



ADDIS ABABA UNIVERSITY
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ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

Cooperative MIMO System for WiMAX Technology

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Declaration

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***DEDICATED TO
MY FAMILY***

Abstract

Multipath fading is one of the primary factors that degrade the performance of wireless networks. One of the most powerful techniques to combat the effect of fading is by using multiple antennas that provides space diversity and spatial multiplexing; this technique is called Multiple-Input Multiple-Output (MIMO).

Cooperative diversity, an alternative form of realizing MIMO, has been recently proposed to realize the diversity advantage in a distributed manner. Cooperative diversity exploits the broadcast nature of wireless transmission and creates a virtual antenna array through cooperating nodes. Although, prior research in cooperative diversity considers users equipped with single antenna, in practical scenarios users may be able to accommodate multiple antennas due to the recent advances in semiconductor industry. Hence, the primary purpose of this thesis is to model, and by using simulation, investigates the end-to-end performance of a cooperative diversity system employing multi-antenna at cooperating nodes; the intention is to simultaneously exploit the diversity gain offered by the cooperative diversity and multiple antennas.

One contribution of this work is, we propose a cooperative MIMO system where the cooperation uses amplify-and-forward (AF) relaying strategy and the MIMO is based on Vertical Bell-Labs Layered Space Time architecture (VBLAST). The proposed system is to be used for WiMAX technology. Complexity of the cooperative MIMO system is also analyzed considering Maximum Ratio Combining (MRC) and Equal Gain Combining (EGC) schemes for Zero Forcing (ZF), Minimum Mean Square Error (MMSE) and Maximum Likelihood (ML) detection techniques. Simulation results show that cooperative MIMO system achieves significantly better symbol error rate (SER) performance than conventional cooperative diversity and MIMO systems with comparable complexity. As an example, for SER of 10^{-3} , cooperative MIMO system using MMSE detection has 10 dB SNR gain over systems that employ cooperative diversity or MIMO only.

Key words: Cooperative Diversity, MIMO, AF, VBLAST, WiMAX, SER, Complexity

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List of Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
AF	Amplify and Forward
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLAST	Bell Lab Layered Space Time
BPSK	Binary Phase Shift Key
BWA	Broadband Wireless Access
CSI	Channel State Information
D-BLAST	Diagonal BLAST
EGC	Equal Gain Combining
IEEE	Institute of Electrical and Electronics Engineers
i.i.d	independent, identically distributed
LOS	Line Of Sight
LST	Layered Space Time
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MMSE-SIC	Minimum Mean Square Error with Successive Interference Cancellation

MRC	Maximum Ratio Combining
NLOS	Non-Line-Of Sight
OSIC	Ordered Successive Interference Cancellation
QPSK	Quadrature Phase Shift Keying
SD	Spatial Diversity
SER	Symbol Error Rate
SIC	Successive Interference Cancellation
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SM	Spatial Multiplexing
SNR	Signal to Noise Ratio
STBC	Space Time Block Code
V-BLAST	Vertical BLAST
WMANs	Wireless Metropolitan Area Networks
WiMAX	Worldwide Microwave Access
ZF	Zero Forcing
ZF-SIC	Zero Forcing with Successive Interference Cancellation

Chapter 1

Introduction

Next generation wireless communication system demand both high transmission rates and a quality of service guarantee. These demands are hardly achievable due to properties of the wireless medium. As a result of scatterers in the environment and mobile terminals, signal components received over different propagation paths may add destructively or constructively and cause random fluctuations in the received signal strength. This phenomenon, which is called fading, degrades the system performance [1].

Diversity combats multipath fading by providing the receiver with redundant signal information through uncorrelated channels thereby allowing the receiver to average individual channel effects. The most common forms of diversity are space, time and frequency; however, space and time diversity are the most widely used.

Spatial diversity is achieved by transmission and/or reception of multiple copies of a signal from physically different points in space (e.g., multiple transmit and/or receive antennas). If an appropriate distance separates the points from where the signals are transmitted or received, then the characteristics of the channel are probabilistically uncorrelated and full diversity can be obtained [2].

The Multiple-Input Multiple-Output (MIMO) term originally describes the use of multiple antennas concept or exploitation of spatial diversity techniques. The MIMO concept was proposed to fulfill the demand for providing reliable high speed wireless communication links in harsh environments. Subsequently, MIMO technology has been proposed to be used in wireless local area networks and cellular networks, particularly at the basestation and access point sides to tackle the challenges of low transmission rates and low reliability [3].

However, in case if multiple antennas are not applicable cooperative diversity is used to adverse the effect of fading in wireless channels. It is a form of wireless communication where a message can be delivered from a source to a destination via different paths with the help of assisting relays.

This implies that one or several neighboring nodes overhear direct source to destination transmission and may retransmit the message (or a modification of it) to the destination. Such diversity, called cooperative diversity, at the receiver can be particularly beneficial in fading rich environments, where channel quality can experience high variations over time. Cooperative diversity can also be advantageously applied in small and low cost radios (such as sensors) where use of multiple antennas and complex signal equalization methods for fading mitigation are hardly possible due to strict hardware constraints [4].

While most of the current researches on user cooperation assume that user nodes are equipped with a single antenna, there have been some recent results which exploit further the benefits of multiple antenna deployment [5]. Cooperative MIMO technology allows a wireless network to achieve better performance gains than provided by either conventional MIMO or cooperative systems. It promises significant improvements in spectral efficiency and network coverage for various next generation wireless communication systems [6].

In wireless communication, the path towards techniques that provide high service quality and data rate has been through the use of the diversity provided by the rich scattering wireless channels. Owing to their great promises, MIMO and cooperative systems have found their way into several standards for future wireless communication systems, especially wireless local area networks and cellular networks. Examples of these standards include IEEE 802.11, 802.16 and the 3rd Generation Partnership Project (3GPP). The IEEE 802.16 standard, called Worldwide Interoperability for Microwave Access (WiMAX), is intended to deliver high data rates over long distances. 2×1 and 4×4 MIMO communications has been incorporated as an option in the IEEE 802.16e version of this standard. The 3GPP LTE (Long Term Evolution) technology, also known as wideband code division multiple access (W-CDMA) is used for the Third Generation (3G) cellular networks. In Release 7, 2×1 and 4×2 MIMO configurations employing space time block coding are used, whereas 2×2 and 4×4 MIMO configurations are used for Release 8 of this standard [7].

In addition to MIMO, relaying and cooperative transmission technologies are also being incorporated into the recent IEEE 802.16j and LTE-Advanced, specified by the 3rd

Generation Partnership Project (3GPP), standards. Here, the goal is also to extend coverage of high data rates and improve group mobility, facilitate temporary network deployment, and increase cell edge throughput. The relays in IEEE 802.16j and LTE advanced can be classified into transparent or nontransparent depending on whether or not the User Equipments (UEs) are aware of their existence. Moreover, the relays can also be classified into inband or outband relays depending on whether or not the communication to the basestation (or called eNodeB) and to the end user (or called UE) are over the same frequency band.

Overall, regardless of the specific relay and/or cooperation strategy that will be employed in IEEE 802.16j and LTE-Advanced, the above discussion demonstrate the importance of relay and cooperative communication technology in next generation wireless networks. In this thesis our focus is on WiMAX technology.

1.1. WiMAX Technology

The rapidly growing demand for flexible, high speed broadband services requires advanced communication technologies. The more conventional family of high rate broadband access techniques has relied on wired access, such as Digital Subscriber Line (DSL), cable modems, Ethernet and optical fibers. However, the extension of the coverage area results in a significantly increased cost imposed by building and maintaining wired networks. This is particularly true for less densely populated zones, for example suburban and rural areas [8].

Hence, Broadband Wireless Access (BWA) techniques have emerged as potent competitors of their conventional wired counterparts, facilitating the provision of broadband services for subscribers that are far from the coverage area of the wired networks. Being flexible, efficient and cost effective, BWA provides an excellent solution to overcome the above mentioned coverage problem. During the past decade or so, a number of proprietary wireless access systems have been developed by the wireless industry. Naturally, these proprietary products were based on diverse specifications, which inevitably limited their applications and markets. As a matter of fact, the potential

benefits of BWA services were not expected to be widely achieved due to the lack of a common international standard, until the emergence of the WiMAX standard [9].

WiMAX is one of the most popular BWA technologies, aiming to provide high speed broadband wireless access for Wireless Metropolitan Area Networks (WMANs). As a standardized technology, WiMAX ensures the interoperability of equipment certified by the WiMAX Forum, resulting in a significant cost reduction for service providers that would like to use products manufactured by diverse vendors. This distinct advantage has paved the way for global broadband wireless services. Another key benefit of WiMAX is that it has been optimized for offering excellent non line-of-sight (NLOS) coverage with the aid of advanced wireless transmission techniques, such as **MIMO**, multihop relaying, and **cooperative diversity** etc, combined with Orthogonal Frequency Division Multiplexing (OFDM) or Orthogonal Frequency Division Multiple Access (OFDMA).

MIMO techniques have become an essential part of the IEEE 802.16e-2005 [10], specifications for mobile broadband wireless access systems. The IEEE 802.16e specifications include three MIMO profiles having 2 transmit antennas, from which two are defined as MIMO schemes on both the downlink and uplink transmission of mobile WiMAX systems. The first one is the Alamouti code, namely, Matrix A, uses two antennas at the transmitter, and 1 or 2 antennas at the receiver. The Matrix A achieves full transmit diversity, but it is only half-rate since it transmits two symbols over two symbol periods. The second one is spatial multiplexing (SM), namely, Matrix B, which achieves full rate at the expense of diversity loss. But it offers second-order diversity at the receiver side. On the other hand, the third MIMO profile with two transmit antennas in IEEE 802.16e specifications, known as Matrix C, is both a full-rate and full-diversity code. More specifically, Matrix C is a variant of the Golden code [11].

In WiMAX system, Space Time Coding (STC) is used in order to exploit space and time diversity. The information symbols at the output of the modulator are encoded by the STC encoder and transmitted over the MIMO channel. At the receiver side, proper MIMO decoding techniques are used in order to recover the transmitted symbols. It is also worth noting that for uplink transmission we have collaborative SM in addition to

the above single user schemes in which two users transmit collaboratively in the same slot as if two streams are spatially multiplexed from two antennas of the same user.

Cooperative communication and relaying technologies have gradually made their way towards wireless standards. Specifically, IEEE 802.16j [6], an amendment to IEEE 802.16e WiMAX standard [10], supports relay functionalities that can be used to increase the throughput of cell edge users and extend system coverage to the interior of buildings, to temporary locations, and also to within mobile transportation vehicles [12]. Relay stations (RSs) can also forward messages to other RSs further away from the base station (BS) to form a multihop relay network. Depending on whether or not mobile stations (MSs) are aware of the relays' existence, relays in the IEEE 802.16j standard can be categorized as transparent and nontransparent relays. Transparent relays are used when subscriber stations (SSs) are able to receive control information directly from the BS. Thus, the RSs are used purely to enhance throughput of the SSs without transmitting additional control information. On the other hand, nontransparent relays can be used to serve MSs that are located outside or near the edge of the BS coverage by serving as a virtual BS to the MSs. In this case, the RS must be able to transmit control information and synchronization messages to the MS. With transparent relays, bandwidth allocation must be achieved through centralized scheduling while, with nontransparent relays, this can be done in a distributive fashion at the RSs. Moreover, transparent relays must communicate with the BS and the MS using the same frequency band while nontransparent relays may utilize different frequency bands on the two links. Although more flexibility is allowed with nontransparent relays, increased implementation complexity is also required [13].

Furthermore, cooperative relaying functionalities that enable the BS and the RSs to transmit cooperatively to the MS have also been defined in IEEE 802.16j. In particular, three types of cooperative transmission schemes have been specified, namely, the cooperative source diversity, the cooperative transmit diversity, and the cooperative hybrid diversity techniques. In the cooperative source diversity scheme, the cooperating transmitters will simultaneously transmit the same signal to the MS using the same frequency band to enhance the SNR at the MS. In the cooperative transmit diversity

scheme, transmitters will together form a distributed antenna array where space time codes can be used across the distributed antennas. The cooperative hybrid diversity scheme, which is a combination of the above two schemes, also employs space-time codes across the distributed RSs (or the BS), but two or more antennas may be transmitting identical signals in this case.

1.2. Problem statement

MIMO is an advanced technology that can effectively exploit the spatial domain of wireless fading channels to bring significant performance improvements. Conventional MIMO systems require both the transmitter and receiver of a communication link to be equipped with multiple antennas. In a case that, wireless devices do not support multiple antennas due to size, cost and/or hardware limitations, cooperative diversity can be used. Cooperation aims to utilize distributed antennas on multiple radio devices to achieve some benefits similar to those provided by conventional MIMO systems.

However, in case implementing multiple antennas in a given node is possible, cooperative diversity in addition to MIMO strategy can further improve the performance of the communication system by providing substantial additional diversity benefits [4]. The problem is how to combine MIMO techniques with cooperative diversity to improve the system performance further. Also, how does the performance of the resulting system looks like? Moreover, there are different types of detection techniques so that the performance of each technique should be investigated so as to find the optimal one. Most of the previous studies in cooperative communication either use single antenna on either each node or one of their nodes. This research analyzes cooperative diversity with multiple antennas at each node and taking various detection and combining strategies.

1.3. Objective

General objective

The main objective of this research is to combine MIMO techniques with user cooperative diversity and investigate the application of the resulting system in WiMAX technology and also study its performance.

Specific objectives:

Specific objectives of the research are:

- Review of MIMO, cooperative systems, and future wireless technologies and their demands.
- Combine MIMO system with cooperative diversity and evaluate the performance improvement of the resulting system in terms of SER for various detection techniques. For the study of the performance, parameters of WiMAX technology are considered.
- Study the performance of cooperative MIMO system for various SNR based scenarios.
- Compare cooperative MIMO system with conventional MIMO system in terms of SER and throughput.
- Analyze the complexity of the cooperative MIMO, considering two different combining schemes and various detection techniques, and compare it with conventional MIMO system.

1.4. Related Work

Flat fading MIMO channels were shown to offer relatively huge spectral efficiencies compared to Single-Input and Single-Output (SISO) channels [14]. Capacity increases linearly with the number of transmit antennas as long as the number of receive antennas is greater than or equal to the number of transmit antennas. To achieve this capacity increment, Diagonal BLAST (D-BLAST) was proposed by Foschini [14]. This scheme utilizes multiantenna arrays at both ends of wireless link. However, the complexities of D-BLAST implementation led to Vertical BLAST (V-BLAST) which is a modified version of BLAST [15]. Two nulling criteria, namely Zero-Forcing (ZF) and Minimum Mean Squared Error (MMSE), are utilized as detection algorithms in [16], and [17], respectively.

To achieve spatial diversity without multiple antennas, cooperative network has been proposed to achieve virtual MIMO systems with single antenna devices [3]. In [18], the

source and relay nodes form a distributed antenna array and are used to send a space time codeword. However, each node contains only a single antenna.

Though, prior work on cooperative diversity has generally considered networks with only a single antenna at each node, recent researches suggest the use of antenna arrays at the individual nodes. In [19], the error rate performance of a cooperative network with single antenna source and destination nodes and a number of multiantenna relays operating based on decode-and-forward (DF) model, was investigated. It observed that the threshold-based multiantenna relay systems yield significant gains over the referenced single antenna fixed protocol relaying. Z. Bai et.al in [20] evaluated BEP of a STC cooperative model in which a double antenna source and a single antenna relay and destination node are presented. They try to show that STC cooperative scheme have advantages in system performance and cooperative diversity compared to conventional MIMO and cooperative systems.

In [21], performance of DF protocol with multiple antenna terminals was presented and performance improvement in BER has been observed compared to conventional MIMO system; however, amplify-and-forward (AF) was not considered.

H. Muhaidat et.al in [5] investigated the performance of a single relay cooperative scenario with single antenna destination where the source and relay terminals are equipped with multiple transmit/receive antennas and consider both AF and DF relaying techniques for Alamouti space time coding transmission. The authors demonstrated the maximum achievable diversity order under some assumptions for various scenarios. However, they combined cooperative diversity and Alamouti STC which both have diversity gain at expense of rate loss.

In this thesis, we study the joint impact of cooperative diversity and antenna diversity, called cooperative MIMO system. A three-node network scenario consisting of one source, one destination and one relaying nodes is considered; the relaying node employs AF relaying technique. This is followed by complexity analysis of the system. All the assumptions and simulation parameters are based on WiMAX technology standard; this helps to investigate the application of cooperative MIMO system in future wireless

technologies. VBLAST is used as a detection strategy; using VBLAST helps to increase the data rate in addition to the diversity gain obtained from the cooperative MIMO.

1.5. Contributions of the Work

The contributions of this thesis are summarized as follow.

1. To the best of our knowledge, performance study of cooperative MIMO system that uses VBLAST scheme and AF relaying strategy has never been investigated before. This thesis contributes to the study of such system; comparison with conventional MIMO and cooperative diversity systems for Rayleigh fading channel is also conducted.
2. Both cooperative diversity and MIMO system are proposed for use in the WiMAX standard. This work investigates the performance of cooperative MIMO in WiMAX technology with the intention to see its potential application in such emerging technology.
3. End-to-end system performance of cooperative MIMO system has been analyzed subject to different SNR based scenarios.
4. The work extends the complexity analysis of the cooperative MIMO system assuming three-node cooperation, AF relaying, two different combining schemes, and various detection schemes.

1.6. Thesis Outline

This thesis is organized as follows. The fundamental concepts of MIMO system is presented in Chapter II. Cooperative diversity and relaying schemes are presented in Chapter III. Chapter IV describes cooperative diversity when each node is equipped with multiple antennas. Chapter V presents simulation results of cooperative MIMO system compared with conventional MIMO system. Finally, chapter VI provides conclusions and suggestions for future study.

Chapter 2

MIMO System

2.1. Introduction

Multipath fading makes reliable communication in wireless networks hardly achievable. One effective way to solve this problem is to employ diversity. Diversity can be considered as a scheme that uses multiple independent paths to transfer the same signals. The idea is that through a single path received signals may suffer deep fading easily, but the received signals through other independent paths may not be in deep fade, provided each path are statistically “independent”. Hence, combination of these independently faded received signals can mitigate multipath fading effectively [22].

In wireless channels, there are three commonly used diversity types: time diversity, frequency diversity, and space diversity. The general idea behind time diversity and frequency diversity is to transfer the same signals at different time slots or different carrier frequencies. However, they both have drawbacks. Time diversity consumes extra transmission time and frequency diversity needs extra bandwidth. Fortunately, space diversity can eliminate these shortcomings. For space diversity, implementing multiple antennas is desirable since multiple antennas can generate space diversity naturally. When multiple antennas are placed at the transmitter side, transmit diversity is achieved. When multiple antennae are placed at the receiver side, receive diversity is achieved. Apparently, MIMO system covers them both [23].

MIMO communication systems can be defined intuitively that multiple antennas are used at the transmitting end as well as at the receiving end. Assume that a MIMO system contains M antennas at the transmitter side and N antennas at the receiver side. Each pair of transmitter antenna and receiver antenna forms one channel. Accordingly, in the system there will be $M \times N$ different independent channels between the transmitter and the receiver. If we transmit the same signals through M transmit antennas using repetition scheme, the receiver then obtains $M \times N$ copies of signals, which are certainly more reliable than one copy of signals received from merely one channel. And if we transmit

different signals through the M transmit antennas, we will increase the data rate M times. Generally, in MIMO system signals sampled in the spatial domain at both ends are combined in such a way that they either create effective multiple parallel spatial data pipes (therefore increasing the data rate), and/or add diversity to improve the quality (BER) of the communication [24].

A MIMO system can provide both spatial diversity and spatial multiplexing gains. It is important to note that all the gains provided by this scheme may not be realized simultaneously. Instead, there is a tradeoff occurring between them [14].

2.2. System Model

Consider a MIMO system as shown, where M transmit and N receive antennas are used. The antennas are assumed to be omnidirectional, which means that the antennas transmit and receive equally well in all directions.

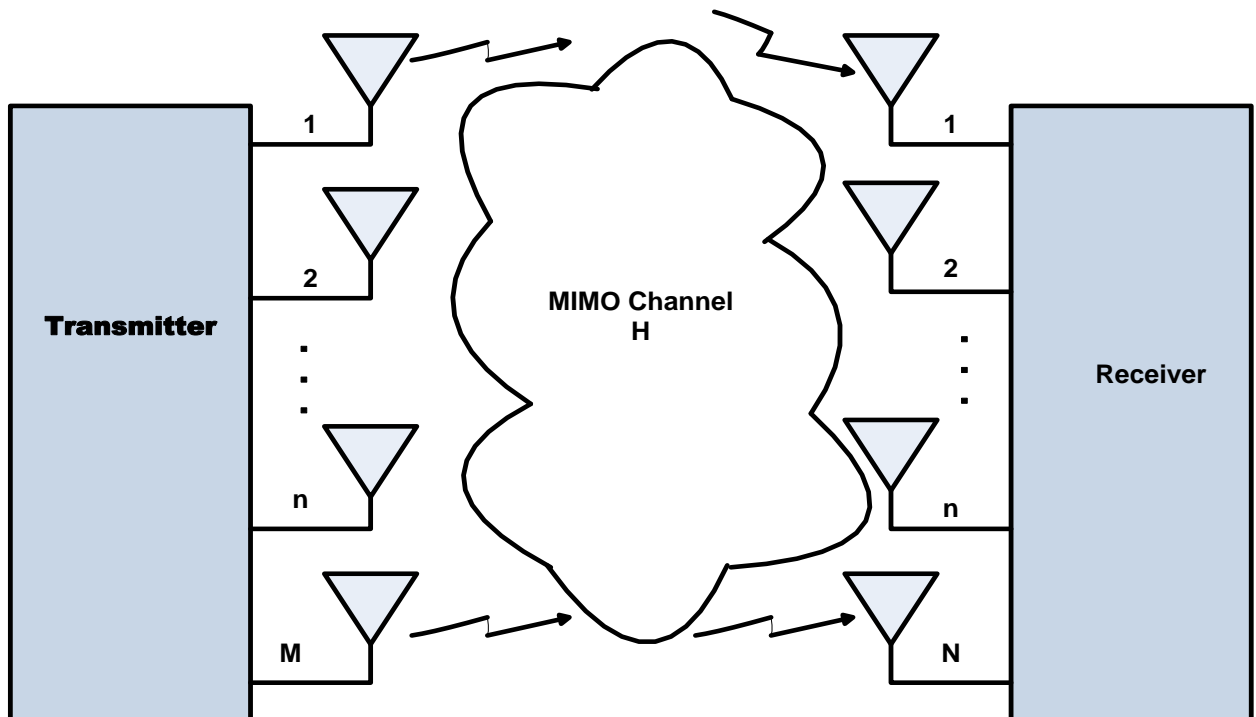


Fig 2.1.: Block diagram of a MIMO system.

The linear link model between transmit and receive antennas can be represented in the vector notation as:

$$\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (2.1)$$

where \mathbf{Y} is the $N \times 1$ received signal vector, \mathbf{x} is the $M \times 1$ transmitted signal vector, \mathbf{n} is the $N \times 1$ complex Gaussian noise vector with zero mean and equal variance, which is equal to σ^2 , and \mathbf{H} is the $N \times M$ normalized channel matrix, which can be represented as

$$\begin{pmatrix} h_{11} & \cdots & h_{M1} \\ \vdots & \ddots & \vdots \\ h_{1N} & \cdots & h_{MN} \end{pmatrix} \quad (2.2)$$

Each element h_{mn} represents the complex gains between the m^{th} transmit and n^{th} receive antennas. The elements of the channel matrix \mathbf{H} can be either deterministic or random. We will focus on Rayleigh distribution, as it is most representative for non-line-of-sight (NLOS) radio propagation.

2.3. System Capacity

Channel capacity is the maximum information rate that can be transmitted and received with arbitrarily low probability of error at the receiver. A common representation of the channel capacity is within a unit bandwidth of the channel and can be expressed in bps/Hz. This representation, also known as spectral (bandwidth) efficiency, is used as performance metric in this thesis. MIMO channel capacity depends heavily on the statistical properties and antenna element correlations of the channel [25]. It also depends on what is known about \mathbf{H} at the transmitter and receiver. We will consider two different scenarios regarding this knowledge. We start by discussing the capacity with channel knowledge unavailable at the transmitter and we introduce the capacity with perfect channel state information at the transmitter.

2.3.1. Channel Unknown at the Transmitter

We assume that the channel knowledge is unavailable at the transmitter but known at the receiver. In all the following cases, we focus on the single user form of capacity, the received signal is corrupted by additive white Gaussian noise (AWGN) only, and the value of the signal-to-noise ratio (SNR) at the receiver is given as SNR.

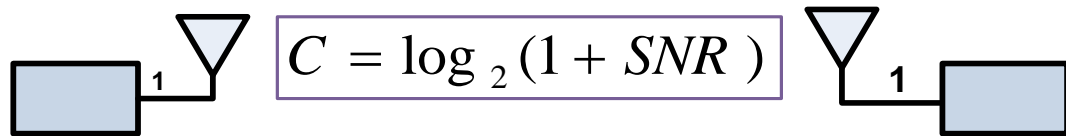


Figure 2.2.: Capacity of SISO

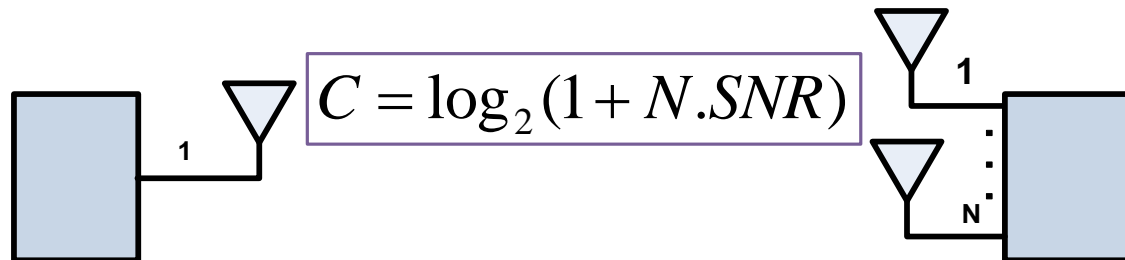


Figure 2.3.: Capacity of SIMO

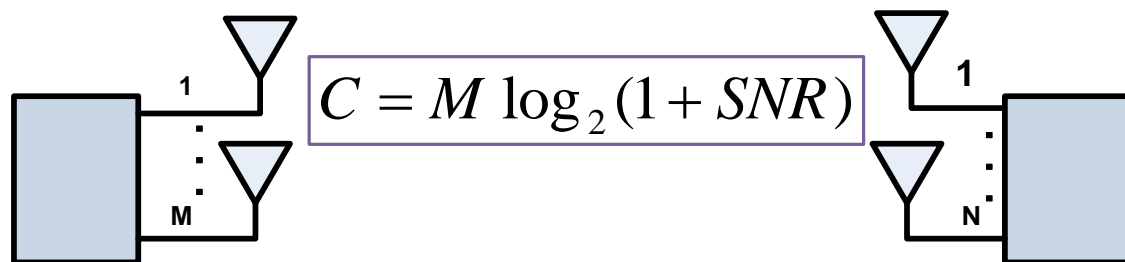


Figure 2.4.: Capacity of MIMO

From the figures, we can see that the SIMO channels improve the capacity compared with the SISO channel by exploiting more antennas. However, the SIMO channels can only offer a logarithmic increase in capacity with the number of antennas. If the MIMO system sends M different symbols using all the antennas at the transmitter, its capacity will grow linearly (or there will be a linear growth of bandwidth efficiency) [25].

2.3.2. Channel Known at the Transmitter

When the transmitter has perfect knowledge of the channel, the water filling method is used to optimize the transmitted signal power scheme. The principle of the water filling theorem sees the division of total power in such a way that greater portions goes to the channels with higher gain and less or even none to the channels with small gains [26].

$$C_{MIMO-WF} = W \sum_{i=1}^n \log_2 \left(1 + \frac{s_i \mu_i}{N} \right) \quad (2.3)$$

where s_i is the signal power transmitted in the i^{th} subchannel, with $\sum_{i=1}^n s_i = s$, μ_i

eigen value of i^{th} subchannel.

2.4. Spatial Multiplexing

The main advantage of using spatial multiplexing is to increase transmission data rate. This is achieved by dividing the data stream and transmitting it through multiple independent non-interfering channels. A signal is spatially multiplexed when different portions of the signal are being transmitted through different independent fading channels. Thus, if a channel suffers from fading in one of the sub-channels, then only a small portion of the information will be lost. Also the achieved transmission rate is increased by a factor equal to the number of independent channels used compared to single antenna system.

As an example, for $M = N = 2$ spatial multiplexing scheme is depicted in Figure 2.5, which divides the stream $[X_1 X_2]$ such that symbol X_1 is transmitted by transmission antenna 1 and symbol X_2 is transmitted by transmission antenna 2. Each symbol is transmitted through two independent fading channels h_{ij} ; symbol X_1 is transmitted through h_{11} and h_{12} [27].

Spatial multiplexing offers $\min(M, N)$ increase in the transmission rate for the same bandwidth and no additional power expenditure. The system in Figure 2.5 has multiplexing gain of 2.

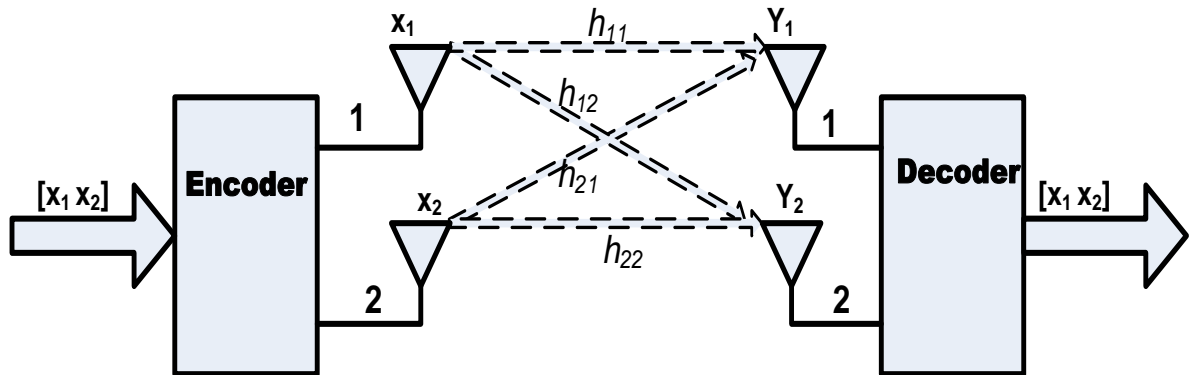


Figure 2.5.: Spatial diversity scheme with multiplexing gain

2.5. Spatial Diversity

In contrast to spatial multiplexing, where the main objective is to provide higher bit rates compared to a single antenna system, spatial diversity techniques predominantly aim at improving the error performance (reliability). The improvement of reliability is directly proportional to the diversity gain. The maximum diversity gain for the MIMO system with M transmit and N receive antennas is $M \times N$ [23]. As an example, the system in Figure 2.6 has a maximum diversity order of four since it has two transmission and two reception antennas, respectively.

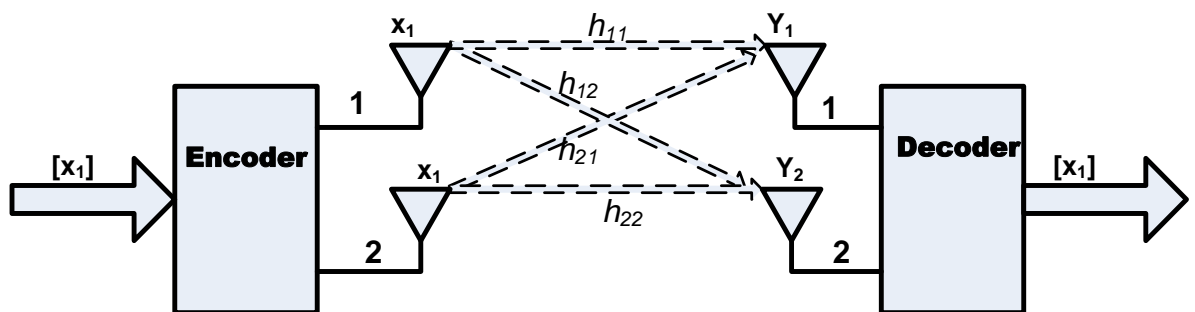


Figure 2.6.: Spatial diversity scheme with diversity gain

Both spatial diversity and spatial multiplexing gains grow with the number of antennas, since more alternative independent channels are provided to the system. However, in the case of multiplexing, a given antenna at the receiver will receive signals transmitted by all antennas at the transmitter. Hence, there will be interference at the receiving antennas

that will definitely reduce the capacity. In the subsequent sections, various interference mitigation techniques will be covered.

The earliest form of spatial transmit diversity is the delay diversity scheme where a signal is transmitted from one antenna, then delayed onetime slot, and transmitted from the other antenna. By viewing multiple antenna diversity as independent information streams, more sophisticated transmission schemes can be designed to get closer to theoretical performance limits. Using this approach, we focus on STC schemes which introduce temporal and spatial correlation in to the signals transmitted from different antennas without increasing the total transmitted power or the transmission bandwidth. There is in fact a diversity gain that results from multiple paths between the basestation and user terminal, and a coding gain that results from how symbols are correlated across transmit antennas.

2.6. Space-time Coding

Space time coding, performed in both spatial and temporal domains, is one effective way to implement reliability as well as data rate over MIMO systems in fading wireless channels. Hence, there are two broad categories of space-time codes: those targeted to increase reliability/QoS of MIMO communications, e.g., Space-time Block Coding (STBC), and those developed to offer higher data rates, e.g., BLAST [27].

2.6.1. Alamouti Space-time Coding

Alamouti proposed an algorithm that offers transmit diversity to increase reliability in a flat fading channel. The technique is optimum for two transmit antennas and as many receive antennas as possible. The Alamouti space-time coding scheme can achieve full spatial diversity gain (a gain of two for the 2×1 scheme and a gain of four for the 2×2 scheme) without decreasing the achieved data rates. The reduction of the achieved rate that occurs because of the retransmission of the symbols at the second time slots is offset by the simultaneous increase of the rates since at each time slot two symbols are transmitted. In the next section, we will discuss 2×1 and 2×2 Alamouti schemes.

2.6.1.1. 2×1 Alamouti STC Scheme

The Alamouti space time coding scheme for two transmission antennas and one reception antenna is shown in Figure 2.7. It is assumed that the complex channel coefficients $h_{i,j}$ are constant across two consecutive symbol periods and that it is a frequency flat fading environment for the allocated frequency bandwidth. Assume that the information symbols to be transmitted are x_1 and x_2 . In the first time slot x_1 and x_2 are transmitted by antennas 1 and 2, respectively. Similarly, $-x_2^*$ and x_1^* are transmitted by antennas 1 and 2 in the second time slot, as given in Table 2.1 (where x_1^* denotes the complex conjugate of x_1 and T denotes the symbol transmission period).

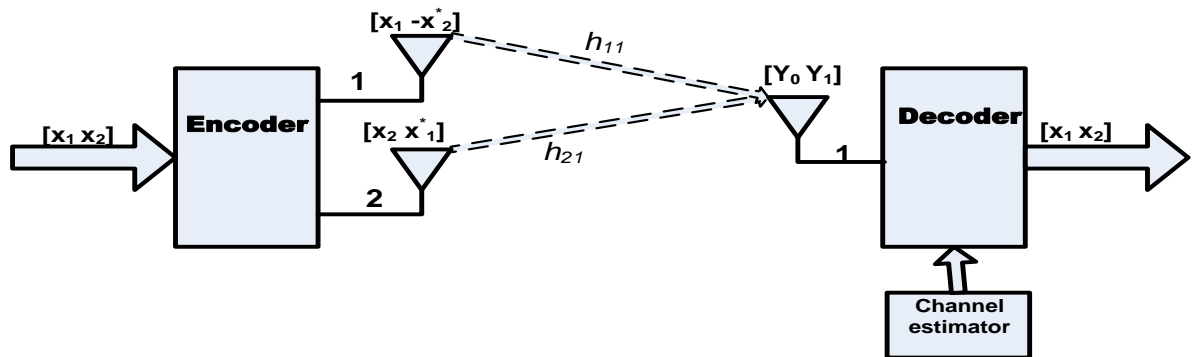


Figure 2.7.: 2×1 Alamouti Scheme

Table 2.1.: Transmission Sequence for the 2×1 Alamouti Scheme.

	Antenna 1	Antenna 2
Time t	x_1	x_2
Time $t+T$	$-x_2^*$	x_1^*

Assuming that fading is constant across two consecutive symbols, we can write

$$h_{11}(t) = h_{11}(t + T) = h_{11}$$

$$h_{21}(t) = h_{21}(t + T) = h_{21} \quad (2.4)$$

The received signals at times t and $t+T$ in antenna 1 are [28]:

$$\begin{bmatrix} Y_0 \\ Y_1^* \end{bmatrix} = \begin{bmatrix} Y(t) \\ Y(t+T) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} \\ h_{21}^* & -h_{11}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_0(t) \\ n_0(t+T)^* \end{bmatrix} \quad (2.5)$$

where n_0 represent noise at the receiver. The estimates of the signals are calculated in the decoder/combiner as follows [28]:

$$\begin{aligned} \hat{x}_1 &= h_{11}^* Y_0 + h_{21} Y_1^* \\ \hat{x}_2 &= h_{11}^* Y_0 - h_{21} Y_1^* \end{aligned} \quad (2.6)$$

These combined signals are then sent to the maximum likelihood detector.

2.6.1.2. 2×2 Alamouti STC Scheme

The Alamouti space-time coding scheme for the system with two transmission antennas and two reception antennas is shown in Figure 2.8. The transmission scheme is the same as with the 2×1 system case.

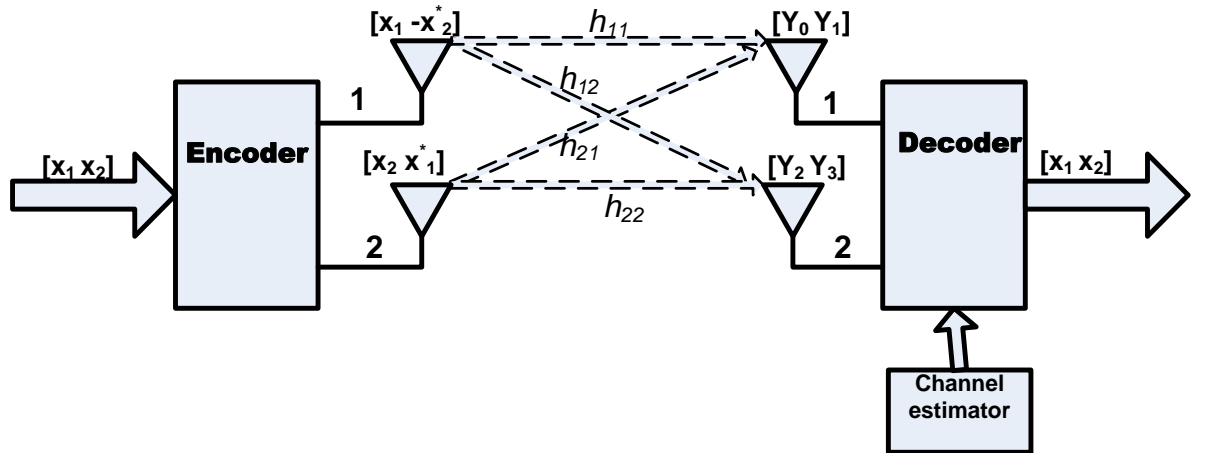


Figure 2.8.: 2×2 Alamouti Scheme

Received signals at receive antenna 1 in the two symbol period are given as:

$$\begin{aligned} Y_0 &= h_{11}x_1 + h_{21}x_2 + n_0(t) \\ Y_1 &= -h_{11}x_2^* + h_{21}x_1^* + n_0(t+T) \end{aligned} \quad (2.7)$$

At receive antenna 2 the received signals at time instances t and $t+T$, respectively are:

$$\begin{aligned} Y_2 &= h_{12}x_1 + h_{22}x_2 + n_1(t) \\ Y_3 &= -h_{12}x_2^* + h_{22}x_1^* + n_1(t+T) \end{aligned} \quad (2.8)$$

Again, the estimates of the signals in the decoder/combiner are given as:

$$\begin{aligned} \hat{x}_1 &= h_{11}^*Y_0 + h_{21}Y_1^* + h_{12}^*Y_2 + h_{22}Y_3^* \\ \hat{x}_2 &= h_{11}^*Y_0 - h_{21}Y_1^* + h_{12}^*Y_2 - h_{22}Y_3^* \end{aligned} \quad (2.9)$$

These combined signals are then sent to the maximum likelihood detector for detection. A detailed analysis of Alamouti STC is presented in [28].

2.6.2. BLAST

The notion of layered space-time (LST) coding, first introduced by Foschini (1996), has emerged since then as a powerful architecture suitable for applications with high data rates.

Several LST coding architectures exist, including Horizontal Bell Laboratories Layered Space-Time (HBLAST), Vertical BLAST (VBLAST), and Diagonal BLAST (DBLAST) architectures. A common feature of these architectures is that M independent substreams are transmitted simultaneously from the available M transmit antennas. Consequently, these LST architectures achieve a spatial rate of $R_c b M$ where R_c denotes the rate of the channel code employed and 2^b is the signal constellation size. These BLAST schemes are sometimes referred to as spatial multiplexing schemes. Other LST schemes also exist, including the multilayered space-time coding scheme and the threaded space-time coding scheme. These schemes combine channel coding and LST coding, resulting in a trade-off between diversity and rate [7]. In this thesis we focus only on VBLAST system.

2.6.3. VBLAST

In the VBLAST transmitter shown in Figure 2.9, the message bit stream is demultiplexed into M parallel substreams. Each substream is modulated using 2^b ary constellation, interleaved and then assigned to a transmit antenna. As such, the number of layers is M and the spatial rate is bM . Since each layer is associated with a fixed transmit antenna, this architecture can accommodate applications with possibly different data rates and/or different users [7].

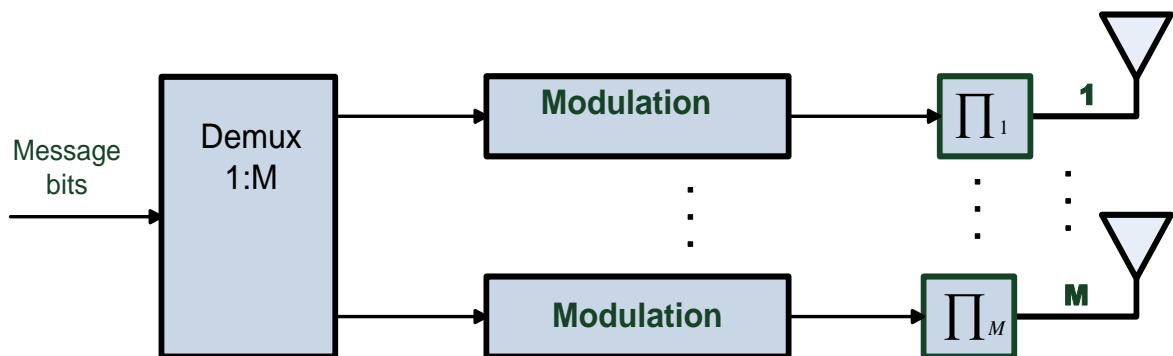


Figure 2.9.: VBLAST transmitter structure

The spatial diversity achieved by this scheme varies between one and M , depending on the detection scheme employed at the receiver. For instance, when interference cancellation and suppression is used, the first layer detected will have a spatial diversity of $N - M + 1$ because the other layers are suppressed where they are treated as interference. The last layer detected, on the other hand, will have a spatial diversity of M since the $M - 1$ previously detected layers are subtracted from the last layer, i.e., there is no suppression but rather cancellation [7].

2.7. MIMO Detection Techniques

As explained before, in MIMO multiple antennas are used to simultaneously transmit different streams of data on the different transmit antennas (at the same carrier frequency). Although these parallel data streams are mixed in the air, when the MIMO channel is well conditioned they can be recovered at the receiver by using spatial sampling (i.e., multiple receive antennas) and corresponding signal processing

algorithms. These techniques which are used to recover the original signal are referred to as MIMO detection techniques.

MIMO detection techniques are categorized into two main categories; linear and non linear. Linear signal detection methods treat all the transmitted signals as interference except for the desired stream from the target transmit antenna. Although linear detection schemes are easy to implement, they lead to high degradation in the achieved diversity order and error performance due to the linear filtering. Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) are linear detection techniques.

On the other hand, non-linear detection techniques optimally take into account the properties of noise and interference. Maximum Likelihood (ML), Successive Interference Cancellation (SIC), Ordered Successive interference cancellation (OSIC) and Sphere Decoding Algorithms (SDAs) are examples of non-linear detection techniques. This section briefly reviews some of these MIMO signal detection algorithms which are used in this thesis.

2.7.1. Zero Forcing

ZF can be implemented by using the inverse of the channel matrix H to produce the estimate of transmitted vector x .

$$\hat{\mathbf{x}} = \mathbf{H}^\dagger \mathbf{Y}$$

$$\hat{\mathbf{x}} = \mathbf{x} + (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H \mathbf{n} \quad (2.10)$$

where: $\mathbf{H}^\dagger = (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H$ denotes the pseudo-inverse matrix

ZF estimate, i.e. $\hat{\mathbf{x}}$, consists of the decoded vector \mathbf{x} plus a combination of the inverted channel matrix and the unknown noise vector i.e., there is an addition of the noise vector. Because the pseudo-inverse of the channel matrix may have high power when the channel matrix is ill-conditioned, the noise variance is consequently increased and the performance could be degraded.

ZF is the simplest MIMO detection technique, where filtering matrix is constructed using the ZF based performance criterion. The drawback of ZF scheme is the susceptible noise enhancement and loss of diversity order due to linear filtering [29].

To improve for the noise enhancement introduced by the ZF detector, the MMSE detector was proposed, where the noise variance is considered in the construction of the filtering matrix G_{MMSE} .

2.7.2. Minimum Mean Square Error

MMSE approach reduces the noise enhancement by taking into consideration the noise power when constructing the filtering matrix using the MMSE performance base criterion. The vector estimates produced by an MMSE filtering matrix becomes [30]

$$\hat{\mathbf{x}} = \mathbf{G}_{MMSE} \mathbf{Y} \quad (2.11)$$

where the MMSE filter matrix G_{MMSE} is given by:

$$\mathbf{G}_{MMSE} = (\mathbf{H}^H \mathbf{H} + \sigma_n^2 \mathbf{I}_N)^{-1} \mathbf{H}^H \quad (2.12)$$

where, $\sigma_n^2 = N/SNR$ and \mathbf{I}_N is $N \times N$ identity matrix.

The added term (σ_n^2) offers a trade-off between the residual interference and the noise enhancement. As the SNR grows large, the MMSE detector converges to the ZF detector, but at low SNR it prevents the worst Eigen values from being inverted. At low SNR, MMSE becomes Matched Filter [31]:

$$(\mathbf{H}^H \mathbf{H} + \sigma_n^2 \mathbf{I}_N)^{-1} \mathbf{H}^H \approx \sigma_n^2 \mathbf{H}^H$$

At high SNR, MMSE becomes ZF:

$$(\mathbf{H}^H \mathbf{H} + \sigma_n^2 \mathbf{I}_N)^{-1} \mathbf{H}^H \approx (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H$$

2.7.3. Maximum Likelihood

The ML receiver performs optimum vector decoding and is optimal in the sense of minimizing the error probability. ML receiver is a method that compares the received signals with all possible transmitted signal vector which is modified by channel matrix H and estimates transmit symbol vector \mathbf{x} over the set \mathbf{x}^N according to the Maximum Likelihood principle, which is shown below and corresponds to the minimum Euclidean distance rule [32]:

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}} |\mathbf{Y} - \mathbf{H}\mathbf{x}|^2 \quad (2.13)$$

In (2.13) the minimization is performed over all possible transmitted symbol vectors \mathbf{x}^N . Although ML detection offers optimal error performance, it suffers from complexity issues. It has exponential complexity in the sense that the receiver has to consider $|A^N|$ possible symbols for N transmitter antenna system with A is the modulation constellation [33].

CHAPTER 3

Cooperative Communication

3.1. Introduction

The wireless channel suffers from fading. The fading can cause a significant fluctuation in signal strength that increases bit error rate. Hence, repetitive transmission of signal can effectively mitigate the effect of fading by generating diversity. Especially spatial diversity is generated by transmitting signals from different locations, so allowing receiving independently faded versions of the transmitted signal at the receiver. Spatial diversity techniques are particularly attractive as they can be easily combined with other forms of diversity, for example time and frequency diversity. From this point of view, MIMO system provides a number of advantages. Although MIMO systems have spatial diversity, they cannot be used to provide diversity when transmitter or receiver cannot support multiple antennas due to size, cost or hardware limitations. In this case, alternative techniques have to be exploited in order to guarantee capacity and diversity gains.

To overcome size, cost and hardware limitations, another form of spatial diversity called cooperative diversity, has recently been proposed for mobile wireless communication. In this approach, single-antenna mobiles in a multi-user environment share their antennas in order to generate virtual multiple antenna arrays that allows them to exploit spatial diversity [34].

Cooperative communication is built on the broadcast nature of wireless channel which suggests that the transmitted signal between source and destination can be overheard at neighboring nodes. Cooperation communication aims at processing and retransmitting of this overheard information towards destination to create spatial diversity, hence to obtain higher throughput or reliability.

The key advantage of cooperation is that it allows a network of relatively simple, inexpensive, single antenna devices to achieve many of the distinguished advantages of physical antenna arrays. In addition, cooperative diversity can be combined with other

forms of diversity, such as temporal and frequency diversity, to further exploit the available degrees of freedom in the wireless propagation environment and improve overall network performance [35].

3.2. Phases of Cooperative Transmissions

Most cooperative communication schemes involve two transmission phases: A *coordination phase and a cooperation phase*. In coordination phase (phase 1) users exchange their own source data and control messages with each other and/or the destination. Coordination is especially required in cooperative systems since the antennas are distributed among different terminals, as opposed to that in centralized MIMO systems. Coordination can be achieved either by direct inter-user communication or by the use of feedback from the destination.

In cooperation phase (phase 2), the users cooperatively retransmit their messages to the destination. A basic cooperation system consists of two users transmitting to a common destination. One user acts as the source while the other user serves as the relay and the two users may interchange their roles as source and relay at different instants in time.

A basic cooperation system is shown in Figure 3.1. In Phase I, the source user broadcasts its data to both the relay and the destination and in Phase II; the relay forwards the source's data either by itself or by cooperating with the source to enhance reception at the destination [36].

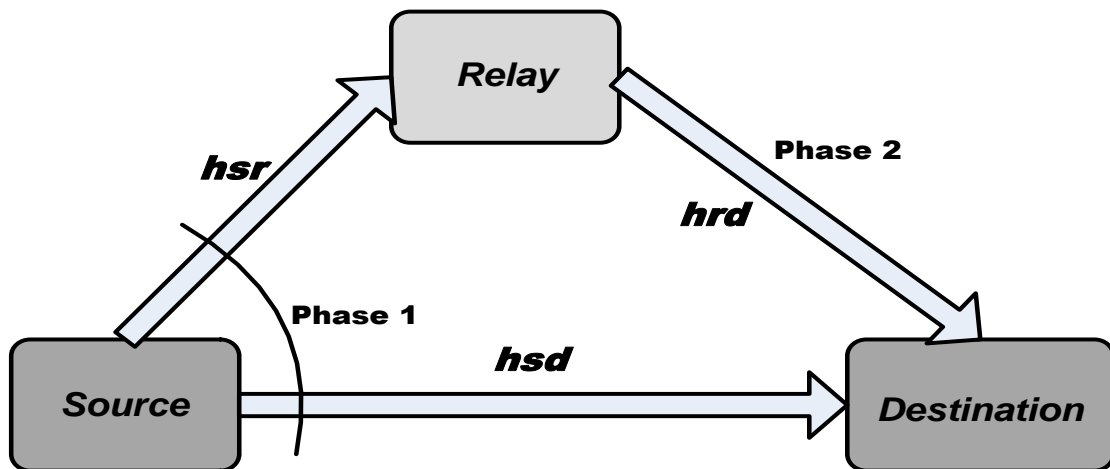


Figure 3.1.: A basic two user cooperative communication network

Information signals that were transmitted from source and relay are multiple accessed to destination, and then they are combined. So, cooperative communication enables single antenna mobiles to generate a virtual multiple antenna transmitter by exploiting relay. Thus, it can achieve spatial diversity. It is also very useful when channel environment of direct path is experiencing deep fading. Each node shares their antennas and other resources, and source acts as relay as well as information source.

The two user cooperation described so far can be readily extended to a large network by having one user serve as the source and the remaining users serve as relays. It can also be extended to cooperative communication systems with multiple sources and/or multiple receivers.

3.3. Cooperative Communication Protocols

Cooperative transmission requires relaying strategies in relays and combining techniques at the destination. Relaying strategies are methods that define how data is processed at the relays before onward transmission to the destination. A number of cooperative relaying techniques can be used in the relay station namely, the amplify-and-Forward (AF), decode-and-forward (DF), detect-and-forward (DtF), selective detect-and-forward and compress-and-forward (CF). In this thesis, we use AF relaying strategy. The next section will provide more details on the above mentioned relay processing strategies.

3.3.1. Amplify-and-Forward

In this scheme, the relay simply amplifies the received signal without decoding and forwards the amplified signal to destination. In doing so the noise in the signal is amplified as well, this is the main downfall of this protocol. In practice, the AF scheme is more attractive for its low complexity since the cooperative terminal simply forward the signal and do not decode it.

Assuming that the channel characteristic can be estimated perfectly, the gain for the amplification can be calculated as follows.

The signal at the relay from the source in the 1st phase is:

$$Y_{sr} = \sqrt{p_1} h_{sr} x + n_{sr} \quad (3.1)$$

where s denotes the sender, r is the relay, p_1 is the average transmit power per antenna at source, h_{sr} is the source relay channel and n_{sr} is the Gaussian noise.

The power of the incoming signal (3.1) is given by

$$E[|y_{sr}|^2] = E[|h_{sr}|^2]E[|x|^2] + E[|n_{sr}|^2] = |h_{sr}|^2 p_1 + N_0 \quad (3.2)$$

To send the data with the same power the sender did, the relay has to use a gain of

$$\beta = \sqrt{p_2 / (p_1 |h_{sr}|^2 + N_0)} \quad (3.3)$$

where, p_2 is the average transmit power per antenna at relay; this term has to be calculated for every block and therefore the channel characteristic of every single block needs to be estimated.

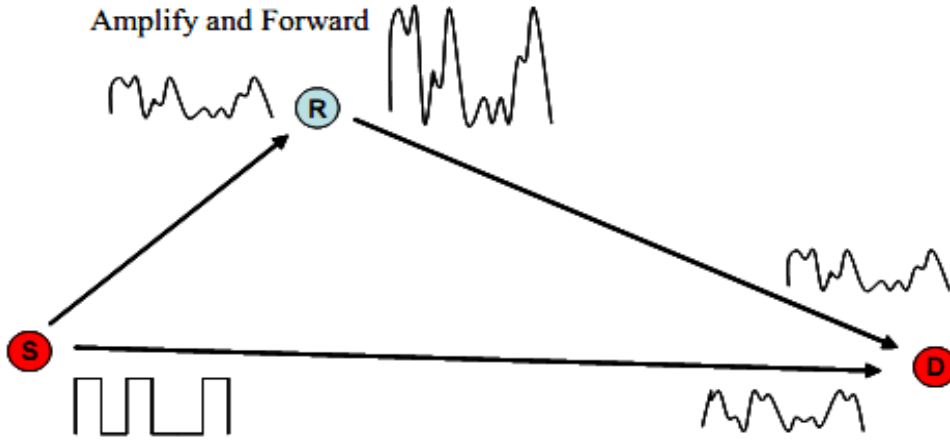


Figure 3.3.: Amplify and Forward

AF relaying can further be categorized as CSI-assisted AF and blind AF; this classification is based on the availability of CSI at the relay terminal. In CSI-assisted AF scheme, the relay uses instantaneous CSI of the source-relay link to scale its received noisy signal before forwarding. This ensures that the same output power is maintained for each realization. On the other hand, blind AF scheme does not have access to CSI and employs fixed power constraint. In this thesis we use CSI-assisted AF scheme.

3.3.2. Decode and Forward

In DF mode, the relay act as digital regenerative repeater, i.e. the relay demodulates, decodes, re-encode and re-modulate the received signal prior to retransmission. The forwarded signal does not contain additional degradation; rather it is affected only by bit errors resulting from the decoding process. Compared to AF strategy, DF scheme provides better QoS (when the SNR of the source-relay link is high); however, there is an increase in cost, complexity, and power consumption involved on the part of relay nodes [37].

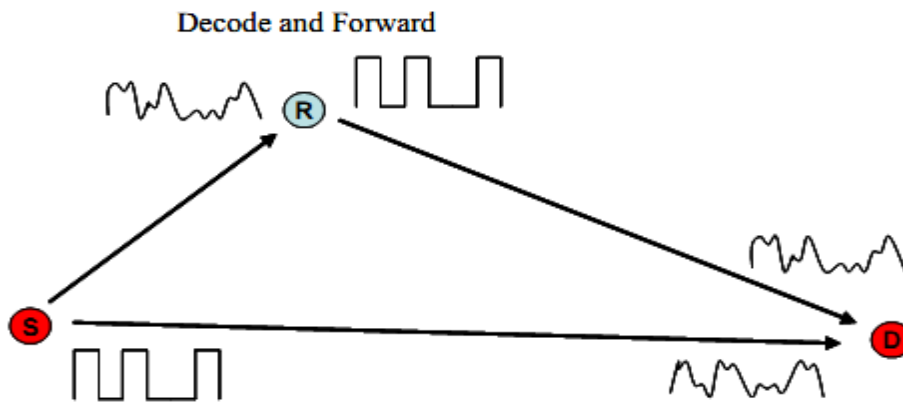


Figure 3.4.: Decode and Forward

3.3.3. Detect-and-Forward

In this scheme, the signal is demodulated or detected by the relay and sent to the destination but the channel encoded signal is not fully decoded by the relay. The DtF scheme is less complex when compared to the Decode and Forward (DF) protocol. It is a re-generative scheme as the signal is detected and re-generated before transmission. DF fully decodes the received signal while DtF retransmits the symbols without fully decoding them [36].

3.3.4. Selective Detect-and-Forward

In this scheme, the relay detects the source transmission; if the detection is error free then it is forwarded to the destination; otherwise, it keeps silent in the second phase. To detect the source transmission correctly there must be some error detection mechanism like

cyclic redundant check (CRC) implemented at the relay. This kind of scheme eliminates the problem of error propagation.

3.3.5. Compress and Forward

The CF scheme is a hybrid solution, an attempt to retain the better features of both AF and DF strategies. In this method the relay does not decode the input data, but it quantizes and compresses (via source coding) the received signal and transmits it to the destination. The possible estimation errors in quantization and coding process are the main sources of signal degradation in this case. CF is also sometimes referred as estimate and forward (EF) technique in literatures. In absence of the channel coding, CF becomes identical to DF scheme [37].

3.4. Combining Techniques

A diversity combining technique is used to combine the multiply received copies of a signal into a single improved signal before further signal processing takes place. Proper combining of the multiple signals will greatly reduce severity of fading and improve reliability of transmission. There are several diversity combining techniques employed in communication receivers including maximal ratio combining (MRC), equal gain combining (EGC), Signal-to-Noise-Ratio Combining (SNRC), Fixed Ratio Combining (FRC), Enhanced Signal-to-Noise-Ratio Combining (ESNRC). In this thesis, we use MRC and EGC schemes; however, we will briefly discuss these and other diversity combining methods next.

3.4.1. Equal Gain Combining (EGC)

In this scheme, the receiver corrects the phase rotation of the received signals caused by the fading channel and combines the received signals of different paths with equal weight. It could be represented as follows:

$$y = \sum_{i=1}^k y_{i,d} \quad (3.4)$$

For three node cooperation the equation is simplified to:

$$y = y_{s,d} + y_{r,d} \quad (3.5)$$

where $y_{s,d}$ represents the received signal from the source and $y_{r,d}$ represents that from the relay [36]. EGC is an attractive method due to its relative ease of implementation.

3.4.2. Fixed Ratio Combining (FRC)

In FRC scheme, instead of just being adding up, the received signals are weighted with a constant ratio which will not change a lot during the whole communication period. Average channel quality is represented by the ratio and temporary influences on the channel due to fading are not taken into account. This requires little amount of computing time and can be expressed as:

$$y = \sum_{i=1}^k d_{i,d} \cdot y_{i,d} \quad (3.6)$$

where $d_{i,d}$ denotes weighting of the incoming signal $y_{i,d}$. For three node cooperation, the equation is simplified to:

$$y = d_{s,d} \cdot y_{s,d} + d_{s,r,d} \cdot y_{r,d} \quad (3.7)$$

where $d_{s,d}$ denotes the weight of the direct link and $d_{s,r,d}$ represents the weight of the multihop link [38]. FRC achieves a much better performance than EGC.

3.4.3. Maximum Ratio Combining (MRC)

This method achieves best performance by taking each input signal and multiplying it by its corresponding conjugated channel gain assuming the channels phase shift and attenuation is known by the receiver, i.e., coherent reception assumed [36]. This could be expressed as:

$$y = \sum_{i=1}^k h_{i,d}^* \cdot y_{i,d} \quad (3.8)$$

For a single relay scenario, the equation is written as:

$$y = h_{s,d}^* y_{s,d} + h_{r,d}^* y_{r,d} \quad (3.9)$$

3.4.4. Enhanced Signal-to-Noise-Ratio Combining (ESNRC)

This combining method ignores an incoming signal when the signal from other incoming channels has a much better quality. EGC is done for channels with more or less the same quality as regards the incoming signals [38]. This can be expressed as:

$$y = \begin{cases} y_{s,d} & SNR_{s,d}/SNR_{s,r,d} > 10 \\ y_{s,d} + y_{s,r,d} & 0.1 < SNR_{s,d}/SNR_{s,r,d} \leq 10 \\ y_{s,r,d} & SNR_{s,d}/SNR_{s,r,d} < 0.1 \end{cases} \quad (3.10)$$

Chapter 4

Cooperative MIMO System

4.1. Introduction

One of the main advantages of cooperative communications is the ability to achieve spatial diversity gains without employing multiple antennas on each terminal. However, if the users can be equipped with multiple antennas, more spatial degrees of freedom can be exploited and more design flexibility would be available since the antennas are not completely distributed. In fact, similar to conventional MIMO systems, precoders and decoders can be designed to decompose the MIMO channel into multiple independent channels and appropriate power and rate allocation policies can be employed to exploit the available spatial dimensions.

4.2. System model

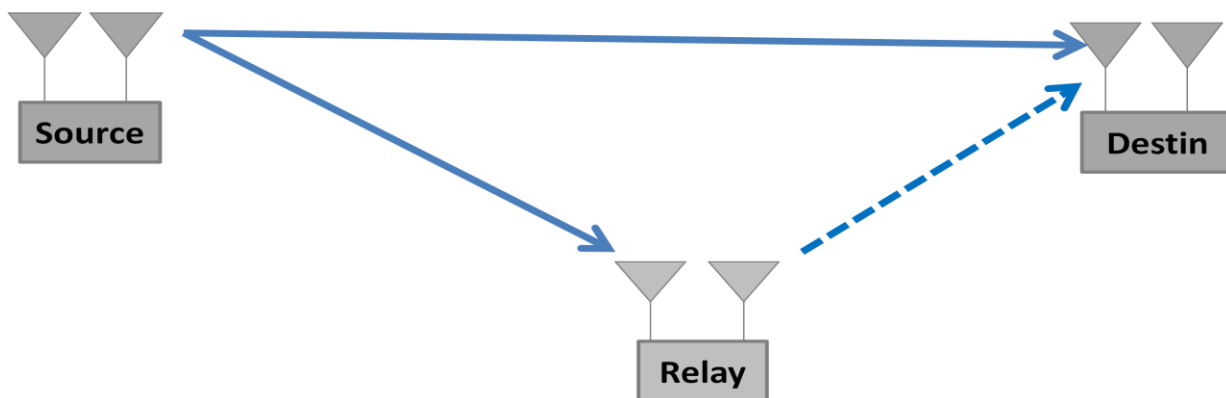


Figure 4.1.: system model of cooperative MIMO system

Consider the three node network shown in Figure 4.1. Let N_s , N_r and N_d denote the number of antennas at the source, relay, and destination, respectively. Let us assume that, $N_s \leq N_d$ for diversity and $N_s = N_r$ to ease combining. The source and relay transmit with identical power, and if a particular terminal uses multiple transmit antennas, the power is divided across that terminal's antennas. To remove the effects of topology, we assume that the path loss between terminals is identical, which is true if the three terminals are located at the corners of an equilateral triangle.

The channels between nodes are independent, and each channel assumed to be quasi-static Rayleigh flat fading. Communication takes place through two time slots of equal duration.

In the first phase, the source transmits and both relay and destination listen. In the second phase, the relay will retransmit the initial source's message or modification of it to the destination. Different relaying techniques could be employed depending on relative channel condition, transceiver complexity and user location. In this thesis, we use amplify and forward relaying technique for its low relaying complexity and its linear nature.

The signal at the relay from the source in the 1st phase is

$$\mathbf{Y}_{sr} = \sqrt{p_1} \mathbf{H}_{sr} \mathbf{x} + \mathbf{N}_{sr} \quad (4.1)$$

While the signal at the destination due to the source transmission is

$$\mathbf{Y}_{sd} = \sqrt{p_1} \mathbf{H}_{sd} \mathbf{x} + \mathbf{N}_{sd} \quad (4.2)$$

where s denotes the sender, r is the relay, p_1 is the average transmit power per antenna at source, \mathbf{H}_{sr} is the $N_r \times N_s$ channel gain matrix for the source relay channel, \mathbf{H}_{sd} is the $N_d \times N_s$ channel gain matrix for the source destination channel, \mathbf{x} is a length $N_s \times 1$ transmitted signal vector, and \mathbf{N}_{sr} , \mathbf{N}_{sd} are the respective channel noise vectors drawn from an ensemble of i.i.d complex Gaussian random variables with zero mean and variance N_0 .

In the second phase, the relay transmits the signal

$$\mathbf{x}_R = \boldsymbol{\beta} \mathbf{Y}_{sr} \quad (4.3)$$

For a 2 X 2 antenna system $\boldsymbol{\beta} = \begin{bmatrix} \beta_1 & 0 \\ 0 & \beta_2 \end{bmatrix}$ is the amplification matrix at the relay. It is shown in [5], that

$$\beta_1 = \sqrt{\frac{p_2}{p_1(H_{sr,11}^2 + H_{sr,21}^2) + N_0}} \quad \text{and} \quad \beta_2 = \sqrt{\frac{p_2}{p_1(H_{sr,12}^2 + H_{sr,22}^2) + N_0}}$$

to ensure the average transmit power per antenna at the relay to be p_2 .

Since we consider orthogonal transmission (OT), the relay transmits only in the second phase. The received signal at the destination in the second phase is given as:

$$\mathbf{Y}_{rd} = \mathbf{H}_{rd}\boldsymbol{\beta}\mathbf{Y}_{sr} + \mathbf{N}_{rd} = \sqrt{p_1}\mathbf{H}_{rd}\mathbf{H}_{sr}\boldsymbol{\beta}\mathbf{x} + \mathbf{H}_{rd}\boldsymbol{\beta}\mathbf{N}_{sr} + \mathbf{N}_{rd} \quad (4.4)$$

where \mathbf{H}_{sd} is the $N_d \times N_r$ channel gain matrix of the relay-destination path, \mathbf{Y}_{sr} is a length $N_r \times 1$ received signal vector, and \mathbf{N}_{rd} is a vector of i.i.d. Gaussian noise vector with zero mean and variance N_0 .

At destination, after the first and second phase i.e. and collecting terms in Equations (4.2) and (4.4), the received signal is given by:

$$\begin{bmatrix} \mathbf{Y}_{sd} \\ \mathbf{Y}_{rd} \end{bmatrix} = \begin{bmatrix} \sqrt{p_1}\mathbf{H}_{sd} \\ \sqrt{p_1}\mathbf{H}_{rd}\mathbf{H}_{sr}\boldsymbol{\beta} \end{bmatrix} \mathbf{x} + \begin{bmatrix} \mathbf{I}_{N_r} & 0 & 0 \\ 0 & \mathbf{H}_{rd}\boldsymbol{\beta} & \mathbf{I}_{N_d} \end{bmatrix} \begin{bmatrix} \mathbf{N}_{sr} \\ \mathbf{N}_{sd} \\ \mathbf{N}_{rd} \end{bmatrix} \quad (4.5)$$

In cooperative mode, the equivalent channel is $N_s \times 2N_d$ MIMO channel with $2N_d$ virtual receiving antennas.

$$\mathbf{Y} = \mathbf{H}_{eq}\mathbf{x} + \mathbf{N}_{eq} \quad (4.6)$$

where:

$$\mathbf{H}_{eq} = \begin{bmatrix} \sqrt{p_1}\mathbf{H}_{sd} \\ \sqrt{p_1}\mathbf{H}_{rd}\mathbf{H}_{sr}\boldsymbol{\beta} \end{bmatrix}$$

$$\mathbf{N}_{eq} = \begin{bmatrix} \mathbf{I}_N & 0 & 0 \\ 0 & \mathbf{H}_{rd}\boldsymbol{\beta} & \mathbf{I}_N \end{bmatrix} \begin{bmatrix} \mathbf{N}_{sr} \\ \mathbf{N}_{sd} \\ \mathbf{N}_{rd} \end{bmatrix}$$

After two phases of transmission the received signals at the destination will be combined using one of the combining techniques discussed in Section 3.4. Equations (4.7) and (4.8) show the received signal for MRC and EGC combining techniques respectively.

$$\mathbf{Y} = \mathbf{H}_{sd}^H \mathbf{Y}_{sd} + \mathbf{H}_{sr}^H \mathbf{H}_{rd}^H \mathbf{Y}_{rd} \quad (4.7)$$

$$\mathbf{Y} = \mathbf{Y}_{sd} + \mathbf{Y}_{rd} \quad (4.8)$$

Since \mathbf{Y} is in the form of $\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{n}$, then this will be fed to ZF, MMSE or ML for signal detection.

4.3. Cooperative Space-Time Transmission Architectures

Using the system model describe in Figure 4.1, we can use orthogonal space-time block codes and vertical-BLAST for the transmission with multiple antennas at all terminals. In this thesis, we consider VBLAST system.

4.3.1. Cooperative Transmission Using STBC

In this scheme, during the first phase the source broadcasts an Alamouti space time code word. The relay and destination listen to the source. During the second phase, the relay amplifies the information and retransmits the message to the destination.

Since the two channels i.e. the source to destination (S-D) and relay to destination (R-D) paths are separable we perform independent combining for each path and then the resulting estimates are summed to yield the final decision statistic.

4.3.2. Cooperative Transmission Using VBLAST

In the cooperative VBLAST transmission scheme, during the first phase the source transmits independent messages over two antennas. During the second phase, the relay forwards the information to the destination.

At the receiver, since the paths S-D and R-D are separable, we perform independent combining on both channels. For S-D path,

$$Y_1 = H^H_{sd} Y_{sd} \quad (4.9)$$

Next we perform similar operation in R-D path,

$$Y_2 = H^H_{sr} H^H_{rd} Y_{rd} \quad (4.10)$$

The estimates from both paths after two phases of transmission are summed up to yield the statistic $\hat{Y} = Y_1 + Y_2$. \hat{Y} is of the form $Y = Hx + n$ which allows to perform ZF, MMSE or ML detection.

4.4. Complexity Analysis

Cooperative MIMO techniques will only become part of future wireless technologies if they are feasible in real world systems. A complexity analysis and comparison will be carried out for the most promising MIMO algorithms. This allows to estimate the potential cost of such systems and to identify possible bottlenecks for the hardware implementation. Even though there is no real consensus on how exactly to interpret the concept of complexity, it is generally defined as the number of floating point operations (additions, multiplications etc.) which are required to compute the estimate of the transmitted vector \mathbf{x} or the running time of the algorithm when implemented on some specific platform. In this thesis, the complexity will be computed in terms of floating point operations i.e. additions and multiplications.

There is a typical tradeoff between the complexity of a detector and its performance in terms of error probability. The optimal, ML, detector which provides the minimum probability of error is often prohibitively complex while the computationally simplest detectors will have a poor performance in terms of error probability [39].

Generally, complexity of cooperative MIMO system depends on the type of SM algorithm and type of combining used in the receiver.

4.4.1. Complexity of Arithmetic Operations

Before determining the complexity of the system, we introduce a number of general rules, such as, the complexity of a matrix multiplication, the conversion from complex complexity figures to real complexity figures, the complexity of a slicer, and the complexity of finding a minimum value from a set of values.

The complexity of a matrix product is determined as follows. Suppose two matrices \mathbf{A} and \mathbf{B} (real or complex) with dimensions $C \times D$ and $D \times E$ are multiplied, then the $(i, j)^{th}$ element of the resulting matrix is given by:

$$a^i b_j = \sum_{k=1}^D a_{ik} b_{kj} \quad (4.11)$$

Where a^i represents the i^{th} row of matrix \mathbf{A} , b_j denotes the j^{th} column of \mathbf{B} and a_{ik} and b_{kj} stand for the k^{th} element of this row and column, respectively. Thus, in order to obtain one element of the resulting matrix, $D - 1$ additions and D multiplications need to be performed. The resulting matrix is CE dimensional and, therefore, a total of $C(D - 1)E$ additions and CDE multiplications are needed to multiply A and B .

To represent complex additions and complex multiplications in terms of real additions and real multiplications, it is easily verified that one complex addition consists of two real additions; the real and the imaginary part of the two complex numbers are added.

$$(a + jb)(c + jd) = (ac - bd) + j(ad + bc) \quad (4.12)$$

One complex multiplication consists of 4 real multiplications, ac , bd , bc and ad , and 2 real additions, $ac - bd$ and $ad + bc$. A subtraction is counted as an addition and the addition before the j does not count because the real and imaginary parts are stored separately.

The complexity of a slicer is minimal in terms of additions and/or multiplications. For an M-PSK constellation scheme, the phase range $[-\pi, \pi]$ is divided in M equal parts. In such a regular structure, a recursive search is done in which half of the (remaining) range the phase of the estimated symbol best fits. This results in a complexity equivalent to $\log_2(M)$ comparisons. For an M-QAM constellation diagram, the real and imaginary parts are split. Each of these parts is regularly divided in \sqrt{M} slicing ranges. Also in this case, a recursive search is achieved in which half of the (remaining) range the real or imaginary part of the estimated symbol best fits, and the complexity is equal to $\log_2(\sqrt{M})$ comparisons for the real and for the imaginary part, or $2\log_2(\sqrt{M}) = \log_2(M)$ comparisons in total. It is reasonable to assume that a comparison is as complex as a real addition and, therefore, the slicing of the N_t dimensional vector \mathbf{x}_{est} requires at most $N_t \cdot \log_2(M)$ R_ADDs [40].

To find the minimum of N numbers in hardware, the easiest thing to do is start with the first two elements, subtract the second number from the first, and compare the result with

zero. If the result is larger than zero, the second number is the smallest; otherwise the first number is the smallest, etc. Clearly, finding the minimum between two real numbers has complexity of one real addition. As a result, determining the minimum of N values has a complexity of $N - 1$ real additions.

Based on these general rules, the complexity of cooperative MIMO system for ZF, MMSE and ML detection techniques are determined in the following sections. Before determining complexity of each detector in detail we analyze complexities which are common to all detection techniques. These are estimation of \mathbf{H} in the preamble processing and combining in the payload processing. Thus complexity depends not only on the type of detector but also on the type of combining used. In this thesis we consider both MRC and EGC.

From Equation (4.7) given above using MRC the received signal is given by:

$$\mathbf{Y} = \mathbf{H}_{sd}^H \mathbf{Y}_{sd} + \mathbf{H}_{sr}^H \mathbf{H}_{rd}^H \mathbf{Y}_{rd}$$

This can be written as:

$$\mathbf{Y} = \mathbf{H}_{eq} \mathbf{x} + \mathbf{N}_{eq} \quad (4.13)$$

Where:

$$\begin{aligned} \mathbf{H}_{eq} &= \mathbf{H}_{sd}^H \mathbf{H}_{sd} + \mathbf{H}_{sr}^H \mathbf{H}_{rd}^H \mathbf{H}_{rd} \boldsymbol{\beta} \mathbf{H}_{sr} \\ \mathbf{N}_{eq} &= \mathbf{H}_{sd}^H \mathbf{N}_{sd} + \mathbf{H}_{sr}^H \mathbf{H}_{rd}^H (\mathbf{H}_{rd} \boldsymbol{\beta} \mathbf{N}_{sr} + \mathbf{N}_{rd}) \end{aligned}$$

Using the general rules given above estimation of \mathbf{H}_{eq} in the preamble processing has a complexity of

$$\begin{aligned} &2N_s^2(4N_d - 1) + 4N_s(N_r^2 + 2N_d N_r - N_d) - 2N_r^2 \text{ R_ADDs} \\ &8N_s^2 N_d + 4N_s(N_r^2 + 2N_d N_r) \text{ R_MULs} \end{aligned} \quad (4.14)$$

Similarly in the payload processing calculating \mathbf{Y} has complexity of

$$\begin{aligned}
& N_s(4N_d - 1) \text{ R_ADDs} \\
& 4N_sN_d \text{ R_MULs}
\end{aligned} \tag{4.15}$$

When N_x vectors are transmitted within a packet, these numbers must be multiplied by N_x to obtain the complexity per packet.

Similarly for EGC, using Equation (4.8) and the same approach as that of MRC, estimation of H_{eq} in the preamble and calculating Y in the payload processing has complexities given in Equations (4.16) and (4.17) respectively.

$$\begin{aligned}
& 4N_s(N_r^2 + N_dN_r) - 2N_r^2 \text{ R_ADDs} \\
& 4N_s(N_r^2 + N_dN_r) \text{ R_MULs}
\end{aligned} \tag{4.16}$$

$$N_s \text{ R_ADDs (assuming } N_s = N_d \text{)} \tag{4.17}$$

4.4.2. Complexity of ZF

Zero Forcing technique is based on calculation of the pseudo-inverse of the channel transfer matrix \mathbf{H} . Because it is assumed that the system is operating in quasi-static environment, i.e., \mathbf{H} is constant during transmission of symbols, the pseudo-inverse of \mathbf{H} needs to be calculated only once per transmitted MIMO vector. The pseudo-inverse can be calculated after the channel training in the preamble processing. During the payload processing, the pseudo-inverse is used for the estimation of every transmitted MIMO vector \mathbf{x} . For determining the complexity of the calculation of the pseudo-inverse, the following equation is used

$$\mathbf{H}^\dagger = (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H \tag{4.18}$$

The dimensions of \mathbf{H}^\dagger , \mathbf{H} and \mathbf{H}^H are $N_s \times N_d$, $N_d \times N_s$ and $N_s \times N_d$ respectively, for EGC and all have the same dimension in MRC which is $N_s \times N_s$.

To find the pseudo inverse of \mathbf{H} , first, determine the complexity of the matrix product $\mathbf{H}^H \mathbf{H}$.

Hence, the complexity of the matrix product $\mathbf{H}^H \mathbf{H}$ yields $N_s^2(N_d - 1)$ C_ADDs and $N_s^2 N_d$ C_MULs. The result is a square matrix with dimension $N_s \times N_s$. The inverse of this square matrix $\mathbf{H}^H \mathbf{H}$, needs to be determined. The direct inversion of a given square matrix \mathbf{A} (with dimension $N \times N$) has a complexity in the order of N^3 additions and N^3 multiplications in total. So, inverting $\mathbf{H}^H \mathbf{H}$ has a complexity of N_s^3 C_ADDs and N_s^3 C_MULs.

Finally, the inverse of $\mathbf{H}^H \mathbf{H}$ is multiplied by \mathbf{H}^H . The complexity of this is equal to $N_s(N_s - 1)N_d$ C_ADDs and $N_s^2 N_d$ C_MULs.

This leads to a total complexity of $N_s^3 + N_s^2(N_d - 1) + N_s(N_s - 1)N_d$ C_ADDs and $N_s^3 + N_s^2 N_d$ C_MULs in the training phase. The complexity in terms of real operations equals

$$4N_s^3 + N_s^2(8N_d - 2) - 2N_s N_d \text{ R_ADDs and } 4N_s^3 + 8N_s^2 N_d \text{ R_MULs} \quad (4.19)$$

Using similar approach we can find the complexity of MRC combining

$$12N_s^3 - 4N_s^2 \text{ R_ADDs and } 12N_s^3 \text{ R_MULs} \quad (4.20)$$

The payload processing for ZF consists of a matrix-vector multiplication per transmitted vector and a slicing step to translate the estimated elements of x to the possible transmitted symbols. Recalling from Subsection 2.1, the matrix-vector multiplication is given by

$$\hat{\mathbf{x}} = \mathbf{H}^\dagger \mathbf{Y} \quad (4.21)$$

The complexity of this product is equal to $N_s(N_d - 1)$ complex additions and $N_s N_d$ complex multiplications for EGC and $N_s(N_s - 1)$ C_ADDs and N_s^2 C_MULs for MRC.

As explained earlier, the complexity of slicing N_s M-ary constellation points equals $N_s \log_2(M)$ R_ADDs.

Summarizing, the complexity of the ZF algorithm during payload processing per transmitted vector \mathbf{x} equals:

$N_s(N_d - 1)$ C_ADDs + $N_s \log_2(M)$ R_ADDs and $N_s N_d$ C_MULs for EGC and $4N_s^2 - 2N_s + N_s \log_2(M)$ R_ADDs and $4N_s^2$ R_MULs for MRC.

When N_x vectors are transmitted within a packet, these numbers must be multiplied by N_x to obtain the complexity per packet.

4.4.3. Complexity of MMSE

The complexity of the MMSE algorithm is almost equal to the complexity of the ZF method described in the previous section. In the preamble processing phase, the following MIMO processing matrix needs to be determined:

$$(\mathbf{H}^H \mathbf{H} + \sigma_n^2 \mathbf{I}_N)^{-1} \mathbf{H}^H \quad (4.22)$$

The calculation of this matrix has almost the same complexity as the determination of the pseudo-inverse in case of the ZF algorithm. The only additional complexity consists of the N_s real additions (i.e., the addition of σ_n^2 to the diagonal elements of $\mathbf{H}^H \mathbf{H}$). This leads to a total complexity in the preamble processing, which is

$4N_s^3 + N_s^2(8N_d - 2) - 2N_s N_d + N_s$ R_ADDs and $4N_s^3 + 8N_s^2 N_d$ R_MULs for EGC and $12N_s^3 - 4N_s^2 + N_s$ R_ADDs and $12N_s^3$ R_MULs for MRC

The complexity of MMSE during the payload processing is equal to that of ZF and consists of a matrix-vector product with the same dimensions and slicing.

4.4.4. Complexity of ML

Since the search in ML over all transmitted vectors x_i , with $i = 1, \dots, M^{N_s}$, the complexity is proportional to the number of candidates M^{N_s} . Furthermore, each candidate's x_i has to be multiplied by the channel matrix \mathbf{H} . This can be written as

$$\sum_{p=1}^{N_s} \mathbf{h}_p(x_i)_p \quad (4.23)$$

Where h_p denotes the p^{th} column of \mathbf{H} . All the elements of \mathbf{x}_i are taken from the set of M^{N_s} constellation points.

It can be observed that the amount of candidates grows exponentially with the number of transmission antennas. When the memory is not large enough, not all candidates can be stored and they have to be calculated for every transmitted vector to perform ML. So, the complexity of ML largely depends on the amount of memory used.

I. Preamble processing

All the candidates are determined during the preamble processing and used in the data phase. The complexity of the matrix $\mathbf{H}\mathbf{x}_i$ can be obtained, starting with h_1x_1 to h_1x_M . Thus, first, the products of every column of \mathbf{H} with every constellation point should be determined. This has total complexity of $2MN_dN_s$ R_ADDs and $4MN_dN_s$ R_MULs. After that, the additions have to be performed. This has complexity of

$$\sum_{p=2}^{N_s} M^p N_d = M^2 N_d \frac{M^{N_s-1}-1}{M-1} \text{ C_ADDs} \quad (4.24)$$

This gives total complexity of:

$$4MN_dN_s \text{ R_MULs}, \quad 2M^2N_d \frac{M^{N_s-1}-1}{M-1} + 2MN_dN_s \text{ R_ADDs}, \quad 4MN_s^2 \text{ R_MULs} \quad \text{and} \\ 2M^2N_s \frac{M^{N_s-1}-1}{M-1} + 2MN_s^2 \text{ R_ADDs} \text{ for EGC and MRC respectively}$$

II. Payload processing

During this phase the vector subtraction $\mathbf{y} - \mathbf{H}\mathbf{x}_i$ and the square norm of the result have to be determined for the M^{N_s} possible \mathbf{x} vectors. The next step is to obtain the minimum of the squared norms. The vector subtraction $\mathbf{y} - \mathbf{H}\mathbf{x}_i$ is performed for $i = 1, \dots, M^{N_s}$ and has a complexity equal to $N_d M^{N_s}$ C_ADDs. Next the norms of the M^{N_s} results have to be determined. This has a complexity of $(2N_d - 1)M^{N_s}$ R_ADDs and $2N_d M^{N_s}$ R_MULs. Finally, the minimum of the M^{N_s} norms must be obtained which has a complexity of $M^{N_s} - 1$ R_ADDs.

The total complexity per transmitted vector \mathbf{x} , for EGC and MRC is given in equations (4.25) and (4.26) respectively:

$$4N_d M^{N_s} - 1 \text{ R_ADDs and } 2N_d M^{N_s} \text{ R_MULs} \quad (4.25)$$

$$4N_s M^{N_s} - 1 \text{ R_ADDs and } 2N_s M^{N_s} \text{ R_MULs} \quad (4.26)$$

To obtain the complexity for the entire packet, these complexity numbers have to be multiplied by the number of spatial vectors within a packet N_x . Note that these complexity figures increases linearly with the number of receiving antennas and exponentially with the number of transmit antennas.

Based on the complexity figures in the previous sections, it is possible to compare the complexity of the described SM algorithms. In order to express the complexity using a single equation, i.e. equivalent ADDs it is reasonable to assume that complexity of multiplier is ten times higher than that of adder [26].

Tables 4.1 and 4.2 summarize total complexity of cooperative MIMO system for the described SM algorithms using MRC and EGC combining techniques respectively.

Table 4.1.: Complexity of MIMO detection schemes for MRC combining

Combining	Detector	Real addition	Real multiplication	Equivalent addition
MRC	ZF	$12N_s^3 - 4N_s^2$ $+ Pr_{MA} N_x \cdot (4N_s^2$ $+ N_s(N_d + \log 2(M) - 4))$	$12N_s^3 +$ $Pr_{MM} +$ $N_x \cdot (4N_s^2 +$ $4N_s N_d)$	$132N_s^3 - 4N_s^2$ $+ 10Pr_{MM} + Pr_{MA}$ $+ N_x \cdot (44N_s^2$ $+ 41N_s N_d$ $+ N_s(+\log 2(M)$ $- 4))$
	MMSE	$12N_s^3 - 4N_s^2 + Pr_{MA} + N_s$ $+ N_x \cdot (4N_s^2 + N_s(N_d$ $+ \log 2(M) - 4))$	$12N_s^3 +$ $Pr_{MM} +$ $N_x \cdot (4N_s^2 +$ $4N_s N_d)$	$132N_s^3 - 4N_s^2$ $+ 10Pr_{MM} + Pr_{MA}$ $+ N_s + N_x \cdot (44N_s^2$ $+ 41N_s N_d$ $+ N_s(+\log 2(M)$ $- 4))$
	ML	$2M^2 N_s \frac{M^{N_s-1} - 1}{M - 1} + 2MN_s^2$ $+ Pr_{MA}$ $+ N_x \cdot (N_s(4N_d + 4M^{N_s}$ $- 1) - 1)$	$Pr_{MM} + 4MN_s^2$ $+ N_x \cdot (2N_s M^{N_s}$ $+ 4N_s N_d)$	$2M^2 N_s \frac{M^{N_s-1} - 1}{M - 1} +$ $42MN_s^2 + Pr_{MA} +$ $10Pr_{MM} + N_x \cdot (24N_s M^{N_s}$ $+ 44N_s N_d - N_s - 1)$

Where

$$Pr_{MA} = 2N_s^2(4N_d - 1) + 4N_s(N_r^2 + 2N_d N_r - N_d) - 2N_r^2$$

$$Pr_{MM} = 8N_s^2 N_d + 4N_s(N_r^2 + 2N_d N_r)$$

Table 4.2.: Complexity of MIMO detection schemes for EGC combining

Combining	Detecto	Real addition	Real multiplication	Equivalent addition
EGC	ZF	$4N_s^3$ $+ N_s^2(8N_d - 2)$ $- 2N_sN_d + Pr'_{MA}$ $+ N_x \cdot (4N_s^2 - 3N_s)$ $+ N_s \log 2(M) + 4N_sN_d$	$4N_s^3 + 8N_s^2N_d$ $+ Pr'_{MM}$ $+ N_x \cdot (4N_s^2$ $+ 4N_sN_d)$	$44N_s^3 + 88N_s^2N_d$ $- 2N_s^2 + Pr'_{MA}$ $+ 10Pr'_{MM}$ $+ N_x \cdot (44N_s^2$ $+ 44N_sN_d - 3N_s$ $+ N_s \log 2(M))$
	MMSE	$4N_s^3 + N_s^2(8N_d - 2)$ $- 2N_sN_d + N_s + Pr'_{MA}$ $+ N_x \cdot (4N_s^2 - 3N_s)$ $+ N_s \log 2(M) + 4N_sN_d$	$4N_s^3 + 8N_s^2N_d$ $+ Pr'_{MM}$ $+ N_x \cdot (4N_s^2$ $+ 4N_sN_d)$	$44N_s^3 + 88N_s^2N_d$ $- 2N_s^2 + N_s + Pr'_{MA}$ $+ 10Pr'_{MM}$ $+ N_x \cdot (44N_s^2$ $+ 44N_sN_d - 3N_s$ $+ N_s \log 2(M))$
	ML	$2M^2N_d \frac{M^{N_s-1} - 1}{M - 1}$ $+ 2MN_dN_s + Pr'_{MA}$ $+ N_x \cdot (4N_dN_s$ $- N_s + 4N_sM^{N_s} - 1)$	$4MN_dN_s$ $+ Pr'_{MM}$ $+ N_x \cdot (2N_dM^{N_s}$ $+ 4N_sN_d)$	$2M^2N_d \frac{M^{N_s-1} - 1}{M - 1}$ $+ 42MN_dN_s + Pr'_{MA}$ $+ 10Pr'_{MM}$ $+ N_x \cdot (20N_dM^{N_s}$ $+ 44N_sN_d$ $- N_s + 4N_sM^{N_s} - 1)$

Where

$$Pr'_{MA} = 4N_s(N_r^2 + N_dN_r) - 2N_r^2$$

$$Pr'_{MM} = 4N_s(N_r^2 + N_dN_r)$$

Chapter 5

Simulation Results

In this chapter, simulation results and discussions on the performance of cooperative MIMO system using AF relaying for different detection techniques is presented. In Section 5.1 simulation parameters and assumptions are stated. Performance of cooperative diversity, MIMO and cooperative MIMO system with AF relaying for various detection techniques in terms of SER are discussed in Sections 5.2, 5.3 and 5.4, respectively. Finally, the complexities of conventional MIMO and cooperative MIMO system are described in Section 5.5.

5.1. Simulation Parameters

The simulation parameters used for performance evaluation of MIMO and cooperative MIMO systems are shown in Table 5.1.

Table 5.1.: Simulation parameter

System	Cooperative MIMO system VBLAST
# transmit antenna	2
# receive antenna	2
# relay antenna	2
Channel	Rayleigh flat fading
Noise	AWGN
Modulation	BPSK, QPSK, 16QAM and 64QAM
Detectors	ZF, MMSE and ML
# transmission symbols	10^6
CSI	Perfectly known at receiver
SNR range	0 to 30 dB
Arrangement	Equidistance
Power	Equal power at all nodes

All the assumptions and simulation parameters are based on the standard of WiMAX technology.

5.2. SER Performance of Cooperative Diversity

Figure 5.1 presents SER performance of conventional cooperative diversity using AF relaying technique for QPSK modulation. The theoretical SER performance of AF-based cooperative diversity using QPSK modulation can be tightly approximated as [41],

$$P_s \approx \frac{127}{88} \cdot \frac{1}{P_1 \delta_{sd}^2} \left(\frac{1}{P_1 \delta_{sr}^2} + \frac{1}{P_1 \delta_{rd}^2} \right) \quad (5.1)$$

where h_{sd} , h_{sr} and h_{rd} are the channel coefficients with zero mean and variance δ_{sd}^2 , δ_{sr}^2 and δ_{rd}^2 , respectively.

This theoretical SER performance is also plotted in Figure 5.1. This is used as benchmark to validate the simulation results; as can be observed, the analytical plot closely follows the simulated one especially at high SNR values.

The conventional SISO system is also included in the figure to see the diversity gain achieved by AF in comparison with SISO. From the figure, we can see that the AF-based cooperative diversity achieves 11 dB benefit at 10^{-3} SER as compared to the SISO system.

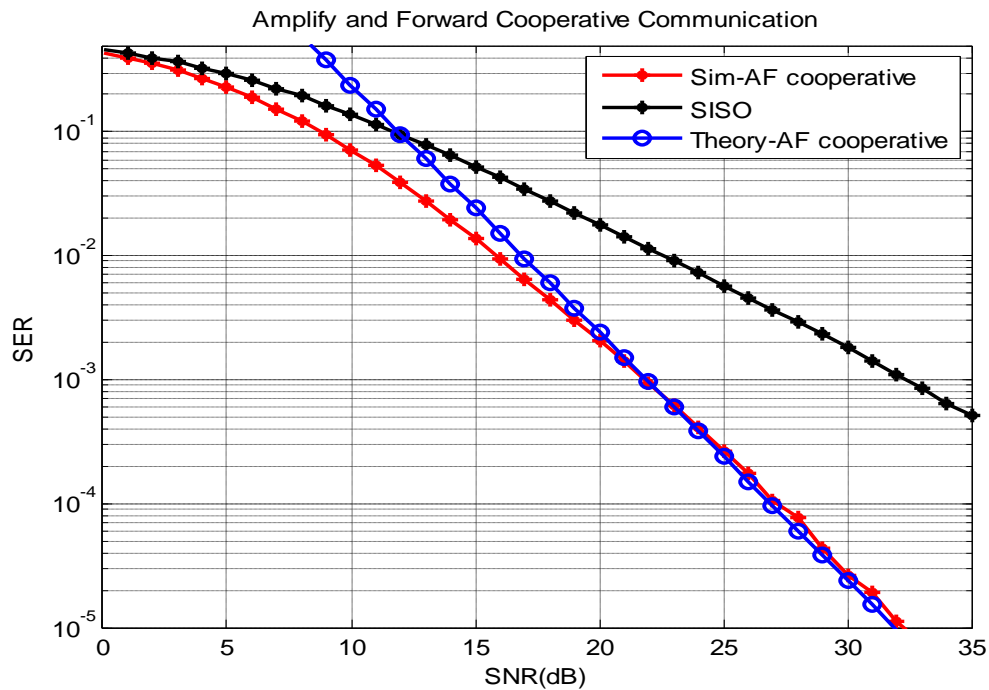


Figure 5.1.: SER performance of cooperative diversity using AF relay for QPSK modulation

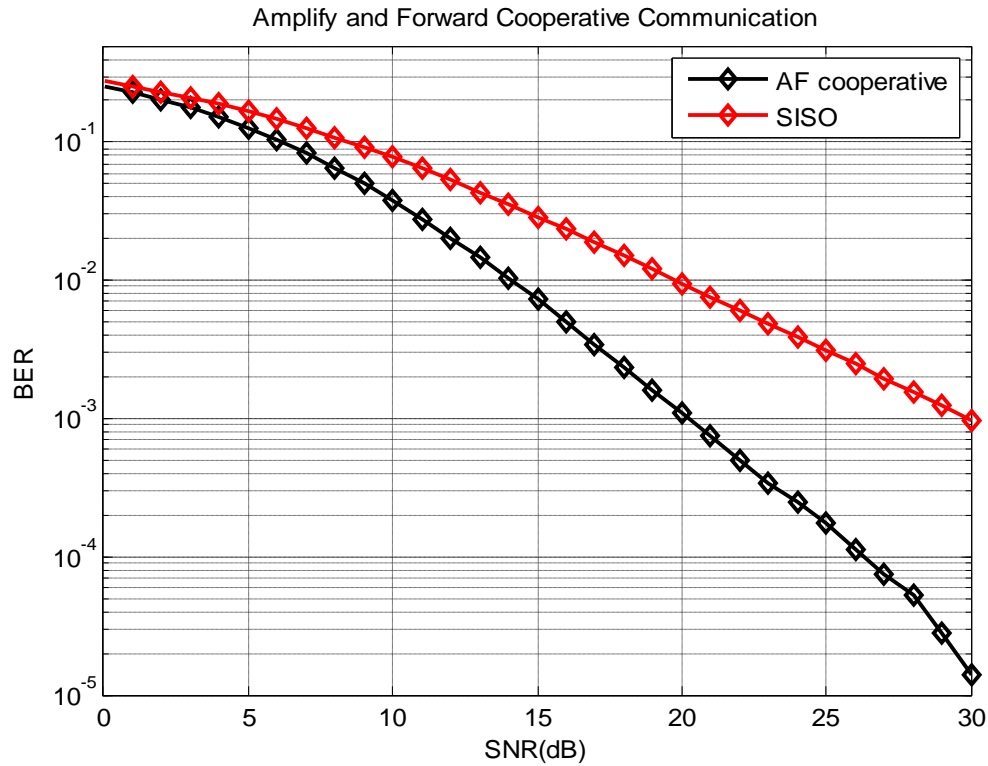


Figure 5.2.: BER performance of cooperative diversity using AF relay for BPSK modulation

Figure 5.2 presents BER performance of conventional cooperative diversity using AF relaying technique for BPSK modulation. Comparing the required SNR to achieve a BER of 10^{-3} for BPSK modulation, we see that AF based cooperative diversity improves performance by 9.5 dB. Table 5.2 summarizes the required SNR to achieve a particular BER of 10^{-3} for both BPSK and QPSK modulation schemes.

Table 5.2.: SNR required to achieve 10^{-3} BER for AF based cooperative diversity and SISO systems using BPSK and QPSK modulation

Modulation	AF based cooperative	SISO	SNR gain of cooperative diversity
BPSK	20 dB	29.5 dB	9.5 dB
QPSK	22 dB	33 dB	11 dB

5.3. Performance Comparison of MIMO Detection Techniques

Figure 5.3 shows the BER performance of MIMO detection techniques for a 2×2 MIMO system and BPSK modulation. From the figure, we can see that ML outperforms both ZF and MMSE. At a BER of 10^{-3} we can observe that the performance of ML detection has SNR gain of 9 dB when compared to the performance of MMSE and 12 dB to that of ZF. An intuitive explanation for this is that ML performs detection and uses a prior knowledge about the possible constellation points that are sent, whereas the other techniques just perform estimation. Furthermore, MMSE scheme provides 3 dB SNR gain over ZF scheme at 10^{-3} BER. This improvement is due to the fact that in addition to nulling out the interferers, the MMSE scheme takes into consideration the noise on the channel represented by the σ_n^2 term in Equation 2.12.

BER Performance of Different V-BLAST Detection Schemes over 2×2 MIMO Channels with Rayleigh Channel

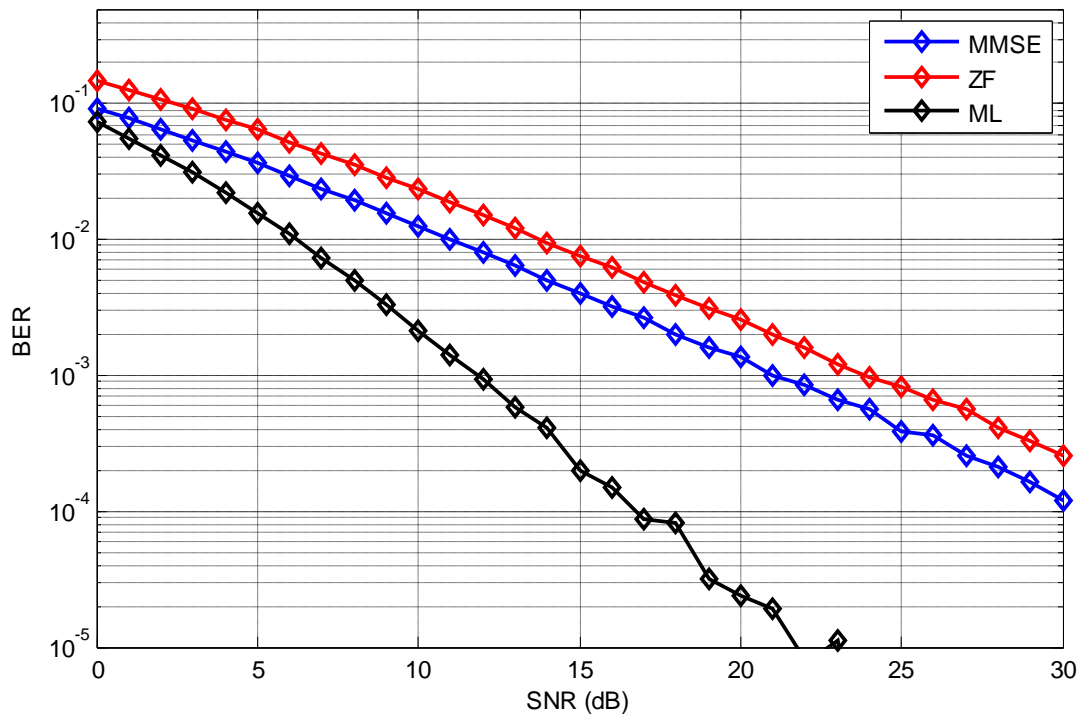


Figure 5.3.: Performance comparison of MIMO detection techniques for a 2×2 MIMO system and BPSK modulation

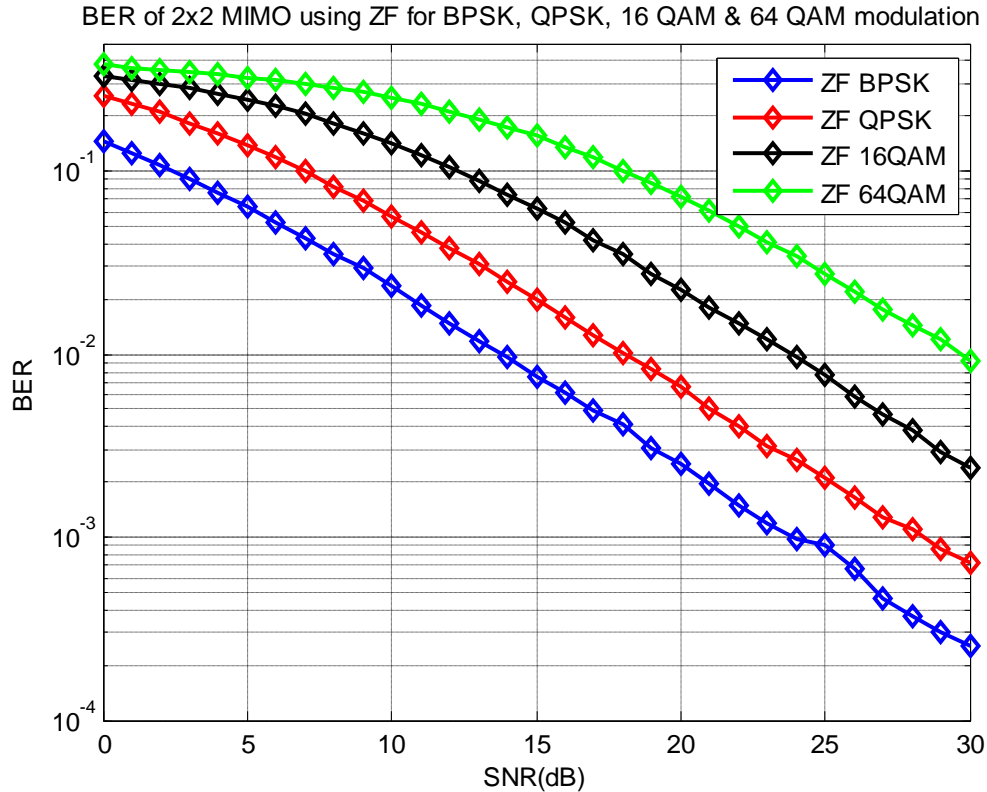


Figure 5.4.: BER performance of a 2 X 2 MIMO system using ZF detector for different modulation schemes.

Figure 5.4 shows the BER performance of a 2 X 2 MIMO system using ZF detector for different modulation schemes. To achieve a BER of 10^{-2} BPSK needs 14 dB SNR whereas QPSK needs 18 dB. But for 16QAM and 64QAM modulation schemes we need an SNR of 24 dB and 30 dB, respectively, to achieve BER of 10^{-2} . We can see that, lower order modulations perform better than high order modulation schemes. This can be explained by the fact that higher constellation orders are more vulnerable for noise, resulting in more errors and, correspondingly, resulting in a performance loss.

5.4. Performance of cooperative MIMO system

We analyze performance of cooperative MIMO system compared to conventional MIMO system based on SER and throughput for Rayleigh fading channel. We also investigate the performance of cooperative MIMO system for various scenarios.

5.4.1. SER Performance of Cooperative MIMO System

Performance of Different V-BLAST Detection Schemes for 2x2 Co-MIMO and BPSK

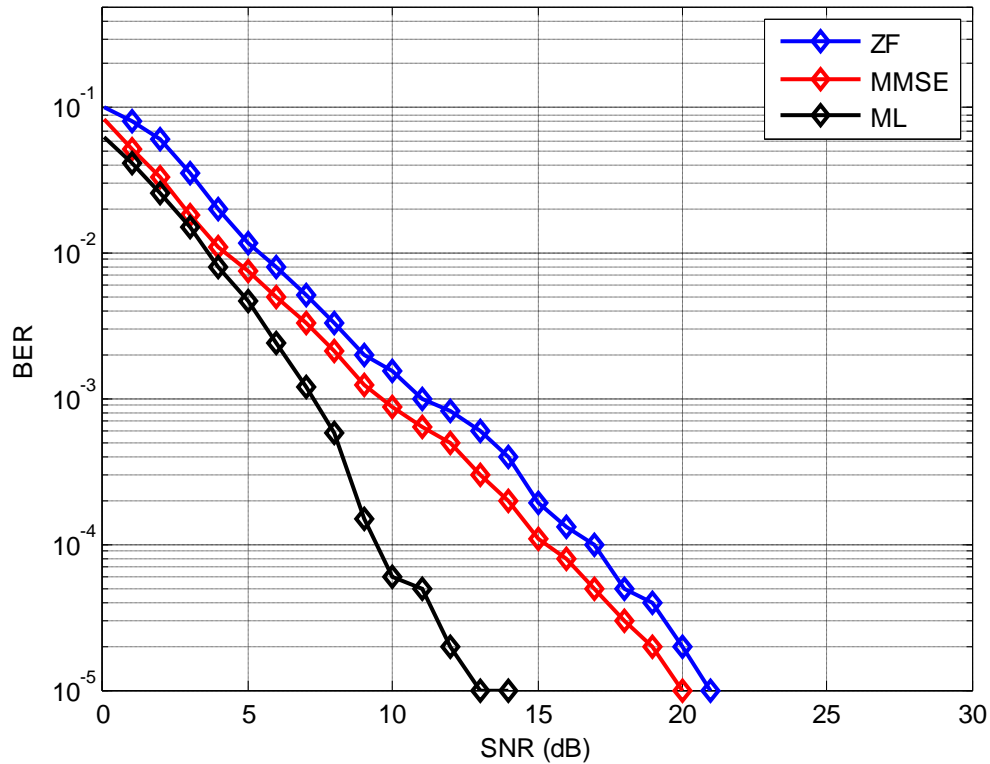


Figure 5.5.: performance comparison of SM algorithms for cooperative MIMO system with BPSK modulation

In Figure 5.5, the results of similar simulations are presented in Fig 5.3, but now for a cooperative MIMO system. For Cooperative MIMO system, at BER of 10^{-3} , there is approximately 1 dB SNR difference between the MMSE and ZF detectors. The ML detector shows 4 dB improvements than the ZF one. The ML detector shows highest power margin improvement among these detectors. For ML scheme, cooperative MIMO system provides SNR gain of 13 dB and 5 dB compared to cooperative diversity and MIMO system respectively. Table 5.3 summarizes SNR gains of cooperative MIMO system compared to conventional MIMO and cooperative diversity system for ZF, MMSE and ML detections at 10^{-3} BER.

Table 5.3.: SNR (dB) gain of cooperative MIMO over cooperative and MIMO systems at 10^{-3} BER

Cooperative diversity	MIMO			Cooperative MIMO			SNR gain of Cooperative MIMO					
	ZF	MMSE	ML	ZF	MMSE	ML	MIMO			Cooperative		
							ZF	MMSE	ML	ZF	MMSE	ML
20	24	21	12	11	10	7	13	10	7	9	10	13

Fig 5.6 shows BER performance of a cooperative MIMO system using ZF detector for BPSK, QPSK, 16QAM and 64 QAM modulation schemes. Comparing the required SNR to achieve a BER of 10^{-2} , we see that cooperative MIMO system improves performance by 9 dB for BPSK and QPSK modulation schemes. Table 5.4, provides the required SNR to achieve a particular BER for both MIMO and cooperative MIMO systems.

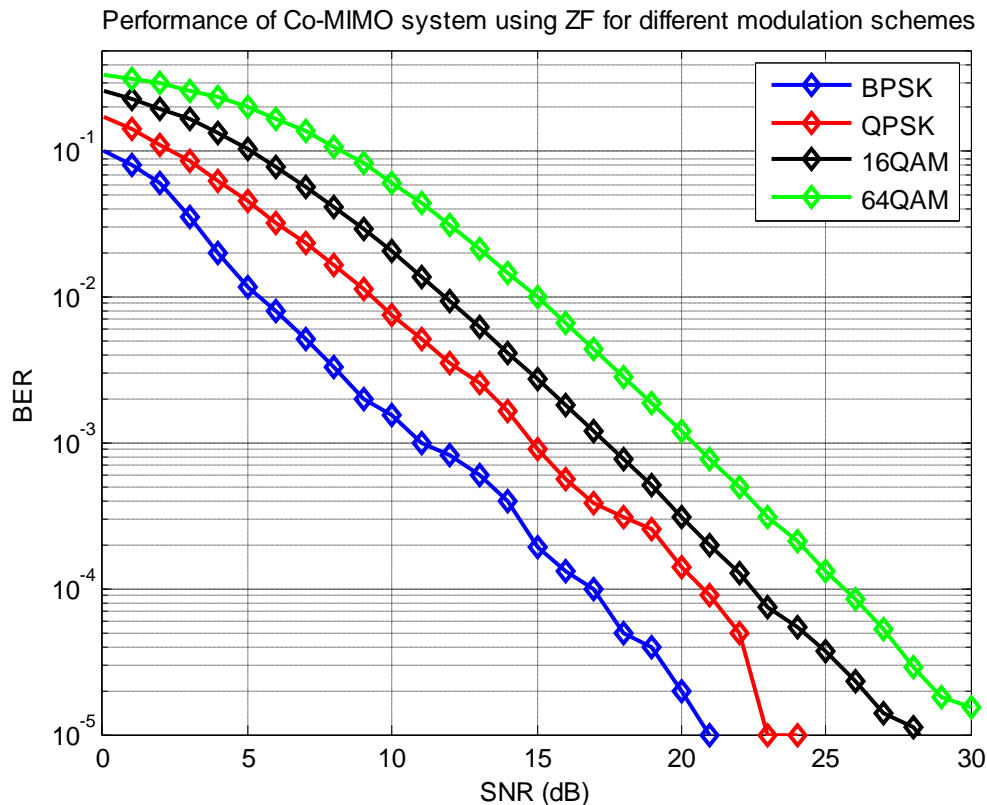


Figure 5.6.: BER performance of cooperative MIMO system using ZF detector for different modulation schemes.

Table 5.4.: Required SNR to achieve BER of 10^{-2} for both MIMO and cooperative MIMO systems for different modulation schemes.

Modulation	SNR at 10^{-2} BER		SNR gain of Cooperative MIMO
	MIMO	Cooperative MIMO	
BPSK	14	5	9
QPSK	18	9	9
16 QAM	24	12	12
64 QAM	30	15	15

In Fig. 5.7, we present the SER performance results of cooperative AF VBLAST with zero forcing (ZF) detection technique for QPSK modulation. The 2×2 VBLAST using the same detection and the 1×2 theoretical result are also presented for comparison purposes.

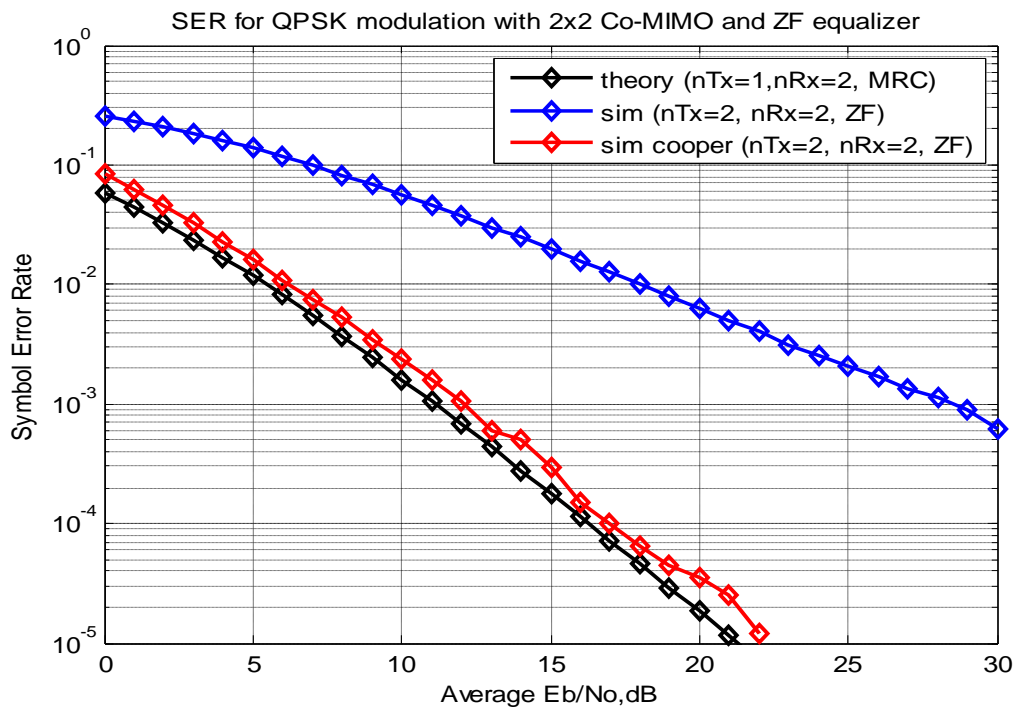


Figure 5.7.: SER performance of cooperative MIMO AF VBLAST using ZF detection and QPSK modulation

The simulation result indicates that there is an increase in diversity gain due to the presence of cooperative AF MIMO relay in wireless network. For a SER rate of 10^{-3} ,

cooperative MIMO system results in 15 dB improvement compared to MIMO system using ZF detection schemes.

Figure 5.8 presents the SER performance of cooperative AF VBLAST with MMSE detection technique for QPSK modulation. The 2×2 VBLAST using the same detection and the 1×2 theoretical result are also presented for comparison purposes. We can easily see that there is an increase in diversity gain due to the presence of the relay. For a SER rate of 10^{-3} , the system with relay results in an improvement of roughly 13 dB.

Form Figures 5.7 and 5.8 we can conclude that the performance of cooperative MIMO system for ZF and MMSE detection techniques almost coincides. Both require approximately 12 dB SNR to achieve a SER of 10^{-3} .

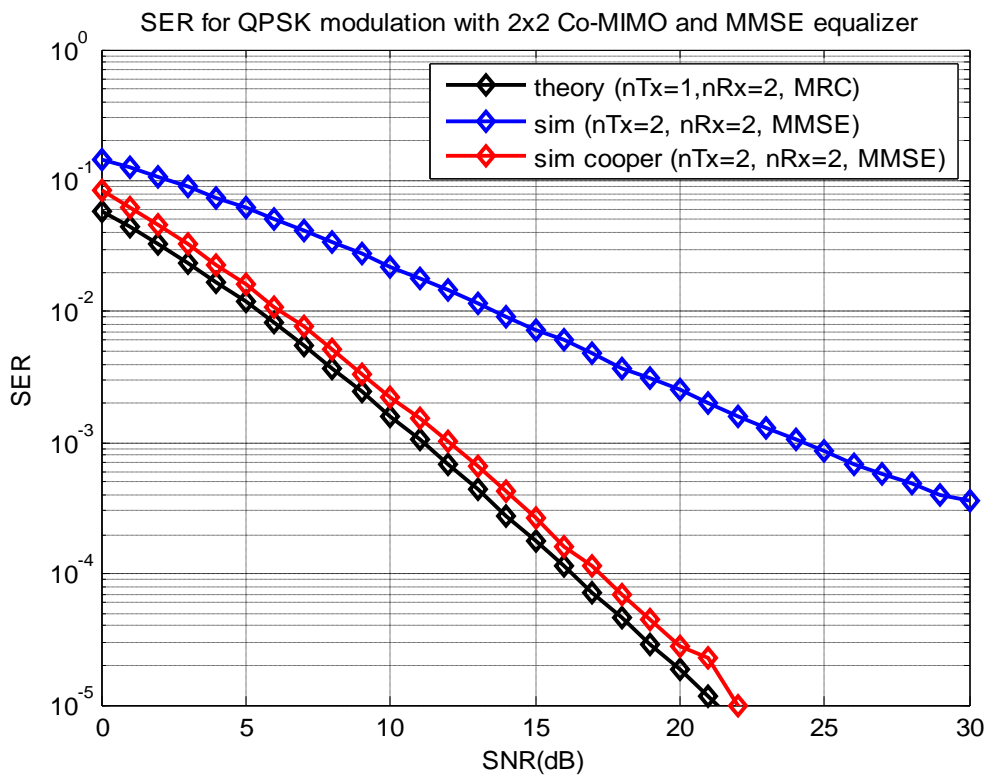


Figure 5.8.: SER performance of cooperative MIMO AF VBLAST using MMSE detection and QPSK modulation

5.4.2. SER Performance Comparison of Cooperative MIMO System for Various Scenarios

In the following, we consider various SNR based scenarios and we compare them based on their respective SER.

Scenario 1 (Balanced $S \rightarrow D$ and $S \rightarrow R$ links and poor SNR in $R \rightarrow D$ link)

We assume that SNR in $R \rightarrow D$ link is poor which likely to occur in practical scenarios when the relay is far from the destination. We further assume that $S \rightarrow D$ and $S \rightarrow R$ links are balanced, i.e. $E_{RD}/N_0 \ll E_{SD}/N_0 = E_{SR}/N_0$.

Scenario 2 (Balanced $S \rightarrow D$ and $S \rightarrow R$ links and high SNR in $R \rightarrow D$ link)

We now assume that $R \rightarrow D$ link experiences a high SNR which is likely to occur in practical scenarios when the relay is close to the destination terminal. We further assume that $S \rightarrow D$ and $S \rightarrow R$ links are balanced, i.e. $E_{RD}/N_0 \gg E_{SD}/N_0 = E_{SR}/N_0$.

Scenario 3 (Non-fading $R \rightarrow D$ link)

Now, we focus on the case where the channel between the relay and the destination terminals is AWGN, i.e., $h_{RD} = 1$. Physically, this assumption corresponds to a case where the destination and relay terminals are static and have a very strong LOS connection. Further assuming that $S \rightarrow D$ and $S \rightarrow R$ links are balanced and high SNR in the $R \rightarrow D$ link.

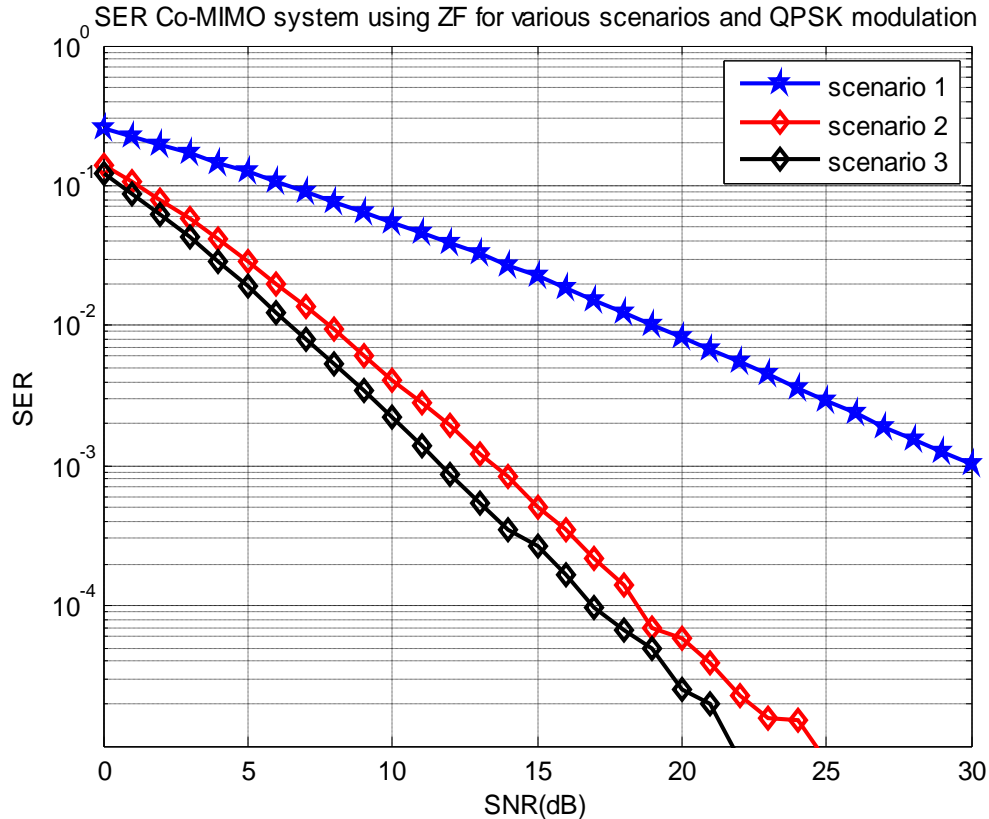


Figure 5.9.: SER performance of cooperative AF VBLAST system for various scenarios

From Figure 5.9, we can see that at $SER = 10^{-3}$, scenario 3 has 17 dB and 3 dB SNR gain over Scenario 1 and Scenario 2 respectively. Scenario 3 outperforms both Scenario 1 and Scenario 2, because of the non fading $R \rightarrow D$ link. And scenario 1 is the worst scenario because the SNR in the $S \rightarrow R$ link is poor.

5.4.3. Throughput Performance of Cooperative MIMO System

For the cooperative AF relay transmission using VBLAST the throughput (spectral efficiency) is calculated as [42]:

$$Throughput = \frac{N_t \log_2(M)}{2} (1 - BER)^{N_x}$$

where M is modulation order, N_t is number of transmit antennas and $N_x = 512$ is the packet size.

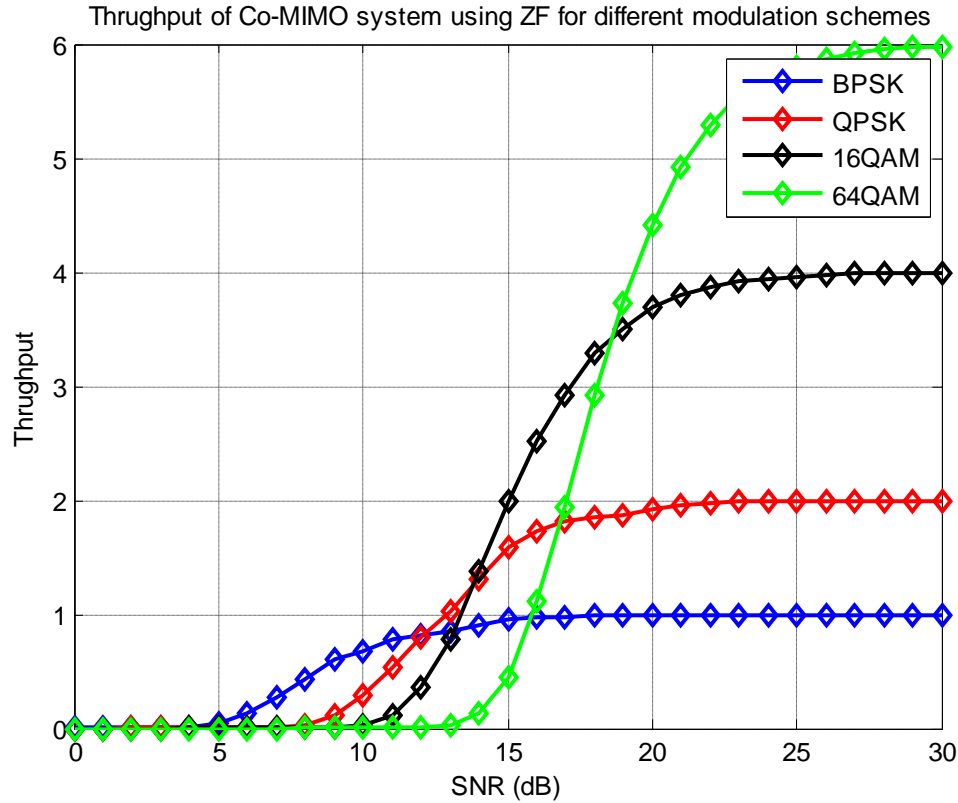


Figure 5.10.: Throughput of Cooperative MIMO system using ZF for different modulation techniques

Fig. 5.10 presents the normalized throughput of cooperative MIMO system with AF relay for different modulation schemes. At low SNR regime, a smaller constellations like BPSK and QPSK results in a better throughput because of fewer bit errors. And at high SNR regime, 64 QAM and 16 QAM achieve higher throughput.

Fig. 5.11 presents the normalized throughput result for the cooperative VBLAST AF relay transmission using ZF for QPSK modulation. Also the 2×2 VBLAST using the same detection scheme is shown for comparison purposes. We can see that in the mid-SNR regime i.e. from 7 dB to 19 dB the cooperative VBLAST using ZF exhibits a better performance when compared to 2×2 VBLAST system for the same detection.

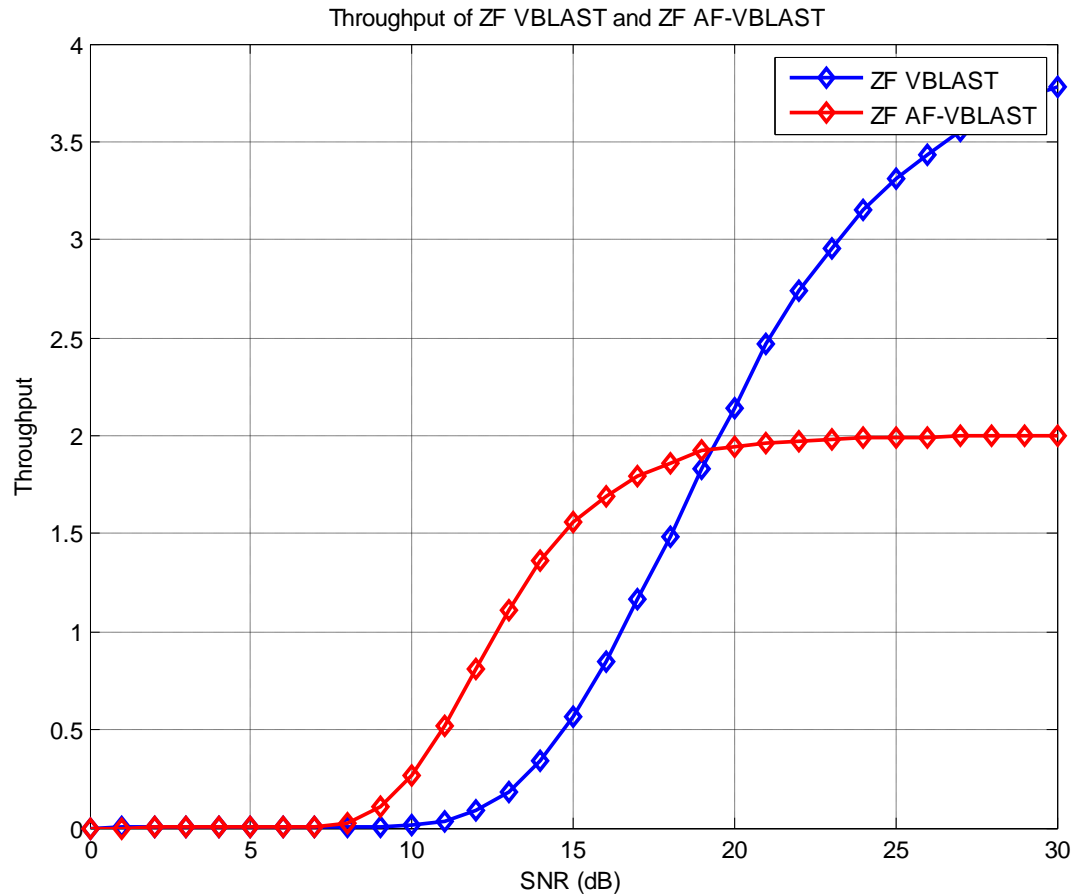


Figure 5.11.: Throughput performance of cooperative AF VBLAST and MIMO using ZF for QPSK modulation

Fig 5.12 shows the normalized throughput curve of MMSE detection using a cooperative AF VBLAST scheme, along with a 2×2 VBLAST MMSE detection for comparison. These results indicate a better performance in the mid-SNR regime i.e., from 7 dB to 18 dB, by the cooperative MIMO system when compared to the respective 2×2 VBLAST.

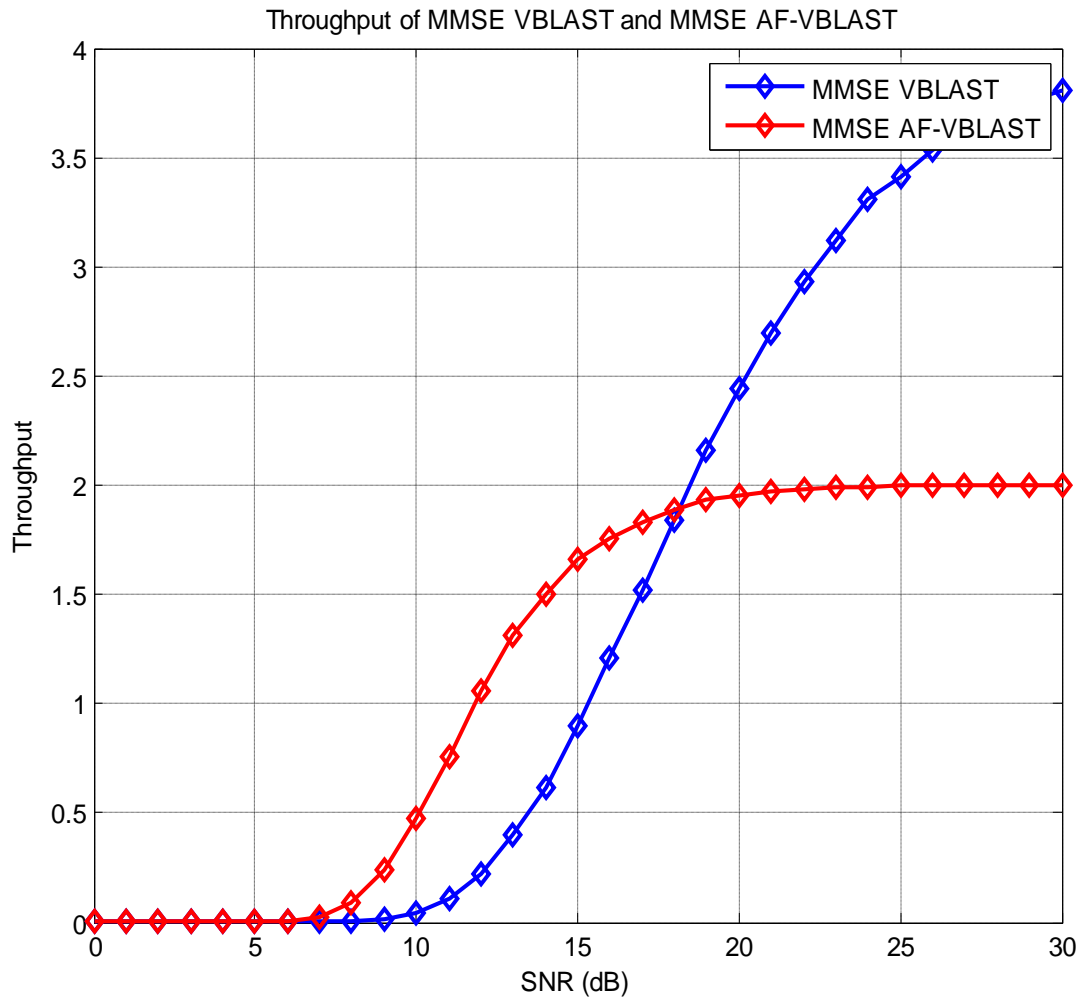


Figure 5.12.: Throughput performance of cooperative AF VBLAST and MIMO using MMSE for QPSK modulation

From Figure 5.11 and 5.12, for a MIMO system, we can observe that the throughput obtained using the MMSE criterion has a performance gain of 1 dB SNR when compared to the ZF counterpart.

5.5. Complexity Comparison

So far we have considered comparison of MIMO detection schemes based on BER performance, as a result of which the ML is found to be optimal in any case. However, MIMO detection schemes can also be compared in terms their computational complexities. Based on the complexity figures of the previous sections, it is possible to compare the complexity of the described algorithms. The complexity figures are shown in Tables 4.1 and 4.2 for MRC and EGC respectively.

5.5.1. Complexity of MIMO

Figure 5.13 presents a comparison of ZF, ZF-OSIC, MMSE, MMSE-OSIC and ML algorithms for BPSK modulation in terms of Computational complexity. From the figure it can be seen that the complexity of ZF and MMSE is similar, as well as that of ZF-OSIC and MMSE-OSIC. It can be noted that the complexity of ML is reasonable for BPSK and a small number of antennas. While performance wise ML out performs the other schemes.

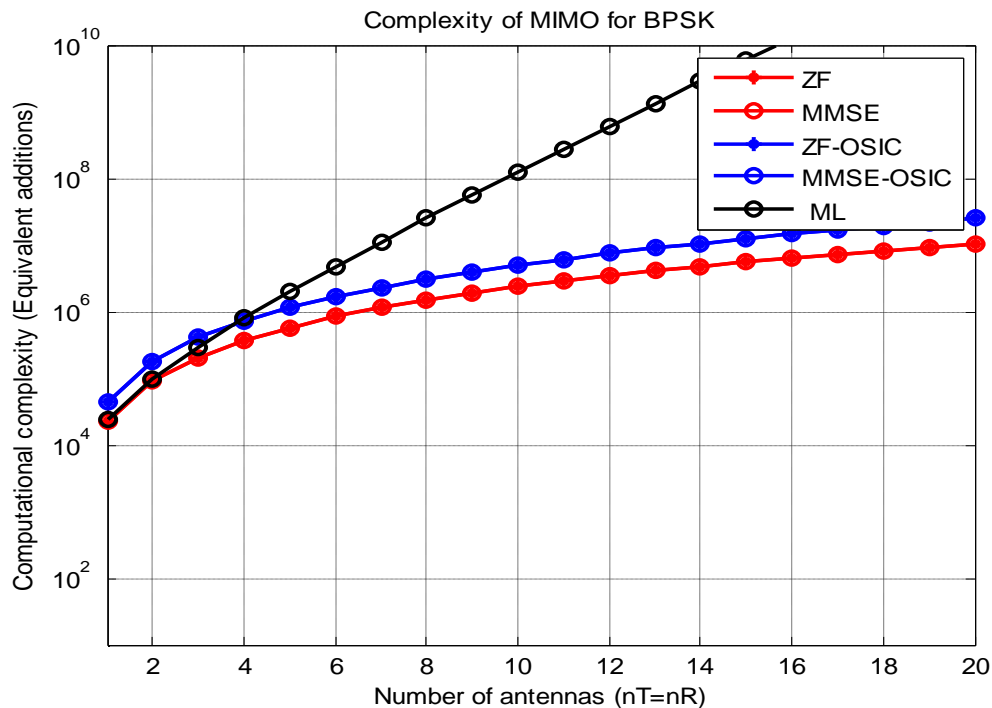


Figure 5.13.: Computational complexity MIMO system for BPSK modulation

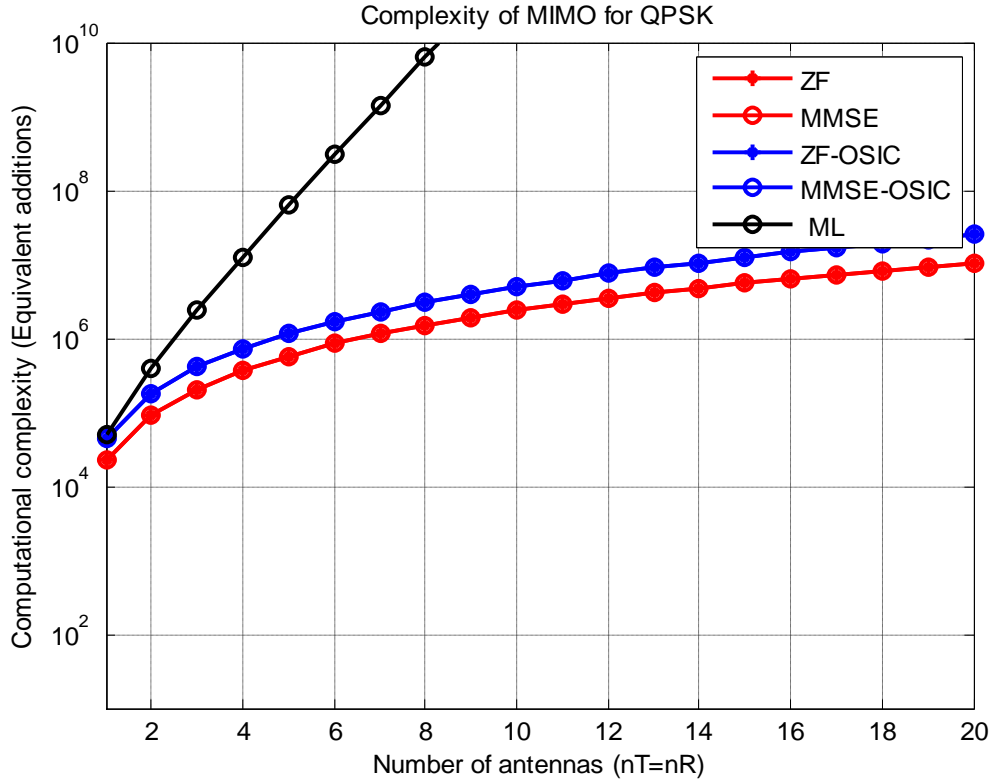


Figure 5.14.: Computational complexity of MIMO system for QPSK modulation

For higher constellation sizes, however, the complexity of ML quickly diverges from the complexity of the other techniques (see Figure 5.14). We can see from Figure 5.13 that the complexity of the other schemes is almost the same for BPSK and QPSK modulation.

Given the fact that the ZF and MMSE detectors simplify the calculation, if the calculation complexity is more important than the calculation accuracy in a system, we choose to use ZF or MMSE detector; otherwise we choose ML detector.

5.5.2. Complexity of Cooperative MIMO System

Figure 5.15 and Figure 5.16 present complexity of cooperative MIMO system for different SM algorithms for BPSK and QPSK modulation respectively.

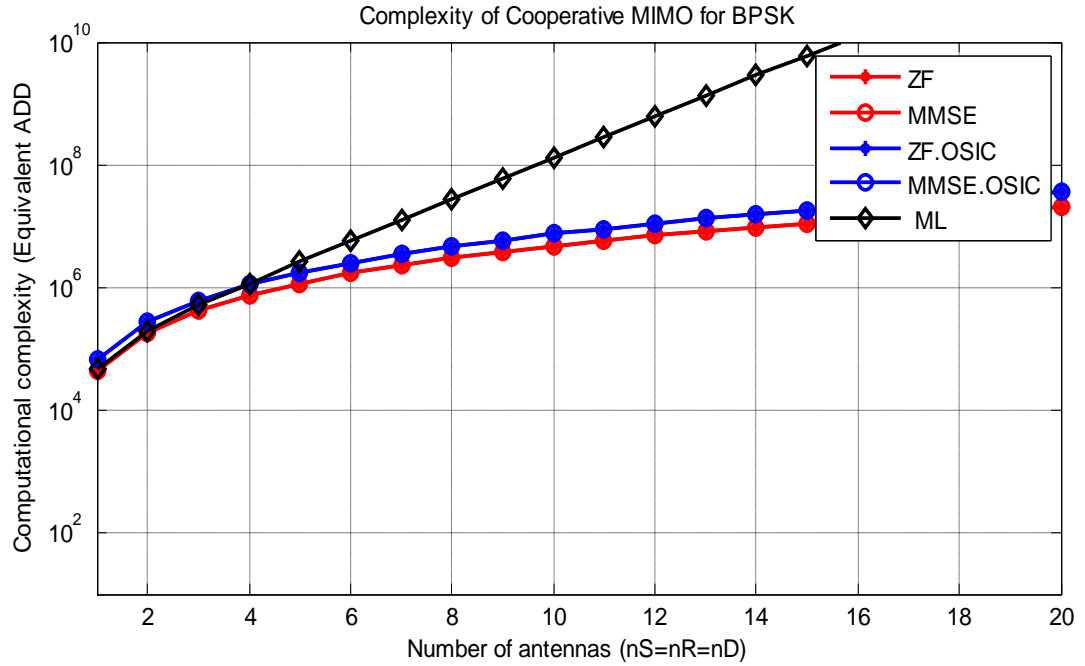


Figure 5.15.: Computational complexity of cooperative MIMO system for BPSK modulation

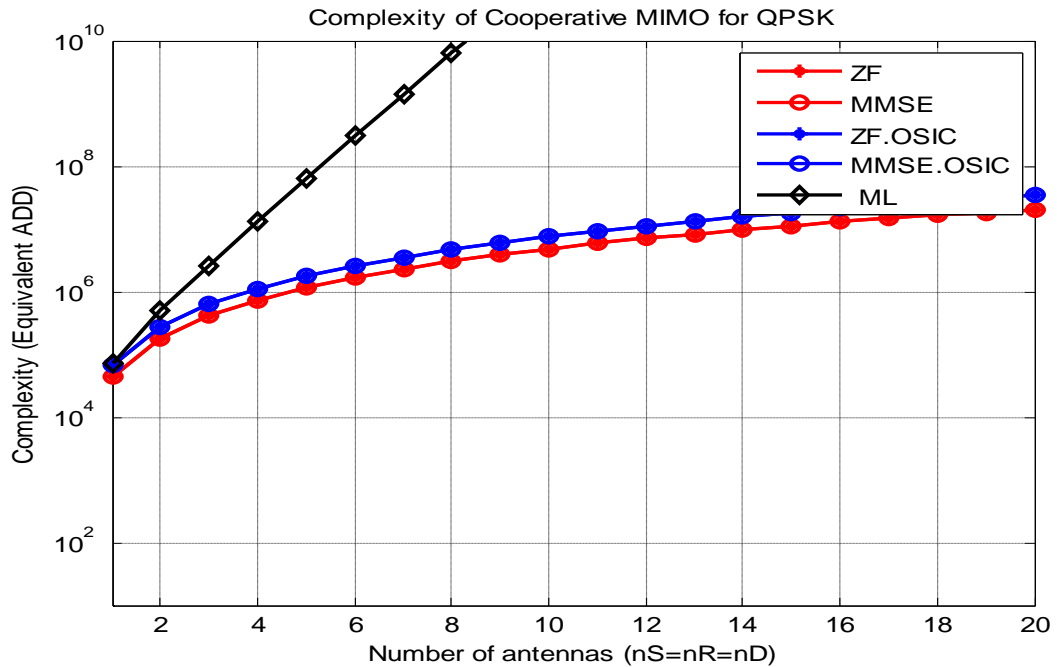


Figure 5.16.: Computational complexity of cooperative MIMO system for QPSK modulation

5.5.3. Complexity Comparison of Cooperative MIMO and Conventional MIMO System

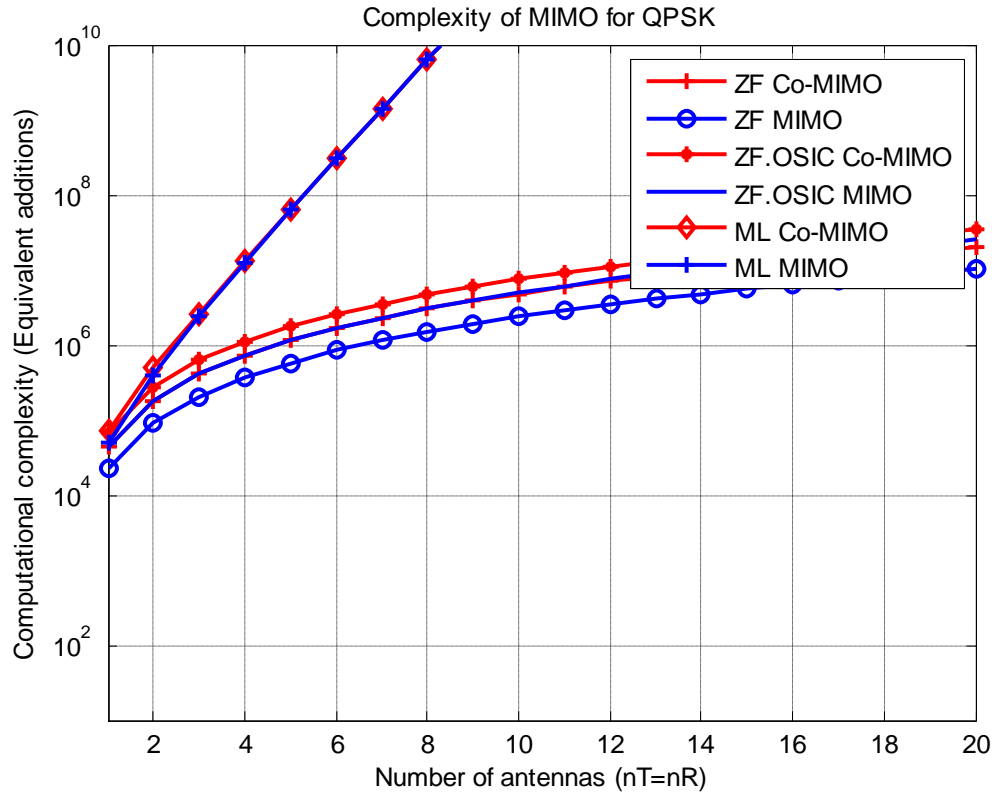


Figure 5.17.: Computational complexity comparison of cooperative MIMO and MIMO system for QPSK modulation

Figure 5.17 presents a comparison of MIMO and cooperative MIMO systems for different SM algorithms for QPSK modulation in terms of Computational complexity. From the figure we can see that complexity of cooperative MIMO is higher than MIMO system for ZF and ZF-OSIC and it is obvious because the expected performance improvement by cooperative MIMO system will be paid by complexity increase. However, the computational complexity of ML is almost the same for both cooperative MIMO and MIMO systems especially when the number of antennas increased.

Chapter 6

Conclusion

6.1. Summary of Results and Conclusions

In Chapter 2 we initially describe the MIMO system and performance of various antenna array architectures in terms of capacity for quasi-static flat fading environments. Additionally, we introduce the practical space-time codes such as the Alamouti scheme and VBLAST architecture and its detection techniques.

In chapter 3, we describe a single antenna three terminal cooperative diversity using different relaying and combining techniques.

In Chapter 4 we describe the simple three terminal relay network employing multiple antennas at all nodes of a wireless network.

Simulation results of a three terminal multiantenna relay network using spatial multiplexing architecture, VBLAST, are described with the following conclusions:

Conventional MIMO detection schemes such as ZF, MMSE and ML are extensively studied for both MIMO and cooperative MIMO systems in this work. As it shown in Figures 5.3 and 5.5, ML is obtained to have optimal performance while ZF and MMSE are suboptimal in performance when compared to ML.

Cooperative MIMO systems achieve significantly better performance in symbol error rate (SER) than conventional cooperative diversity and MIMO systems. For instance; Comparing Figure 5.3 and Figure 5.5 for BER of 10^{-3} , cooperative MIMO system have 13 dB, 11 dB and 5 dB SNR gain over MIMO system for ZF, MMSE and ML detection schemes respectively.

Also, we conclude that cooperative MIMO system has high throughput in low SNR regime when compared to the conventional point-to-point system. However, the rate of conventional VBLAST is twice that of cooperative MIMO systems. Finally it is worth mentioning that performance of ZF and MMSE almost coincide in cooperative MIMO system with AF relaying.

Computational complexity of cooperative MIMO system using AF at the relay for MRC and EGC combining schemes with various detection schemes at the destination is also evaluated. Accordingly, the computational complexity of both cooperative MIMO and MIMO systems is almost the same especially when the number of antennas increased.

6.2. Future work

This section describes the possible extensions of research presented in this thesis.

1. We assume that the channel is Rayleigh flat fading. This analysis can be extended assuming the channel is frequency selective using OFDMA system.
2. In this thesis, we use only AF relaying technique and MRC combining technique. This work can be extended by analyzing the end-to-end diversity achieved by different relaying and combining schemes.
3. Another way to enhance this research would be to use more than one relay. Such a system should show higher levels of diversity and might have a lot of potential.
4. The performance measure used in the simulation was the SER and throughput as a function of SNR. The actual performance of the investigated schemes cannot be completely evaluated only by the error probability, but also needs to take into account other parameters such as outage probability and power consumption. A future thesis effort may analyze the behavior of the schemes as a function of these parameters.

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