ADDIS ABABA UNIVERSITY

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INSTITUTE OF TECHNOLOGY

ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

Adaptive modulation based cooperative MIMO in fading channel for future wireless technology

By

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Date of Submission: ________________

This thesis has been submitted for examination with my approval as a university advisor.

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Abstract

With the rapid growth of multimedia services, future generations of cellular communications require higher data rates and a more reliable transmission links while keeping satisfactory quality of service. The data rate and reliability of wireless communication links can be improved by employing multiple antennas at both ends, thereby creating Multiple-Input Multiple-Output (MIMO) channels. However, the use of multiple antennas in mobile terminals may not be very practical. Certainly there is limited space and other implementation issues which make this a challenging problem. Therefore, to harness the diversity gains order by MIMO transmitter diversity techniques, while maintaining a minimal number of antennas on each handset, cooperative diversity techniques have been proposed. The main drawback of cooperative diversity is the throughput loss due to the extra resources needed for relaying. Therefore, cooperative MIMO together with adaptive modulation is used to meet the demands for high data rate and transmission reliability.

This thesis presents performance analysis of a cooperative MIMO schemes with adaptive modulation for different detection techniques in Long Term Evolution network. In this scheme, each link uses MIMO Vertical Bell-Labs Layered Space Time architecture over Rayleigh flat fading channels and the cooperation strategy uses amplify and forward protocol with one relay node. For cooperative and non-cooperative MIMO, the SNR criterions to switch from one modulation order to the next for attaining maximum spectral efficiency subject (SE) at a target bit-error rate are determined. The simulation results shown that the cooperative MIMO system with adaptive modulation not only compensate for the throughput loss but also achieve considerable throughput gain compared with fixed modulation at comparable complexity. The switching criterion of optimal schemes for adaptive modulation of cooperative hybrid network with minimum mean square error (MMSE) detection, as it has a lower complexity compared to maximum likelihood (ML) detection, is also investigated. As an example, in the downlink scenario adaptive modulation based cooperative and non-cooperative MIMO network have shown optimal SE performance for $SNR \leq 36dB$ and for $SNR > 36dB$ respectively, while satisfying target BER constraint, $BER_{th} \leq 10^{-2}$.

Key words: Adaptive Modulation, Cooperative Diversity, MIMO, LTE, SNR, Spectral Efficiency

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Acronyms and abbreviations

3GPP LTE	3rd Generation Partnership Project Long Term Evolution
ABER	Average Bit Error Rate
AF	Amplify and Forward
AS	Antenna Selection
ASE	Average Spectral Efficiency
BC	Broadcast Channel
BER	Bit Error Rate
BLAST	Bell Labs Layered Space Time
CF	Compress and Forward
CP	Constant Power
CRC	Cyclic Redundancy Check
CSI	Channel State Information
DF	Decode and Forward
EGC	Equal Gain Combiner
ESNRC	Estimated Signal to Noise Ratio Combining
FDD	Frequency Division Duplexing
FRC	Fixed Ratio Combining
I-BER	Instantaneous Bit Error Rate
OFDM	Orthogonal Frequency Division Multiplex
OSIC	Ordered Successive interference cancellation

QoS	Quality of Service
QAM	Quadrature modulation
PERs	Packet Error Rates
LA	Link Adaptation
MAC	Multiple Access Channel
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single –Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MRC	Maximum ratio combining
NMT	Nordic Mobile Telephony
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDAs	Sphere Decoding Algorithms
SE	Spectral Efficiency
SIC	Successive Interference Cancellation
SIMO	Single Input Multiple Output
SINR	Signal to Noise plus Interference Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SNRC	Signal to Noise Ratio Combining
STC	Space Time Code

STBC	Space Time Block Code
TDD	Time Division Duplexing
UMTS	Universal Mobile Telecommunications System
VBLAST	Vertical Bell-Labs Layered Space Time architecture
VP-AM	Variable Power Adaptive Modulation
WLAN	Wireless Local Area Network
ZF	Zero Forcing

Nomenclature

B_C	Channel Bandwidth
N_t	Transmit Antenna
N_r	Receive Antenna
y_{N_r}	Received Vector
x_{N_t}	Transmitted Vector
n	Additive white Gaussian
σ^2	Variance
C_{MIMO}	Capacity of the MIMO system
E_S	Total transmitted power
N_0	Noise power
λ_i	Eigen Value
$C_{MIMO-WF}$	Capacity of the MIMO system when water-filling algorithm is used
BER_{th}	Target BER
P_b	Error Probabilities
β	Path loss exponent
α_{nl}	Gain factor
l	l^{th} Symbol period
L	Number of symbol periods for one channel block
n	n^{th} Fading block

N	Number of fading channel blocks
h_{rdnl}	Channel coefficient from the relay to the destination for the l^{th} symbol period
h_{srnl}	Channel coefficient from the source to the relay for the l^{th} symbol period
h_{sdnl}	Channel coefficient from the source to the destination for the l^{th} symbol period
R_{SUMS}	Real Summation
R_{MULS}	Real Multiplications
M	Number of points in a modulation constellation
ξ	Threshold of the BER upper bound

Chapter 1

Introduction

From the first generation analog Nordic mobile telephony (NMT) system in the early 1980's to the current wireless broadband systems like 3GPP-long term evolution (LTE) and LTE-advanced, the peak data rates for wireless communication have increased many orders of magnitude. Significant advances have been made in many aspects during this evolution in the last three decades. Some of these advances are in terms of channel access methods, modulation methods and efficient signal processing algorithms. The main contributions to this evolution involve the usage of multi-carrier modulation techniques and the invention of multi-antenna systems [20].

Reliable and efficient communication over wireless networks has been the focus of research in the telecommunications field for a long time. Often, reliability over wireless networks is affected by fading, which causes the signal strength to vary at the receiver and these results in a loss of data packets. Even though fading is not good for reliable communication, the idea of independent fading channels lead to the concept of diversity. Diversity is an approach used in wireless systems to combat the effects of fading and thereby to provide reliable data transfer [1], [2].

Multiple-input multiple-output (MIMO) can also overcome the signal fading in wireless channels, and therefore holds the potential to drastically improve the capacity and reliability of wireless communication system. MIMO wireless systems exploit the spatial dimension in rich scattering environment by using multiple transmit and receive antennas. Multiple streams of data are transmitted in the same time and frequency channel. The result is an extraordinary bandwidth-efficient approach to wireless communication especially in rich multi-path environment [3]. Due to the increasing capacity obtained, MIMO has already started to find applications in commercial wireless products and networks such as broadband wireless access systems, wireless local area network (WLAN), and third-generation (3G) cellular networks and beyond. Although the advantages of MIMO systems have been widely acknowledged, this option requires co-located antenna elements with sufficient antenna spacing. Due to the size or Hardware limitations of terminals, it may be impractical to apply multiple antenna techniques in the uplink of wireless communication systems.

To solve this problem, cooperative communication is proposed. Cooperative communication can generate spatial diversity by using a collection of distributed antennas belonging to multiple users. The basic idea of cooperative communication is that one user may receive other users' signals due to the broadcasting nature of wireless communications, in which case it can forward some version of the "overheard" signal along with its own information, which emulates a virtual Multiple- Input-Multiple-Output (MIMO) system. But cooperative communication has a disadvantage that the transmission rate is decreased for relaying in cooperation phase. So a hybrid MIMO cooperative communication system is proposed to compensate the disadvantage.

As stated above, wireless multimedia services require good link reliability and high spectral efficiency through the communication systems. Adaptive modulation is a promising technique to increase the data rate that can be reliably transmitted over fading channels. Adaptive modulation denotes the matching of modulation/protocol parameters to the conditions on radio link in wireless communication especially over fading channels. An adaptive scheme increases the energy and spectral efficiency when implemented with proper codes [4], [5]. It also improves rate of transmission and Bit Error Rate (BER). In [6], the adaptive coded modulation facilitating bandwidth efficient multimedia communication in wireless system was observed, according to which maximum spectral efficiency is utilized in coding schemes which adapt the information rates according to the quality of wireless rates. Adaptive modulation and cooperative MIMO combining schemes can be jointly used for finding low hardware complexity, bandwidth-efficient, and processing-power efficient transmission schemes for future wireless networks. The modulation constellation size, the number of combined MIMO, and the needed power level are jointly determined to achieve the highest spectral efficiency with the lowest possible processing power consumption quantified in terms of the average number of combined paths, given the fading channel conditions and the required bit error rate (BER) performance. This research analyzes the performance of adaptive modulation based cooperative MIMO systems in LTE technology under fading channel.

1.1. Problem Statement

The major challenges in wireless communication are include spectral efficiency, link reliability, coverage and energy efficiency. This is due to the limited available bandwidth, the fading nature of the propagation channel and the mobility and autonomy of the wireless nodes. The rapid growth in demand for high speed and high quality multimedia services with diverse QoS requirements is also creating the opportunities and challenges for the system designers. Providing diverse QoS guarantees to the mobile users and various applications is an important objective of next generation wireless networks. However the wireless channel is affected by time-dispersive effects, Doppler and multipath fading, as a result the spectral efficiency of the wireless system is degraded.

In order to increase the data rates offered, a simple approach is to increase the allocated bandwidth. This approach is difficult, since the radio-frequency spectrum is scarce resource. Therefore, research over the last years has been focused towards improving spectral efficiency, so that higher data rates can be achieved within a given bandwidth. To improve the spectral efficiency, the conventional scheme and the new MIMO cooperative scheme are used adaptively according to channel condition between source and destination.

1.2. Objectives

1.2.1. General Objective

Hence the primary objective of this thesis is to analysis the performance of cooperative MIMO communication with and without of adaptive modulation for fading channel in LTE networks based on different parameters.

1.2.3. Specific objectives

The specific objectives of this thesis are to:

- Investigate the performance of cooperative MIMO in fading channel based on BER and spectral efficiency
- Investigate the performance of adaptive modulation using BER and spectral efficiency in cooperative MIMO systems
- Comparing the result of adaptive modulation with that of fixed modulation in cooperative MIMO system for LTE technology
- Analyze the complexity versus performance improvement trade-off cooperative MIMO with and without adaptive modulation
- proposed selection of the optimal modulation and cooperative scheme based on the results

1.3. Literature Review

Based on the improvement of spectral efficiency, a lot of researches have been done which most of them are focused on adaptive modulation for MIMO or cooperative system. Here are some of researches that are conducted on adaptive cooperative and MIMO Systems.

The work in [7] offered a new joint AM and MIMO transmission algorithm for link adaptation in a MIMO-OFDMA cellular system under factual conditions (spatially correlated fading and imperfect CSI at the transmitter owing to user mobility). Modulation order and MIMO transmission mode are together chosen in order to optimize the ASE when conservation the BER under the specific target. A systematic study of AM schemes in MIMO-OSTBC systems for the improvement of the spectral efficiency were investigated in [8]. The authors demonstrated the optimal SNR thresholds for maximizing the ASE under the average bit error rate (ABER) constraint. So that, for the reduced complexity of the optimal algorithm, a suboptimal solution based on the instantaneous bit error rate (I-BER) constraint was proposed which can attain approximately the same execution as the optimal method, and these methods are applied in a practical situation. The channel estimation noise which affected the overall system execution is also investigated.

In [9], the performance of adaptive modulation for OFDM system over frequency selective fast fading channel was analyzed. The performance has been investigated in terms of BER and throughput. In this work a perfect feedback channels was considered. The performance analysis of adaptive modulation for MIMO system based Imperfections CSI is investigated by [13]. The result showed that rate adaptation provides significant gains even with imperfect CSI. In this work both the transmitter and receiver have two antennas.

The work in [12] analyzed the performance of adaptive modulation with multiple inputs multiple output orthogonal space time blocks coding MIMO-OSTBC over frequency selective fading channel using Bit Error Rate (BER) and spectral efficiency (SE) as performance measures. The results showed that, as SNR increases, the spectral efficiency increases while the BER reduces for different antenna configurations. In this model constant power (CP) adaptation scheme is considered. The authors in [10] analyzed rate adaptation of MIMO systems for both perfect and imperfect CSI, with variable-power adaptive modulation (VP-AM) and antenna selection (AS) over Rayleigh fading channels. The result showed that the evaluation of the SE of the VP-AM system will provide execution best than the counterpart and the VP-AM system with STBC.

In reference [11] the authors suggested a novel hybrid cooperative AMC mechanism in which adaptation is designed for the hybrid link quality. The authors aim at evaluating the energy saving achieved through cooperation due to the improvement in average bit/symbol transmission. Furthermore, the authors studied the performance improvement as a function of cooperating user's location to identify areas where cooperation is useful. In this work, all the terminals have only one transmit and receive antenna. In [14], the performance of cooperative MIMO system based WiMAX technology was analyzed. The result showed that BER performance of cooperative MIMO system using MMSE detection better that cooperative diversity or MIMO. This paper studied for fixed modulation schemes only and also throughput loss of the system due to the relaying scheme is not considered.

Adaptive modulation techniques, where the constellation size of the transmitted signal is adapted to the changing channel conditions that can track time varying characteristics of wireless channels. Therefore, by transmitting more bits under good channel conditions and smaller bits under poor conditions, a higher spectral efficiency without sacrificing performance can be achieved. Moreover, adaptive modulation of cooperative MIMO system for LTE technology under Rayleigh fading channel has not been previously analyzed and is the major contribution of this thesis.

1.4. Thesis Contributions and Outline

The main contributions of this thesis are summarized as follows:

- A cooperative virtual-MIMO system using two transmits and receive antennas that implements VBLAST transmission and AF cooperation protocol for different detection schemes is presented. The system throughput expression and BER over Rayleigh fading channels are derived. With different detection scheme, the cooperative MIMO achieve better performance.

- The achievable spectral efficiency and BER are computed for AF 2×2 V-BLAST MIMO system, when Zero Forcing (ZF), minimum mean square error (MMSE) and Maximum Likelihood (ML) detections are used at the destination. Due to the relaying node it is shown that throughput of cooperative MIMO system is low. Accordingly, an adaptive modulation is proposed, adopting constellation size based on SNR Switching criterion strategy. The system could therefore adapt its modulation type to the prevailing channel conditions. It is shown that the proposed scheme enables the system to achieve better performance.
- The optimum switching levels for adaptive modulation of AF hybrid cooperative in LTE technology are found. The performance analysis for adaptive modulation of AF cooperative and non-cooperative MIMO with given target of BER are compared. Specifically Rayleigh fading environments are considered. To enhance the performance of cooperative communications, a hybrid cooperative schemes combining with adaptive modulation is proposed.
- The complexities analyze of cooperative MIMO with and without adaptive modulation are considered.

The remainder of this thesis is organized as follows:

Chapter 2, 3 and 4 includes the background studies of the MIMO system, cooperative diversity networks and adaptive modulation respectively are provided in detail. In chapter 5, the Performance Assessment of adaptive modulation in cooperative MIMO for LTE technology over Rayleigh fading channel is investigated. At the end of this chapter, complexity analysis of adaptive modulation cooperative MIMO for all combining and detection schemes that have been described and discussed in previous chapter is presented. Chapter 6 provides the simulation results and discussion of adaptive modulation in cooperative MIMO for system including the proposal of optimal modulation and cooperative scheme based hybrid cooperative MIMO system. Finally, in chapter 7, the conclusion and suggestions for future work were presented.

Chapter 2

Multiple Input and Multiple Output Systems

2.1. Introduction

In this chapter, a basic background for the thesis is provided. Some fundamental principles of multiple-input multiple-output (MIMO) systems are introduced. The MIMO system model will firstly be described, followed by an introduction to the benefits from using multiple antennas at the transmitter and receiver. A study of MIMO channel capacities when the channel is known or unknown to the transmitter will be illustrated. This study will also be carried out for both deterministic and random channels. The content of this chapter includes three main parts, MIMO wireless systems, MIMO system capacity, and benefits of MIMO technology. This chapter will provide the reader with a basic background of the current state of the art and will be frequently referred to in the rest of the thesis.

2.2. MIMO Wireless Systems

The performance of wireless communication systems is mainly governed by the wireless channel environment. As opposed to the typically static and predictable characteristics of a wired channel, the wireless channel is rather dynamic and unpredictable, which makes an exact analysis of the wireless communication system often difficult [22]. In recent years, optimization of the wireless communication system has become critical with the rapid growth of mobile communication services and emerging broadband mobile Internet access services. In fact, the understanding of wireless channels will lay the foundation for the development of high performance and bandwidth-efficient wireless transmission technology. The use of multiple antennas at the transmitter and receiver in wireless systems, known as the multiple-input multiple-output (MIMO) techniques (Figure 2.1), has been shown to provide significant improvements in terms of both higher channel capacity and better link reliability [45]. In this section, we will firstly introduce fading channels and then investigate the MIMO system model. This will be followed by a discussion of the benefits of MIMO technology and a study of MIMO channel capacity results.

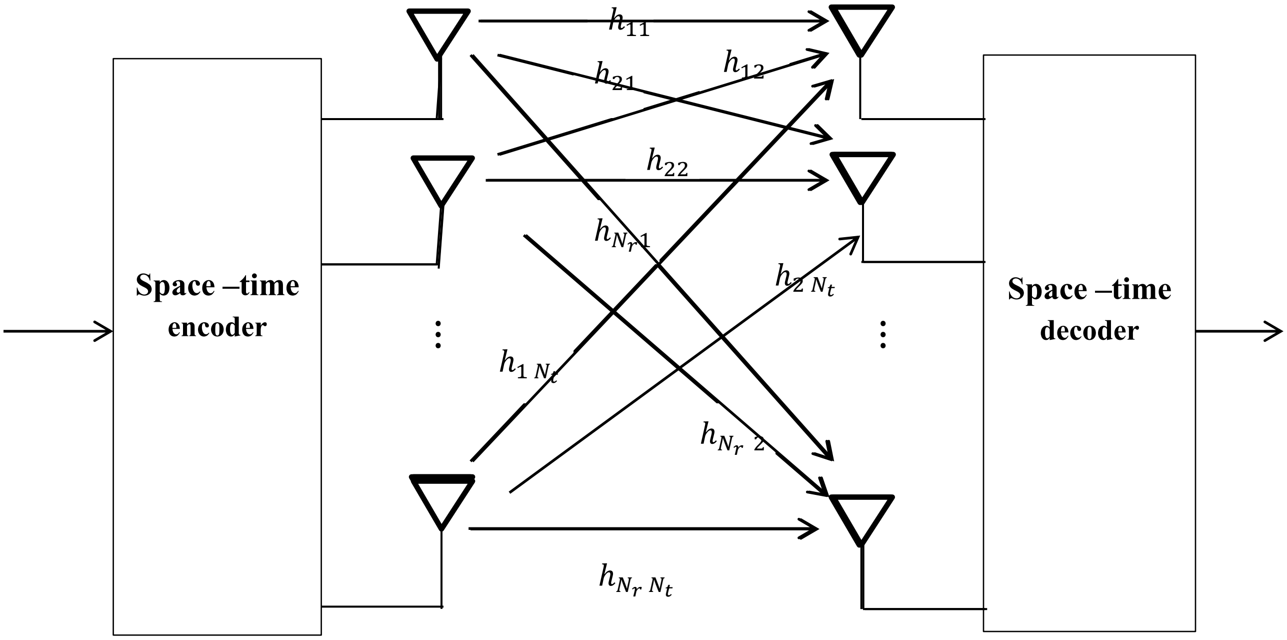


Figure 2.1: $\boldsymbol{N_r} \times \boldsymbol{N_t}$ MIMO system

2.2.1. Wireless Fading Channels

A unique characteristic in a wireless channel is a phenomenon called ‘fading,’ the variation of the signal amplitude over time and frequency. In contrast with the additive noise as the most common source of signal degradation, fading is another source of signal degradation that is characterized as a non-additive signal disturbance in the wireless channel. Fading may either be due to multipath propagation, referred to as multi-path fading, or to shadowing from obstacles that affect the propagation of a radio wave, referred to as shadow fading, form a large-scale fading. In addition, the signal amplitudes and phases also suffer from small-scale fading which is caused by the constructive and destructive interference of the multiple signal paths between the transmitter and receiver. Large-scale fading is more relevant to issues such as cell-site planning. Small-scale fading is more related to reliable and efficient communication systems design [15]. Thus, in this thesis, channel with effect of small-scale fading is considered.

Small-scale fading is normally frequency dependent. An important characteristic for small scale fading is coherence bandwidth of the channel B_C. If B_C is larger than the bandwidth of the transmitted signal, the channel fading is referred to as flat fading channel. All frequency components of the signal experience the same magnitude of fading. On the other hand, if B_C is smaller than the bandwidth of the signal, the signal is said to undergo frequency-selective fading. Different frequency components of the signal therefore experience uncorrelated fading. For this work, flat fading channels is used.

2.2.2. MIMO System Model

Consider a point to point MIMO system with N_t transmit antennas and N_r receive antennas. The channel state information (CSI) is perfectly known at the receiver. The channel H is assumed to be flat Rayleigh fading, where the channel matrix entries are constant during each block, but independently Rayleigh distributed on different blocks.. The discrete-time baseband equivalent model can be written as:

$$\begin{bmatrix} \boldsymbol{y_1} \\ \boldsymbol{y_2} \\ \vdots \\ \boldsymbol{y_{N_r}} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \dots & h_{N_rN_t} \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{N_r} \end{bmatrix} \tag{2.1}$$

Where $y_{N_r}$is the received vector and x_{N_t} is the transmitted vector, n is additive white Gaussian noise with covariance $\sigma^2 I$ and the component h_{ji} is the fading coefficient from the i^{th} transmit antenna to the j^{th} receive antenna.

The CSI at transmitter can be obtained by communicate a training information to the transmitter from the receiver via a feedback channel. When CSI is known at transmitter, an optimal energy allocation algorithm will be used to assign various levels of transmitted power to the transmitting antennas. However, it should be noted that the feedback requirements are not only affected by the channel fading states, but also grow with the number of transmit and receive antennas . Because of the limitation on the feedback channel, it is not always possible to obtain CSI at the transmitter in realistic wireless systems [1].

2.2.3 MIMO System Capacity

The system capacity is defined as the maximum possible transmission rate for which arbitrarily small error probability can be achieved [16]. In other words, capacity is the maximum attainable mutual information between the channels input-output. In this section, at first, we derive the most general formula to calculate the channel capacity for both cases where channel coefficients are known as well as unknown at the transmitter. Based on this general formula, we will then derive the formulas for channel capacity in some particular cases. The most general formula for calculating channel capacity in the case where channel coefficients are either known or unknown at the transmitter is:

$$C_{MIMO} = \max_{try(Q_s) \leq E_s} . \log_2 \left[det \left(I_{N_r} + H \frac{Q_s}{N_o} H^{\dagger} \right) \right] \qquad \frac{bits}{s} / Hz \tag{2.2}$$

Where $H^{\dagger}$ denotes the conjugate transpose of H. Here, $try(Q_s) \leq E_s$ holds to provide a global power constraint.

2.2.3.1 Channel Unknown to the Transmitter

When the channel is not known at the transmitter but known at the receiver side, the transmitting signal x is chosen to be statistically non-preferential, which implies that the N_t components of the transmitted signal are independent and equip-powered at the transmit antennas. If the channel knowledge is unknown at the transmitter, we assume that the signals transmitted from each antenna have equal powers of E_s/N_t, where E_s is the total transmitted power. From the general formula of the deterministic channels in Equation 2.2 we will compare SISO, MISO, SIMO, and MIMO capacities in table 2.1 [30].

Table 2.1: MIMO System Capacity

Multi antenna type	Channel capacity (C) in	Description
SISO: means that the transmitter and receiver of the radio system have only one antenna.	$\log_2\left[\mathbf{1}+\frac{\boldsymbol{E_s}}{\boldsymbol{N_o}}\lvert\boldsymbol{h}\rvert^{\mathbf{2}}\right]$	Similar to the Shannon capacity formula approximated theoretically the maximum achievable transmission rate for a given channel
SIMO: means that the receiver has multiple antennas while the transmitter has one antenna	$\log_2\left[1+\frac{E_s}{N_o}\sum_{i=1}^{N_r}\lvert h_i\rvert^2\right]$	The capacity N_r of SIMO increasing the value of only results in a logarithmic increase in average Capacity than of SISO.
MISO: means that the transmitter has multiple antennas while the receiver has one antenna	$\log_2\left[1+\frac{E_s}{N_o N_t}\sum_{i=1}^{N_t}\lvert h_i\rvert^2\right]$	Compared to the SIMO case where the channel energy can be combined coherently. Again, note that the capacity increases logarithmic with N_t.
MIMO: means that the both the transmitter and receiver have multiple antennas	$\sum_{i=1}^{\min(N_t,N_r)}\log_2\left(1+\frac{E_s}{N_t N_O}\lambda_i\right)$ Where λ_i is eigenvalue of $HH^\dagger$	capacity of the MIMO channel as a sum of the capacities of $\min(N_t, N_r)$ equivalent parallel SISO channels

2.2.3.2 Channel known to the Transmitter

Consider a MIMO channel where the channel parameters are known at the transmitter. The channel capacity can be increased if channel coefficients are known at the transmitter. In this case, the transmitted power is assigned unequally to the transmitter an antenna, according to the "water-filling" rule, i.e., a larger power is assigned to a better sub-channel and vice versa. This is an optimal energy allocation algorithm [17].the capacity of MIMO channel is:

$$C_{MIMO-WF} = \sum_{i=1}^{\min(N_t,N_r)} \log_2\left(1+\frac{E_i}{N_o}\lambda_i\right) \tag{2.3}$$

Where $E_i\ is$ power that allocated for transmitter antenna i^{th} and λ_i is eigenvalue of $HH^{\dagger}$. For this work, the CSI at transmitter is unknown.

2.2.4. Benefits of MIMO Technology

The performance improvements resulting from the use of MIMO systems are due to spatial diversity gain, and spatial multiplexing gain. We briefly review each of these benefits of MIMO in the following, considering a system with N_t transmit antennas and N_r receive antennas.

2.2.4.1 Spatial diversity

Diversity techniques help to mitigate the effects of fading by providing multiple copies of the same signal to the receiver via different branches or paths (in frequency, time or even space) so that the probability that all paths will undergo the same amount of fading, or even deep-fades, is reduced to a great extent [18]. Thus the receiver can be provided good versions of the signal through one or more paths.

In wireless communications systems, there are three types of diversity: time diversity, frequency diversity, and spatial diversity. In time diversity, data is transmitted over multiple time slots. In frequency diversity, the same data is transmitted multiple spectral bands to achieve diversity gain. Time diversity and frequency diversity techniques require additional time resource and frequency resource, respectively. However, antenna or space diversity techniques do not require any additional time or frequency resource. Depending on the diversity side we have two types of diversity, transmitter and receiver diversity.

Receiver diversity: The simplest method to achieve spatial diversity is to use multiple antennas at the receiver. The scheme is based on the assumption that the receiver has perfect channel knowledge. Maximum ratio combining (MRC) is a frequently used scheme in receivers to obtain receives diversity gain.

Fig. 2.2 shows that receive diversity with two antennas at the receiver side. At a given time, a x_1 signal is sent from the transmitter. The channel between the transmit antenna and the receive antenna one is denoted by h_1 and between the transmit antenna and the receive antenna two is denoted by h_2 . Assuming that the channels have flat fading, received signals with additive noise are expressed by

$$\begin{aligned} y_{1=}h_1x_1 + n_1 \\ y_{2=}h_2x_1 + n_2 \end{aligned} \tag{2.4}$$

The MRC uses the CSI and the received signals y_1 and y_2 to compute the estimated value of x_1. The MRC obtains an estimate of x_1 using the relation [19]

$$\widetilde{x_1} = h^*{}_1 y_1 + h^*{}_2 y_2 \tag{2.5}$$

Where the asterisk $(*)$ indicate complex conjugation. Then the maximum likelihood decision or other rule at the receiver is used for these received signals in order to obtain the transmitted signal.

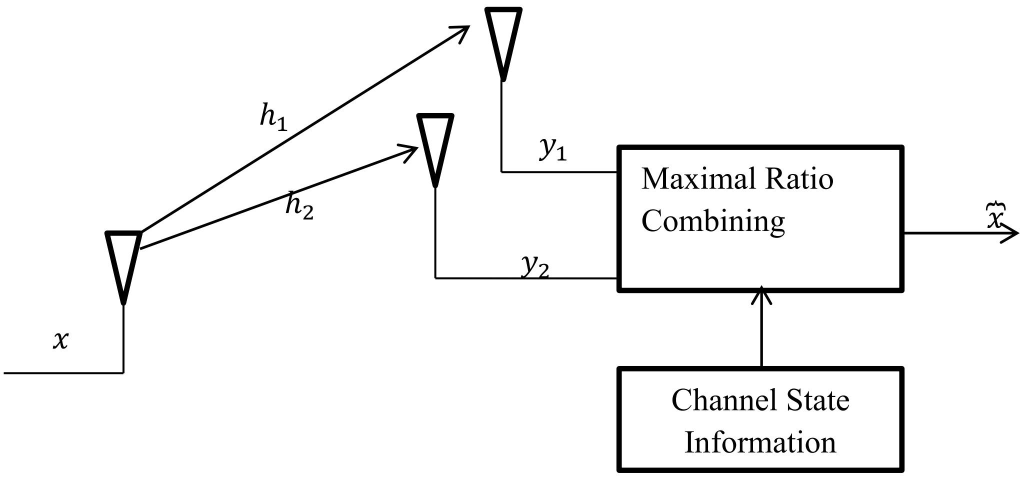


Figure 2.2: Maximal Ratios Combining for a 1×2 Systems

Transmitter diversity: is type of spatial diversity which uses multiple antennas at the transmitter to obtain diversity at the transmitter. It requires complete channel state information at the transmitter. But by using advent type of space time coding such as alamouti space time coding, the diversity can takes place without need of channel state information at the transmitter. Alamouti scheme is one of the first space coding schemes developed for the MIMO systems.

Alamouti Scheme for 2×1 Systems: Fig. 2.3 shows the alamouti scheme for a system with two transmit antennas and a single receive antenna. Two consecutive symbols x_1 and x_2 are transmitted simultaneously during the first symbol period (at time = t). During the next symbol period (at time = t + T), $-x^*{}_2$ and $x^*{}_1$ are transmitted from antenna 1 and 2, respectively, where the asterisk $*$ is the complex conjugate operation. The transmission sequence is shown in Table 2.2.

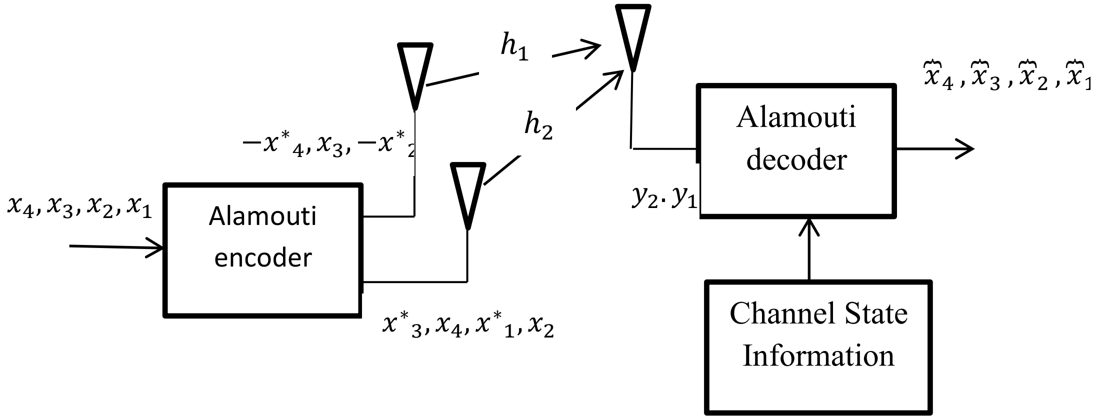


Figure 2.3: Alamouti Scheme for a 2×1 System

The received signal at time t, which is the superposition of the two incoming signals, can be expressed by

$$y_{1=}h_1x_1 + h_2x_2 + n_1 \tag{2.6}$$

Assuming that the channel is constant across two consecutive symbol periods, we can express the received signal at time t+T as

$$y_{2=}h_2x^*{}_1 - h_1x^*{}_2 + n_2 \tag{2.7}$$

Where n_1 *and* n_2 is the additive complex noise component.

Two consecutive received signals and the CSI are employed at the Alamouti decoder. The estimates of the transmitted symbols are computed by

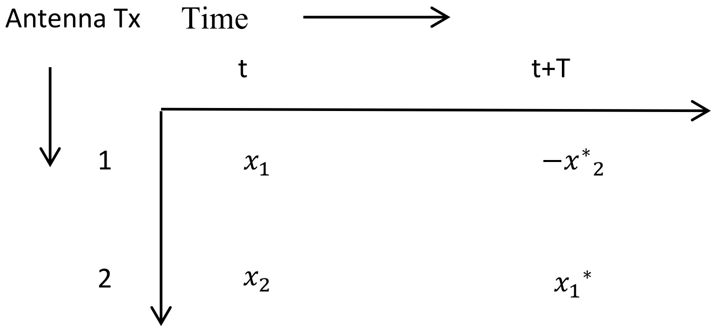
$$\begin{aligned} \widetilde{x_1} &= h^*{}_1 y_1 + h_2 y^*{}_2 \\ \widetilde{x_2} &= h^*{}_2 y_1 - h_1 y^*{}_2 \end{aligned} \tag{2.8}$$

Substituting Equations (2.6) and (2.7) into Equation (5.7), we can rewrite the decoder equations as

$$\begin{aligned} \widetilde{x_1} &= (|h_1|^2 + |h_2|^2) x_1 + h^*{}_1 n_1 + h_2 n^*{}_2 \\ \widetilde{x_2} &= (|h_1|^2 + |h_2|^2) x_2 + h^*{}_2 n_1 - h_1 n^*{}_2 \end{aligned} \tag{2.9}$$

The resulting combined signals in Equation (2.9) are equivalent to that obtained from two-branch MRC. The only difference is phase rotations on the noise components which do not degrade the effective SNR. Therefore, the resulting diversity order from the new two-branch transmit diversity scheme with one receiver is equal to that of two-branch MRC.

Table 2.2 : Transmission Sequence of the 2×1 Alamouti Scheme



Antenna Tx	t	t+T
1	x_1	$-x^*{}_2$
2	x_2	$x_1{}^*$

Alamouti Scheme for 2×2 Systems: We can extend the 2×1 Alamouti scheme to a 2×2 system by adding one more receiving antenna. Fig. 2.4 shows a schematic of the Alamouti scheme for a 2×2 system scheme with two transmit and two receive antennas. The transmission sequence is identical to the one in the 2×1 system, but the decoding scheme will be different. Table 2.3 defines the notation for the received signal at the two receive antennas.

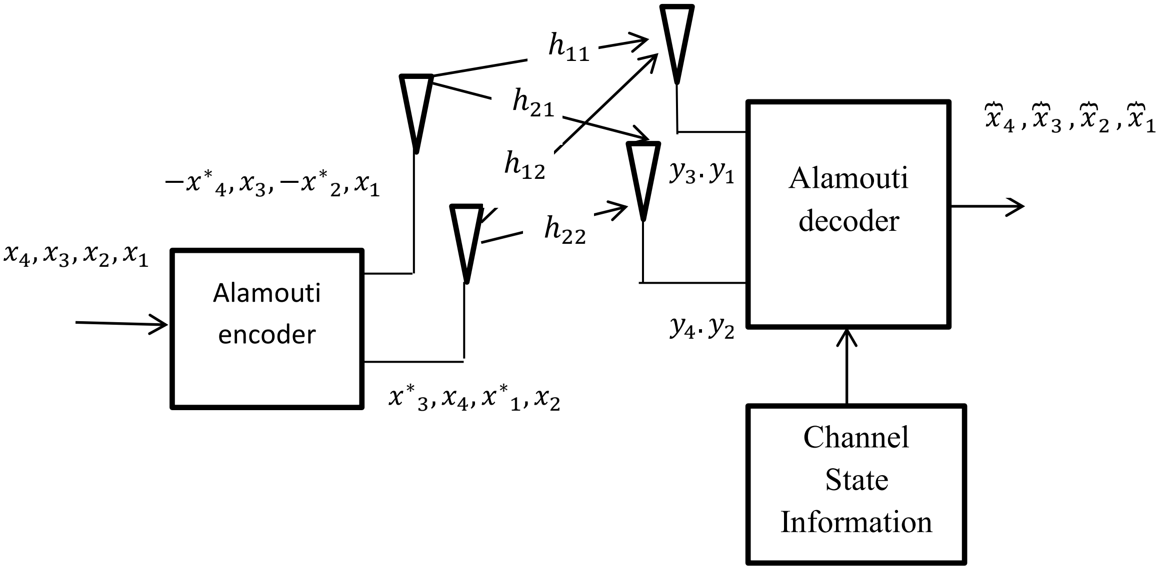


Figure 2. 4: Alamouti Scheme for a 2×2 system

Assuming that the channel is constant across consecutive symbol periods, the received signals can be expressed by

$$\begin{aligned} y_1 &= h_{11}x_1 + h_{12}x_2 + n_1 \\ y_2 &= h_{21}x_1 + h_{22}x_2 + n_2 \\ y_3 &= -h_{11}x^*_2 + h_{12}x^*_1 + n_3 \\ y_4 &= -h_{21}x^*_2 + h_{22}x^*_1 + n_4 \end{aligned} \tag{2.10}$$

Where n_i, $i = 1,2,3,4$ are the complex noise components and the channel impulse responses h_{ji}, i, j =1,2 , represent the four possible paths in the scheme.

Table 2. 3: Received Signals in 2×2 alamouti Scheme

Antenna Rx ↓	Time → t	t+T →
1	y_1	y_3
2	y_2	y_4

The alamouti decoder constructs the estimates of x_1 and x_2 using the CSI, the received signals and the decoding equations given by

$$\begin{aligned} \overbrace{x_1} &= h^*{}_{11}y_1 + h^*{}_{21}y_2 + h_{12}y^*{}_3 + h_{22}y^*{}_4 \\ \overbrace{x_2} &= h^*{}_{12}y_1 - h^*{}_{22}y_2 + h_{11}y^*{}_3 - h_{21}y^*{}_4 \end{aligned} \tag{2.11}$$

Substituting Equation (2.10) into Equation (5.3), we can rewrite the decoder equations as

$$\begin{aligned} \overbrace{x_1} = {} & (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2)x_1 + h^*{}_{11}n_1 + h_{12}n^*{}_3 + h^*{}_{21}n_2 \\ & + h_{22}n^*{}_4 \\ \overbrace{x_2} = {} & (|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2)x_2 + h^*{}_{12}n_1 - h_{11}n^*{}_3 + h^*{}_{22}n_2 \\ & - h_{21}n^*{}_4 \end{aligned} \tag{2.12}$$

Clearly, it can be seen that the estimates mostly depend on the magnitudes of the channels so that the scheme is resistant to phase changes.

2.2.4.2 Spatial Multiplexing and BLAST Architectures

As stated above, the advantage of a MIMO system is: to increase the reliability of the system by providing a diversity gain and/or to increase the data rate by providing multiplexing gain. The term spatial multiplexing gain refers to the fact that one can use multiple antennas to achieve a higher throughput at the cost of an increased SNR requirement [3]. In 1996 Foschini proposed a multi-layer MIMO structure, known as the Bell Labs' Layered Space-Time (BLAST) scheme, which is in principle capable of approaching the substantial capacity of MIMO systems.

There are several BLASTS coding architectures exist, including Horizontal Bell Laboratories Layered Space-Time (HBLAST), Vertical BLAST (VBLAST), and Diagonal BLAST (DBLAST) architectures. A simplest method to achieve spatial multiplexing, pioneered at Bell laboratories as one of the Bell Labs Layered Space Time (BLAST) architectures for MIMO channels [21], is parallel encoding, illustrated in Figure 2.5. The source bit sequence at the transmitter side is split into N_t sequences, which are modulated and then transmitted simultaneously from the N_t transmit antennas using the same frequency band. This process can be considered to be the encoding of the serial data into vertical vectors, and hence also referred to as vertical encoding or V-BLAST. Each receive antenna observes a superposition of the transmitted signal sub-streams, and the detector recovers these individual sub-streams and combines them to recover the original bit stream. Various detector architectures, such as ML, zero-forcing (ZF), minimum mean-squared error (MMSE), and successive interference cancellation (SIC) detector etc., can be used to realize the spatial multiplexing gain. Each of the detection method for spatial diversity and spatial multiplexing will be discussed in the next section.

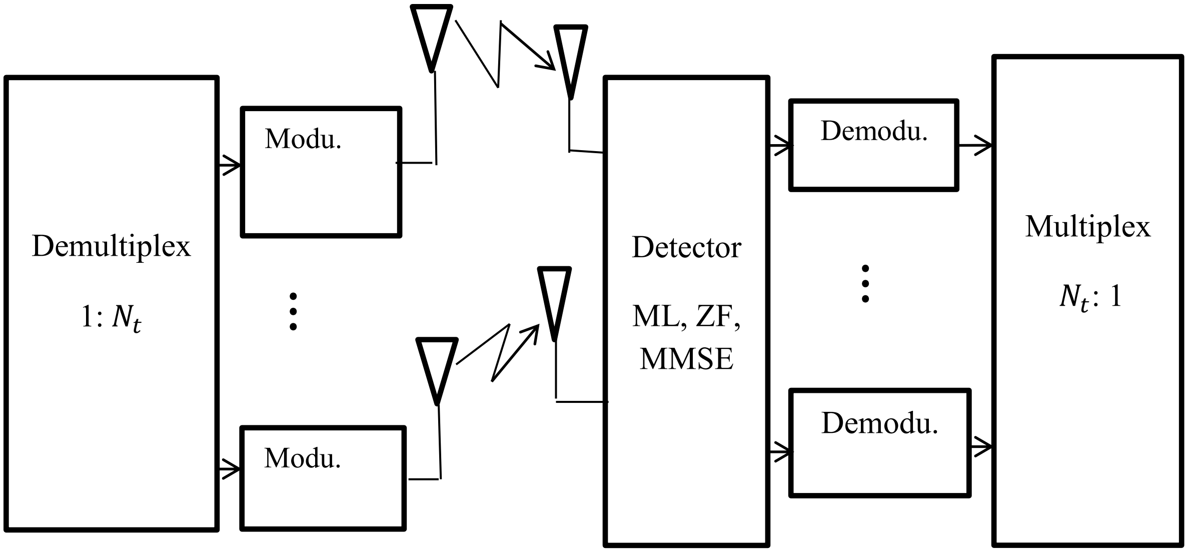


Figure 2. 5: Spatial multiplexing with parallel encoding: VBLAST

2.2.5. Detection techniques for MIMO system

The received signal vector can be expressed as the product of the channel matrix with the transmitted signal vector corrupted by the noise vector. Therefore the received signal at each receive antenna is a superposition of all the transmitted signals corrupted by the channel fading and additive noise. The objective of the detection is to separate the transmitted signals based on the observation of the received signal vector and the channel matrix. Many detection algorithms have been proposed for MIMO systems. These detection algorithms can be classified as linear detections and non-linear detections [32]. The most practical operating condition is the transmission channel itself. Linear detectors do not require prior knowledge of the channel unlike nonlinear detectors. Nonlinear detectors would normally require knowledge of the channel gains of each user. The transmission channel is never constant and varies over time; hence, determining the channel gains leads to added complexity. The standard linear detection methods include the zero-forcing (ZF) technique and the minimum mean square error (MMSE) technique.

A major drawback of linear equalizers is their vulnerability and ineffectiveness to deep fades [24]. In other words, linear equalizers suffer when the frequency response of the frequency selective channel contains deep fades. This is not apparent in nonlinear equalizers and their performance under deep fades can also be harnessed significantly. Maximum Likelihood (ML), Successive Interference Cancellation (SIC), Ordered Successive Interference Cancellation (OSIC) and Sphere Decoding Algorithms (SDAs) are examples of non-linear detection techniques. Here, some of the detection techniques for MIMO systems used in this thesis are study.

Linear Detector: Linear signal detection method treats all transmitted signals as interferences except for the desired stream from the target transmit antenna [22]. Therefore, interference signals from other transmit antennas are minimized or nullified in the course of detecting the desired signal from the target transmit antenna. To facilitate the detection of desired signals from each antenna, the effect of the channel is inverted by a weight matrix W such that $\overbrace{x} = Wy$. That is, detection of each symbol is given by a linear combination of the received signals.

Zero-Forcing: ZF technique nullifies the interference by W_{ZF} matrix, which is the pseudo inverse of channel matrix H [23].

$$W_{ZF} = (H^{\dagger}H)^{-1}H^{\dagger} \tag{2.13}$$

Where $(.)^{\dagger}$denotes the Hermitian transpose operation.

$$\begin{gathered} \overbrace{x} = W_{ZF}y \\ \overbrace{x} = x + (H^{\dagger}H)^{-1}H^{\dagger}n \end{gathered} \tag{2.14}$$

Note that the error performance is directly connected to the power of the noise .The noise enhancement effect plaguing the ZF detector can be reduced by using the minimum Mean square error (MMSE) detectors.

Minimum Mean Square Error (MMSE): This is an algorithm which performs better than the ZF under noisy conditions. Although, it does not fully eliminate ISI like the ZF algorithm; it substantially reduces the total noise power experienced at the receiver [47]. The MMSE filter can be found by minimizing the mean-square error (MSE) as

$$W_{MMSE} = (H^{\dagger}H + \sigma^{2}I_{N})^{-1}H^{\dagger}$$

Thus, the result of MMSE detector is

$$\tilde{\hat{x}} = x + (H^{\dagger}H + \sigma^{2}I_{N})^{-1}H^{\dagger}n \tag{2.15}$$

Where σ represent the ratio of received signal power to noise power and I_N represent an identity matrix. It should be noted that when noise power is much greater than of received signal power; the MMSE estimate equates to the ZF estimate.

Nonlinear Detector: Non-linear detectors provide good results as compared to that of linear but with a little bit more complexity. Nonlinear decoders are complex but the performance is good.

Maximum Likelihood (ML): The decision is taken according to the minimum Euclidean distance. The Euclidean distance is calculates between the received signal vector and the product of all possible transmitted signal vectors with the given channel H, and finds the one with the minimum distance.

$$\tilde{\hat{x}} = \underset{x \in C^{N_t}}{argmin} \|y - Hx\|^{2} \tag{2.16}$$

Where $\|y - Hx\|^{2}$ corresponds to the ML metric and C and N_t denote a set of signal constellation symbol points and a number of transmit antennas, respectively. The ML method is the optimal detector for MIMO systems. It gives the best BER performance but the complexity is increases exponentially as modulation order and/or the number of transmit antennas increases [25].

Chapter 3

Cooperative Communication

3.1 Introduction

As discussed in chapter 2, MIMO systems have recently emerged as one of the most significant wireless techniques, as they can greatly improve the channel capacity and link reliability of wireless communications. However, these improvements come at the cost of requiring the antennas on a MIMO device to have sufficient spacing for uncorrelated fading. If the antenna spacing reduces, i.e. independent fading cannot be obtained for each pair of antennas, the efficiency will be degraded, resulting in lower MIMO capacity. Moreover, practical implementation of multiple antennas in a small device is unrealistic or cost ineffective because of the requirement of additional radio-frequency hardware [26].

To overcome the difficulty, a new Cooperative communication is a practical alternative to a MIMO system is used, which allows the source node communicates with the destination node by making use of wireless relays. With the help of node cooperation, relay-based wireless networks are able to achieve spatial diversity in a distributed manner [27-29]. This similar to MIMO, cooperative communication could generate diversity, but in a new and interesting way.

Figure 3.6 shows that two mobile users communicating with a base station. Due to the inherently broadcast nature of wireless communications at the base station, it may be possible for one user to receive the information intended for another user, in which case it can help to forward some version of the received information to the destination. Because the fading channels to the two users are statistically independent, this could generate receive diversity.

Because of diversity, the negative effects of shadowing and small scale fading can be effectively combated [27]. Furthermore, due to cooperation diversity, the error probabilities at the destination will be reduced. However, one of the main challenges of cooperative diversity is the throughput loss due to the extra resources needed for relaying. For instance, for a single- relay system, throughput is reduced by 50% (compared with that of direct-transmission) for the same bandwidth. To combat this effect adaptive modulation is proposed. This will be study in next chapter.

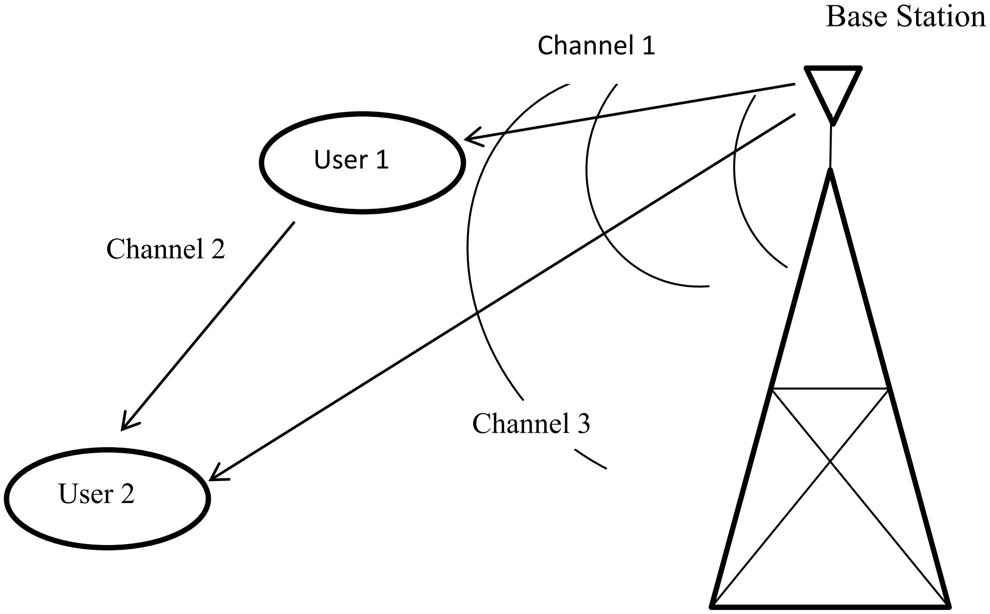


Figure 3.1: Cooperative communications

3.2. Cooperation Configurations and Operation Types

Many options arise for cooperative Configurations in wireless settings. The 3-node relay channel was introduced by Van der Meulen, but we start our literature review with Cover and El Gamal's landmark paper "Capacity theorems for the relay channel", which introduces most of the concepts that are used in the thesis on the so called one way relay channel or a classical relay channel. This channel involves three nodes: a source (S), a relay (R) and a Destination (D) as shown in Figure 2.7. For this thesis assume that all nodes operate in the same band. From the viewpoint of the source, the system becomes to a point to multiple point channel, which is often called a broadcast channel (BC). And from the viewpoint of the destination, it represents a multiple-point to point channel which behaves like the so-called multiple access channel (MAC) [31].

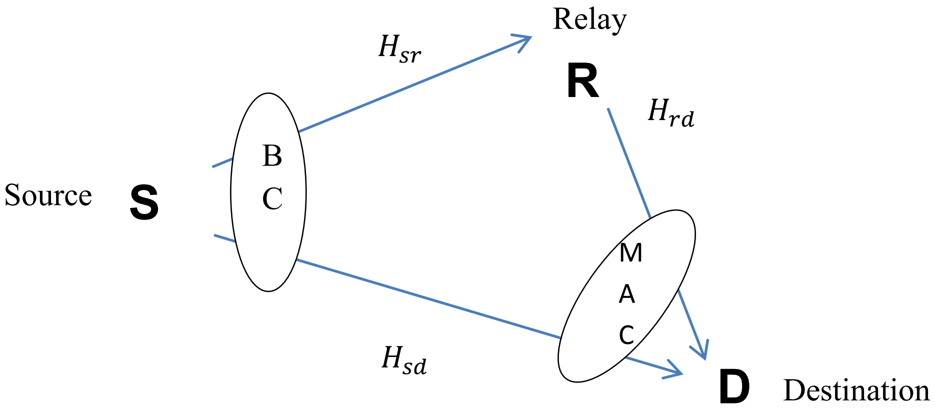


Figure 3. 2: A time-division one-relay network

There are three types of classical relay channel operations , which implement by varying degrees of broadcasting and receive collision in the network. The degree of broadcasting is given by the number of nodes simultaneously (i.e., in the same time slot) sending to the source node (i.e., 2 if both R and D received, 1 if only R or D receiver). Furthermore, receive collision is said to be maximum if the destination node receives information simultaneously from both S and R.

Type I: the source terminal communicates with the relay and destination terminals during the first time slot (phase one). In the second time slot (phase two), both the relay and source terminals communicate with the destination terminal. Type I realize maximum degrees of broadcasting and receive collision [29].

Type II: only the relay terminal communicates with the destination terminal in the second time slot. This type realizes a maximum degree of broadcasting but exhibits no receive collision [33]. Thus, for analyzing the classical (three-terminal) relay channel is Type II is uses.

Type III: The third type is identical to type I apart from the fact that the destination terminal chooses not to receive the direct $S \rightarrow D$ signal during the first time slot. This type does not implement broadcasting but realizes receive collision [34].

A typical cooperation strategy can be modeled with two orthogonal phases, either in TDMA or FDMA, to avoid interference between the two phases [48]:

- In phase 1, a source sends information to its destination, and the information is also received by the relay at the same time.
- In phase 2, the relay can help the source by forwarding or retransmitting the information to the destination.

3.3. Cooperation transmission Protocols

Cooperative transmission protocols describes that how the received data is processed at the relay station, before forwarding it to the destination, employ different types of processing at each relay terminal. In this subsection, we will review and compare several cooperative strategies.

3.3.1 Amplify-and-Forward (AF)

As the name suggests, the Amplify and Forward technique simply amplify the signal received by the relay before forwarding it to the destination [46]**.** This scheme is ideal when the relay station has minimal computing power. The relay does the amplification by simply scaling the received signal by a factor that is inversely proportional to the received power, which is denoted by

$$\alpha = \sqrt{\frac{p}{p|h_{sr}|^2 + N_0}} \tag{3.1}$$

This term has to be calculated for every block and therefore the channel characteristic of every single block needs to be estimated. Depending on CSI the AF protocol divided in to two. These are:

- CSI-assisted AF scheme: the relay uses instantaneous CSI of the source-relay link to scale its received noisy signal before forwarding. In this case we assumed that the channel state information at the relay is known.
- Blind AF scheme does not have access to CSI and employs fixed power constraint. No need CSI at the relay.

The signal transmitted from the relay is thus given by αy_r and has power p equal to the power of the signal transmitted from the source.

One major drawback of this technique is that the noise in the signal is also amplified at the relay station, and the destination receives two independently faded versions of the signal. Although the noise of the relay is amplified, the destination still receives two independently faded versions of the signal and is thus able to make better decisions for the transmitted symbols. A potential challenge in this scheme is that sampling, amplifying, and retransmitting analog values may be technologically non-trivial. Nevertheless, amplify-and-forward is a simple method that lends itself to analysis, and therefore has been very useful in furthering the understanding of cooperative communication system.

3.2.2. Decode and Forward (DF)

In DF the received signal is first decoded and then re-encoded. So there is no amplified noise in the sent signal, as is the case using Amplify and Forward protocol. There are two main implementations of such a system. The relay can decode the original message completely. This requires a lot of computing time, but has numerous advantages. If the source message contains an error correcting code, received bit errors might be corrected at the relay station. Or if there is no such code implemented a checksum allows the relay to detect if the received signal contains errors. The relay now demodulates, decodes, re-encodes and retransmits the signal [49],

$$x_r = \overbrace{x}_s \tag{3.2}$$

Where $\overbrace{x}_s$ denotes the relay's estimate of x_s . Depending on the implementation an erroneous message might not be sent to the destination. But it is possible that detection by the relay is unsuccessful, in which case cooperation could be detrimental to the eventual detection at the destination terminal. To avoid the problem of error propagation, Laneman *et al.* [33] proposed an adaptive relaying scheme where the relay only transmits when it successfully decodes the transmitted data.

3.2.3. Compress and Forward (CF)

The main difference between compress and forward and decode/amplify and forward is that while in the later the relay transmits a copy of the received message, in compress and forward the relay forwarding a quantized and compressed version of the received signal. The relay node can employ standard quantization, or some source coding technique, when compressing the signal. Source encoding operation at the relay falls into the realm of the set of coding techniques known as distributed source coding, Sleppian–Wolf coding, or Wyner–Ziv coding [35]. Therefore, the destination node will perform the reception functions by combining the received message from the source node and its quantized and compressed version from the relay node.

Compared to AF, the CF protocol can provide better performance, but it is a little more complicated as the relay needs to quantize the signal before forwarding. Moreover, the DF protocol outperforms CF when the relay is closer to the source.

For this work the amplify and forward relaying (AAF) technique is considered, because it is efficient in fading environments where the cost of decoding (DAF) the signal would be expensive.

3.3. Combining Techniques

Diversity methods implemented at the receiver are effective in combating the effects of multipath. If there is more than one incoming transmission with the same burst of data, the incoming signals have to be combined before they will be compared [29]. In section, the implementation of popular combining techniques like the equal gain combining, signal to noise ratio combining, maximum ratio combining and other combining techniques are studies.

3.3.1. Equal Gain Combiner (EGC)

Where the signals received on the antenna array at the receiver are just combined with unit channel gain at each array element. This is the easiest way to combine the signals, but the performance will not be that good in return because the fluctuations caused due to small scale fading is ignores [1]. The combining signal is:

$$y_d = \sum_{i=1}^{k} y_{id} \tag{3.3}$$

If one relay station is used, so the equation simplifies to

$$y_d = y_{sd} + y_{rd} \tag{3.4}$$

Where y_{sd} denotes the received signal from the sender and $y_{rd}$the one from the relay. This technique can be used where the channel quality information is not known.

3.3.2. Fixed Ratio Combining (FRC)

If channel gains can be approximated to have a fixed ratio on the multi-path channels based on little knowledge of channel quality, then the equal gain diversity can be converted to fixed ratio combining [36]. In FRC the incoming signals are weighted with a constant ratio then adding up together. The ratio should represent the average channel quality and therefore should not take account of temporary influences on the channel due to fading or other effect. But influences on the channel, which change the average channel quality, such as the distance between the deferent stations, should be considered. The combining signal can be represented

$$y_d = \sum_{i=1}^{k} w_{id} y_{id} \tag{3.5}$$

For one relay station the above equation is simplified to

$$y_d = w_{sd} y_{sd} + w_{rd} y_{rd} \tag{3.6}$$

Where $w_{sd} \quad and \; w_{rd}$ determine the fixed channel weights (or gain) applied to the respective direct and relay paths.

This combining technique is less used in practical as the ratio cannot be determined without estimating the channel quality but it gives an idea about how significant it is to estimate the channel quality for better diversity.

3.3.3. Signal to Noise Ratio Combining (SNRC)

The channel quality is generally measured in terms of signal to interference noise ratio (SINR) for the transmission of the signal over a fading channel. The output SNR at each channel is used to weight the received signals, and the interference from the co-channels is ignored. The SNRC can be expressed as [50]

$$y_d = \sum_{i=1}^{k} SNR_{id} y_{id} \tag{3.7}$$

Using one relay, the equation can be written as

$$y_d = SNR_{sd}y_{sd} + SNR_{rd}y_{rd} \tag{3.8}$$

Where, SNR_{sd}represents output SNR on direct path and SNR_{rd} represents SNR on relay path.

3.3.4. Estimated SNR Combining (ESNRC)

This technique is a variation of the SNR combining technique where only that symbol sequence is considered output SNR is better than another by a factor while combining. This technique can also be referred as sort of selection diversity but more sophisticated as estimation of the channel quality is considered. The combining signals can be expressed as [50]

$$y_d = \begin{cases} y_{sd} & SNR_{sd}/SNR_{rd} > 10 \\ y_{sd} + y_{rd} & 0.1 \le SNR_{sd}/SNR_{rd} \le 10 \\ y_{rd} & SNR_{sd}/SNR_{rd} < 0.1 \end{cases} \tag{3.9}$$

3.3.5. Maximum Ratio Combining (MRC)

In MRC, each radio channel is weighted with the complex conjugate of the respective channel gain [37]. This assumes that the channels' phase shift and attenuation is perfectly known by the receiver. The MRC can be expressed as

$$y_d = \sum_{i=1}^{k} h^*{}_{id}y_{id} \tag{3.10}$$

For classical relay channel, this equation can be written as

$$y_d = h^*{}_{sd}y_{sd} + h^*{}_{sr}h^*{}_{rd}y_{rd} \tag{3.11}$$

Chapter 4

Adaptive Modulation

The goal for future wireless networks of mobile communications system is to seamlessly integrate a wide variety of communication services (i.e. high speed data, voice, and multimedia) via electromagnetic waves in free space is changing the way people interact in their daily lives. This requires high speed wireless data transmission for efficient communication which must be robust and spectrally efficient. But the wireless channel faces a lot of problem of channel impairments such as noise, interference and these impediments change over in unpredictable ways due to used movements, which result in distorted received signal [15]. A radio channel behaves like a time-varying filter; the received version of the transmitted signal is a distorted version of the transmitted signal, and the distortion varies with time. A typical realization of a fading signal over time is represented in Fig. 4.1. Link adaptation techniques, where the modulation, coding rate, and/or other signal transmission parameters are dynamically adapted to the changing channel conditions that can track time varying characteristics of wireless channels, carry the promise of significantly increasing data rates, reliability, and spectrum efficiency of future wireless networks.

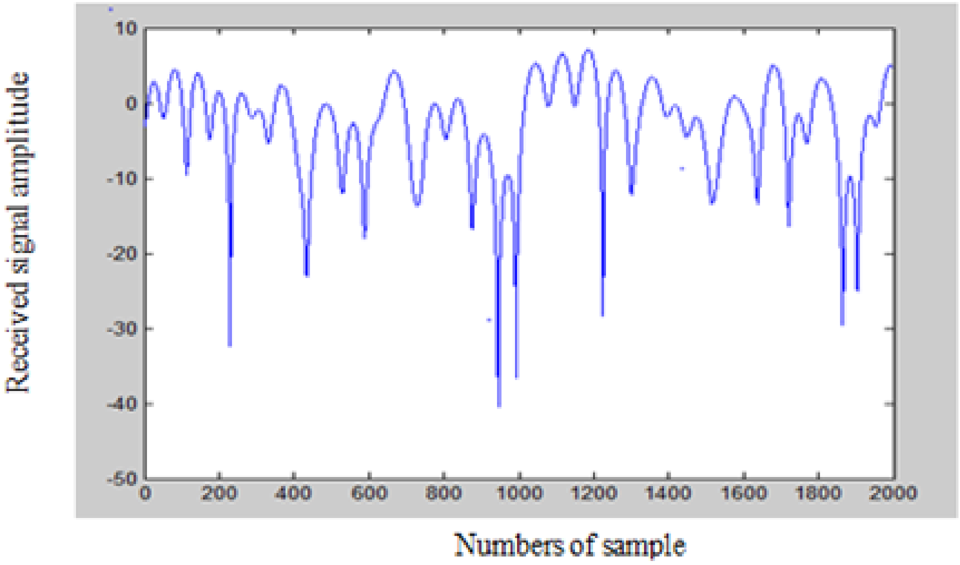


Figure 4.1: Fading Signal

In this chapter, adaptive modulation with wireless networks especially LTE is introduces. Adaptive modulation scheme aims to improve link spectral efficiency by adjusting the modulation order depending on the quality of fading channels. Nevertheless for a high quality radio link condition the higher modulation scheme will be utilized which provides the highest throughput of the system or the best spectral efficiency. During a signal fade, the wireless network system may be shifted to a lower modulation scheme in order to maintain the connection quality and link stability. In comparison to fixed modulation order strategy, where signal to noise ratio on channels is varying means that the bit error rate is changing with the channel quality, this scheme is advantageous because it can achieve higher rate and more efficient use in the resources, e.g., time, frequency, and power.

Link adaptation has been widely used in wireless networks, e.g., Universal Mobile Telecommunications System (UMTS), Wireless Local Area Network (WLAN) and 3GPP Long Term Evolution (LTE), to boost the spectral efficiency. In particular, in frequency selective channels, an adaptive allocation of time and frequency resources based on users' channel quality can significantly improve the system throughput [38]. Long Term Evolution (LTE) is the latest standard in the 3rd Generation Partnership Project (3GPP), mobile network technology tree that produced the GSM/EDGE and UMTS/HSPA network technologies. The LTE specification provides downlink peak rates of at least 100 Mbps, an uplink of at least 50 Mbps and RAN round trip times of less than 10 ms. LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz and supports both frequency division duplexing (FDD) and time division duplexing (TDD) [39] . The main advantages with LTE are:

- Decrease the traffic communication while sending data (low latency)
- FDD and TDD in the same platform, an improved end user experience and a simple architecture resulting in low operating costs
- allows more users to use with same frequency in a cell (high throughput)
- To optimized terminal power efficiency
- Offers fastest data transfer which in higher download and upload rate
- Support seamless passing to cell towers with older network technology such as GSM, CDMA, UMTS, and CDMA2000

- Enables spectrum flexibility: depending on the available spectrum the transmission bandwidth will selected from 1.4MHz to 20MHz.
- The multiple access schemes in LTE is
  - Downlink - Orthogonal Frequency Division Multiple Access (OFDMA)
  - Uplink- Single Carrier Frequency Division Multiple Access (SC-FDMA).
- Both in uplink and downlink the resource allocation is 180 kHz which is in frequency domain

In LTE the quality of the received signal depends on path loss, shadowing, multipath fading, interfering signals, and sensitivity of the receiver [39]. Link adaptation is used to alleviate the negative impacts of such variations, guarantying the QoS, and maximizing the system throughput. For this thesis, LTE network in fading channels with link adaptation (LA) will be used.

The general principle of LA is to define a channel quality indicator, or so called channel state information (CSI), that provides some knowledge on the channel and feedback it to the transmitter. The CSI makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in wireless networks. The feedback accomplished by two ways [40]:

- ➢ Feedback the CSI to transmitter so that the transmitter can adjust the parameters based on the feedback information with respect to the channel conditions. This technique is consumes resource
- ➢ Only the adaptive parameter is feedback to the transmitter. This option is usually more efficient since there are typically a small number of modes, thereby limiting the amount of feedback. For this reason, this method will be used.

Adaptive Techniques

Based on the measurement of the parameters describing the quality of the transmission channel and on the selection of transmission parameters we have different type adaptive techniques [15]:

- ❖ Variable power adaptation:
  - o Through power control, only the transmission power level is varied compensate for SNR variation due to fading

    - It maintains constant rate and adapts its power to the inverse of the channels fading
    - The goal is to minimized transmission power with fixed bit error probability (BER) or constant received SNR
- ❖ Variable Rate adaptation:
    - The goal is to maximized spectral efficiency by varied The Rate and modulation or constellation size according to the channel condition with fixed BER
        - ✓ Fixing the symbol rate of the modulation and using multiple modulation schemes or constellation sizes.
        - ✓ Fixing the modulation and changing the symbol rate (varying signal bandwidth is impractical)
- ❖ Variable coding adaptation:
    - The coding scheme can be changed so as to respond to the channel state by selecting the optimum code rate
    - Can be implemented by multiplexing together codes with different error correction capabilities
    - The goal is to minimized BER with fixed rate

Among adaptive transmission techniques, adaptive modulation plays a central role, because it increases the data transmission efficiency without increasing the multi-access interference power [3]. The receiver needs only to calculate the total SNR and select the appropriate transmission rate and send this information back to the transmitter. This makes adaptive techniques based on adaptive modulation such as those proposed in [41] viable. To maximize the spectrum efficiency or total throughput for the AF cooperative MIMO system in LTE network with adaptive modulation under the constraint of the received BER requirement is formulated as:

$$P_b \leq BER_{th} \tag{4.1}$$

Where BER_{th} is the predefined target BER, P_b is the error probabilities. The set of adaptation/ switching thresholds is then obtained by reading the SNR points corresponding to a target BER after that feedback the selected SNR threshold to the transmitter. The throughput of adaptive modulation is determined by constellation size used for transmission signal.

Chapter 5

Performance Assessment of adaptive modulation in cooperative MIMO for LTE technology

5.1. Introduction

As mentioned in Chapter 3, the cooperative diversity system has been proposed as an alternative to a point to point MIMO system, to improve channel capacity and link reliability of wireless communications. However, cooperative diversity schemes usually decrease the spectrally efficiency of the system because of their repetition based structure and channel variations. It is well known that, adapting the transmission parameters such as the modulation and coding rate to the changing channel conditions have recently emerged as a powerful technique for improving the system in terms of the data rate. For potential increasing the system throughput, adaptive modulation combining with cooperative MIMO system is used. This chapter studies the performance of the cooperative MIMO system using adaptive modulation scheme over the Rayleigh fading channel under perfect CSI.

5.2. Cooperative MIMO system over Rayleigh fading channel Simulation model

To focus on the performance assessment cooperation MIMO with all nodes placed at equal distance, simplify the system to the $N_s = N_d = 2$ antennas case, as shown in Figure 5.1. The communication takes place through a relay with N_r = 2 antennas. Where N_s, N_d and N_r are number of antennas at source, destination and relay respectively. Where the number of receive antennas must be equal or greater than the number of transmit antennas ($N_d \geq N_s = N_r$) in order to separate and detect the x transmitted signals. Assume that the channels are half-duplex, which means that terminals, and in particular relay, cannot receive and transmit at the same time. The channels between them are block fading, which is practical and particularly relevant in wireless communications situations .Thus a block fading channel model with N fading blocks is assumed here, with each block having length L symbol periods. Fading is flat and constant on each block, but independently Rayleigh distributed on different blocks.

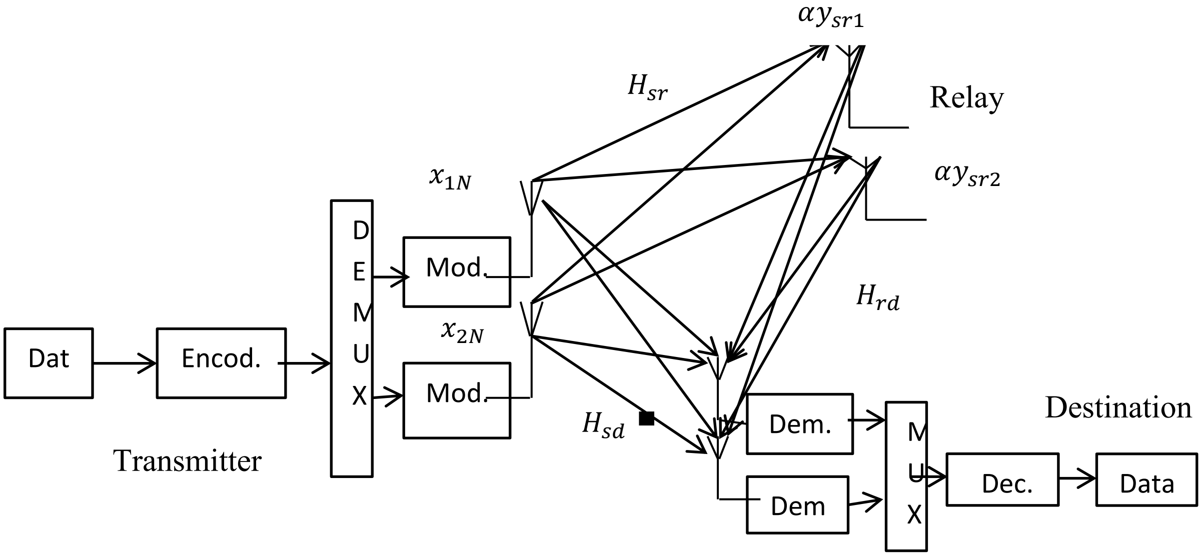


Figure 5.1: System model of cooperative MIMO

Furthermore, to investigate the effect of the path loss into the channel model, the variance of the average powers of the channel coefficients source-relay and relay-destination respectively given by [51]:

$$\sigma_{sr}{}^2 = \sigma_{sd}{}^2 \left(\frac{d_{sd}}{d_{sr}}\right)^{\beta} \tag{5.1}$$

$$\sigma_{rd}{}^2 = \sigma_{sd}{}^2 \left(\frac{d_{sd}}{d_{rd}}\right)^{\beta} \tag{5.2}$$

Where $\sigma_{sr}{}^2, \sigma_{rd}{}^2$ variance and d_{sr} , d_{rd} distance, of the fading coefficient source to relay and relay to destination respectively. Assume that the variance of source to destination $\sigma_{sd}{}^2 = 1$ and the path loss exponent β= 1. If all terminals are placed at equal distance($d_{sd} = d_{sr} = d_{rd}$) then Equations (5.1) and (5.2) become σ_{sd}.

A uniform energy distribution between the sources and relay that means a fixed power per user is considered. To provide a fair comparison platform for the cooperative diversity network, the classical direct transmission system will uses the same total energy consumed in the two networks. Let E_s is the Symbol Energy of the source in direct transmission. Then, $E = \frac{E_s}{2}$ is the transmitted symbol energy for each of the source and relay. Also assume that perfect CSI is available only at the receiver side.

The communication is assumed to take place through two phases. In the first phase the source broadcasts a message. The transmitted signal undergoes fading and is received by relay and destination. In the second phase, using its own process employed, depending on relative channel condition, transceiver complexity and user location, relay cooperates with source by sending the signal received in the first phase to destination [42]. Because of the low complexity and short delay in signal processing at the relay node, AF strategy is used.

In the first phase, the received signal is:

$$y_{rnl} = \sqrt{\frac{E_s}{2}} H_{srnl} x_{nl} + n_{srnl}\, , with\ H_{srnl} = \begin{bmatrix} h_{11\,rsnl} & h_{12\,rsnl} \\ h_{21\,rsnl} & h_{22\,rsnl} \end{bmatrix} \tag{5.3}$$

$$y_{d,1\,nl} = \sqrt{E_s} H_{sdnl} x_{nl} + n_{sdnl}\, , with\ H_{sdnl} = \begin{bmatrix} h_{11\,dsnl} & h_{12\,dsnl} \\ h_{21\,dsnl} & h_{22\,dsnl} \end{bmatrix} \tag{5.4}$$

Where y_{rnl} and $y_{d,1\,nl}$ are the received signals at the relay and destination during the first phase, respectively, E_s is the average power per antenna of each symbol at the source.H_{srnl} and H_{sdnl} denotes the n^{th} block fading channel matrix of source-relay and source-destination link respectively, with each $h_{ij\,rsnl}$ and $h_{ij\,dsnl}$ (i, j∈{1,2}) are independent and identically distributed. Also define the vector x_{nl}=$[x_{i\prime nl}\, , x_{i\prime nl}\,]^T$, where $x_{i\prime nl}$ (i'∈ [1,2]) presents the l^{th} $M-ary$ symbol transmitted on the n^{th} channel from the i'^{th}antenna. The vectors n_{srnl} and n_{sdnl} are the noise due to source transmit the signal to relay and destination respectively. The noise vector is represent by n_{ijnl}= $[n_{1ijnl}\, , n_{2ijnl}\,]^T$(i=s; j=r, d), which is composed of a zero mean complex Gaussian random variable with variance N_o. Note that the index notation (nl) is used to emphasize the block fading nature of the MIMO channel.

The transmit signal from relay is:

$$x_{rnl} = \alpha_{nl} y_{rnl} \tag{5.5}$$

The relay terminal can be classified based on the different amplifying gains in the relay terminal. In general, the relay terminal is categories into two. One is the fixed relay gain category, the other one is the variable relay gain category. In the former case, the relay gain is always a constant, which means whatever receives at the relay terminal is sent to the destination terminal without any change. In the latter case, the relay gain is a variable. In this thesis, variable relay gain is considered.

An amplifying relay must use a gain factor α_{nl} ,

$$\alpha_{nl} = \sqrt{\frac{E_r}{E_s \, {\|H_{srnl}\|_F}^2 + N_o}} \; I_{N_s N_r} \tag{5.6}$$

$${\|H_{srnl}\|_F}^2 = |h_{11\,rsnl}|^2 + |h_{12\,rsnl}|^2 + |h_{21\,rsnl}|^2 + |h_{22\,rsnl}|^2$$

Where $\|H_{srnl}\|_F$ is the Frobenius norm of the fading channel H_{srnl} [42], E_r is the average power of each symbol at the relay, and $I_{N_s N_r}$ is the 2×2 identity matrix.

For second phase, the relayed signal at the destination is given by:

$$y_{d,2\,nl} = \sqrt{\frac{E_s}{2}} H_{rdnl} x_{rnl} + n_{rdnl} \quad , with \; H_{rdnl} = \begin{bmatrix} h_{11\,drnl} & h_{12\,drnl} \\ h_{21\,drnl} & h_{22\,drnl} \end{bmatrix} \tag{5.7}$$

Where n_{rdnl} is $[n_{1rdnl}\, , n_{2rdnl}\,]^T$ noise vector that is measured at the destination during the second time slot , $y_{d,2\,nl}$ is the received signal at destination during the second phase and H_{rdnl}denotes the n^{th} block fading channel matrix of relay to destination, with each $h_{ij\,drnl}$ (i, j∈{1,2}) is independent and identically distributed.

When we insert Equations (5.5) and (5.3) into Equation (5.7) then the received signal for second phase at destination is:

$$y_{d,2\,nl} = \frac{E_s}{4} \; H_{rdnl} \, \alpha_{nl} H_{srnl} x_{nl} + \sqrt{\frac{E_s}{2}} H_{rdnl} \, \alpha_{nl} n_{srnl} + n_{rdnl} \tag{5.8}$$

The equivalent cooperative MIMO $N_dN_r \times N_s$ (4×2) with N_dN_r (4) virtual receiving antennas representation of the proposed MIMO relaying system is given as follows [42]

$$\begin{bmatrix} y_{d,1\,nl} \\ y_{d,2\,nl} \end{bmatrix} = \underbrace{\begin{bmatrix} \sqrt{E_s} H_{sdnl} \\ \frac{E_s}{4} H_{rdnl}\, \alpha_{nl} H_{srnl} \end{bmatrix}}_{H_{eqnl}} x_{nl} + \begin{bmatrix} I_{N_sN_r} & 0 & 0 \\ 0 & \sqrt{\frac{E_s}{2}}\, H_{rdnl}\, \alpha_{nl} & I_{N_sN_r} \end{bmatrix} \begin{bmatrix} n_{sdnl} \\ n_{srnl} \\ n_{rdnl} \end{bmatrix} \tag{5.9}$$

Therefore, the equivalent channel matrix for relayed link is:

$$H_{eqrsdnl} = F_{nl} = H_{rdnl} H_{srnl}$$

While equivalent noise that is measured at the output is:

$$n_{eqrsdnl} = H_{rdnl}\, \alpha_{nl} n_{srnl} + n_{rdnl}$$

After two phases of transmission, the receive signals at the destination will be combining by one of the techniques which are considered in section 3.3. In this thesis, MRC and EGC will be use. Since the two networks, i.e., the source-destination and source-relay-destination links are separable we perform independent combining for each networks and then the resulting estimates are summed to yield the final decision.

5.3. Cooperative transmission using space time code architectures

There exist two main approaches to apply the Space time technique in cooperative systems. In the first one, i.e., cooperation using distributed STBC (alamouti code), is applied to create a virtual transmit array in a distributed multiple transmitter network. In the second approach, the STC matrix (VBLAST) is completely broadcast to the relay and destination**.**

5.3.1. Cooperation based on space time block coding scheme

In this scheme the source terminal is broadcast an alamouti space time code to the relay and destination terminals in the first phase. During the second phase, relay terminal retransmits the modify signal to destination. An alamouti STBC, a cooperative relaying network with a single relay system and two receive antennas can be considered as a virtual MIMO system with four receive antennas. Thus, the performance of the cooperative diversity system is improved without increasing the number of receives antennas.

5.3.2. Cooperation based on VBLAST scheme

In the cooperative VBLAST transmission scheme, during the first phase the source transmits independent STC matrix messages over two antennas. During the second phase, the relay forwards the modify signal to the destination. It achieves high spectral efficiencies by spatially multiplexing coded or uncoded symbols over the fading channel. Since increasing the bit rates is the goal of this thesis, transmission based on the VBLAST scheme is considered.

At the receiver, since the paths source- destination and source –relay-destination are separable, we perform independent combining on both channels then the estimates signal from both paths after two phases of transmission are summed up to yield the total receive signal [52].Using MRC technique the total receive signal at the destination is given as follows

$$y_{nl} = H_{sdnl}^{H} y_{d,1\,nl} + {H_{eqrsdnl}}^{H} y_{d,2\,nl} \tag{5.10}$$

For EGC technique, the total receive signal:

$$y_{nl} = y_{d,1\,nl} + y_{d,2\,nl} \tag{5.11}$$

Since y is in the form of $y = Hx + n$ to detect transmits signal x launch y into ZF, MMSE and ML detection schemes that studied in chapter 2.

5.4. Adaptive modulations in cooperative MIMO

As mentioned in Chapter 4, the basic idea of the adaptive modulation is to adjust the modulation scheme based on the current channel state information. When the channel is in good state, a higher modulation scheme is chosen to communicate. Otherwise, a lower modulation scheme will be employed. There are various metrics that may be used as channel state information (CSI). Typically, signal to noise ratio (SNR) or signal to noise plus interference ratio (SINR) may be available from the physical layer. At the link layer, packet error rates (PERs) are normally extracted from the cyclic redundancy check (CRC) information. BERs are sometimes available.

In this thesis, the post detection of SNR at the output of ZF, MMSE and ML detection is used as the metric since it directly determines the performance of communication system. This SNR information will convert into BER information for each mode candidate then we select SNR Threshold Based on the mode that yields the largest throughput while remaining within the BER target bounds.

Since the exact SNR at the receiver side is impossible to know in advance, the only way to do this is to estimate the post SNR before each transmission. However, the estimation of the post SNR requires the knowledge of current CSI, which can be obtained by sending a pilot sequence through the channel. In this thesis, assume that source to relay, relay to destination and source to destination channels are perfectly known on the destination terminal (receiver terminals have perfect knowledge of channels state information).

5.4.1.Adaptation based SNR in assisted cooperative AF MIMO with VBLAST transmission

To determine the threshold of SNR for selection suitable modulation based on the target of BER, at the output of the ZF, MMSE and ML, first derive the post detection of SNR at the ZF, MMSE and ML, output considering the direct link and indirect links together. Consider a VBLAST with zero forcing, MMSE and ML at the destination only. This corresponds to many practical scenarios, including those where there is cooperation at the destination nodes. In addition, the source nodes send independent data streams to the relay and destination nodes, which then forward them to the destination node. The destination node then collaboratively processes the signal to recover the desired data.

The modified matrix H_{sdnl} and F_{nl} describing the equivalent channels matrix for direct and relayed links respectively. Applying the MRC or EGC technique to the received signals from two links, then the estimated signal [49], [52] are:

For MRC technique the receive signal is

$$y_{nl} = \sqrt{E_s}\, H^{H}{}_{sdnl} H_{sdnl} x_{nl} + \frac{E_s}{4}\, F^{H}{}_{nl} F_{nl} \alpha_{nl} x_{nl} + \tilde{n}_{nl} \tag{5.12}$$

When we rearrange above equation, the receive signal is

$$y_{nl} = \left(\sum_{i=1}^{N_r} \sqrt{E_s} (|h_{i1\,dsnl}|^2 + |h_{i2\,dsnl}|^2) + \frac{E_s}{4} \alpha_{nl}\, (|f_{i1\,nl}|^2 + |f_{i2\,nl}|^2) \right) x_{nl} + \tilde{n}_{nl} \tag{5.13}$$

Where $F_{nl} = H_{rdnl}H_{srnl}$and $\tilde{n}_{nl}$ is the equivalent noise channel that is measured at the output of the MRC, i.e.

$$\tilde{n}_{nl} = F^{H}{}_{nl}\ (H_{rd}\alpha_{nl}n_{srnl} + n_{rdnl}) + H^{H}{}_{sdnl}\ \ n_{sd} \tag{5.14}$$

While the entries $f_{i,j\ nl}$ of the matrix product F_{nl} are given as follows:

$$f_{i,j\ nl} = \sum_{k=1}^{N_r} h_{ik\ drnl}\ h_{kj\ rsnl}\ ,\quad 1 \leq i \leq N_r\ and\ 1 \leq j \leq 2$$

In matrix form Equation (5.13) can be written as:

$$\begin{bmatrix} y_{1nl} \\ y_{2nl} \end{bmatrix} = \sqrt{E_s}\underbrace{\begin{bmatrix} u_{11\ nl} & 0 \\ 0 & u_{22\ nl} \end{bmatrix}}_{H_{nl}}\begin{bmatrix} x_{1\ nl} \\ x_{2\ nl} \end{bmatrix} + \begin{bmatrix} \tilde{n}_{11nl} \\ \tilde{n}_{21nl} \end{bmatrix} \tag{5.15}$$

$$u_{11\ nl} = \sqrt{E_s}(|h_{11\ dsnl}|^2 + |h_{21\ dsnl}|^2) + \tfrac{E_s}{4}\alpha_{nl}(\ |f_{11\ nl}|^2 + |f_{21\ nl}|^2)$$

$$u_{22\ nl} = \sqrt{E_s}(|h_{12\ dsnl}|^2 + |h_{22\ dsnl}|^2) + \tfrac{E_s}{4}\alpha_{nl}\ (|f_{12\ nl}|^2 + |f_{22\ nl}|^2)$$

The covariance matrix of the equivalent noise $\tilde{n}$ (noise power) is

$$\begin{aligned} E\{\tilde{n}_{nl}\tilde{n}_{nl}{}^{H}\} = N_0\left(\sum_{i=1}^{N_r}(|f_{i1\ nl}|^2 + |f_{i2\ nl}|^2\left(\ 1 + \alpha^2{}_{nl}\sum_{k=1}^{N_r}|h_{ik\ drnl}|^2\right)\right. \\ \left. + \sum_{i=1}^{N_r}|h_{i1\ dsnl}|^2 + |h_{i2\ dsnl}|^2\right) \end{aligned} \tag{5.16}$$

Where $E\{.\}$ the expectation of $\{.\}$.

Next we perform the similar operation for EGC technique the receive signal is:

$$y_{nl} = \sqrt{E_s}\ H_{sdnl}x_{nl} + \frac{E_s}{4}F_{nl}\alpha_{nl}x_{nl} + \tilde{n}_{0nl} \tag{5.17}$$

The equivalent noise channel $\tilde{n}_{0nl}$ at output of EGC is given by

$$\tilde{n}_{0nl} = H_{rdnl}\ \alpha_{nl}n_{srnl}\ + n_{rdnl} + n_{sdnl} \tag{5.18}$$

In matrix form Equation (5.17) can be written as:

$$\begin{bmatrix} y_{1nl} \\ y_{2nl} \end{bmatrix} = \underbrace{\begin{bmatrix} g_{11\,nl} & g_{12\,nl} \\ g_{21\,nl} & g_{22\,nl} \end{bmatrix}}_{G_{nl}} \begin{bmatrix} x_{1\,nl} \\ x_{2\,nl} \end{bmatrix} + \begin{bmatrix} \tilde{n}_{011nl} \\ \tilde{n}_{021nl} \end{bmatrix} \tag{5.19}$$

$$g_{ijnl} = \sqrt{E_s} h_{ijdsnl} + \frac{E_s}{4} \alpha_{nl} f_{ijnl} \;, \quad 1 \le i \le N_r \; and \; 1 \le j \le 2$$

Using Equation (5.18) the covariance matrix of the equivalent noise $\tilde{n}_{0nl}$ at the output of EGC is

$$E\{\tilde{n}_{0nl}\tilde{n}_{0nl}{}^{H}\} = N_0 \left(2 + \alpha^2{}_{nl} \sum_{i=1}^{N_r} |h_{i1\,drnl}|^2 + |h_{i2\,drnl}|^2 \right) \tag{5.20}$$

Zero Forcing detection scheme:

The received signal in Equations (5.15) and (5.19) can be viewed as the sum of the desired signal x_{nl} together with the noise. Extract $\widehat{x_{nl}}$ out of the received signal by estimate the values that minimize the least square of $y_{nl} - H_{nl}\widehat{x_{nl}}$ and $y_{nl} - G_{nl}\widehat{x_{nl}}$ [43].

$$\mu_{MRCnl} = \|y_{nl} - H_{nl}\widehat{x_{nl}}\|^2$$

$$\mu_{EGCnl} = \|y_{nl} - G_{nl}\widehat{x_{nl}}\|^2$$

This is solved by multiplying by a pseudo inverse matrix:

$$W_{MRCzfnl} = (H^H{}_{nl} H_{nl})^{-1} H^H{}_{nl} \tag{5.21}$$

$$W_{EGCzfnl} = (G^H{}_{nl} G_{nl})^{-1} G^H{}_{nl} \tag{5.22}$$

To estimate the transmitted signals $\widehat{x_{nl}}$ multiplying Equation (5.15) by Equation (5.21) and Equation (5.19) by Equation (5.22), this given as

$$\begin{bmatrix} \hat{x}_{1nl} \\ \hat{x}_{2nl} \end{bmatrix} = \begin{bmatrix} x_{1\,nl} \\ x_{2\,nl} \end{bmatrix} + (H^H{}_{nl} H_{nl})^{-1} H^H{}_{nl} \begin{bmatrix} \tilde{n}_{11nl} \\ \tilde{n}_{21nl} \end{bmatrix} \tag{5.23}$$

$$\begin{bmatrix}\hat{x}_{1nl}\\ \hat{x}_{2nl}\end{bmatrix} = \begin{bmatrix}x_{1\,nl}\\ x_{2\,nl}\end{bmatrix} + (G^{H}{}_{nl}G_{nl})^{-1}G^{H}{}_{nl}\begin{bmatrix}\tilde{n}_{011nl}\\ \tilde{n}_{021nl}\end{bmatrix} \tag{5.24}$$

The post SNR detection $j\ ^{th}$receive antenna at the output of ZF detector obtained from Equations (5.23) and (5.24) given by:

$$\gamma_{j,nl} = \frac{E_s}{N_0\left\|W_{i,MRCzfnl}\right\|^2{}_F\left(\left\|F_{i,nl}\right\|^2{}_F + \alpha^2{}_{nl}\left\|F_{i,nl}\right\|^2{}_F\left\|H_{i,rdnl}\right\|^2{}_F + \left\|H_{i,sdnl}\right\|^2{}_F\right)} \tag{5.25}$$

$$\gamma_{j,nl} = \frac{E_s}{N_0\left\|W_{i,EGCzfnl}\right\|^2{}_F\left(2 + \alpha^2{}_{nl}\left\|H_{i,rdnl}\right\|^2{}_F\right)} \tag{5.26}$$

MMSE detection scheme: In this scheme the transmitted signal x_{nl} for Equations (5.15) and (5.19) can be estimate by minimizing the mean square error (MSE), MMSE detection matrix as [22]

$$W_{MRCmmse\;nl} = \left(H^{H}{}_{nl}H_{nl} + N_0 I_{N_s}\right)^{-1}H^{H}{}_{nl} \tag{5.27}$$

$$W_{EGCmmse\;nl} = \left(G^{H}{}_{nl}G_{nl} + N_0 I_{N_s}\right)^{-1}G^{H}{}_{nl} \tag{5.28}$$

Multiplying Equation (5.15) by Equation (5.27) and Equation (5.9) by Equation (5.28), the estimate signal $\widehat{x_{nl}}$ is

$$\begin{bmatrix}y_{1nl}\\ y_{2nl}\end{bmatrix} = W_{MRCmmse\;nl}\underbrace{\begin{bmatrix}u_{11\,nl} & 0\\ 0 & u_{22\,nl}\end{bmatrix}}_{H_{nl}}\begin{bmatrix}x_{1\,nl}\\ x_{2\,nl}\end{bmatrix} + W_{MRCmmse\;nl}\begin{bmatrix}\tilde{n}_{11nl}\\ \tilde{n}_{21nl}\end{bmatrix} \tag{5.29}$$

$$\begin{bmatrix}y_{1nl}\\ y_{2nl}\end{bmatrix} = W_{EGCmmse\;nl}\underbrace{\begin{bmatrix}g_{11\,nl} & g_{12\,nl}\\ g_{21\,nl} & g_{22\,nl}\end{bmatrix}}_{G_{nl}}\begin{bmatrix}x_{1\,nl}\\ x_{2\,nl}\end{bmatrix} + W_{EGCmmse\;nl}\begin{bmatrix}\tilde{n}_{011nl}\\ \tilde{n}_{021nl}\end{bmatrix} \tag{5.30}$$

From Equations (5.29) and (5.30) the post SNR detection for MMSE detection are given by:

$$\gamma_{i,nl} = \frac{\left|W_{i,MRCmmse\;nl}\right|^2\left(E_s\left(|h_{i1\,dsnl}|^2 + |h_{i2\,dsnl}|^2\right) + \frac{E_s}{4}\alpha_{nl}\left(|f_{i1\,nl}|^2 + |f_{i2\,nl}|^2\right)\right)^2}{N_0\left\|W_{i,MRCmmse\;nl}\right\|^2{}_F\left(\left\|F_{i,nl}\right\|^2{}_F + \alpha^2{}_{nl}\left\|H_{i,rdnl}\right\|^2{}_F + \left\|H_{i,sdnl}\right\|^2{}_F\right)} \tag{5.31}$$

$$\gamma_{i,nl} = \frac{E_s \left|W_{i,EGCmmse\,nl}\right|^2 \left(\left|E_s h_{i1\,dsnl} + \frac{E_s}{4} \alpha_{nl} f_{i1\,nl}\right|^2 + \left|E_s h_{i2\,dsnl} + \frac{E_s}{4} \alpha_{nl} f_{i2\,nl}\right|^2 \right)^2}{N_0 \left\|W_{i,EGCmmse\,nl}\right\|^2_F \left(2 + \alpha^2{}_{nl} \left\|H_{i,rdnl}\right\|^2_F\right)} \quad (5.32)$$

ML detection scheme: Maximum likelihood (ML) detection calculates the Euclidean distance between the received signal vector in Equations (5.15) and (5.19), and the product of all possible transmitted signal vectors with the given channel H_{nl}, G_{nl}, and select the $\widehat{x_{nl}}$ with the minimum distance metrics [25]

$$d^2(y_{1nl}, u_{11nl} x_{1nl}) + d^2(y_{2nl}, u_{22nl} x_{2nl}) \quad (5.33)$$

$$d^2(y_{1nl}, g_{11nl} x_{1nl}) + d^2(y_{2nl}, g_{22nl} x_{2nl}) \quad (5.34)$$

The ML detection determines the estimate of the transmitted signal vector x as

$$\hat{x}_{nl} = \underset{\{\hat{x}_{1nl}, \hat{x}_{2nl}\} \in c}{arg\min} \|y_{nl} - H_{nl} x_{nl}\|^2 \quad (5.35)$$

$$\hat{x}_{nl} = \underset{\{\hat{x}_{1nl}, \hat{x}_{2nl}\} \in c}{arg\min} \|y_{nl} - G_{nl} x_{nl}\|^2 \quad (5.36)$$

Where c is set of signal constellation symbol point possible value of $\{\hat{x}_{1nl}, \hat{x}_{2nl}\}$

The post detection SNR $\gamma_{j,nl}$ MRC and EGC of the receive signal at the output of ML respectively from Equations (5.35) and (5.36) given by

$$\gamma_{i,nl} = \frac{\left(E_s(|h_{i1\,dsnl}|^2 + |h_{i2\,dsnl}|^2) + \frac{E_s}{4} \alpha_{nl} (|f_{i1\,nl}|^2 + |f_{i2\,nl}|^2)\right)^2}{N_0\left((|f_{i1\,nl}|^2 + |f_{i2\,nl}|^2)\left(1 + \alpha^2{}_{nl} \sum_{k=1}^{N_r} |h_{ik\,drnl}|^2\right) + |h_{i1\,dsnl}|^2 + |h_{i2\,dsnl}|^2\right)} \quad (5.37)$$

$$\gamma_{i,nl} = \frac{\left(\left|E_s h_{i1\,dsnl} + \frac{E_s}{4} \alpha_{nl} f_{i1\,nl}\right|^2 + \left|E_s h_{i2\,dsnl} + \frac{E_s}{4} \alpha_{nl} f_{i2\,nl}\right|^2 \right)^2}{N_0(2 + \alpha^2{}_{nl}(|h_{i1\,drnl}|^2 + |h_{i2\,drnl}|^2))} \quad (5.38)$$

The adaptive modulation threshold for AF VBLAST ZF, MMSE and ML detection using MRC is determined by the post detection SNR constraints given by Equations (5.25), (5.31) and (5.37) respectively evaluated for each of the modulation types in use as a function of channel state information. In next chapter their performance simulations will be considers.

5.5. Complexity Analysis

General Adaptive modulation and cooperative MIMO techniques bring about substantial gains in rate and reliability performance, although usually at the expense of prohibitive algorithmic complexity. In the multi-dimensional delay and outage limited channels brought to the fore by radio networks, the aspects of rate, reliability and algorithmic complexity constitute interrelated bottlenecks that need to be jointly analyzed and handled. 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. Complexity is commonly measured in floating point operations, i.e., flops (summations, multiplications, etc.), which are required to compute the estimate of the transmitted vector or the running time of the algorithm when implemented on some specific platform [44]. This running time, may be defined in literature as time latency or CPU. The comparison of the EGC and MRC in terms of the detectors complexity design will be investigated in this section. This complexity will be computed in terms of real summations and multiplications, which is measure proportional to the running time. Before determining the complexity of adaptive modulation of cooperative MIMO VBLAST algorithms, first will introduce a number of general rules [13], [44], namely,

- Two complex multiplications requires 4 real multiplications and 2 real summations whereas two complex summations consists of only 2 real summations
- Product of two complex matrices A and B with dimensions $M \times N$ and $N \times P$ equals $2MP(2N-1)$ real summations and $4MNP$ real multiplications
- Inverses of Matrices of C with dimensions $N \times N$ has a complexity of $4N^3$ real summations and $4N^3$ real multiplications
- Complexity of a slicer is minimal in terms of real summations is $\log_2 M$, for M-PSK and M-QAM constellation scheme
- Finding the minimum N value has a complexity of $N-1$ real summations

5.5.1. Computational complexity of adaptive modulation for cooperative MIMO with different detection mechanisms

Based on these general assumptions given in section 5.5, the complexities of ZF, MMSE and ML for adaptive cooperative MIMO VBLAST detection techniques are determined and compared in the following section. From Equations (5.10) and (5.11), the equivalent channel matrices H_{nl} and G_{nl} are

$$H_{nl} = H^{H}{}_{sdnl}H_{sdnl} + (H_{rdnl}H_{srnl})^{H}H_{rdnl}\alpha_{nl}H_{srnl} \tag{5.39}$$

$$G_{nl} = H_{sdnl} + H_{rdnl}\alpha_{nl}H_{srnl} \tag{5.40}$$

The dimension H_{nl} is $N_s \times N_s$ for MRC and G_{nl} is $N_d \times N_s$ for EGC techniques are used to analyze the computational complexity of the ZF, MMSE and ML detection. The complexity figures are split in complexity number for preamble processing (computing the pseudo inverse of the channel matrix and SNR calculation) and a complexity number for the payload processing (linear convolution of equalizer weights and received signal vector). The detail of computational complexity of each mechanism is presented in the following sub sections.

Complexity of Zero-Forcing:

From Equations (5.21) and (5.22), the Zero Forcing technique is based on calculation of the pseudo-inverse of the channel transfer matrices $H_{nl} and\ G_{nl}$. Because it is assumed that the MIMO system is operating in quasi-static environment, i.e., channel state information is constant during transmission of symbols, the pseudo-inverse of the channel transfer matrices $H_{nl} and\ G_{nl}$ needs to be calculated only once per transmitted MIMO vector. We consider separated the calculation of the pseudo-inverse of the channel transfer matrix, i.e., preamble processing from the payload processing. For determining the complexity of the calculation of the pseudo-inverse (preamble), equation 5.21 and 5.22 are used.

$$W_{MRCzfnl} = (H^{H}{}_{nl}H_{nl})^{-1}H^{H}{}_{nl}\ \ and\ \ W_{EGCzfnl} = (G^{H}{}_{nl}G_{nl})^{-1}G^{H}{}_{nl}$$

The dimensions of $W_{MRCzfnl}$, $H^{H}{}_{nl}$ and H_{nl} are $N_s \times N_s$ for MRC technique and $W_{EGCzfnl}$, $G^{H}{}_{nl}$ and G_{nl} are $N_s \times N_d$, $N_s \times N_d$ and $N_d \times N_s$ respectively for EGC technique.

The process to calculate the ZF equalizer filter matrix $W_{EGCzfnl}$is divided into four steps.

Step 1 involves multiplication of $G^{H}{}_{nl}\, with\, G_{nl}$, it requires $4{N_s}^2 N_d$ real multiplications and $2{N_s}^2(2N_d-1)$ real summations.

Step 2 involves Gaussian elimination matrix inversion of $G^{H}{}_{nl}G_{nl}$. According to general rules given in section 5.5, the computational complexity of Gaussian elimination matrix inversion $G^{H}{}_{nl}G_{nl}$ with dimension $N_s \times N_s$ has $4{N_s}^3$ real multiplications and $2{N_s}^2(2N_s-1)$ real summations.

Step 3 performs multiplication of $(G^{H}{}_{nl}G_{nl})^{-1}$ with $G^{H}{}_{nl}$, it requires $4{N_s}^2 N_d$ Real multiplications and $2N_sN_d(2N_s-1)$ real summations.

Finally, the total real arithmetic operations of ZF preamble process is equal to

$$4{N_s}^3 + {N_s}^2(8N_d-4) - 2N_sN_d \quad R_{SUMS} \quad and \quad 4{N_s}^3 + 8{N_s}^2N_d \quad R_{MULS} \tag{5.41}$$

Using similar approach we can find the complexity of MRC combining

$$12{N_s}^3 - 6{N_s}^2 \quad R_{SUMS} \; and \; 12{N_s}^3 \quad R_{MULS} \tag{5.42}$$

The decoded symbols with ZF mechanism (payload processing) are calculated by multiplying equalizer filter matrices $W_{MRCzfnl}\, and\, W_{EGCzfnl}$ with the receive vector y_{nl} . Which is consists of a matrix with vector multiplication per transmitted vector and a slicing step to translate the estimated elements of x_{nl} to the possible transmitted symbols. The Matrix with vector multiplication is given by

$$\widehat{x_{nl}} = W_{EGCzfnl}\, y_{nl}$$

It needs $2N_s(2N_d-1)$ real summations and $4N_sN_d$ real multiplications. As stated in section 5.5, the complexity of slicing $N_s \quad M-ary$ constellation points equals $N_s\log_2 M$ real summations.

So, the total number of real arithmetic operations per transmitted vector x_{nl} for ZF payload processing is given as

$$2N_s(2N_d-1) + N_s\log_2 M \; R_{SUMS} \; and \; 4N_sN_d\, R_{MULS} \; for\, EGC \tag{5.43}$$

$$2N_s(2N_s-1)+\ N_s\log_2 M\ \ R_{SUMS}\ and\ \ 4{N_s}^2R_{MULS}\ \ \ for\ MRC \tag{5.44}$$

Complexity of Minimum mean - squared error (MMSE): The complexity of the MMSE algorithm is almost equal to the complexity of the ZF method described in the previous sub section. For preamble processing, Equations (5.27) and (5.28) are used.

$$W_{MRCmmse\ nl}=\left({H^H}_{nl}H_{nl}+N_0I_{N_s}\right)^{-1}{H^H}_{nl}$$

$$W_{EGCmmse\ nl}=\left({G^H}_{nl}G_{nl}+N_0I_{N_s}\right)^{-1}{G^H}_{nl}$$

The calculation of this complexity has almost the same complexity as the determination of the pseudo-inverse in case of the ZF algorithm. N_0 Is real, the only different is in the preamble processing real summations, which consists of N_s additional summations. The total complexity of MMSE in the preamble process is given in Equations (5.45) and (5.46) for EGC and MRC techniques respectively.

$$4{N_s}^3+{N_s}^2(8N_d-4)-2N_sN_d\ +N_s\ \ R_{SUMS}\ and\ \ 4{N_s}^3+8{N_s}^2N_d\ \ R_{MULS} \tag{5.45}$$

$$12{N_s}^3-6{N_s}^2+N_s\ R_{SUMS}\ and\ \ 12{N_s}^3\quad R_{MULS} \tag{5.46}$$

During the payload processing, the complexity MMSE is equal to that of ZF. Which is consists of a matrix by vector product with the same dimensions and slicing.

Complexity of Maximum Likelihood (ML):

In this scheme the transmitted signal x_{nl} can be estimated by calculates Euclidean distance between the received signal vectors and the product of all possible transmitted signal vectors with the given channel and finds the one with the minimum distance. This detection can be carried out by exhaustively searching for all the candidate vectors and selecting the maximum likely one with the smallest error probability (smallest Euclidean distance).However, it has the highest computational complexity which moreover exhibits exponential growth in the number of transmit 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 [13].

Computational Complexity of Equations (5.35) and (5.36) can be divided into two parts: the processing during the preamble and processing of the payload.

In the preamble processing all the candidate vectors are determined; this will be performed by two steps,

Step 1 involves multiplication of every column of equivalent channel matrix G_{nl} with every constellation point x_{nlM}, which requires $2MN_dN_s$ real summations and $4MN_dN_s$ real multiplications.

Step 2 adding all the candidate vectors has a complexity of $2\sum_{i=1}^{N_s} M^i N_d = 2M^i N_d \frac{M^{N_s-1}-1}{M-1}$ real summations.

The total complexity of the preamble processing is given

$$2MN_dN_s + 2\sum_{i=1}^{N_s} M^i N_d = 2MN_dN_s + 2M^2N_d\frac{M^{N_s-1}-1}{M-1} \quad R_{SUMS}\ and\ 4MN_dN_s \quad R_{MULS} \tag{5.47}$$

Using same technique for MRC is

$$2M{N_s}^2 + 2\sum_{i=1}^{N_s} M^i N_s = 2M{N_s}^2 + 2M^2N_s\frac{M^{N_s-1}-1}{M-1} \quad R_{SUMS}\ and\ 4M{N_s}^2 \quad R_{MULS} \tag{5.48}$$

During payload processing the vector subtraction, square norm of the result and minimum of the squared norms have to be determined for the M^{N_s} possible x_{nl}vectors. This can be done in three steps

Step 1 computing of the vector subtraction $y_{nl} - G_{nl}x_{nli}$ has a complexity equal to $2N_dM^{N_s}$ real summations.

Step 2 performs the norms of $y_{nl} - G_{nl}x_{nli}$ for $i = 1,2 \ldots\ldots M^{N_s}$ has a complexity $(2N_d - 1)M^{N_s}$ real summations and $2N_dM^{N_s}$ real multiplications.

Step 3 finding the minimum M^{N_s} of the norms value has a complexity of $M^{N_s}-1$ real summations.

The total complexity of payload processing per transmitted vector x_{nl} for EGC and MRC are respectively given by

$$4N_dM^{N_s}-1\ \ R_{SUMS}\ and\ 2N_dM^{N_s}\ \ R_{MULS} \tag{5.49}$$

$$4N_sM^{N_s}-1\ \ R_{SUMS}\ and\ 2N_sM^{N_s}\ \ R_{MULS} \tag{5.50}$$

Note that the complexity of MLD grows exponentially with the number of transmit antennas resulted in the search for less complex algorithms.

The computational complexities of ZF, MMSE and ML in the preamble and payload processing were analyzed and discussed in previous sub sections. Based on that, next we will compare the complexity of adaptive modulation of cooperative MIMO VBLAST algorithms for each of detection techniques with different combining schemes. In order to compare the complexities, we have to express the complexity as single number in terms of equivalent summations. Expressing the number of multiplications in terms of summations is depends on the numbers of bits operation we used [45]. Assume that the algorithms will be implemented with 8-bits operation as basis; thus, the complexity of an 8-bits multiplier is ten times higher than that of an 8-bits adder. In addition we will look at the complexity of post SNR calculation. The computational complexity of SNR calculation will be evaluated based on post-detection SNR studied in Section 5.4.1. For example, Equation (5.25) with 2×2 VBLAST ZF cooperative has $57\ R_{MULS}$ and $41\ \ R_{SUMS}$ which results 611 equivalent summations.

Based on above Equations, the overall complexity, i.e., the sum of the SNR calculation, preamble and payload processing complexity, of the adaptive modulation of cooperative 2×2 VBLAST algorithm with different detection and combining techniques is summarized in the Table 5.1 [13].

Table 5.1: Overall complexity of adaptive modulation cooperative $\mathbf{2 \times 2}$ VBLAST

Combining schemes	Detection Techniques	Complexity of preamble		Complexity of payload in Terms of E_{sums}	overall complexity in terms of E_{sums}
		Complexity of channel matrix in terms of E_{sums}	Complexity of SNR calculation in terms of E_{sums}		
EGC	ZF	1080	137	$172 + 2log_2 M$	1389+ $2log_2 M$
	MMSE	1082	469	$172 + 2log_2 M$	1723+ $2log_2 M$
	ML	$4M^2 + 168M$	363	$48M^2 - 1$	$52M^2 + 168M + 362$
MRC	ZF	1032	611	$172 + 2log_2 M$	1815+ $2log_2 M$
	MMSE	1034	712	$172 + 2log_2 M$	1918+ $2log_2 M$
	ML	$4M^2 + 168M$	642	$48M^2$	$52M^2 + 168M + 642$

From table 5.1, it can be seen that the complexity of ZF and MMSE detection scheme is similar and also significantly reduces the arithmetic complexity compared to ML detection mechanisms with EGC and MRC techniques. It can be also observed that the performance improvement of the scheme with adaptive modulation is paid by a complexity increase compared to the scheme without adaptive modulation. For example, adaptive 4-QAM with MMSE detection scheme and EGC technique has a complexity of 1727 E_{sums} but without adaptive modulation the complexity is 1258 E_{sums} , i.e., adaptive one is 1.37 complexes than of non-adaptive one. However, this complexity increase factor of less than 0.5 and therefore in general it is manageable.

Chapter 6

Simulation Results

6.1. Introduction

In this chapter, Simulation results of adaptive modulation system based on cooperative MIMO in matlab environment with parameters set according to LTE standard, as highlighted in Table 6.1, are presented. Bandwidth has been fixed according to LTE specifications. In this subsection, Cooperative and non-cooperative transmissions are compared for what concerns both BER and spectrally efficiency performance metrics. For all simulations, classical relay model is considered and the channel matrix elements are independent identically distributed (i.i.d) Rayleigh fading. Suppose that the source and relay nodes are transmits with equal power. In Section 5.2 simulation parameters and assumptions are described. The physical layer parameters used for simulation of MIMO and cooperative MIMO systems are given Table 6.1.

Table 6.1: Simulation Parameters

Parameter	Type / Value
Channel	Rayleigh flat fading
Transmit, receive and relay antennas number	2,2,and 2 respectively
Transmit power	normalized at all nodes
Modulation Scheme	BPSK,QPSK,16QAM and 64QAM
Combining techniques	MRC and EGC
Detectors	ZF,MMSE and ML
MIMO scheme	Spatial multiplexing with VBLAST
Relay protocol	AF protocol
Threshold BER or BER_{th}	$BER_{th} \leq 10^{-2}$
Performance Metrics	BER and SE

6.2. Performance of 2×2 V-BLAST scheme with MRC

Figure 6.1 illustrates the BER performance of 2×2 V-BLAST with MRC using BPSK modulation for different detection scheme. It is inferred that, for a fixed BER of 10^{-3} ZF, MMSE and ML detection techniques requires SNR value approximately 24.5, 21.5 dB and 11.5 dB respectively. The Performance of ZF and MMSE detection techniques are almost same but the performance of ML is better than ZF and MMSE detections. For optimal solution of ML detection, all MN_t possible combination of transmitted symbols must be searched.

The analysis results of ZF detection is exactly match with the simulated performances. This shown that the simulation results of MIMO system for various scenarios are accordance with that the numerical results.

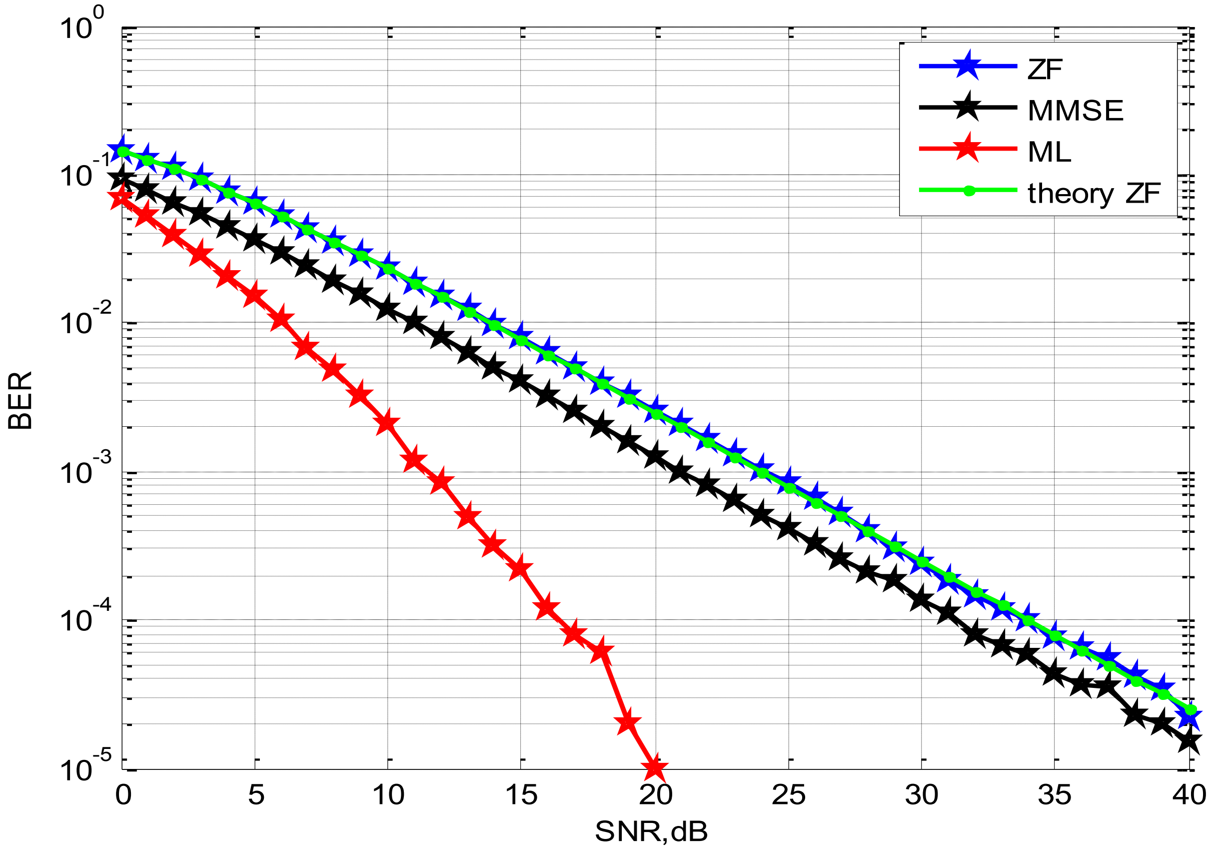


Figure 6. 1: BER performance of 2×2 V-BLAST MIMO using BPSK modulation for different detection scheme

6.2.1. Performance of 2×2 V-BLAST scheme with MRC for MMSE detection

The BER performance of 2×2 V-BLAST MIMO system with various modulations, using MMSE detection is shown in Figure 6.2. From the figure, one can see that an increase in the constellation size M affects the system's error performance. It can be seen that a transition from M = 6 to M =2 leads to a performance improvement close to 8.5 dB at a $BER\ = 10^{-3}$. From the general modulation theory, the BER performance is better for less order modulation technique as compared to high order modulation. Same behavior is also observed in simulation results of 2×2 V- BLAST MIMO system using MMSE detection. Performance is same for all modulation schemes at small value of SNR but when the SNR value increase the performance gap goes on increasing.

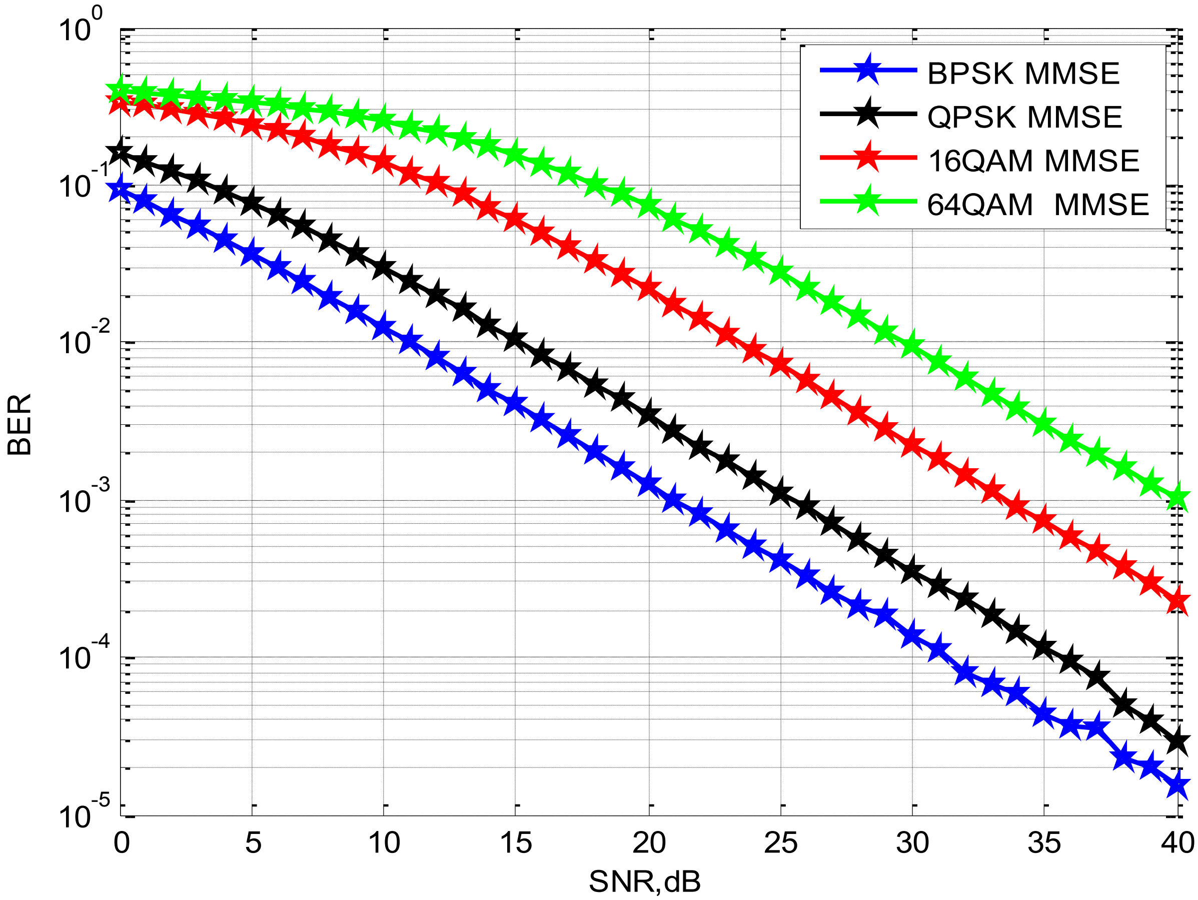


Figure 6. 2: BER performance of 2×2 V-BLAST MIMO system using MMSE detection

For different modulation

Figure 6.3 shows the simulated throughput curves of the MMSE detection using 2×2 V-BLAST MIMO for different modulation schemes. The throughput of 2×2 MIMO with VBLAST scheme at high SNR value is approach to $N_t \log_2 2^M$.where N_t and M are the number of transmit antenna and size of modulation respectively. The simulation results of MIMO with V-BLAST scheme shown in figure 6.3 is exact match with the theoretical value.

From figure 6.3, SNR Switching criterion and the corresponding modulation types are obtained, as shown in table 6.2, which is set up according to the target BER threshold. Assumed that the threshold $\xi = 10^{-2}$ so that the realistic BER will be smaller than 10^{-2} or $BER_{th} \leq 10^{-2}$.

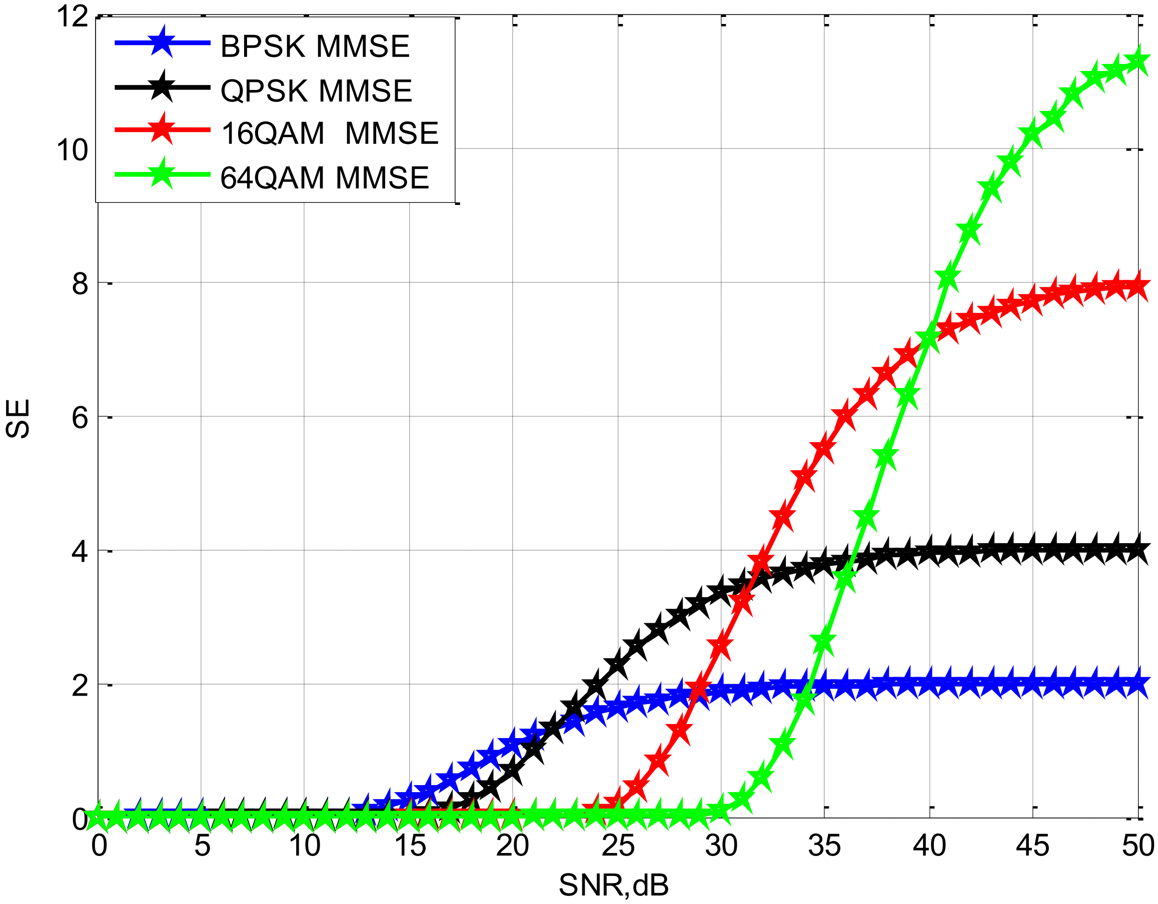


Figure 6. 3: Spectral efficiency of 2×2 V-BLAST MIMO system using MMSE detection

For different modulation

Table 6. 2: SNR switching criterion of 2×2 V-BLAST MIMO system using MMSE detection

SNR, dB, For $BER_{th} \leq 10^{-2}$	Modulation Type
< 11	No transmission
$[11, 22]$	BPSK
$(22,32]$	QPSK
$(32,40]$	16 QAM
> 40	64 QAM

Corresponding to the criterion in Table 6.2, the simulation results of the adaptive modulation 2×2 V-BLAST MIMO system for MMSE detection is presented in Figure 6.4. The probability of choosing different modulation types is shown in Figure 6.4 at low SNR, BPSK and QPSK are always selected to provide reliable communication with acceptable throughputs. As the SNR increases, 16QAM and 64QAM are chosen more frequently to obtain high throughputs.

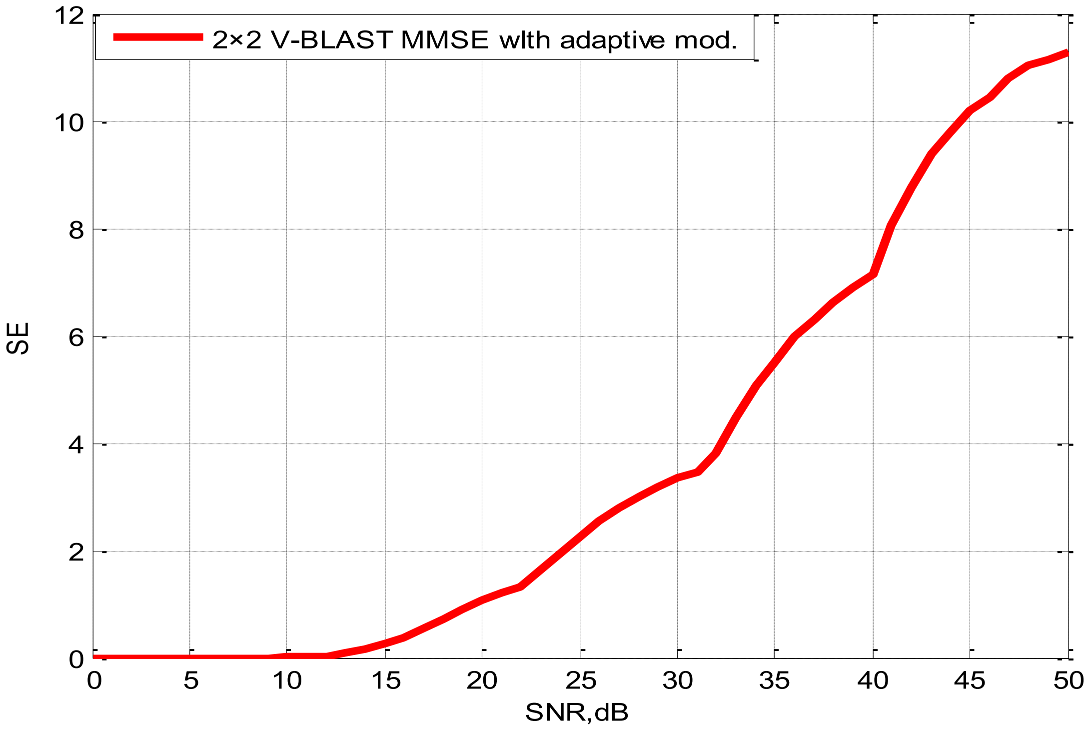


Figure 6.4: Spectral efficiency of adaptive modulation 2×2 V-BLAST MIMO using MMSE detection

In cases of fixed modulation schemes are used as shown in figure 6.3, the bandwidth efficiency is cut in half. For example if QPSK modulation is used, the system would be in outage for SNR regions between 0 and 10 dB, and would be under utilization of throughput for SNR values above 33dB for $BER_{th} \leq 10^{-2}$. Compare with the cases of fixed modulation, the adaptive modulation scheme allows the 2×2 V-BLAST MIMO system using MMSE detection to achieve a high throughput with reliable communication.

6.2.2. Performance of 2×2 V-BLAST scheme with MRC for ML detection

Figure 6.5 depict the Performance of 2×2 V-BLAST with MRC for ML detection under different modulation schemes. Comparing the performance of ML in figure 6.5 with MMSE detection techniques in figure 6.2 using QPSK modulation, it can be seen that at BER of 10^{-3}, the ML improves the performance of MMSE by 10dB.

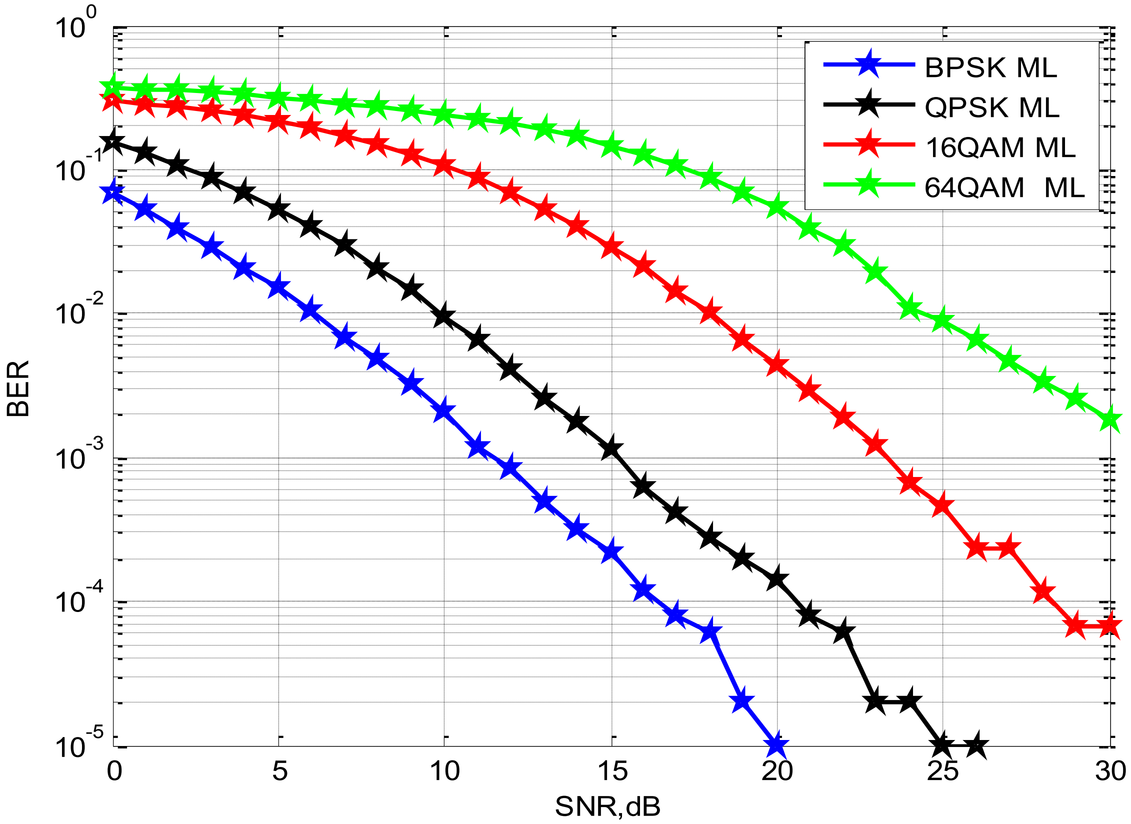


Figure 6. 5: BER performance of 2×2 V-BLAST MIMO system using ML detection for different modulation

From figure 6.2 and 6.5, the required SNR to achieve the BER of 10^{-2} for different modulation scheme summarized in Table 6.3, it is seen that performance of ML is better than MMSE detection. The detector type affects the performances of system.

Table 6. 3: Required SNR to achieve BER equal to $\mathbf{10^{-2}}$ of 2×2 V-BLAST MIMO system for different modulation

System	Modulation type	Detector		SNR gain using ML
		MMSE	ML	
2×2 MIMO	BPSK	11dB	6dB	5dB
	QPSK	15dB	10dB	5dB
	16QAM	23.5dB	18dB	4.5dB
	64QAM	29.5dB	25dB	4.5dB

Figure 6.6 depicts the throughput performance of adaptive modulation 2×2 V-BLAST MIMO system with MRC for ML detection compared to the fixed modulation for $BER_{th} \leq 10^{-2}$.

In cases of fixed modulation schemes are used (for eample 16QAM modulation), the spectral effiency for SNR greater than 32dB is limited to 8bits/sec,but in adaptive modulation spectral effiency can reach the upper limit of 12 bits/s. It is clearly seen that the throughput performance for the adaptive system is better than of fixed modulation system.

From Figures 6.4 and 6.6, adaptive modulation MIMO system for MMSE and ML respectively, it can be seen that at SNR of 20 dB the ML has throughput improvement of 26.3% over MMSE detection in 2×2 V-BLAST MIMO system. The MMSE detection technique has to pay 12 dB to achieve the same throughput. At high SNR the difference in throughput is constant of around 1bit/sec. In generally, for 2×2 V-BLAST MIMO system ML detection have greater throughput than of MMSE detection.

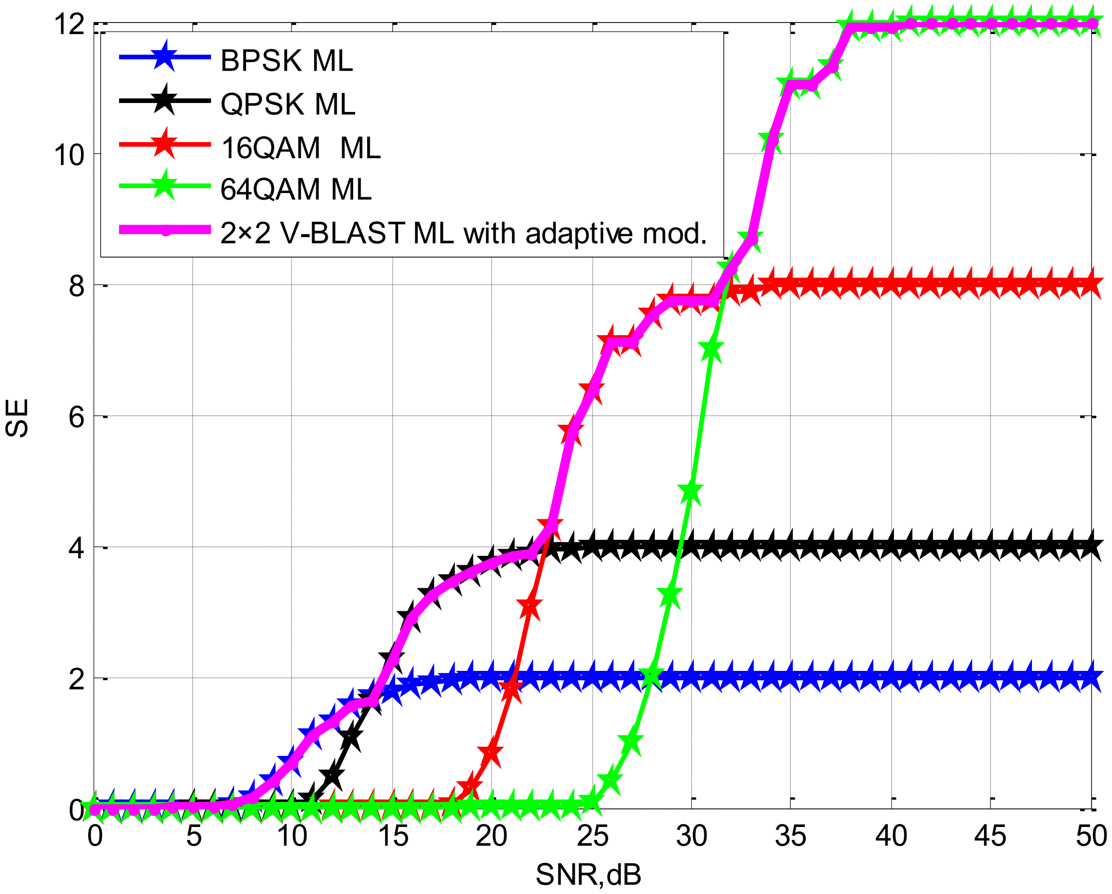


Figure 6.6: Spectral efficiency of adaptive modulation 2×2 V-BLAST MIMO using ML detection

6.3. Performance of Cooperative 2×2 V-BLAST scheme with MRC

Figure 6.7 shows the BER vs. SNR for the various Cooperative and 2×2 V-BLAST MIMO systems with BPSK modulation. The figure shows the theoretical BER values obtained in previous chapter for the cooperative systems with single antenna relay nodes as well as those obtained through simulations for all the systems. Good agreement between theoretical expectations and simulation results is observed for the cooperative diversity. From this figure, it is clear see that the simulation results of cooperative diversity for various scenarios are accordance with that the numerical results.

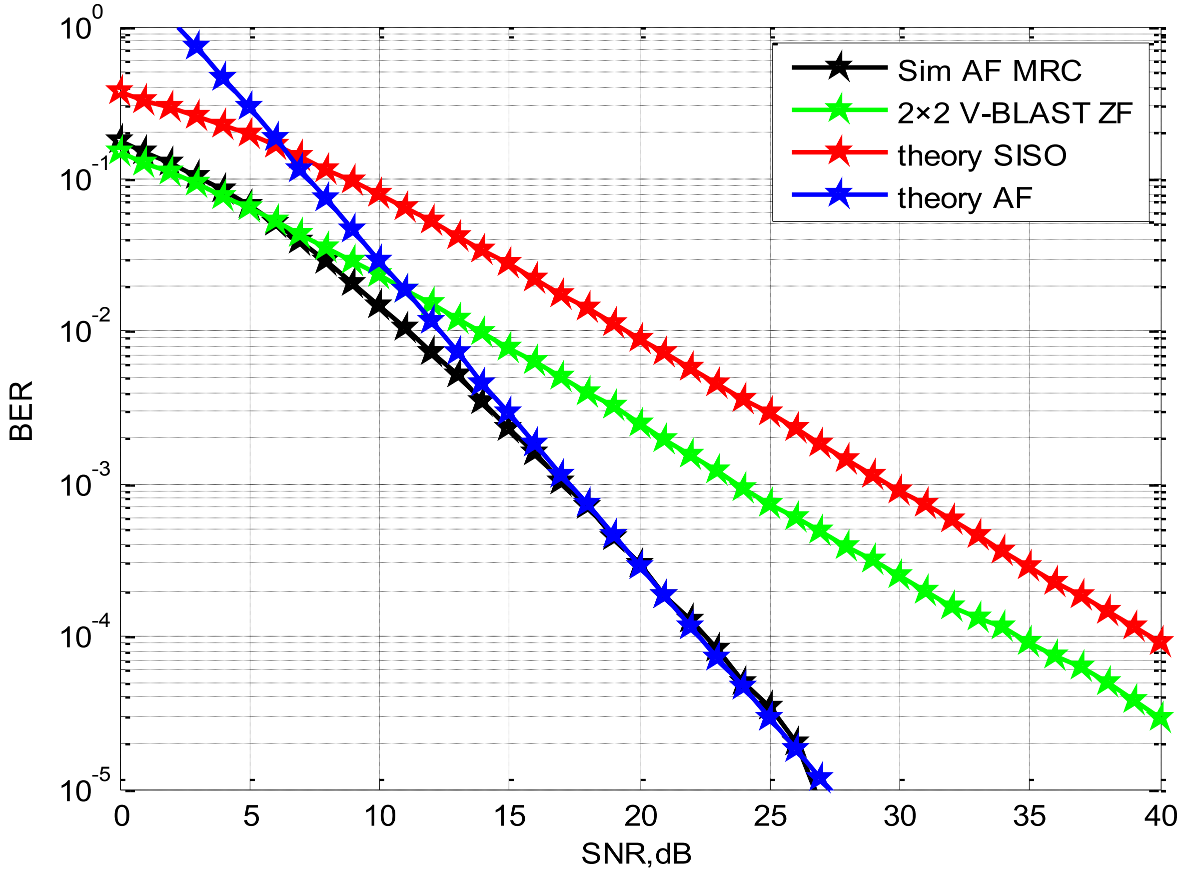


Figure 6. 7: BER performance of cooperative diversity, 2×2 V-BLAST MIMO, and SISO with BPSK modulation

As expected, when the number of antennas of each node increases, the BER performance improves. For example, at BER equal to 10^{-3}, increasing the number of single antenna source and destination nodes from 1 to 2 provides approximately 6dB gain. Moreover, at the same BER, Adding one additional AF relay node provides a 7 dB gain over the non-cooperative 2×2 V-BLAST MIMO system. This is due to two branches diversity that is resulted from direct link and the assistance link from relay. This decreases the amount of losing bits in decoding and thereby decreases the BER.

6.3.1. Performance of Cooperative 2×2 V-BLAST scheme with MRC for MMSE detection

The BER performance of the AF 2×2 V-BLAST MIMO with various modulations for MMSE and ZF detection technique is shown in Figure 6.8. From this figure, the BER performance for both detection schemes i.e., ZF and MMSE with BPSK modulation have almost the same performance in the range of $SNR \leq 18dB$, this due to enhancement of the received signal in cooperative scheme.

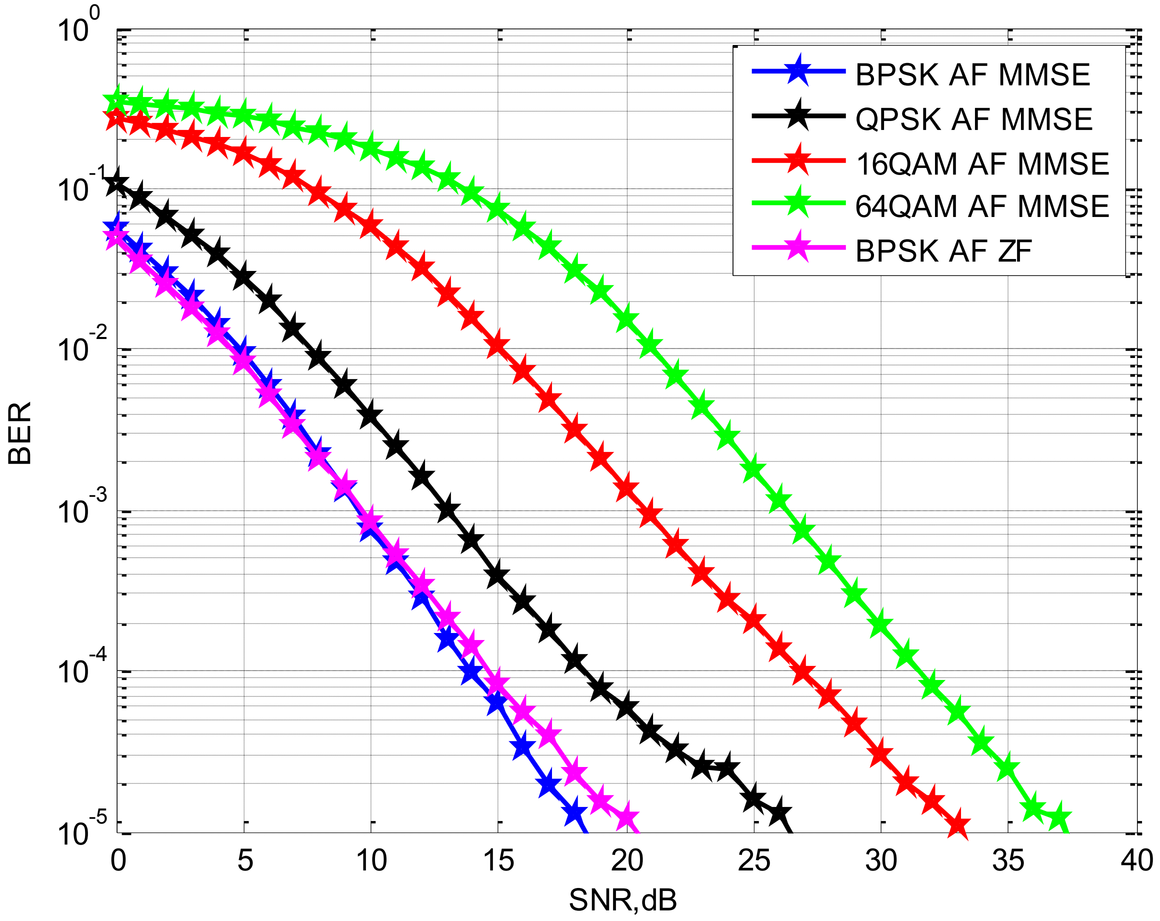


Figure 6. 8: BER Performance of Cooperative 2×2 V-BLAST MIMO system using MMSE and ZF detections for different modulation schemes

BER comparison of the non cooperative and cooperative 2×2 V-BLAST MIMO system using MMSE detection techniques are given in Figures 6.2 and 6.8 respectively. From these figures, the advantage of cooperation is well noticed by improving system performance where improvement is increase with SNR increase. For example, to have 10^{-2} BER in 2×2 V-BLAST MIMO system with BPSK modulation is used, it needs 6.5 dB more than that required without cooperation schemes. The required SNR values of the non-cooperative and cooperative 2×2 V-BLAST MIMO system using MMSE detection schemes to fulfill the target BER of 10^{-2} are given in Table 6.4. As observed from table 6.4, significant signal-to-noise ratio (SNR) improvements can be obtained by the cooperative 2×2 V-BLAST MIMO system compared 2×2 V-BLAST MIMO system to reach a target BER values.

Table 6.4: SNR gain of AF 2×2 V-BLAST MIMO over 2×2 V-BLAST MIMO system

Modulation type	System		SNR gain for Cooperative MIMO
	MIMO with MMSE	Cooperative MIMO with MMSE	
BPSK	11dB	5dB	6dB
QPSK	15dB	8dB	7dB
16QAM	23.5dB	15dB	7.5dB
64QAM	29.5dB	21dB	8.5dB

Figure 6.9 depicts the Throughput performance of Cooperative 2×2 V-BLAST MIMO system using MMSE detection as a function of SNR for different modulation and at target of $BER \leq 10^{-2}$. It is clear seen that, the spectral efficiency saturates to the half of the maximum spectral efficiency of 2×2 V-BLAST MIMO scheme shown in Figure 6.3 ,this is due to that the half-duplex transmission mode is used. From Figure 6.3, a spectral efficiency of 3 bit/sec can be achieved with a SNR of about 31 dB with 16 QAM; for the same modulation this value is reduced to about 22 dB if Cooperative 2×2 V-BLAST MIMO with MMSE scheme is used as shows in Figure 6.9. Generally noting to Figure 6.9, as the SNR increases, the system throughputs of the cooperation for all modulation mappings reach a limit of M bits/s.

The SNR switching thresholds values for adaptive modulation of Cooperative 2×2 V-BLAST MIMO system using MMSE detection are generated from figure 6.10 and listed on Table 6.5, where the target BER is set to $BER \leq 10^{-2}$.

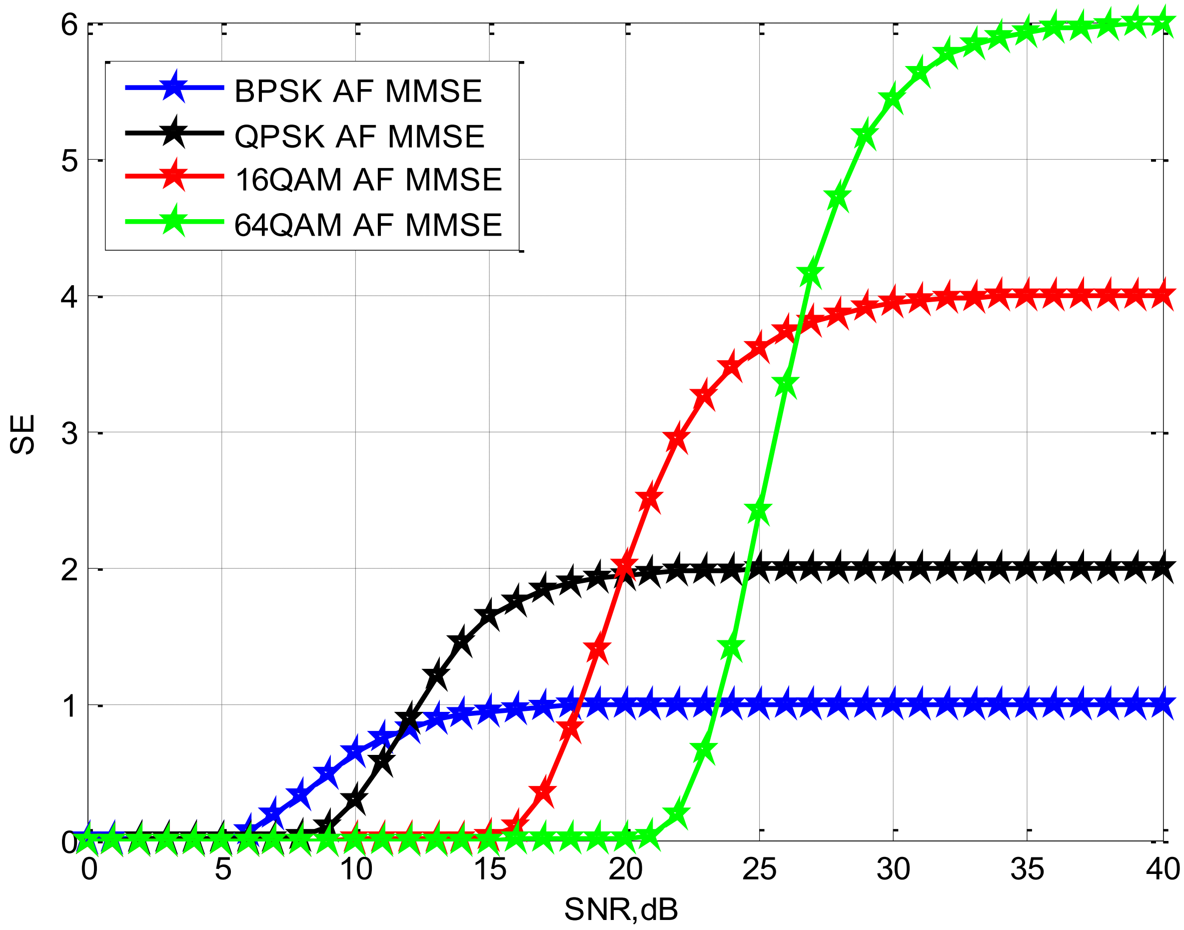


Figure 6.9: Throughput performance Cooperative 2×2 V-BLAST system using MMSE detection for different modulation

Table 6. 5: SNR switching criterion of AF 2×2 V-BLAST MIMO system using MMSE detection

SNR, dB (for $BER_{th} \leq 10^{-2}$)	Modulation Type
< 5	No transmission
[5,12]	BPSK
(12,20]	QPSK
(20,27]	16 QAM
> 27	64 QAM

Figure 6.10 illustrates the Throughput performance of adaptive modulation cooperative 2×2 V-BLAST MIMO system using MMSE detection for SNR Switching criterions are stated in Table 6.5. This clearly shows that the dynamic switching of the modulation orders can enhance the system performance and capacity per given bandwidth with the expected BER performance.

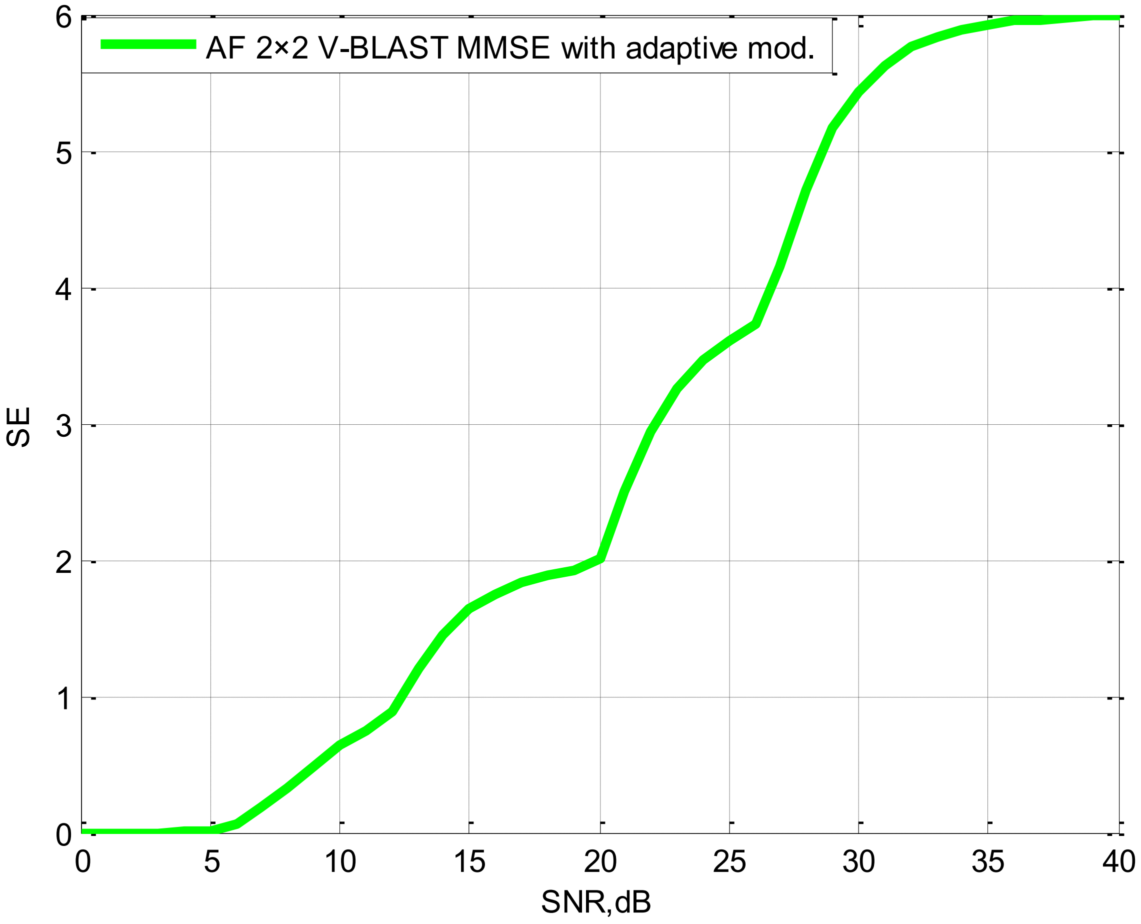


Figure 6.10: Throughput performance of adaptive modulation cooperative 2×2 V-BLAST MIMO system using MMSE detection

6.3.2. Performance of Cooperative 2×2 V-BLAST scheme with MRC for ML detection

Figure 6.11 illustrates the beneficial effect increasing the number diversity gain; this is due to the presence of cooperative AF MIMO relay in LTE network with optimal detection scheme. Observe in Figure 6.11 that the BER performance of cooperative 2×2 V-BLAST MIMO system using ML detection for different modulation improves in comparisons with that of cooperative 2×2 V-BLAST MIMO using MMSE detection and 2×2 V-BLAST MIMO systems. This figure also shows that the performance of the system degrades with the increase in the constellation size

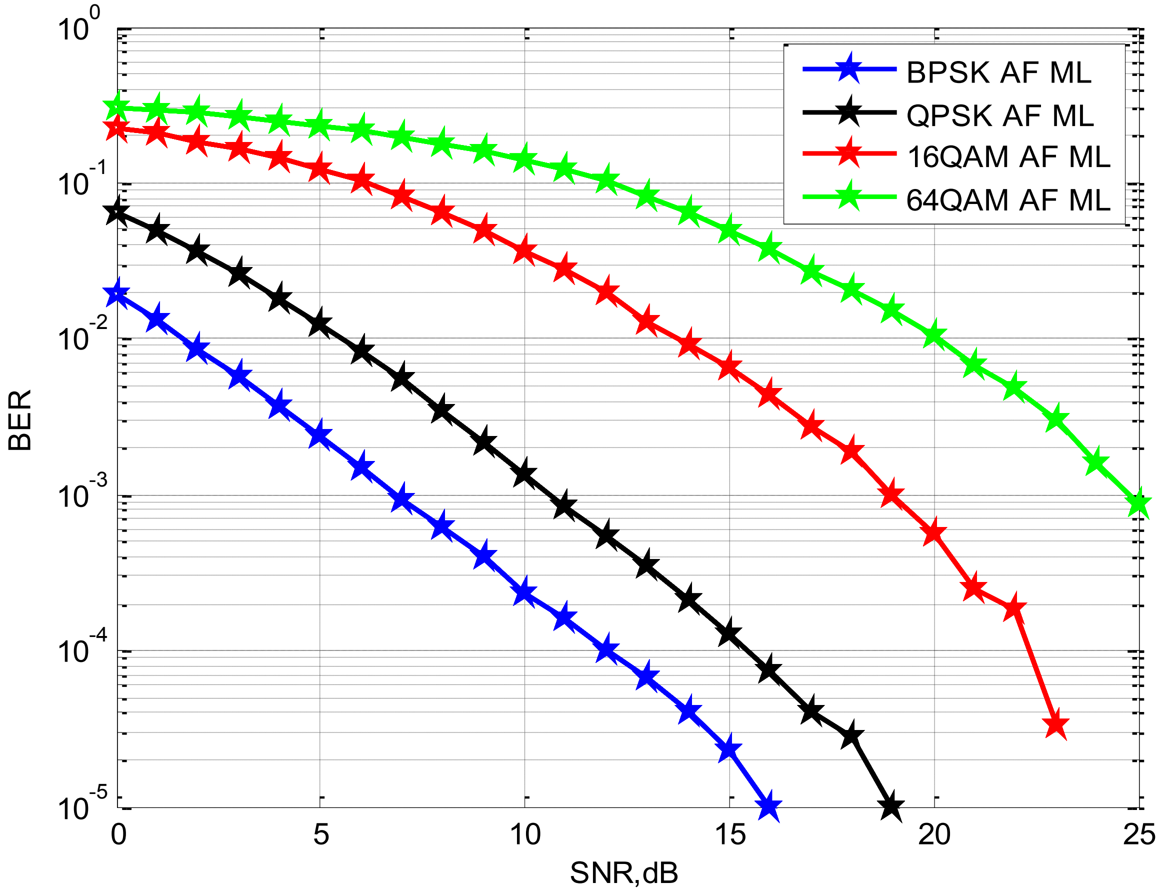


Figure 6.11: BER Performance of Cooperative 2×2 V-BLAST MIMO system using ML detection for different modulation schemes

Figure 6.12 also presents the BER performance results of cooperative AF 2×2 V-BLAST MIMO system using ZF, MMSE and ML detection techniques with QPSK modulation scheme. The 2×2 V-BLAST MIMO system for same detection is also illustrated for comparison purposes. The result revealed that at BER of 10^{-2}, there is approximately 1dB SNR difference between the ZF and MMSE detectors in 2×2 V-BLAST MIMO system. In the case of cooperative 2×2 V-BLAST MIMO system is used, the performance curves of these two detectors are close to each other, especially when the SNR is less than 11dB. The cooperative 2×2 V-BLAST MIMO system with ML detection yields a gain of about 4.5 dB over the corresponding 2×2 V-BLAST MIMO system with ML detection at a BER of 10^{-2}. The SNR gains of cooperative MIMO using QPSK modulation over non cooperative for ZF, MMSE and ML detections at a BER of 10^{-2} are listed in Table 6.6.

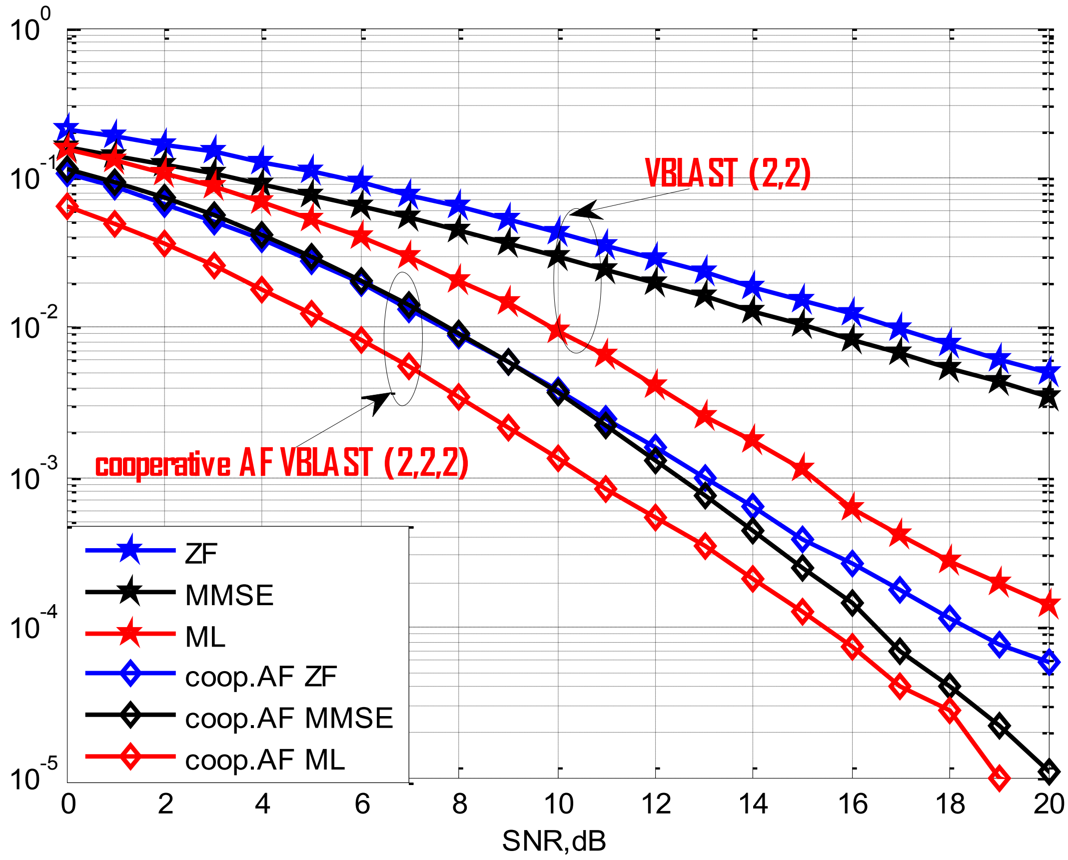


Figure 6.12: BER Performance curves of cooperative 2×2 V-BLAST MIMO system for different detectors (ML, ZF and MMSE)

Table 6. 6: SNR Gains of cooperative over non cooperative MIMO system at BER of $\mathbf{10^{-2}}$

Modulation type	Systems						SNR Gains Cooperative MIMO		
	MIMO			Cooperative MIMO					
	ZF	MMSE	ML	ZF	MMSE	ML	ZF	MMSE	ML
QPSK	16dB	15dB	10dB	8dB	8dB	5.5dB	8dB	7dB	4.5dB

Figure 6.13 shows the Throughput performance of the ML detection scheme of Figure 6.11, at target of $BER \leq 10^{-2}$. From this figure, there is no modulation scheme that gives us performance below 10^{-2} at an SNR below 3dB. In the range of 11 to 19 dB, there was only one scheme that gives us our desired performance that was QPSK. In the range of 20 to 26 dB, 16 QAM gives us performance below 10^{-2} at a better spectral efficiency. And for SNR higher than 27 dB, 64QAM provides us our desired BER performance with the best spectral efficiency. The selection of the optimal algorithm depends not only on the SNR, channel correlation, but also the target BER.

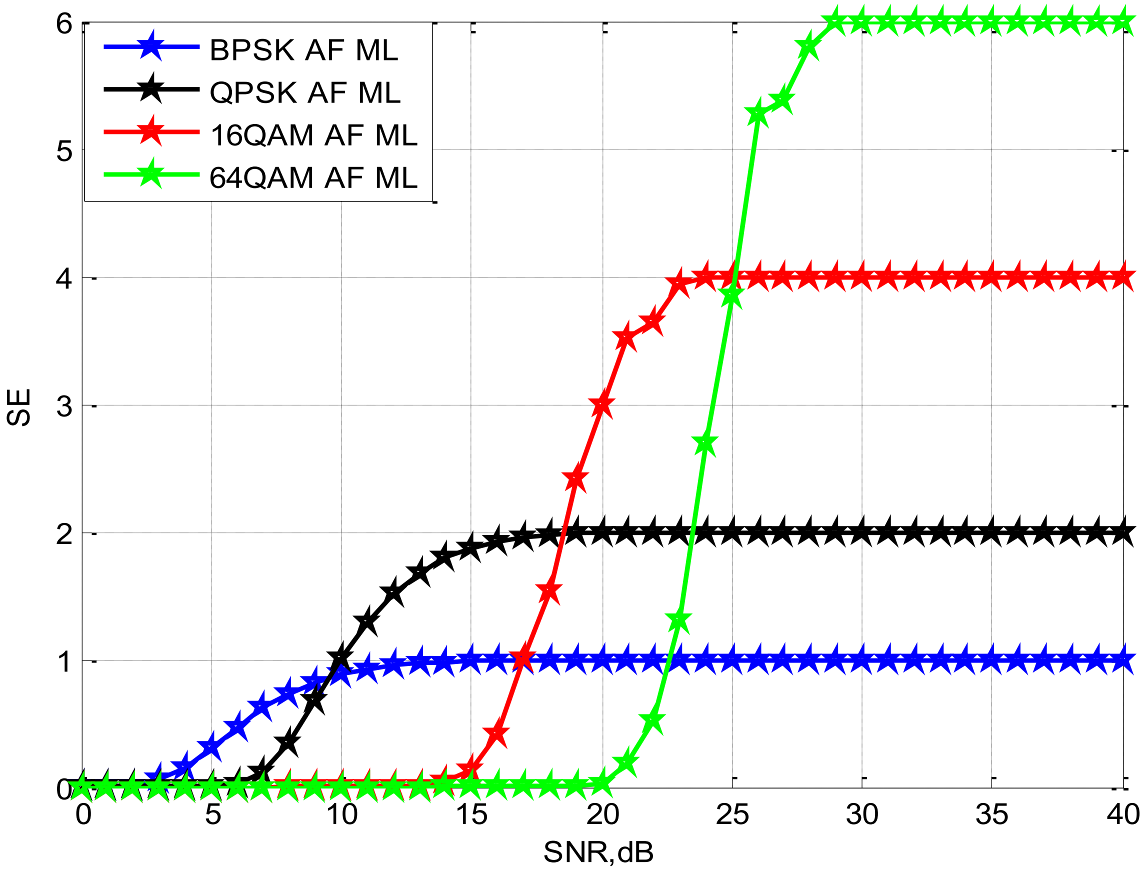


Figure 6.13: Throughput performance of Cooperative 2×2 V-BLAST system using ML detection for different modulation

Generally, with target $BER \leq 10^{-2}$, and Throughput performance plots in Figure 6.13 have the following SNR ranges for each modulation scheme:

Table 6.7: SNR switching criterion of AF 2×2 V-BLAST MIMO system using ML detection

SNR, dB (for $BER_{th} \leq 10^{-2}$)	Modulation Type
< 4	No transmission
$[4,11)$	BPSK
$[11,20)$	QPSK
$[20,27)$	16 QAM
≥ 27	64 QAM

Figure 6.14 shows the Throughput performance curve of the adaptive modulation Cooperative 2×2 V-BLAST system in conjunction with different modulation schemes for ML detection at various SNR values, as outlined in Table 6.7.

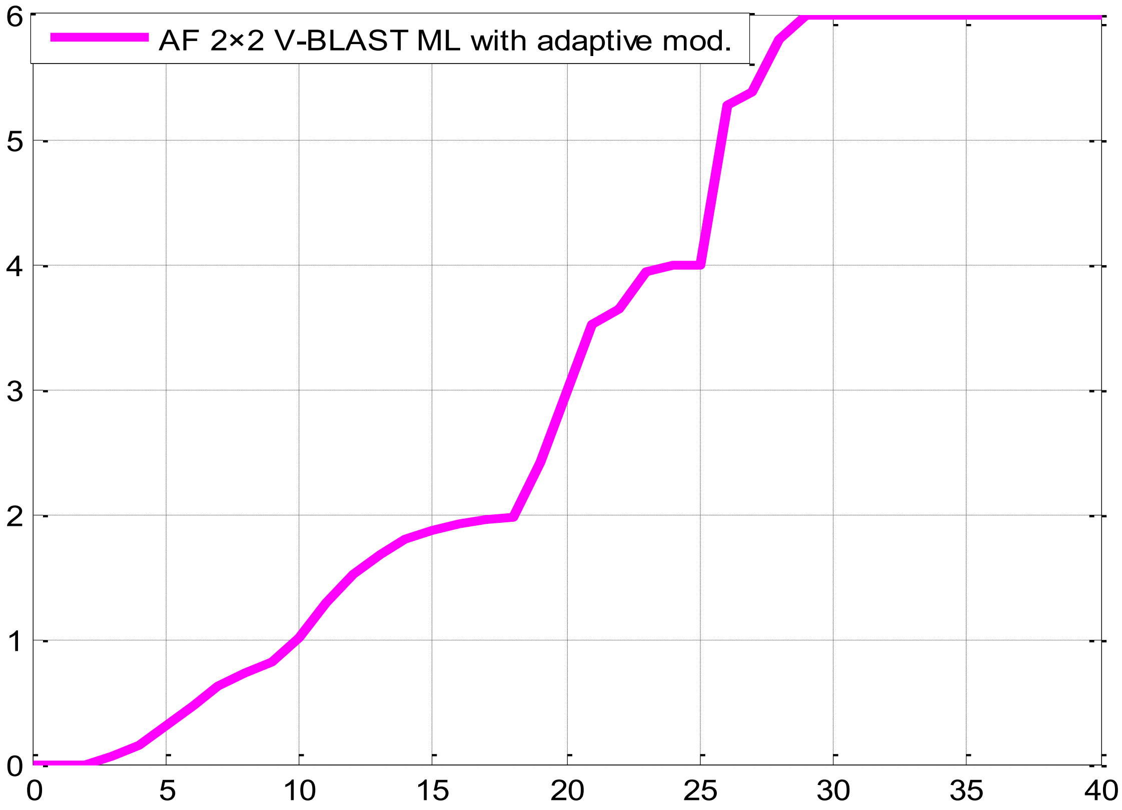


Figure 6.14: Throughput performance of adaptive modulation cooperative 2×2 V-BLAST MIMO system using ML detection

The Throughput performance of adaptive modulation cooperative 2×2 V-BLAST MIMO with MMSE and ML detections are compared in Figure 6.15. It is observe that the ML Detection technique, in contrast to the MMSE Detection technique, improves spectral efficiency by approximately 2.5dB at medium or low SNRs. However, for SNR greater than 35 dB the gap is approximately to 0dB.

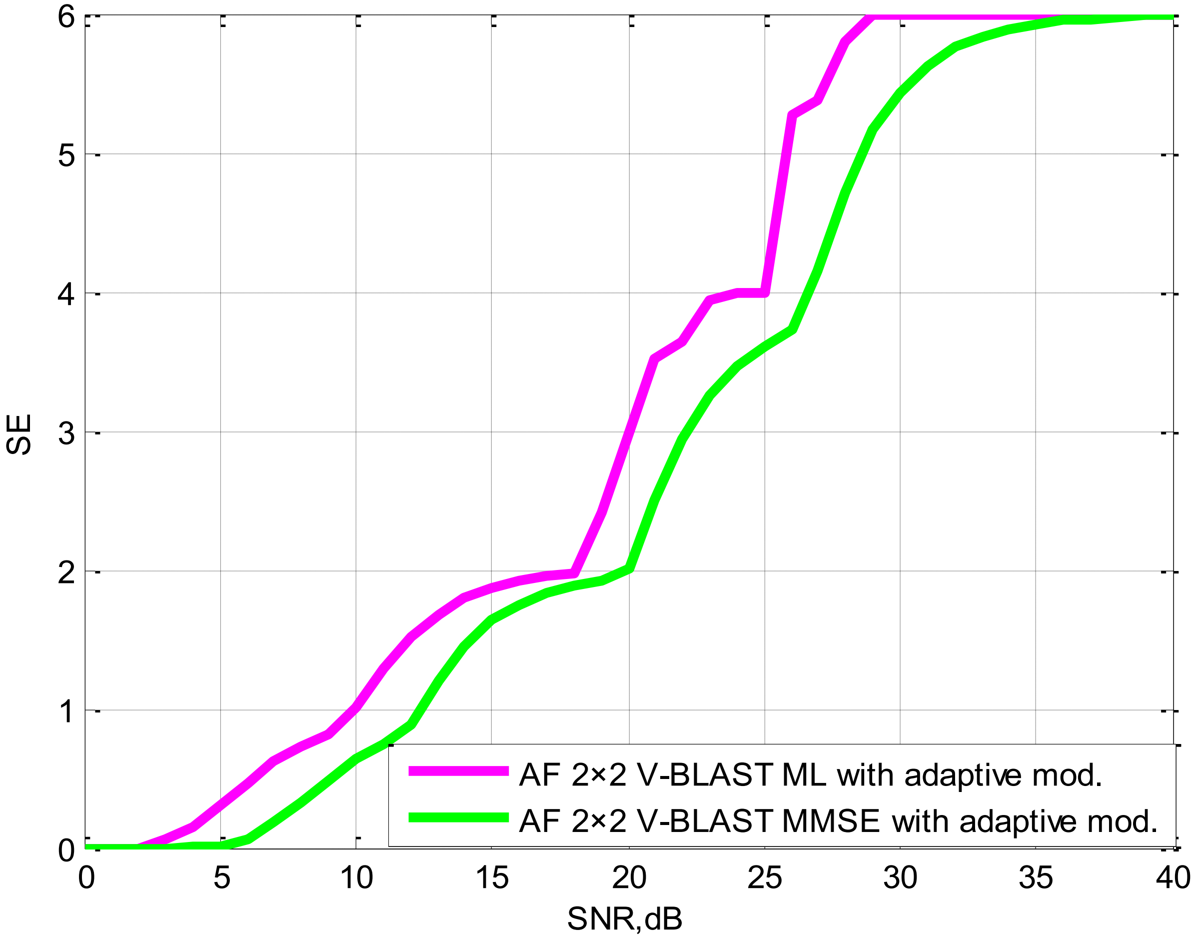


Figure 6.15: Throughput performance of adaptive modulation cooperative 2×2 V-BLAST MIMO using MMSE and ML detection

Generally, when cooperative 2×2 V-BLAST MIMO or 2×2 V-BLAST MIMO system is integrated with ZF, MMSE and ML detectors, the system with ML is achieved best performance with cost of complexity.

6.4. Performance comparison of Cooperative 2×2 V-BLAST scheme with MRC and EGC for MMSE detection

In this section, the simulation results for the AF 2×2 V-BLAST scheme with EGC and compare it with AF 2×2 V-BLAST scheme with MRC is presented. A MMSE detection Scheme for BPSK and QPSK modulations is considered. Figure 6.16 compare the BER simulation results with the MRC results obtained in the previous section for various modulation schemes. As expected, MRC outperforms the EGC for MMSE detection technique. The SNR improvement of MRC is typically about 5 dB better than with EGC.

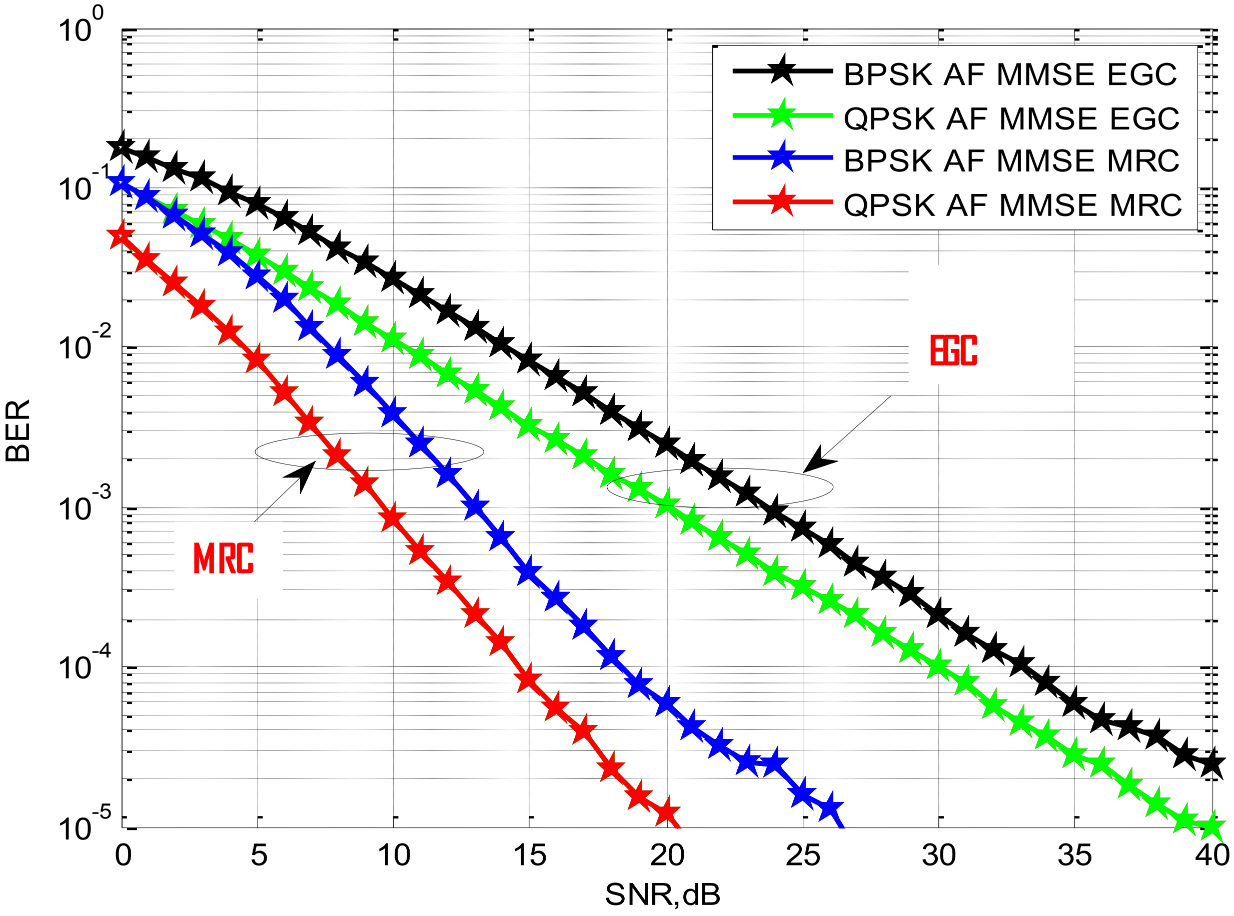


Figure 6.16: BER comparison of the Cooperative 2×2 V-BLAST scheme over MMSE detection with EGC and MRC

Generally, the performance of MRC is greater than of EGC in cooperative 2×2 V-BLAST system with MMSE at comparable complexity, as studied in section 5.5.

6.5 Adaptive Modulation of Hybrid Cooperative Networks

In previous section, simulation results of cooperative and non-cooperative MIMO combined with adaptive modulation in terms of performance metrics are considered. It is clear that the adaptive modulation is able to compensate the expense of required average spectral efficiencies due to the relaying. Moreover, it is important to decide the optimal schemes are used by the source terminal for the next transmitted frame in different SNR margins.

Hence, as a contribution of this thesis, it is advisable to investigate the optimal schemes among the adaptive modulation of hybrid cooperative MIMO schemes with MMSE detection simulated using LTE standard based cellular network were conducted in two typical scenarios. The option of ML detection is not considered further, due to its increased complexity.

Uplink Scenario

Figure 6.17 shows the throughput performance of 2×2 V-BLAST MIMO system using MMSE detection with the adaptive modulation and cooperation scheme for Uplink scenario utilizing the best modulation modes for each scheme. This figure illustrated results for cooperative MIMO at different position of relay node, $d_{sr} = d_{sd} = 1, d_{rd} = 0.2$, $d_{sr} = d_{sd} = d_{rd} = 1$ and $d_{sr} = d_{sd} = 1, d_{rd} = 2.4$.From figure 6.18, a notice remarkable that the optimum throughput is achieved when the relay is close to the destination. In fact, if the relay is very far from the destination, the sent signal will be greatly weakened before reaching the destination and hence, its cooperation cannot be effective. From this figure, it can be clearly seen that the throughput performance of the adaptive modulation cooperative MIMO network is optimal than that of the non-cooperative for SNR < 35dB. On the other hand, the throughput of the direct transmission scheme becomes better at higher SNR. This due to that the largest modulation mode (64QAM) is used, error probability and path loss effect decrease. Therefore, cooperation is activated only when the performance of 2×2 V-BLAST MIMO system is not good (at low and medium values of SNR) enough to support the aimed spectral efficiency.

Generally, It is clear to see that among cooperative 2×2 V-BLAST MIMO and 2×2 V-BLAST MIMO using MMSE detection, when the SNR is [3bB 36dB], adaptive modulation of cooperative 2×2 V-BLAST MIMO using MMSE detection for relay is close to the destination is optimal scheme; when the SNR is greater than 36dB, 2×2 V-BLAST MIMO using MMSE detection is optimal.

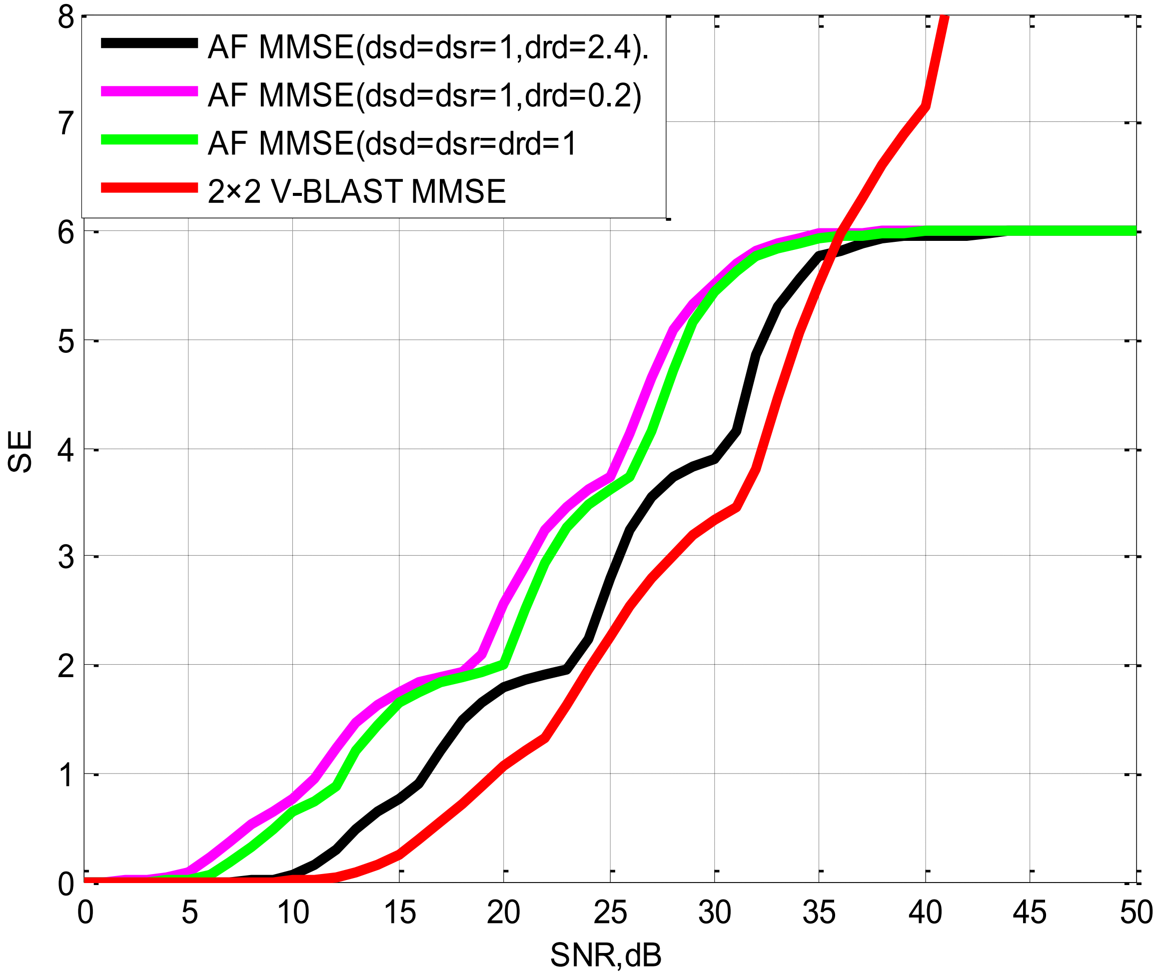


Figure 6.17: Throughput performance of 2×2 V-BLAST -MIMO system with the adaptive modulation and cooperation scheme for Uplink scenario

The objective of this thesis is to choose a constellation size M with optimal scheme (cooperative or non-cooperative scheme) that maximizes the spectral efficiency while satisfying a prescribed BER constraint. Thus, from Figure 6.17, the look up table for adaptive algorithms of uplink scenario given in Table 6.8 is proposed. This table shows the decision rule of optimal hybrid cooperative networks for a $BER \leq 10^{-2}$.

Corresponding to the criterion in Table 6.8, the simulation results of the adaptive optimum hybrid cooperative networks for uplink system is presented in Figure 6.18.

Table 6.8: SNR switching criterion of optimal hybrid cooperative networks for uplink scenario

SNR, dB (for $BER_{th} \leq 10^{-2}$)	Modulation and transmission type
< 3	No transmission
[3 12)	AF 2×2 V-BLAST with BPSK
[12 20)	AF 2×2 V-BLAST with QPSK
[20 27)	AF 2×2 V-BLAST with 16QAM
[27 36]	AF 2×2 V-BLAST with 64QAM
(36 40]	2×2 V-BLAST with 16QAM
>40	2×2 V-BLAST with 64QAM

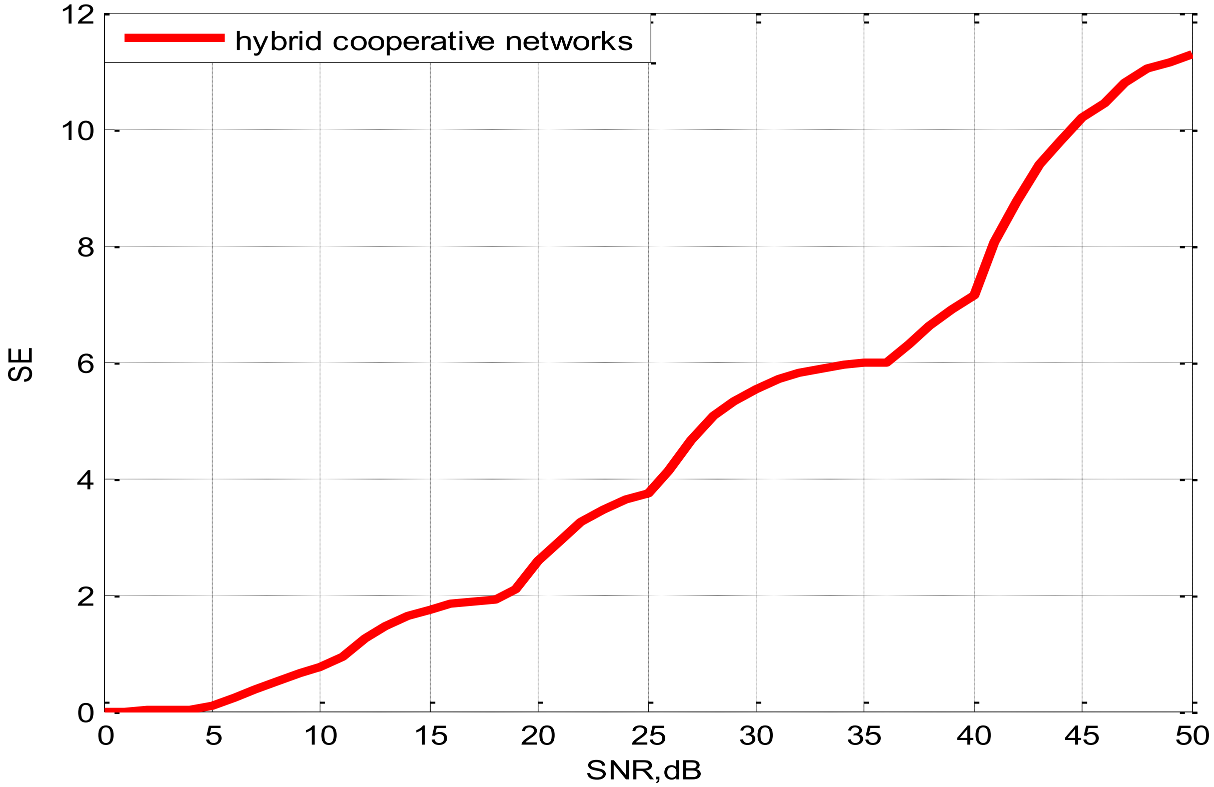


Figure 6.18: Throughput performance of optimum hybrid cooperative networks for uplink scenario

Downlink Scenario

Figure 6.19 shows the throughput performance of 2×2 V-BLAST MIMO system using MMSE detection with the adaptive modulation and cooperation scheme for Downlink Scenario. It shows that the throughput reach its optimum when the relay is close to the destination ($d_{sr} = d_{sd} = 1, d_{rd} = 0.2$). It is clear to see that if the relay is very far from the destination ($d_{sr} = d_{sd} = 1, d_{rd} = 2.4$.), cooperative MIMO does not have any advantage over 2×2 V-BLAST MIMO in terms of throughput for SNR region of [24dB 27dB] and SNR> 32dB . As a result of this, we do find that for SNR between 4 dB and 36 dB, adaptive modulation of cooperative 2×2 V-BLAST MIMO using MMSE detection for relay is close to the destination is optimal scheme(cooperation is activated) and for SNR greater than 36 dB, 2×2 V-BLAST MIMO is optimal scheme.

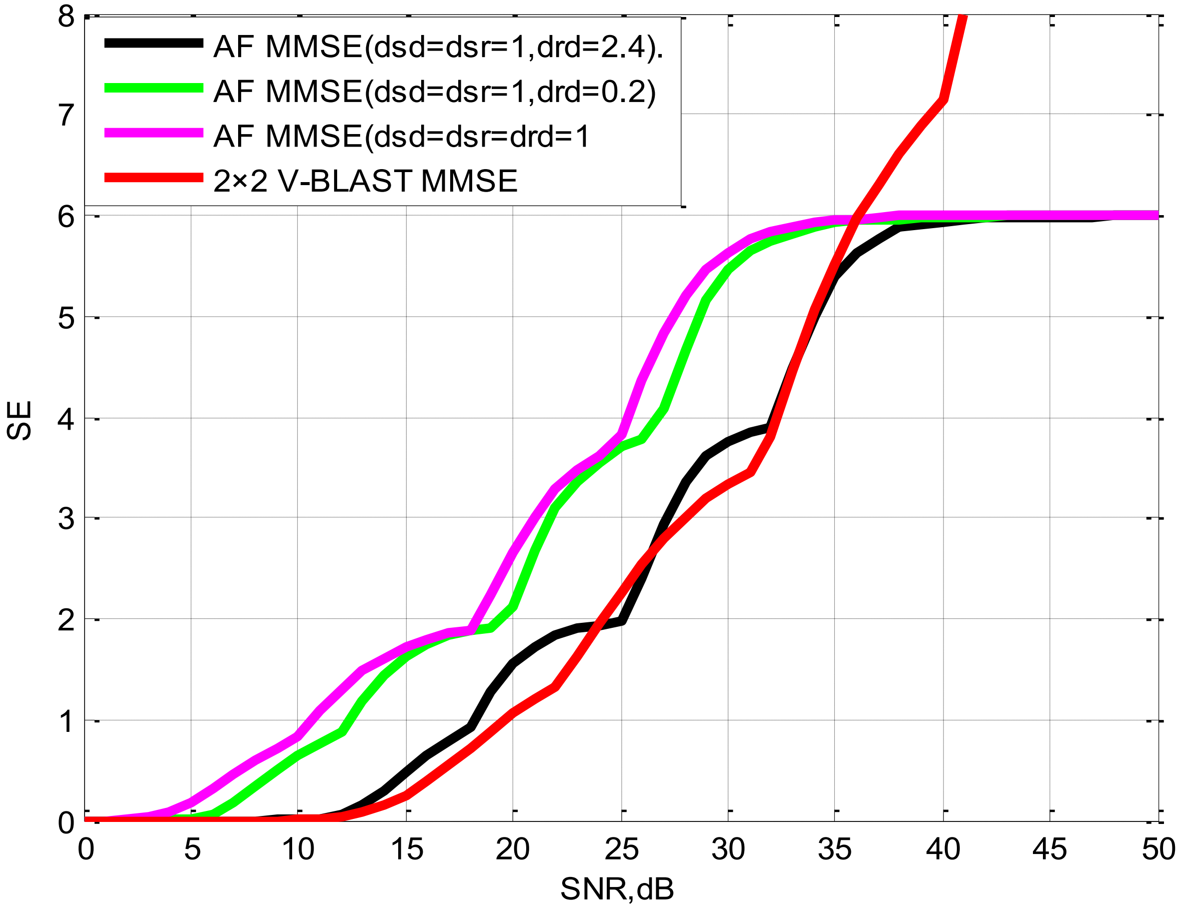


Figure 6.19: Throughput performance of 2×2 V-BLAST -MIMO system with the adaptive modulation and cooperation scheme for downlink scenario

Therefore, for a further characterization the lookup Table 6.9 can be proposed as a contribution of this thesis for downlink scenario, for $BER_{th} \leq 10^{-2}$.

Table 6. 9: SNR switching criterion of optimal hybrid cooperative networks for downlink

SNR, dB (for $BER_{th} \leq 10^{-2}$)	Modulation and transmission type
< 3	No transmission
[3 11)	AF 2×2 V-BLAST with BPSK
[11 20)	AF 2×2 V-BLAST with QPSK
[20 26)	AF 2×2 V-BLAST with 16QAM
[26 36]	AF 2×2 V-BLAST with 64QAM
(36 40]	2×2 V-BLAST with 16QAM
>40	2×2 V-BLAST with 64QAM

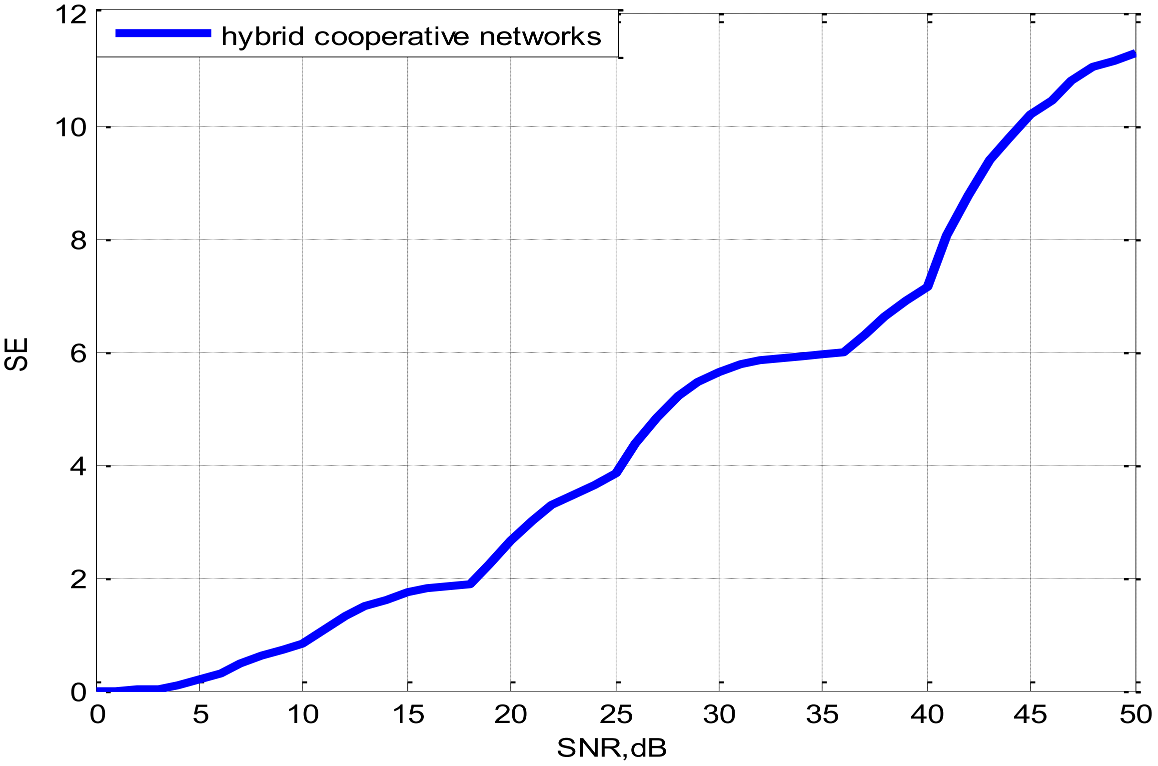


Figure 6.20: Throughput performance of optimum hybrid cooperative networks for downlink scenario

The spectral efficiency of optimum hybrid cooperative networks in downlink system based on Table 6.9 is shown in Figure 6.20. In conclusion, best performance is always reached when using adaptive modulation of hybrid cooperation at comparable complexity. Furthermore, the hybrid scheme alleviates the throughput performance loss of cooperation in the SNR >36dB regions.

Finally, if several modulations and cooperation schemes are simultaneously available at transmitter, the SNR operating point of the system will be used to make the right modulation and cooperation scheme choice from the lookup Tables 6.19 and 6.20.

Chapter 7

Conclusions and Future Work

7.1. Conclusions

In this thesis, the performance of cooperative MIMO networks together with adaptive modulation for LTE uplink and downlink system over Rayleigh fading channel are investigated. Even though cooperative communication is very important for the future of wireless networks to fight multipath effects, it suffers from an inherent decrease in throughput while attaining diversity. As a solution for this problem, adaptive modulation with target of BER to get the SNR Switching criterion margin was suggested. The particular focus was on the performance that can be achieved by using adaptive modulation and hybrid cooperation. To demonstrate the achievable performance improvements, assumed that S_R and S_D paths are equal distance; simplify the system to the $N_s = N_d = N_r = 2$ antennas case.

The simulation results of cooperative and non-cooperative 2×2 V-BLAST MIMO system using MRC technique over Rayleigh fading channel for ML, MMSE, and ZF detection schemes are analyzed. It showed that, the proposed cooperative 2×2 V-BLAST MIMO system, compared with the non-cooperative 2×2 V-BLAST MIMO, is capable of achieving superior BER performance. This performance gain comes at no penalty in complexity. The optimal detector is developed as an ML detector with prohibitive computational complexity. To overcome this complexity, a linear detector is used, namely the MMSE detector. Besides the BER results, gain in spectral efficiency of cooperative schemes with different modulations also introduced. Furthermore, the adaptive modulation were applied to different cooperation schemes to supplement the throughput loss of the system. This led to the exploration of the optimal modulation and cooperation schemes that achieves the highest spectral efficiency with cost of low complexity. The SNR Switching criterion margins of optimum adaptive modulation of hybrid cooperative networks for uplink and downlink LTE system were chosen to fulfill $BER_{th} \leq 10^{-2}$.

An illustrative example for simulation results of different relay position ($d_{sr} = d_{sd} = 1, d_{rd} = 0.2$, $d_{sr} = d_{sd} = d_{rd} = 1$ and $d_{sr} = d_{sd} = 1, d_{rd} = 2.4$) is presented. The illustrative example showed how to find the appropriate switching criterion and the system performance for uplink and downlink LTE system. The simulation result showed that, for uplink scenario, $3 \leq SNR \leq 11$ region , AF 2×2 V-BLAST with BPSK is optimal; $12 \leq SNR \leq 19$ region , AF 2×2 V-BLAST with QPSK is optimal; $20 \leq SNR \leq 26$ region , AF 2×2 V-BLAST with 16QAM is optimal; $27 \leq SNR \leq 36$ region , AF 2×2 V-BLAST with 64QAM is optimal; $37 \leq SNR \leq 40$ region , 2×2 V-BLAST with 16QAM is optimal;$SNR \geq 41$ region , 2×2 V-BLAST with 64QAM is optimal. And for downlink scenario , $3 \leq SNR \leq 10$ region , AF 2×2 V-BLAST with BPSK is optimal; $11 \leq SNR \leq 19$ region , AF 2×2 V-BLAST with QPSK is optimal; $20 \leq SNR \leq 25$ region , AF 2×2 V-BLAST with 16QAM is optimal; $26 \leq SNR \leq 36$ region , AF 2×2 V-BLAST with 64QAM is optimal; $37 \leq SNR \leq 40$ region , 2×2 V-BLAST with 16QAM is optimal; $SNR \geq 41$ region , 2×2 V-BLAST with 64QAM is optimal.

In conclusion, adaptive modulation of cooperative 2×2 V-BLAST MIMO system with comparable complexity provided a better throughput in low SNR, high SNR regime for adaptive modulation of 2×2 V-BLAST MIMO system. It was also shown that the location of the relay is crucial to the performance. The best performance was achieved when the relay is slightly closer to the destination. In general, the relay should not be too far from the destination.

Finally, for practical implementation of LTE uplink and downlink system Table 6.8 and 6.9 respectively are recommendable to ensure reliability and high throughput during data demanding service provision.

7.2. Suggestions for Future Work

Several possible extensions of the research work presented in this thesis are listed below:

- This thesis focused on 2×2 MIMO with only one relay terminal. Further improvements are expected for the case of more than two antennas and more relay terminals.
- The investigation is limited to transmission without power allocation. However, the power allocation among those cooperative terminals should be considered to guarantee fairness and efficiency of the cooperative communications. Further work will focus on the power allocation techniques.
- This thesis focused on AF relay protocol. This can be extended to other cooperative protocols, such as DF and CF relay protocols.

- This study deal with Rayleigh flat fading channel. OFDM provides an attractive and practical solution for high speed future wireless networks. It combines the data rate and spectral efficiency enhancements of SDM with the relatively high spectral efficiency and the robustness against different channel impairments. Thus, this analysis can be extended to frequency selective fading channel using OFDM technique.

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