analysis of LDPC-ADSTBC system on the basis of Pair wise Error Probability (PEP) in Rayleigh and Rician Fading Channels

The Pair wise Error Probability (PEP) for Selective decode and forward (DF) relaying protocol, it is given as

$$P(\boldsymbol{S}_\alpha \rightarrow \boldsymbol{S}_\beta / H, \Omega) = Q\left(\frac{\sqrt{P_2}\left\|\widehat{\boldsymbol{H}}\,(\bar{\boldsymbol{S}}_\alpha - \bar{\boldsymbol{S}}_\beta)\right\|_F^2}{2(P_2 \sum_{k=1}^{\acute{R}} \left|h_{k,2}\right|^2 + 1)}\right) \tag{5.15}$$

where the $P_2 \sum_{k=1}^{R} \left|h_{k,2}\right|^2 + 1$ denotes the noise variance. Using (4.8)-(4.10), (5.15) may be written as

$$P\left(\frac{\bar{\mathrm{S}}_\alpha \rightarrow \bar{\mathrm{S}}_\beta}{\mathrm{H},\Omega}\right) = Q\left(\frac{\sqrt{P_2}\sum_{k=1}^{\acute{R}} \lambda_{\alpha,k} \sum_{\tilde{k}=1}^{R}\left|\tilde{h}_{\tilde{k},k}\right|^2}{2\left(P_2 \sum_{k=1}^{\acute{R}}\left|h_{k,2}\right|^2 + 1\right)}\right) \tag{5.16}$$

Using Craig's bound [106] and (4.), (5.16) is re-written as

$$P(\boldsymbol{S}_\alpha - \boldsymbol{S}_\beta / \boldsymbol{H}, \Omega) \leq \frac{1}{\pi}\int_0^{\pi/2} e^{\frac{-P_2\sum_{k=1}^{\acute{R}} \lambda_{\alpha,k} \sum_{\tilde{k}=1}^{\acute{R}}\left|\tilde{h}_{\tilde{k},k}\right|^2}{4(P_2\sum_{k=1}^{R}\left|h_{k,2}\right|^2+1)\sin^2\theta}}\, d\theta \tag{5.17}$$

Let the expectation over all $\left|h_{k,2}\right|^2$ is approximated by its mean, $\acute{R}$ which is the number of selected relays. The average PEP is given as

$$P\left(\bar{\boldsymbol{S}}_\alpha \rightarrow \bar{\boldsymbol{S}}_\beta\right) \leq \sum_{\alpha=1}^{|S|} \Psi(\Pi_{k=1}^{\acute{R}}(1 + \frac{P_2 \mu \lambda_{\alpha,k}}{4(1+RP_2)\sin^2\theta})) \tag{5.18}$$

For high SNR the total PEP is approximated as

$$P\left(\bar{\boldsymbol{S}}_\alpha \rightarrow \bar{\boldsymbol{S}}_\beta\right) \leq \sum_{\alpha=1}^{|S|} \Psi(\Pi_{k=1}^{\acute{R}} \frac{P_2 \mu \lambda_{\alpha,k}}{4(1+\acute{R}P_2)\sin^2\theta})$$

*F*or, large number of selected relays i.e. $\acute{R} \gg 1$

$$P\left(\bar{\boldsymbol{S}}_\alpha \rightarrow \bar{\boldsymbol{S}}_\beta\right) \leq \sum_{\alpha=1}^{|S|} \Psi(\Pi_{k=1}^{\acute{R}} \frac{\mu \lambda_{\alpha,k}}{4\acute{R}\sin^2\theta}) \tag{5.19}$$

5.6 Results and discussion of LDPC-ADSTBC System in different fading channels

This section demonstrates the PEP performance in Rayleigh and Rician fading channels. The Monte Carlo simulation results have been obtained for 1000 iterations. Different values of K characterize different channels. Figure 5.4 depicts the error performance of the ADSTBC and

LDPC- ADSTBC systems in Rayleigh (K=0) and Rician (K=1) fading channels. It is observed that for PEP of 10^{-3}, a coding gain of approximately 2 dB is achieved with the concatenated LDPC-ADSTBC system over the ADSTBC system in different fading environments. For a PEP of 10^{-4}, the gain is of approximately 1 dB. For the LDPC-ADSTBC system, we assume $N_d = 1, 2$ antennas at the receiver and $\acute{R} = 2$. From the figure 5.4 it is observed that the LDPC-ADSTBC systems improves by approximately 6 dB in Rayleigh fading channel, when $N_d$increases from 1 to 2. A gain of about 3.5 dB is obtained when there is a change of channel from Rayleigh to Rician.

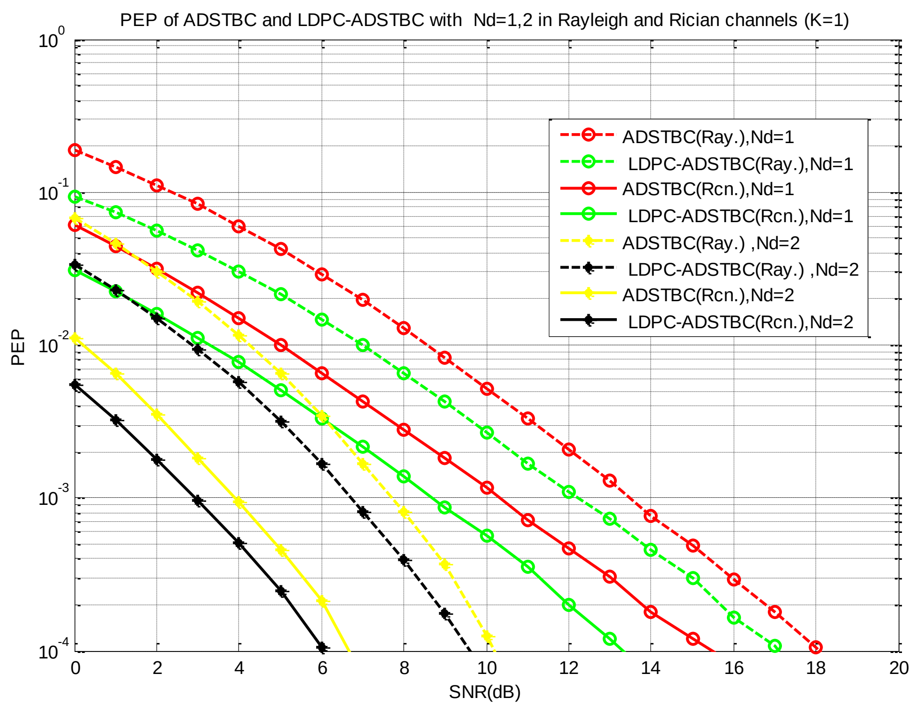


Figure 5.4: PEP of ADSTBC and LDPC-ADTBC system in Rayleigh and Rician (K=1) fading channels

Figure 5.5 depicts the PEP performance of the ADSTBC and its LDPC coded version for Rician (K=3) channel with varying number receive antennas. We observe in figure 5.5 that for a PEP of 10^{-4} the LDPC-ADSTBC shows a gain of 5.5 dB in Rician fading while increasing number of receive antennas from 1 to 2. While shifting from Rayleigh to Rician there is a gain of 5 dB and4 dB for $N_d = 1$ to $N_d = 2$.

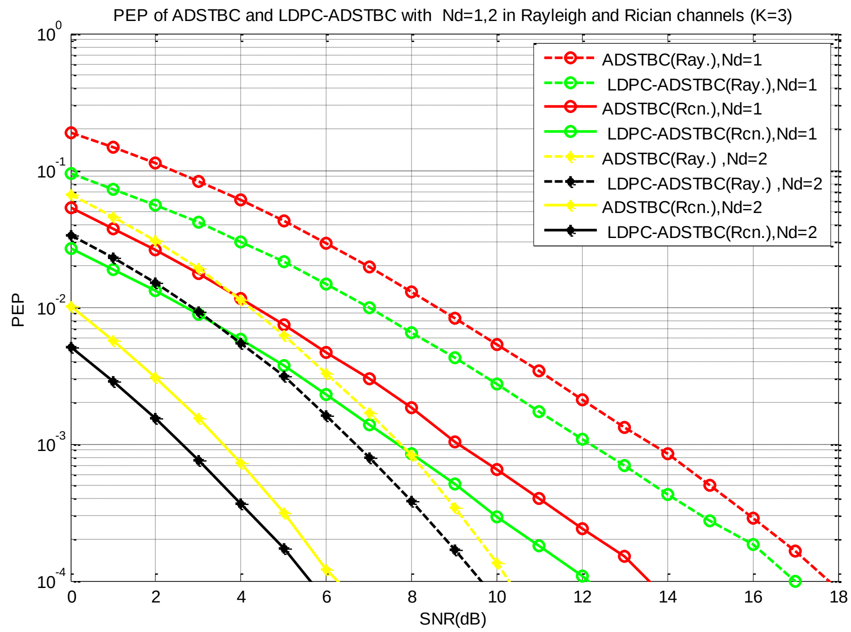


Figure 5.5: PEP of ADSTBC and LDPC-ADTBC system in Rayleigh and Rician (K=3) fading channels

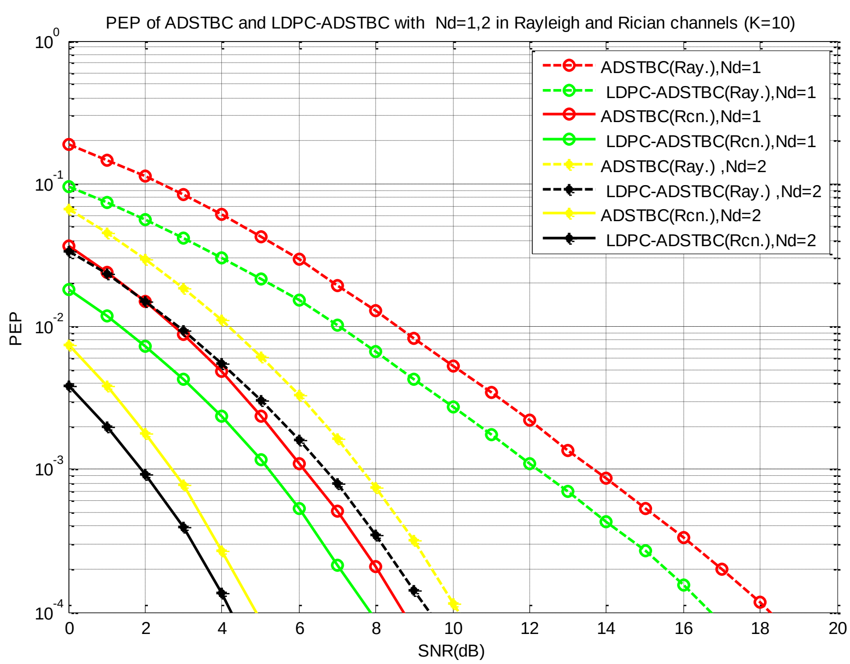


Figure 5.6: PEP of ADSTBC and LDPC-ADTBC system in Rayleigh and Rician (K=10) fading channels

Figure 5.6 illustrates the error performance of the ADSTBC and LDPC-ADSTBC systems in Rician(K=10) channel as compared to their performance in Rayleigh channel for $N_d = 1,2$. The performance increases by about 9.5 dB when the ADSTBC system is observed in Rician channel as compared to that in the Rayleigh scenario for $N_d = 1$. Similarly for the LDPC –ADSTBC system this gain corresponds to 9 dB. While increasing N_d to 2, gain is of 5dB for the channel coded system. Table 5.2 tabulates the SNR (dB) requirement for PEP of 10^{-4}. From the table we observe that the LDPC –ADSTBC system out performs the ADSTBC system in all the different channel scenarios. We can generalize that the error performance improves with increasing value of K in the Rician channel. By increasing the number of receive antennas at the destination, further improves the performance.

Table 5.2 Error performance of LDPC-ADSTBC system for Rayleigh and Rician fading channels

Channel / System		SNR (dB) required for PEP of 10^{-4}			
		Rayleigh (K=0)	Rician (K=1)	Rician (K=3)	Rician (K=10)
ADSTBC	N_d =1	18	15.5	13.6	9.6/9.3
	N_d =2	10.2	6.6	6.3	4.8/5
LDPC-ADSTBC	N_d =1	17	13.4	12	7.8/7.9
	N_d =2	9.6	6	5.5	4.3/4.4

5.7 Conclusion

In this work, we have investigated the performance of a Selective decode and forward based ADSTBC and LDPC-ADSTBC in different fading scenarios. TWDP channel model suffices the worst case scenario, with Rayleigh and Rician as special cases. Closed form expression has been derived for the average bit error rate for ADSTBC system. The AF based LDPC-ADSTBC system introduced in chapter 4 has been evaluated for the above mentioned adaptive relaying protocol in Rayleigh and Rician fading environments. Analytical expression for PEP has been derived and error performance of the system been evaluated using the same.

Chapter 6

Conclusions and Future scope

6.1 Conclusions

The basic requirements of a wireless communication system are high data rates, high reliability with reduced power requirements, complexity and latency. In this thesis, we have proposed a DSTBC system for asynchronous environment known as ADSTBC system. The proposed system is based on linear dispersion codes which are optimized for asynchronous scenario. The basic model of the ADSTBC system is improvised using Optimal Relay selection (ORS), joint Relay and Transmit-receive Antenna Selection (RTRAS), Selective Decode and forward which leads to efficient utilization of system resources, reduced system complexity, power consumption and overall implementation cost. The proposed system fulfils all the aims of this research work defined at Section 1.5, as follows:

- Design of a versatile DSTBC system yielding capacity and diversity gains in asynchronous scenarios.

  The first aim i.e. To design a versatile DSTBC system for the asynchronous scenarios is achieved first by designing an optimized linear dispersion (OALD) matrices and using the same for creating the desired DSTBC system. The proposed system is capable of performing with random number of relays, number of symbols, number of receiver antennas, relaying protocols and different fading channels.
- Reduction in system resources and the overall system complexity.

  The second aim i.e. To reduce the system resources and the overall system complexity is achieved by Optimal Relay Selection (ORS) and joint Relay and Transmit –Receive antenna pair selection (RTRAS)
- Reduction in the error floor by channel coding.

  The third aim of Reducing the error floor by channel coding has been catered to by concatenating the ADSTBC system with Low Density Parity Check (LDPC) codes. The LDPC codes are very powerful codes and thence significantly reduce the error in the system.

First of all, Linear dispersion matrices are optimized for asynchronous scenario and designed to yield optimal capacity and diversity gains. In this work these are known as OALD matrices. These OALD matrices are used to linearly modulate the signals received by the relays and play an important role in the design of a versatile ADSTBC. The ADSTBC system is analyzed after deriving its PDF which is used to evaluate ABER and Ergodic capacity. This system is improvised using relay selection technique and called ORS-ADSTBC system. Closed form expressions of ABER, average post processing SNR and ergodic capacity have been achieved after deriving the PDF of the system. This meets our **objective 1**.

The ADSTBC system designed in chapter 3, has been concatenated with a powerful error correcting channel codes, Low Density Parity Check (LDPC) codes to yield the LDPC-ADSTBC system. The system is analyzed on the basis of PEP. In order to improve the system performance and reduce the complexity, joint Relay and Transmit-Receive Antenna Selection (RTRAS) has been incorporated in the above mentioned system to get RTRAS-LDPC-ADSTBC system. **Objective 2** is achieved by analyzing the performance of the system using materics viz. PEP and Outage Probability. Further we compare the error performance of the LDPC-ADSTBC and a LDPC-TR-STBC system on the basis of ABER fulfilling **objective 4**.

Objective 3 is achieved by analyzing the ADSTBC and LDPC-ADSTBC system in different fading scenarios such as Rayleigh and Rician fading channels. Selective Decode and Forward relaying protocol is used to analyze the system. A Two wave Diffuse Power fading model is used to obtain different fading channels. The PDF of the system is derived and based upon the same ABER is evaluated to analyze the ADSTBC system. The LDPC-ADSTBC system is analyzed based on PEP.

Table 6.1 gives the summary of the work done in this thesis.

Table 6.1 Summary of achieved results at a glance

Proposed systems	Parameters for analysis	Results obtained	Conclusions
ADSTBC system ***(Objective-1)***	ABER Ergodic Capacity	• SNR gain of **5dB** and **8dB** respectively when 'R' increases from 2 to 3 to 4. • Capacity gain of **100%** and **60%** respectively with *'R'* and *N* increasing from 2 to 3	The performance of the system improves while increasing the number of relays and/or number of symbols
ORS-ADSTBC system	ABER Average Post Proc. SNR Ergodic Capacity	• SNR gain of **10dB** over ADSTBC. • APPSNR gain of **8dB** over ADSTBC. • Capacity gain of **3.18 bits/s/Hz** over ADSTBC	Performance increases with increase in number of candidate relays.
LDPC-ADSTBC system ***(Objective-2)***	PEP	• SNR gain of **4.5 dB** and **2.5 dB** over synchronous DSTBC and ADSTBC. • SNR loss of **2.25 dB** when N increases from 2 to 3. • SNR gain of **3.25 dB** when R increases from 2 to 3.	Channel coding reduces error floor. Performance improves with increase in '*R*', and/or N_d. Data rate increases with *N* but with reduced reliability
Comparison between LDPC – ADSTBC and LDPC-TR-STBC ***(Objective-4)***	ABER	SNR gain of **10dB** for BER 0.01 of LDPC-ADSTBC over LDPC-TR-STBC	Better error performance of LDPC-ADSTBC over LDPC-TR-STBC
RTRAS- LDPC-ADSTBC system	PEP Outage Probability	• SNR gain of **6 dB** over ORS-LDPC-ADSTBC • SNR gain of **8.2 dB** over ORS-LDPC-ADSTBC	Performance improves further by increasing number of candidate relays and Tx and/or Rx antennas.
ADSTBC system in different fading channels	ABER	• SNR gain of **7.8 dB** of Rician (K=5, Δ =0) over Rayleigh • SNR loss of **0.1 dB** of Rician (K=5,Δ=1) over Rayleigh	Performance improves with increasing K and deteriorates with increasing Δ. Worst Rician case(Δ= 1)
LDPC-ADSTBC in different fading channels ***(Objective-3)***	PEP	• SNR gain of approx. **9 dB** of Rician (K=10) over Rayleigh • SNR gain of **1 dB** for LDPC-ADSTBC over ADSTBC in Rayleigh • SNR gain of approx. **2 dB** for LDPC-ADSTBC over ADSTBC in Rician (K=10)	Performance increases with increasing values of *K* and N_d

6.2 Future Scope

The present research work considers design and analysis of a DSTBC system in asynchronous environment. The proposed system can be improved further by Optimal Relay Selection. The reliability of the system can be increased by concatenating with LDPC codes and improved further by RTRAS. In future this work can be extended to the following domains:

- In this work a fixed (AF) and an adaptive (Selective DF) has been considered for analysis. Other relaying techniques such as non-regenerative relaying protocols may be used as these put less processing burden on the relay as compared to regenerative mode of operation.
- The present work assumes half duplex and two hop cooperative scenario which may be extended to full duplex system and multi-hop communication.
- Power optimization using energy harvesting and integration of the same with simultaneous wireless information and power transfer (SWIPT) in asynchronous cooperative communication may be exploited.
- The present thesis considers Time Domain Multiple Access (TDMA) for accessing the channel resources. Other techniques such as Code Division Multiple Access (CDMA), Non-Orthogonal Multiple Access (NOMA) can be considered in future.
- In a multi-entity system co-channel and adjacent channel interference are prospective deterrents. Future work may consider the impact of interference and mitigation of the same, may be optimum Combining (OC).
- Depending upon the different application scenarios such as cognitive radios, massive MIMO, mmWave ,IoT different fading channels such as Weibull, $\kappa - \mu$ fading , FSO, etc may be considered.
- The present work relies mainly on the physical layer. Cross layer design may be done for enhanced services and features. But layering demands for more power, hence, investigation of cross-layer optimization may serve as a future work .

The Proposed design of Optimized Asynchronous Linear Dispersion (OALD) matrices under various constraints is given as follows.

Let q be the number of random orthogonal matrices $£_q = [\boldsymbol{A}_1 \dots \boldsymbol{A}_R]$, of dimension *((T ×N) ×R)*. From these matrices, a matrix would be selected that fulfils all the constraints such as tight frame and equal power. The matrix fulfilling the given constraints is termed as optimized OALD matrix. To apply various constraints, Let

- From $£_q$ random matrices, $£_k$ matrices are satisfying the Tight frame criteria, given by

$$\{£_k \times £_k^H\} = \frac{T}{R} I_R \quad , k < q \tag{A.1}$$

- Out of $£_k$ matrices as defined by eq.(A.1) $£_v$, where $v < k$, matrices are selected which are scaled to satisfy the equal power constraint criteria as given by

$$\boldsymbol{A}_i \times \boldsymbol{A}_i^H = I_R \qquad i \in 1, \dots \dots, R \tag{A.2}$$

- In order to achieve the full diversity gain, selected $£_v$ are further tested for full rank and determinant criterion. Thus the codes are said to be diversity optimal. The finally chosen optimized matrix $£_u$ must satisfy the following criteria

$$\max \|\det(\boldsymbol{\varepsilon} - \hat{\boldsymbol{\varepsilon}})\|^2 \tag{A.3}$$

Where, $\boldsymbol{\varepsilon} = [(\boldsymbol{A}_1\boldsymbol{p}_1)^\dagger \cdots (\boldsymbol{A}_R\boldsymbol{p}_R)^\dagger]^\dagger$ is LD codeword and $\hat{\boldsymbol{\varepsilon}}$ is estimated LD codeword respectively. $\boldsymbol{p}_k$ is pilot symbol vector from source to destination via k^{th} relays. Diversity gain is estimated from the rank of the codeword difference matrix. Therefore the matrix should be full rank. Among the matrices having full rank, that matrix would be selected that contains the maximum value of minimum determinant of the codeword difference matrices. Therefore the selected $£_u$ matrices are optimized out of which one is selected as the which is referred as OALD matrix and is given by

$$\bar{\boldsymbol{\chi}} = \begin{bmatrix} \boldsymbol{A}_1 & & \\ & \ddots & \\ & & \boldsymbol{A}_R \end{bmatrix} \tag{A.4}$$

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