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Hybrid BLAST Space-Time Block Code for MIMO Communication Systems

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This Thesis is Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Engineering

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Hybrid BLAST Space - Time Block Code for MIMO Communication Systems

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Abstract

The hottest issue of next generation communication systems is data throughput improvement for any wireless channel conditions. MIMO systems are the key techniques for the next generation communication systems. BLAST system achieves high data rates with acceptable BER performance over a good channels state while STBC system can achieve better BER performance even for a bad-state channel but with lower data rate than BLAST.

Hybrid BLAST-STBC system is the effective solution to achieve a good tradeoff between STBC and BLAST systems since it improves the BER performance and keep them robust over a bad MIMO channel state compared with the conventional BLAST system.

Adaptive switching system is used in order to choose the best transmit or receive scheme for some channel state. When the channel state is known at both the transmitter and the receiver, the receiver informs the transmitter through a feedback link which transmission scheme is to be used.

This thesis will study and compare the BER performance and capacity of hybrid BLAST-STBC systems at ML receiver with BLAST and STBC systems. The effect of a transmit link deep fading in 4×4 BLAST, hybrid BLAST-STBC and STBC will also be comparatively studied . At every possible case of transmit link deep fading, the best throughput system in each case is determined. Thereby, an adaptive switching hybrid 4×4 MIMO system is proposed and tested where the results stated that this system achieves the best throughput for any deep fading case. MATLAB software has been used as the main platform for system simulation.

الملخص

من أكثر المواضيع الساخنة في الجيل القادم لأنظمة الاتصالات هو تحسين و زيادة معدل إرسال و استقبال البيانات بشكل صحيح. هذا وتعتبر أنظمة لاتصالات متعددة المداخل و المخارج من التقنيات الأساسيّة في الجيل القادم لأنظمة الاتصالات.

مع العلم أن أنظمة البلاست حققت معدلات عالية لنقل البيانات بمعدل خطأ مقبول في حالة جيدة للقناة اللاسلكية بينما معدلات الخطأ في أنظمة الأكواد الزمكانية الكتلية أفضل من تلك التي حققتها أنظمة البلاست عبر قناة لاسلكية سيئة الحالة. لذلك كان النظام الهجين من البلاست و الأكواد الزمكانية الكتليّة لأنظمة الاتصالات المتعددة المداخل و المخارج الحل الفعال لتحقيق الوسطية ما بين معدلات الخطأ و سرعة نقل البيانات في ما بين نظامي البلاست و الأكواد الزمكانية الكتلية لأنه يقلل من نسبة الخطأ في الاستقبال و يحافظ عليها بشكل متين خلال حالات خاصة للقناة اللاسلكية متعددة المداخل و المخارج مقارنة مع أنظمة البلاست التقليدية.

كما و تستخدم أنظمة التبديل التكيّفي لتختار أفضل طريقة إرسال و استقبال في بعض الحالات للقناة عندما تكون حالة القناة معروفة لكل من المرسل و المستقبل عندئذ يخبر المستقبل المرسل أي طريقة إرسال يستخدم من خلال وصلة تغذية راجعة. هذه الرسالة سوف تدرس و تقارن قدرة القناة على سرعة نقل البيانات و معدل الخطأ في الاستقبال عند استخدام المستقبل المثالي في الأنظمة المهجنة من البلاست و الأكواد الزمكانية الكتليّة لأنظمة الاتصالات المتعددة المداخل و المخارج مع أنظمة البلاست و الأكواد الزمكانية التقليدية.

كما أنها سوف تدرس أيضا بطريقة المقارنة تأثير اضمحلال بعض وصلات الإرسال ما بين المرسل و المستقبل بشكل عميق في قناة متعددة المداخل و المخارج من نوع 4 × 4 لكل من نظام البلاست و الأكواد الزمكانية الكتلية و النظام الهجين بينهما. و عند كل حالة ممكنة من حالات الاضمحلال العميق لتلك القناة سيتم تحديد النظام ذو أعلى سرعة نقل بأقل نسبة خطأ. من تلك النتائج اقترح الباحث نظام تبديلي تكيفي جديد في القناة اللاسلكية من نوع 4 × 4 يستطيع التبديل بشكل تكيفي ما بين أنظمة البلاست و الأكواد الزمكانية التقليدية و النظام الهجين بينهما وتم اختباره بحيث أنه حقق أعلى سرعة نقل بيانات صحيحة في كل حالة من حالات الاضمحلال العميق لوصلات الإرسال ما بين المرسل و المستقبل.

All praises goes to Allah, the Creator and Lord of the Universe

To the sprite of my father

To my beloved mother

To my dear wife

To my children Maria, Ismail and Mira

To my dear brother

To my great family

To my special friends

To my beloved country

To all whom I love

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ABBREVIATIONS

AWGN: Additive White Gaussian Noise

BLAST: Bell Labs Layered Space-Time

BER: Bit Error Rate

bps/Hz : bits per second per Hertz

D-BLAST: Diagonal Bell Labs Layered Space-Time

DLST: Diagonal Layered Space-Time

EGC: Equal Gain Combining

HLST: Horizontal Layered Space-Time

HMTS: Hybrid MIMO Transmission Schemes

i.i.d : independent and identically distributed

MIMO: Multiple-Input Multiple-Output

ML: Maximum Likelihood

MLSTBC: Multi-Layered STBC

MMSE: Minimum Mean Square Error

MRC: Maximal Ratio Combining

MU: Multi-User

OSTBC: Orthogonal STBC

OC: Optimal Combining

OFDM: Orthogonal Frequency Division Multiplexing

QAM: Quadrature Amplitude Modulation

QOSTBC: Quasi-Orthogonal STBC

QPSK: Quadrature Phase-Shift Keying

QRD: Quadrature Residue Decomposition

SC: Switch/Selection Combining

SD: Sphere Decoding

SIC: Successive Interference Cancellation

SISO: Single-Input Single-Output

SM: Spatial Multiplexing

SNR: Signal to Noise Ratio

STBC: Space-Time Block Codes

STC: Space-Time Coded

STTC: Space-Time Trellis Codes

SVD: Singular Value Decomposition

TV: Tele-Vision

VBLAST: Vertical Bell Laboratories Layered Space Time

WLAN: Wireless Local Area Networks

ZF: Zero-Forcing

LIST OF SYMBOLS

TX: Transmitter's

RX: Receiver's

M : Number of transmit antennas

N : Number of receive antennas

$\boldsymbol{x}$: Transmitted symbol vector

A^S : Constellation set of S

S : Number of symbols in Constellation set

$h_{i,j}$: Channel coefficient between the j^{th} transmit and i^{th} receive antennas

Q : A unitary matrix

R : An upper triangular

Q^H: Hermitian of Q

y : Modified received signal vector

E_b : Average bit energy

E_s : Average symbol energy

N_o : Noise power

σ_n^2 : Noise variance

H : Channel matrix

$CN(0,1)$: Complex Gaussian distribution with zero mean and unity variance

r : Received symbol vector

n : Noise vector

C: Channel Capacity

γ: Average SNR

I_N: ($N \times N$) Identity matrix

$\widetilde{x}$: Estimated symbol

p: Number of time slots

k: Number of transmitted symbols per time slot

Rs**:** STBC coding rate

G: STBC encoder matrix

η: Spectral efficiency

K: Number of bits per symbol

O(w): Algorithm complexity of order *w*

CHAPTER 1
INTRODUCTION

1.1 Preface

Wireless channel may be subjected to several fading conditions, deep fading is a wireless channel destructive element. This thesis studies the effect of deep fading on Multi-Input Multi-Output (MIMO) channels and proposes adaptive switching transmission scheme to overcome deep-fading effects.

For every deep fading case, a suitable transmission system of Bell-Labs Layered Space Time (BLAST), Space-Time Block Codes (STBC) or Hybrid BLAST-STBC system is used. In addition, the performance of Hybrid BLAST-STBC system is widely evaluated and tested throughout this research.

This chapter gives a brief introduction about MIMO, BLAST, STBC and Hybrid BLAST-STBC systems, motivation, problem statement description and the suggested solutions. The organization of thesis will also be introduced. The research objectives are clarified in this chapter.

MIMO

The concept of exploiting the multipath channel rather than attempting to mitigate its effects was emerged in [1], it was demonstrated theoretically that it is possible to exploit the multipath channel and thereby increase the information capacity of a wireless link through receive and transmit diversity using multiple receivers and multiple transmitters MIMO system [2].

This promise of MIMO channels is remarkable. By adding more antennas at the transmitter and/or receiver, a wireless link in the multipath fading environment may have a higher information rate than a Single-Input –Single-Output (SISO) wireless link.

Recently, there are efforts on realizing both capacity and robustness gains simultaneously. In [3], the researchers established that there is a tradeoff between these two types of gains based on how fast error probability can deteriorate and how rapidly data rate can be increased with a given signal to noise ratio (SNR) [4].

Spatial Multiplexing

The first high data rate architecture was the BLAST which was proposed in [5]. In BLAST, multiple parallel data streams are spatially de-multiplexed and transmitted simultaneously on the same frequency through all transmit antennas. However, this architecture is a full spatial multiplexing scheme and it doesn't provide any transmit diversity while receive diversity is achieved on some streams depending on the receiver architecture [6].

Space Time Codes

To achieve linear processing at the receiver, Alamouti in [7] proposed a novel transmit diversity scheme where the transmitted symbols are mapped to a 2×2 space time orthogonal transmission matrix. The orthogonal design achieves maximum likelihood decoding with linear processing per transmitted symbol. Extending Alamouti's work, the researchers in [8] have designed STBC for more than two transmit antennas.

They showed that the orthogonal design couldn't provide a full transmission rate for more that two transmit antennas with complex modulation. The rate-diversity tradeoff is investigated in [9], where they designed Quasi-Orthogonal STBC or (QOSTBC) that achieves a full transmission rate for more than two transmit antennas but at half the transmit diversity.

Hybrid BLAST STBC

Space-Time Trellis Codes (STTC) is used in each BLAST layer with different transmission power [10]. In [11], the researchers introduced multi-user STBC system where STBC is associated with each layer of single user BLAST system as a way of improving energy efficiency and at the receiver. Reduced number of antennas are used to take advantage of the delay structure of STBC with minimum mean-squared error (MMSE).

Performance of Multi-Layer STBC (MLSTBC) with power allocation and pre-determined detection order is compared with equal power allocation schemes in [12], [13], where [13] compares different decoding algorithms for MLSTBC system over flat fading channels. Combining V-BLAST and STBC results in a high data rate architecture with transmit diversity in each layer. Hybrid BLAST-STBC system [14] is a BLAST system with STBC encoders in the lower layers and the other layers leaved as pure uncoded BLAST layers.

An efficient encoder and decoder were proposed in [15], the system aims to send symbols and their negative conjugates in the second time slot excepts that of the Alamouti encoded layers. It is proved that the proposed BLAST-STBC scheme can improve the BER performance obviously compared with conventional VBLAST scheme and keep the BER performance robust over MIMO channels conditions. BLAST-STBC scheme appears to be an effective solution to achieve a good trade off between diversity and multiplexing for MIMO systems.

Throughput is a key measure of the quality of a wireless data link. It is defined as the number of information bits received without error per second and this quantity would naturally to be as high as possible [16], [17]. Fading is one of wireless channel impairments that mainly affects the capacity and the symbol error rate thereby it will determine the net throughput [18].

Adaptive transmission is one of the key enabling techniques in the new generation standards for wireless systems that has been developed to achieve high spectral efficiency on fading channels [19]. Adaptive modulation [16]- [17] and [19]- [20] , switching systems [21]- [25] and antenna subset selection [26]- [31] are considered as common adaptive schemes for MIMO communication systems in high data rate next generation. MIMO antenna selection [32]- [33] achieves full transmit and receive diversity without coding or MIMO processing. These approaches require a feedback of channel state information to select the best set of transmit/receive scheme which limit their applications in high mobility environments [6].

1.2 Motivation

Day by day, wireless communication systems require significantly higher data rate and improved performance. System capacity is increased by assigning additional bandwidth which is not only expensive, but also limited. If BLAST system is used to increase the system capacity, no additional spectral resources are needed.

But in some environments, there may be a deep fade in one or more links which return us to the starting point with more power loss. Surprisingly, STBC may help to improve the BER performance of deeply faded link but with a price of decreasing the capacity; then the problem is still standing. Hybrid BLAST-STBC system gives an amazing results which considered as an intermediate performance and capacity.

The higher transmission rate and improved quality of service are the main important factors in determining the throughput of the system and the suitability of BLAST, hybrid BLAST-STBC and STBC systems to some deep fading cases. This thesis includes detailed performance, capacity and throughput analysis of those systems in some deep fading environments using ML detection techniques in MIMO system. Also, a deep understanding of the effect of some deep fading scenarios on those systems will be covered. This includes, but is not restricted to, proposing and testing a new adaptive switching technique between those system to give the maximum achievable throughput under deep fading cases.

1.3 Problem Statement

Spatial multiplexing where independent signals are transmitted simultaneously via different antennas gives good results to increase the capacity of the channel. The well-known V-BLAST is designed to maximize link spectral efficiency. However, in some environments the independent links may suffer from a considerable fading which cause decreasing in the system throughput. Space-time block codes can mitigate that problem but with occupation of at least two links to transmit one symbol in at least two time slots which decreases the number of transmitting layers and transmitted symbols. The result is a decrease in channel capacity.

Combining spatial multiplexing and STBC can provide both increased capacity and transmit diversity in one system called hybrid BLAST-STBC system. There are two types of hybrid BLAST-STBC system. The first has a dedicated number of links for BLAST transmission and for STBC transmission. The other system uses STBC encoder for every layer. Hybrid BLAST-STBC system gives a better performance but with less capacity than BLAST systems. If a deep fading occurred to one or more transmit links, both of BLAST and hybrid BLAST-STBC systems result in an unacceptable throughput which compel using more transmit power or increase system bandwidth.

1.4 Solutions

BLAST system gives an amazing results for a good state channel. Wireless channels may suffer from a varying fading in a continuous transmission process like WLAN in which a hybrid BLAST-STBC system may give better throughput than BLAST system. Also for some deep fading conditions, the STBC system may the best choice to save throughput.

There is a need to develop a new way to represent hybrid systems in which the transmission process is carried out in an adaptive switching manner between BLAST, hybrid BLAST-STBC and STBC systems. The switching is decided according to the links state or channel CSI without using neither extra power nor bandwidth.

No extra transmit antennas are needed nor switching off is needed for a deeply faded transmit link. By this way, the power wasted in a deeply faded transmit link is saved with a better throughput. Finally, the proposed system will give a better throughput with less transmit power in a deeply faded channel.

1.5 Objectives

MIMO communication system is a challenging hot topic for researchers and designers. Huge researches on MIMO data rate and performance were done recently giving the birth to variety MIMO transmission techniques to get improvement. This thesis is mainly intended to achieves the following objectives:

- To get more fundamental understanding of BLAST, STBC and hybrid BLAST STBC MIMO technologies.
- To evaluate several MIMO techniques by comparing BER performance simulations, analyzing the capacity formula and overall throughput.
- To study the effect of deep fading of transmit links for different scenarios on the effective SNR, BER performance, average capacity and whole throughput.
- To propose an Adaptive Switching Hybrid System and test it in several deep fading scenarios focusing on the whole throughput.

1.6 Thesis Organization

In chapter 2, MIMO communication theory, model, capacity, diversity and detection methods are reviewed. Also BLAST system techniques of VBLAST and DBLAST are introduced. In addition, STBC systems of Alamouti, G_4 and QOSTBC are described in more details with analysis of capacity formulas.

Chapter 3 is the core of this thesis; Hybrid BLAST-STBC MIMO systems is presented and it discusses two types of Hybrid BLAST-STBC systems. Also diversity, spectral efficiency, performance and spectral efficiency tradeoff, efficient detector and capacity formulas are introduced.

Chapter 4 states the simulation environment of this thesis and compares the BER performance and the capacity of Hybrid BLAST-STBC (G2 + 1 + 1) and (G2 + 1), MLSTBC (G2 + G2), V-BLAST, QOSTBC and G4-OSTBC and what are the advantages of Hybrid system.

Chapters 5 studies the effect of transmit antenna multipath channel deep fading on the effective received SNR, BER, capacity and throughput of 4×4 MIMO system for several transmit fading scenarios. A proposed adaptive switching hybrid system is presented and tested.

Chapter 6 concluded the most important attained results and suggested different research topics for future work.

CHAPTER 2
MIMO COMMUNICATION SYSTEMS

Next generations of wireless communication systems made a demand for high data rate with high quality systems. In other words, spectrum has become a scarce and expensive resource while the bandwidth is very limited and restricted. Transmit power is limited in addition to time/frequency domain processing are at limits, but space is not [34].

Multiple-Input-Multiple-Output (MIMO) system is a promising technology for the future communication systems. It offers a significant increase in data throughput, higher spectral efficiency (more bits per second per hertz of bandwidth), and link reliability or diversity (reduced fading) without additional bandwidth or transmit power [35]. MIMO system consists of multiple antennas at both transmitter and receiver to improve communication performance [36]. The idea is to transmit different steams of data on different transmit antennas on the same carrier frequency, then the transmitted signals might find different paths to arrive at different receive antennas through direct and indirect paths (reflections) [37]. Therefore, one receive antenna can receive signals from all M transmit antennas and sums them to one term since they are at the same frequency.

MIMO is a very attractive setup because it offers a great increase in information capacity with the cost of increased complexity only (no need for extra bandwidth nor larger power) [38].

This chapter gives an overview of the MIMO channel model, MIMO capacity and the basic open loop MIMO communication system. It covers Bell Labs Space Time (BLAST) architecture and space time block codes.

2.1 MIMO System Model

In fact the advantages of MIMO are exceeds its fundamental issue of adding diversity benefits. The mathematical nature of MIMO, where data is transmitted over a matrix rather than a vector channel, creates several new opportunities. It was shown in [5] how under certain conditions transmit *min(M,N)* independent data streams simultaneously over the eigenmodes of a matrix channel created by *M* TX and *N* RX antennas. Before *G. Foschini* [5], however the first results pointing to the capacity gains of MIMO were published by J. Winters in 1987 [1], after that in 1994 it was released in [39] for application to broadcast digital TV but a little known yet about this ground breaking result.

Let $\boldsymbol{H}$ be the channel matrix of *N* x *M* dimensions, where *M* is a number of transmit antennas and *N* is a number of receive antennas as shown in Fig.1 . In the ideal case, each path is assumed to be statistically independent from the others. Independent data can be sent from each antenna, increasing the capacity of the system.

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}$$

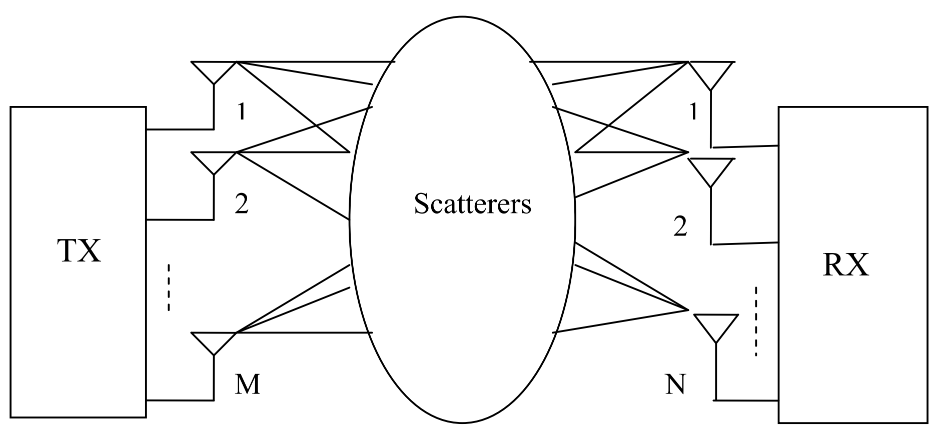


Fig. 2.1 MIMO Channel Model.

Herein, consider a transmitted vector $x = [x_1, x_2, x_3 ......x_M]^T$, The vector is then transmitted via a MIMO channel characterized by the channel matrix $\boldsymbol{H}$ whose element $h_{i,j} \approx CN(0,1)$ is the random Gaussian complex channel coefficient between the j^{th} transmit and i^{th} receive antennas with zero mean and unity variance. The received vector $r = [r_1, r_2, r_3 .....r_N]^T$ can then be give as following.

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{2.1}$$

(2.1) can be expressed as

$$\begin{pmatrix} r_1(k) \\ r_2(k) \\ \vdots \\ r_N(k) \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & \dots & h_{1M} \\ h_{21} & h_{22} & \dots & h_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1} & \dots & \dots & h_{NM} \end{pmatrix} \begin{pmatrix} x_1(k) \\ x_2(k) \\ \vdots \\ x_M(k) \end{pmatrix} + \begin{pmatrix} n_1(k) \\ n_2(k) \\ \vdots \\ n_N(k) \end{pmatrix} \tag{2.2}$$

Capacity of MIMO Systems

It was shown by Shannon that the attainable capacity for a flat fading Single Input Single Output (SISO) communication system is

$$C_{SISO} = log_2(1+\gamma\left|h^2\right|) \qquad bps/Hz, \tag{2.3}$$

where γ is the average SNR and h denotes the fading gain.

In 1998, Foschini has demonstrated that the capacity of the flat fading channel of the MIMO communication systems is given by [40]:

$$C_{MIMO} = log_2(det\,|\,\boldsymbol{I}_N + \frac{\gamma}{M}\boldsymbol{H}^H\boldsymbol{H}|) \qquad bps/Hz, \tag{2.4}$$

with the assumption that numbers of transmit and receive antennas are equal. This theoretical capacity expression for MIMO systems points out that the capacity may be increased linearly with the number of antennas [41]. Thus capacity for MIMO systems is increased in comparison to SISO systems, where the capacity increases logarithmically with SNR.

2.2 Bell Labs Layered Space-Time (BLAST) system

Transmission techniques for MIMO wireless communications may be considered under two broadly defined categories:

1. Unconstrained signaling techniques, or the so-called BLAST architectures, whose aim is to increase the channel capacity by using layered space-time codes designed using standard channel codes.
2. Space-time codes, whose aim is transmit a signal multiple times (copies) at different transmit antennas to increase system diversity.

As pointed out previously, the BLAST architecture consists of multiple antennas at both the transmitting and receiving ends of the system, as illustrated in Fig. 2. In this system, information signals are divided into sub-streams and multiple antennas (array) is used to transmit these sub-streams simultaneously on the same carrier frequency. The same frequency bandwidth is used and the total transmitted power is always held constant. At the receiving end, the transmitted signals are received by an antenna array.

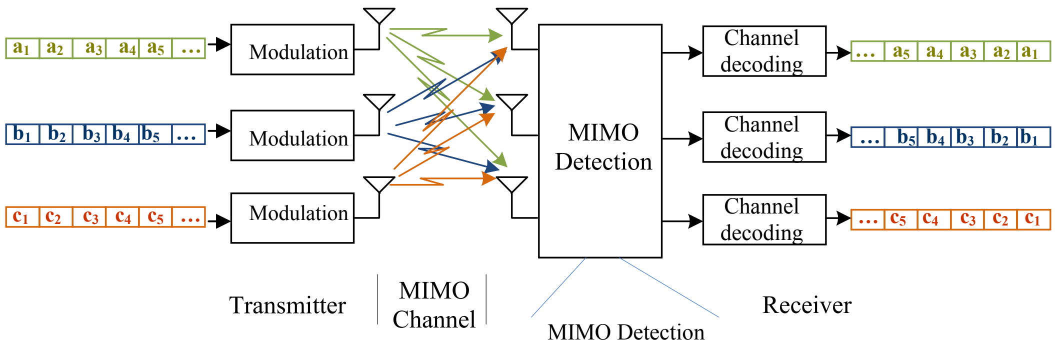


Fig. 2.2 Spatial Multiplexing System Model.

Each antenna element of the array receives all the transmitted signals as one composite signal. Even though the signals are transmitted in the same frequency band, the signals from the different transmit antennas are located at different points in space, and each signal is scattered differently. The received signal at each receive antenna element still contains useful information about the transmitted signal. Since BLAST does not require additional spectrum resources to transmit parallel sub-streams (i.e, each antenna operates in a co-channel manner), the BLAST architecture is spectrally efficient. However, the spatial multiplexing and simultaneous use of the same portion of the spectrum lead to co-antenna interference, which is the major source of channel impairment in the BLAST architecture [42].

2.2.1 DIAGONAL BLAST

The innovative feature of the D-BLAST transmitter is the space-time encoding structure constructed with *M* diagonal layering 1-D coded subsystems of equal capacity, which permits decoding complexity to grow linearly with the number of transmit antennas. However, this architecture requires the use of diagonal layering. The space-time wasted at the start and end is significant for a practical few hundred symbols, even though this boundary waste becomes negligible as the packet length increases. In general, the use of a short packet size is important in wireless communications for two reasons:

1) Long packets require channel tracking inside a packet (channels varies with time).

2) Wireless communication is usually delay-limited.

Fig. 2.3 illustrates the D-BLAST transmitter. A data stream is demultiplexed into *M* data substreams of equal rate, and each data substream is encoded independently using block encoders. Rather than transmitting each of the *M* coded substreams to an antenna, the bit stream per antenna association is periodically cycled [41].

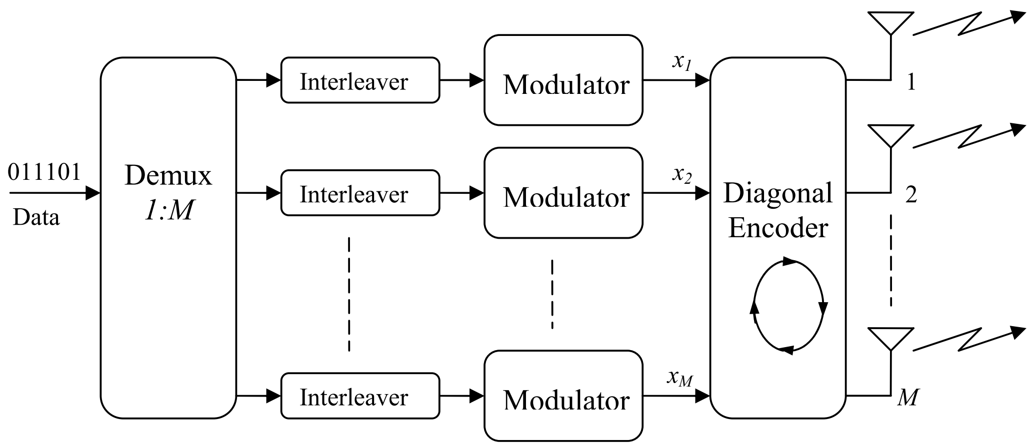


Fig. 2.3 D-BLAST Architecture.

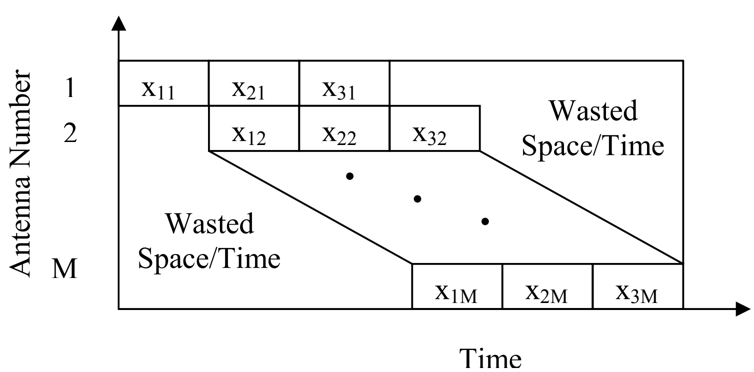


Fig. 2.4 D-BLAST Stream Rotation .

Capacity: Diagonal Layering of Space-Time

Each sub-layer of any diagonal layer will see a different level of the SNR. If we denote $\{\gamma_k\}_{k=1}^{N}$ as the generalized output SNR of sub-layers, the D-BLAST random information rate is the summation of instantaneous capacity of all the sub-layers:

$$C_D(\boldsymbol{H}) = \sum_{k=1}^{N} log_2[1+\gamma_k]$$

where (2.5)

$$\gamma_k = \frac{P}{M.\sigma^2}(\boldsymbol{H}_k \boldsymbol{H}_k^H)$$

$\boldsymbol{H}_k$ is the k^{th} row of channel matrix $\boldsymbol{H}$. The average capacity then will be :

$$C_{DBLAST} = log_2(det\,|\,\boldsymbol{I}_N + \frac{\gamma}{M}\boldsymbol{H}^H_{DBLAST}\boldsymbol{H}_{DBLAST}\,|)\ bps/Hz \quad (2.6)$$

2.2.2 VERTICAL BLAST (V-BLAST)

To reduce the computational complexity of D-BLAST, Wolniansky [43] proposed a simplified version of BLAST known as Vertical BLAST (V-BLAST), which is the first practical implementation of MIMO wireless communications in showing a spectral efficiency in real time. In V-BLAST, the incoming binary data stream is first demultiplexed into M substreams, then they might be encoded and mapped onto its own antenna for transmission over the channel independently. The final result is the conversion of the incoming binary data stream into a vertical vector of encoded substreams. Moreover, in the V-BLAST transmitter, every antenna transmits its own independently coded substream of data. Also, V-BLAST eliminates the space-time edge wastage problem in D-BLAST, the outage capacity achieved by V-BLAST for antenna configurations with $M \geq N$ is lower than that of D-BLAST [43].

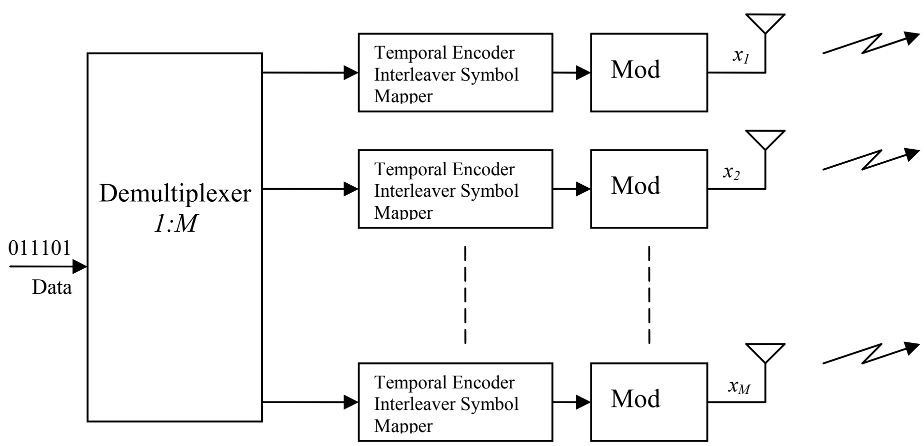


Fig. 2.5 Spatial Multiplexing Transmitter with Parallel Encoding: VBLAST.

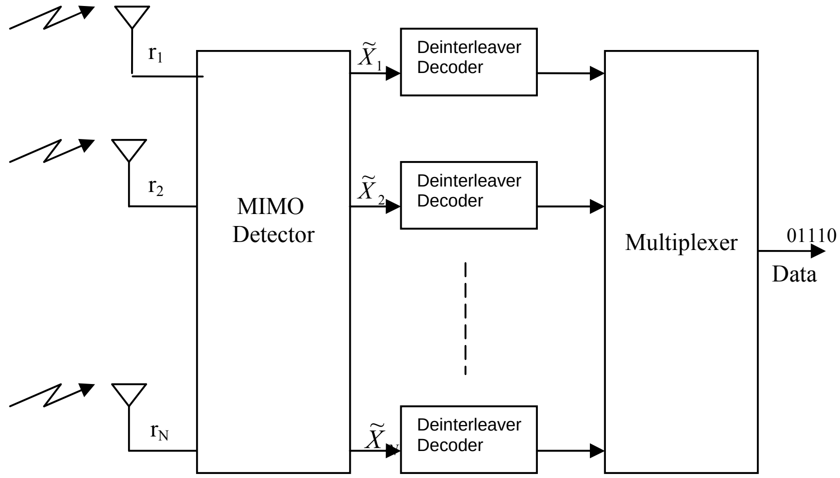


Fig. 2.6 VBLAST Receiver with Parallel Decoding.

Capacity: Vertical Layering of Space-Time

The instantaneous capacity of V-BLAST is given as the random variable [5]

$$C_{V_k}(H) = M \times \min_{k \in [1,2,....,N]} \log_2[1+\gamma_k], \tag{2.7}$$

where C_{V_k} is the capacity of V-BLAST when using all M transmit antennas, and the SNR denoted by γ_k is given by

$$\gamma_k = \frac{P}{M.\sigma^2}(\boldsymbol{H}_k \boldsymbol{H}_{\boldsymbol{k}}^H), \tag{2.8}$$

where $\boldsymbol{H}_k$ is the k^{th} row of channel matrix $\boldsymbol{H}$.

$$C_{VBLAST} = \log_2(\det|\boldsymbol{I}_N + \frac{\gamma}{M}\boldsymbol{H}_{VBLAST}^H \boldsymbol{H}_{VBLAST}|) \quad bps/Hz. \tag{2.9}$$

2.3 BLAST Detection

It is seen from [37] that the receive antennas see the superposition of all the transmitted signals. The task of a BLAST detector is to recover the transmitted data ***s*** from the received signal ***r***. Assuming perfect channel estimation (channel matrix ***H*** is known) at the receiver, the receiver can be configured by variety of detection techniques including linear, successive, tree search and maximum likelihood (ML) detector to remove (cancel) the effect of the channel and recover the transmitted substreams signals [44], [45].

ML detector is the optimal receiver in terms of bit error rate (detector performance) but it is a nonlinear detector with a high complexity. Let A^S be the symbol constellation set of QPSK whose size is 4. Then, the ML detection rule is given by:

$$\tilde{x} = arg \min_{x \in A^S} \left\| \boldsymbol{r} - \boldsymbol{Hx} \right\|^2 \tag{2.10}$$

The minimization problem is performed over all possible transmitted signal vectors $\boldsymbol{x}$ in the set A^S . The computational complexity of an exhaustive search is then $O(M^N)$. Although ML receiver is optimal, its complexity grows exponentially with the number of transmit antennas.

On the other hand, there are other detection methods (equalizers) that have a lower complexity than ML such as Zero Forcing (ZF), Minimum Mean Square Error (MMSE), Quadrature Residue Decomposition (QR), Singular Value Decomposition (SVD), Sphere Decoding (SD). Here is a simple comparison between them [16], [45], [46].

Table 2.1 Comparison of BLAST Detection Schemes.

Scheme	Performance	Complexity	Error enhancement
ZF	Worst	Very Low/Linear	Extra High
MMSE	Poor	Low/Linear	High
QRD	Good	Very Low/Nonlinear	Medium
SVD	Very Good	High	Low
SD	Near Optimum	Depend on channel	Near Minimal
ML	Optimum	Exponentially	Minimal

Successive Interference Cancellation (SIC) which considers the first detected symbol as an interference to the other undetected ones then it will cancel its effect from the received vector by subtracting it from the received vector and so on for all symbols. Additionally, The V-BLAST detector [18], [47] decodes the substreams using a sequence of nulling and cancellation steps. An estimate of the strongest transmitted signal is obtained by nulling out all the weaker transmit signals using the ZF, MMSE or QR criterion, then subtract this strongest signal from the received signal $\boldsymbol{r}$, proceed to decode the strongest signal of the remaining transmitted signals, and so on, but they have worse performance than ML.

Discussing and analyzing BLAST detection schemes are out of scope of this thesis. According to this thesis's contribution, the proposed system performance has to be evaluated and compared to BALST and STBC system. So, it must be evaluated by one detection method. ML detector is used for optimality reasons and to avoid error enhancement problem.

2.4 Diversity

In order to reduce the effects of multipath fading, diversity is a common technique that can be applied either at the transmitter (transmit diversity) or the receiver (receive diversity) in order to achieve lower BER in wireless communication systems without need of extra transmit power. Diversity means that the receiver can get more than one version of the transmitted signal. There are many diversity techniques such as receive, frequency, time, delay, polarization, angel and combinations like space-time and space frequency diversity. Antenna diversity is the most widely used method in mobile communication system since it does not involve using extra power or bandwidth. This thesis considers space time block coding as a transmit diversity techniques as will be explained in section **2.5**.

Antenna diversity concept is using multiple antennas at the receiver to get multiple fading versions of the signal, then these versions can be combined or switched (processed) to improve the received signal to noise ratio. A well known techniques can be applied to derive benefits from these versions like Switch/selection Combining (SC), Equal Gain Combining (EGC), Maximal Ratio Combining (MRC) and Optimal Combining (OC), their performance/complexity is presented in Table 2.2 [45], [48]-[50].

Table 2.2 Multiple-Antenna Combining Comparison.

Technique	Complexity	Performance
Switch/selection combining	Low	Good
Equal gain combining	Middle	Very good
Maximal ratio combining	High	Excellent
Optimal combining	Very high	Ultra Excellent

This thesis studies a 4 × 4 MIMO communication system with ML detector which take the advantages of MRC diversity technique. Therefore, the performance and capacity of 1 × 4, 2 × 4, 3 × 4 and 4 × 4 MIMO systems are shown in Fig. 2.7 and Fig 2.8 respectively whereas they will be discussed later.

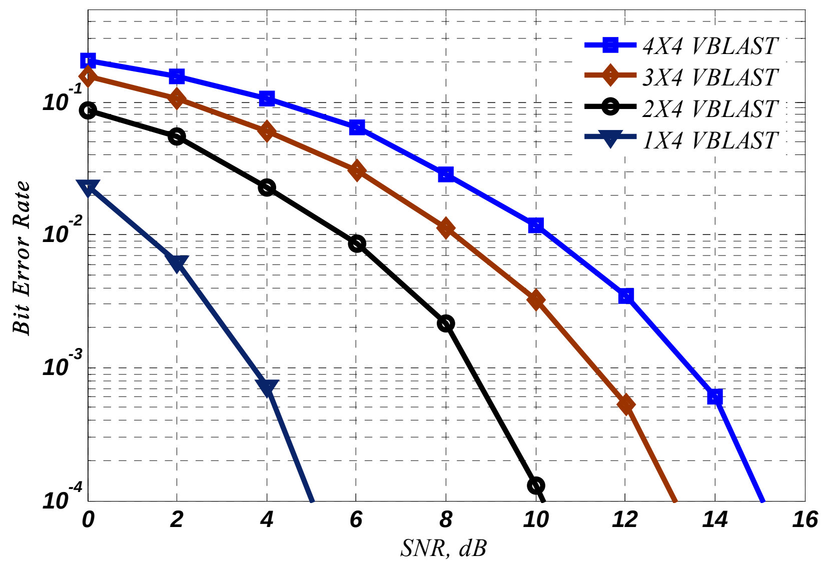


Fig. 2.7 Performance of 4 Rx for Number of Tx Antennas Using ML Detection.

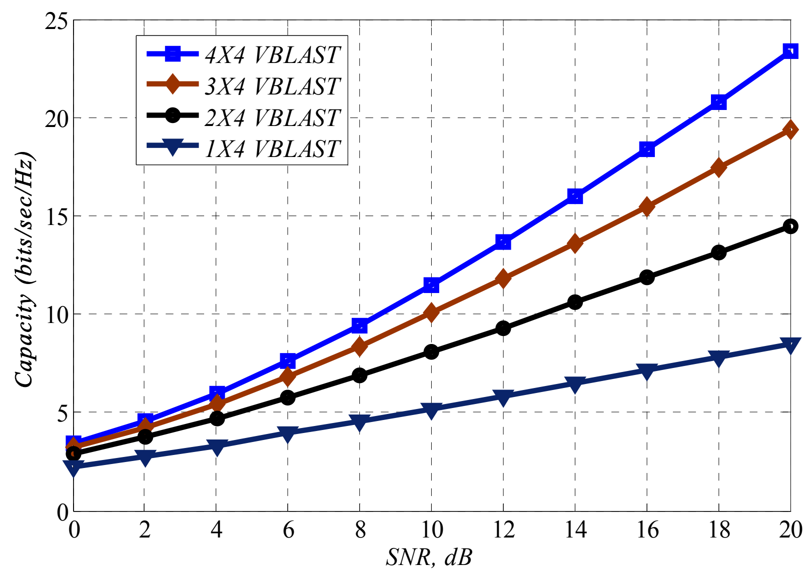


Fig. 2.8 Capacity of 4 Rx for Number of Tx Antennas Using ML Detection.

2.5 Space Time Coding (STC)

Space Time Coding (STC) takes advantage of the additional spatial diversity that MIMO offers. Unlike BLAST system which transmitting independent data streams, in STC, the same signal is transmitted in a predetermined manner instantaneously from different transmit antennas to obtain transmit diversity, in order to combat the channel fading. Generally, Space Time Coding (STC) leads to signal-reliability improvement, so that even when one or more of the paths are in a deep-fade, it is still possible to obtain an error-free signal. Using spatial diversity, however, reduces the number of independent paths, which leads to a decreased maximum possible rate at the transmitter. Fig. 2.9 shows a generalized setup for the space time coded MIMO.

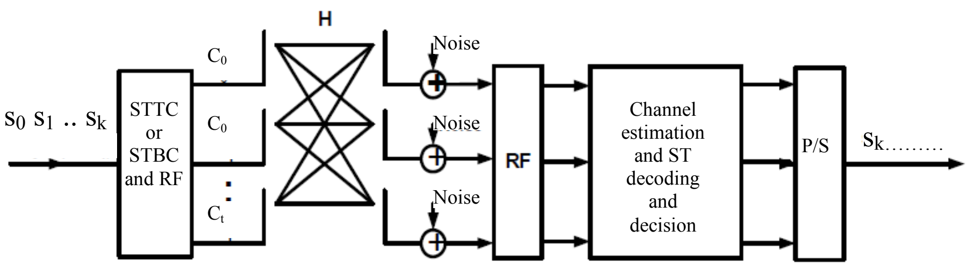


Fig. 2.9 Space Time Coded MIMO System.

The incoming signals s_0, s_1, .., s_k are mapped by a Space-Time Trellis Code (STTC) onto a codeword c_0 ,c_1 , ..., c_t and distributed among t antennas. At the receiver side the channel is estimated, the data is decoded and finally the original data are recovered and converted back into a serial form.

STTCs were developed in [51]. They provide an excellent performance at the expense of high complexity. Usually, a sophisticated Viterbi type decoder is used [52]. Recently Space-Time Block (STBC) codes have emerged as an alternative type of STTC codes [7]. They don't provide a coding gain (a gain in SNR over an uncoded system of the same rate) like STTC do. However, when compared to a SISO system, their BER performance improves much more quickly as SNR increases. In other words, they have a higher diversity gain. They also have a simple decoding technique. The low-complexity advantage has made STBC the preferred Space Time Coding technique in many practical applications, as well as accepting them as part of a 3GPP standard

[53].

2.5.1 Alamouti STBC

A simple Space Time Code suggested by Mr. Siavash M. Alamouti in October 1998 [7]. He offered a simple method for achieving spatial diversity with two transmit antennas. The scheme considers that the system has a transmission sequence, for example $\boldsymbol{x} = [x_1, x_2, x_3\ldots\ldots, x_M]$. In normal transmission, x_1 is sent in the first time slot, x_2 in the second time slot, x_3 and so on. However, Alamouti suggested that the symbols will be divided into two groups.

In the first time slot, x_1 and x_2 are sent from the first and second antennas, respectively. In second time slot - x_2^* and x_1^* are sent from the first and second antennas, respectively as seen in Fig. 2.10 and Fig. 2.11. In the third time slot x_3 and x_4 are sent from the first and second antennas and so on. Notice that although we are grouping two symbols, we still need two time slots to send two symbols. Hence, there is no change in the data rate. This forms a simple explanation of the transmission scheme with Alamouti Space Time Block coding [54].

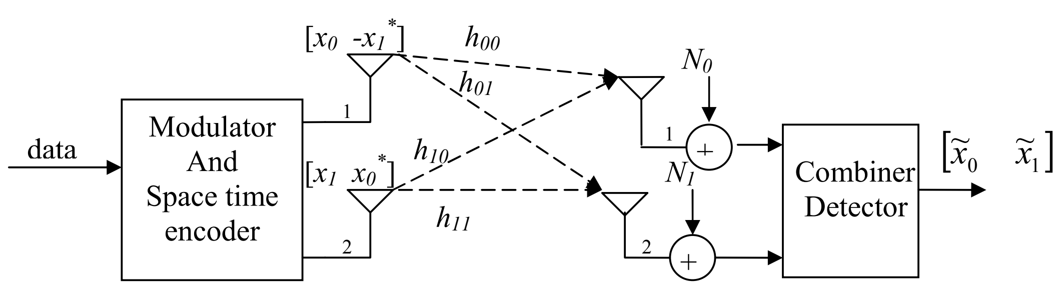


Fig. 2.10 Simple Space Time Code Setup for 2-Tx and 2-Rx Antennas.

The transmitted 2 × 2 STBC codeword is $\boldsymbol{x}$, and the symbols x_i can be any quadrature modulated symbols.

$$\boldsymbol{x} = \begin{pmatrix} x_0 & -x_1^* \\ x_1 & x_0^* \end{pmatrix} \tag{2.11}$$

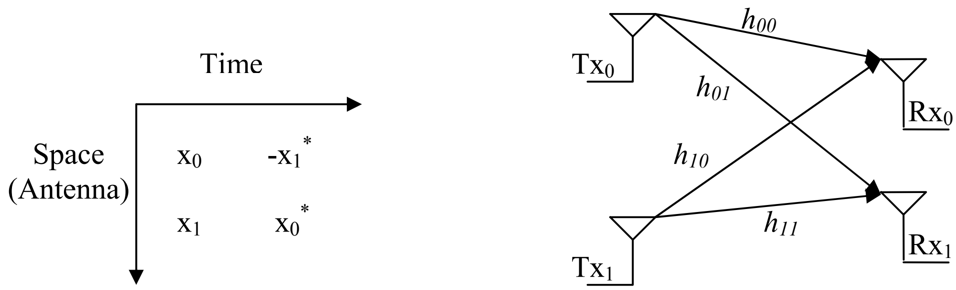


Fig. 2.11 Space Time Code Setup.

The flat faded channel matrix for two transmit and one receive antennas $\mathrm{H} = \begin{bmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \end{bmatrix}$.

The received signal from eq. (1) at the first time slot the received signal is:

$$\begin{pmatrix} r_0^0 \\ r_1^0 \end{pmatrix} = \begin{pmatrix} h_{00}x_0 + h_{01}x_1 \\ h_{10}x_0 + h_{11}x_1 \end{pmatrix} + \begin{pmatrix} n_0^0 \\ n_1^0 \end{pmatrix}, \tag{2.12}$$

and, at the second time slot, the received signal is:

$$\begin{pmatrix} r_0^1 \\ r_1^1 \end{pmatrix} = \begin{pmatrix} -h_{00}x_1^* + h_{01}x_0^* \\ -h_{10}x_1^* + h_{11}x_0^* \end{pmatrix} + \begin{pmatrix} n_0^1 \\ n_1^1 \end{pmatrix} \tag{2.13}$$

Now take the conjugate of (13), and rearrange vectors, it will be:

$$\begin{pmatrix} r_0^{1^*} \\ r_1^{1^*} \end{pmatrix} = \begin{pmatrix} -h_{00}^*x_1 + h_{01}^*x_0 \\ -h_{10}^*x_1 + h_{11}^*x_0 \end{pmatrix} + \begin{pmatrix} n_0^{1^*} \\ n_1^{1^*} \end{pmatrix}. \tag{2.14}$$

Rearrange eq. (2.12) and (2.14) in matrix notation, the received signals for two time slots are:

$$\begin{pmatrix} r_0^0 \\ r_1^0 \\ r_0^{1^*} \\ r_1^{1^*} \end{pmatrix} = \begin{pmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \\ h_{01}^* & -h_{00}^* \\ h_{11}^* & -h_{10}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} n_0^0 \\ n_1^0 \\ n_0^{1^*} \\ n_1^{1^*} \end{pmatrix}, \tag{2.15}$$

where r_0^0 and r_1^0 are the received signals on the first time slot from the first and second receive antenna respectively. r_0^1 and r_1^1 are the received signals on the second time slot from the first and second receive antennas, respectively. h_0 is the channel gain from 1st transmit antenna to receive antenna, h_1 is the channel gain from 2nd transmit antenna to receive antenna. x_0 and x_1 are the transmitted symbols. n_0^0, n_1^0, n_0^1 and n_1^1 are the AWGN modeled as independent identical distribution (i.i.d) complex Gaussian random variables with zero mean and power spectral density $N_0/2$ per dimension on 1st, 2nd time slots and on 1st, 2nd receive antennas, respectively.

So the virtual channel matrix for 2 × 2 MIMO system in two time slots with Alamouti scheme is (Assuming a flat Rayleigh fading channel):

$$\boldsymbol{H}_A = \begin{pmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \\ h_{01}^* & -h_{00}^* \\ h_{11}^* & -h_{10}^* \end{pmatrix} \tag{2.16}$$

The columns of the matrix represent antennas and the rows time slots. Therefore, p time slots are needed to transmit k symbols, resulting in a code rate

$$Rs = k/p \quad \text{Symbols/Time slot,} \tag{2.17}$$

Rs = 1 for Alamouti scheme. It is of special interest to find code matrices achieving the maximum transmission rate permitted by the STC theory, Rs = 1 Symbols/Time slot (full rate) [44].

The demodulator can treat the channel matrix of 2 × 2 as a virtual 4 × 2 matrix for two time slots, then it can do the decoding process by multiplying the received signal by the hermitian of the Alamouti 2 × 2 channel matrix (Assuming a full channel estimation).

$$\tilde{\boldsymbol{r}} = \boldsymbol{H}_A^H \begin{pmatrix} r_0^0 \\ r_1^0 \\ r_0^{1^*} \\ r_1^{1^*} \end{pmatrix} = \begin{pmatrix} h_{00}^* & h_{10}^* & h_{01} & h_{11} \\ h_{01}^* & h_{11}^* & -h_{00} & -h_{10} \end{pmatrix} \begin{pmatrix} r_0^0 \\ r_1^0 \\ r_0^{1^*} \\ r_1^{1^*} \end{pmatrix} \tag{2.18}$$

$$\begin{bmatrix} \tilde{r}_0 \\ \tilde{r}_1 \end{bmatrix} = \begin{pmatrix} h_{00}^* & h_{10}^* & h_{01} & h_{11} \\ h_{01}^* & h_{11}^* & -h_{00} & -h_{10} \end{pmatrix} \begin{pmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \\ h_{01}^* & -h_{00}^* \\ h_{11}^* & -h_{10}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} h_{00}^* & h_{10}^* & h_{01} & h_{11} \\ h_{01}^* & h_{11}^* & -h_{00} & -h_{10} \end{pmatrix} \begin{pmatrix} n_0^0 \\ n_1^0 \\ n_0^{1^*} \\ n_1^{1^*} \end{pmatrix} \tag{2.19}$$

$$\begin{pmatrix} \tilde{r}_0 \\ \tilde{r}_1 \end{pmatrix} = \begin{pmatrix} |h_{00}|^2 + |h_{01}|^2 + |h_{10}|^2 + |h_{11}|^2 & 0 \\ 0 & |h_{00}|^2 + |h_{01}|^2 + |h_{10}|^2 + |h_{11}|^2 \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} n_0' \\ n_1' \end{pmatrix}, \tag{2.20}$$

where $n_0' = h_{00}^* n_0^0 + h_{10}^* n_1^0 + h_{01} n_0^{1^*} + h_{11} n_1^{1^*}$ and $n_1' = h_{01}^* n_0^0 + h_{11}^* n_1^0 - h_{00} n_0^{1^*} - h_{10} n_1^{1^*}$.

The two noise terms are independent and identically distributed so:

$$E\left\{\begin{pmatrix} n_0^0 \\ n_1^0 \\ n_0^{1^*} \\ n_1^{1^*} \end{pmatrix}\begin{pmatrix} n_0^0 \\ n_1^0 \\ n_0^{1^*} \\ n_1^{1^*} \end{pmatrix}^H\right\} = E\left\{\begin{pmatrix} n_0^0 \\ n_1^0 \\ n_0^{1^*} \\ n_1^{1^*} \end{pmatrix}\begin{pmatrix} n_0^{0^*} & n_1^{0^*} & n_0^1 & n_1^1 \end{pmatrix}\right\} = \begin{pmatrix} \left|n_0^0\right|^2 & 0 & 0 & 0 \\ 0 & \left|n_1^0\right|^2 & 0 & 0 \\ 0 & 0 & \left|n_0^1\right|^2 & 0 \\ 0 & 0 & 0 & \left|n_1^1\right|^2 \end{pmatrix} \quad (2.21)$$

Therefore, the noise term is still white.

$$\begin{pmatrix} \tilde{x}_0 \\ \tilde{x}_1 \end{pmatrix} = \arg \min_{x \in A^S} \begin{pmatrix} (\left|h_{00}\right|^2 + \left|h_{01}\right|^2 + \left|h_{10}\right|^2 + \left|h_{11}\right|^2)x_0 \\ (\left|h_{00}\right|^2 + \left|h_{01}\right|^2 + \left|h_{10}\right|^2 + \left|h_{11}\right|^2)x_1 \end{pmatrix} + \begin{pmatrix} n_0' \\ n_1' \end{pmatrix}. \quad (2.22)$$

2.5.2 General STBC Based on Orthogonal Designs

The Alamouti scheme presented previously works only with two transmit antennas. This scheme was later generalized in [8], [55] to any number of transmit antennas. Like Alamouti code in (11), the general STBC is defined by a code matrix with orthogonal columns.

In general, STBC is defined by a ($P \times M$) matrix G. The entries of the matrix G are linear combinations of the variables $x_1, x_2, x_3 ....., x_k$ (representing real or complex symbols). The columns of the matrix represent number of transmit antennas and the rows represent time slots [44]. General STBC based on real orthogonal designs achieving full diversity and full rate can be found for any number of transmit antennas, M [47], [51], [55].

Theorem [8] : A ($p \times M$) generalized orthogonal design □ in variables $x_1, x_2, x_3 ......, x_k$ exists if and only if there exists a generalized orthogonal design G in the same variables and of the same size such that

$$\boldsymbol{G}^T \boldsymbol{G} = (x_1^2 + x_2^2 + x_3^2 + ...x_k^2)\boldsymbol{I}_k , \quad (2.23)$$

where I_k is the identity matrix of size ($k \times k$), $x_1, x_2, x_3 ......x_k$ are real variables, for complex variables transpose process replaced by hermitian process (transpose of conjugates) and it must still imply that

$$\boldsymbol{G}^H \boldsymbol{G} = (x_1^2 + x_2^2 + x_3^2 + ...x_k^2)\boldsymbol{I}_k \quad (2.24)$$

For $M = 3$, real symbols $R_s = 1$ S/Ts and the complex symbols $R_s = 1/2$ S/Ts, $\boldsymbol{G}_3$ is

$$\boldsymbol{G}_3 = \begin{pmatrix} x_1 & -x_2 & -x_3 \\ x_2 & x_1 & x_4 \\ x_3 & -x_4 & x_1 \end{pmatrix} \text{ for real and } \boldsymbol{G}_3 = \begin{pmatrix} x_1 & x_2 & x_3 \\ -x_2 & x_1 & -x_4 \\ -x_3 & x_4 & x_1 \\ x_1^* & x_2^* & x_3^* \\ -x_2^* & x_1^* & -x_4^* \\ -x_3^* & x_4^* & x_1^* \end{pmatrix} \text{ for complex.}$$

Now for $M = 4$, the real symbols with $R_s = 4/4 = 1$ *S/Ts* (full rate)

$$\boldsymbol{G}_4 = \begin{pmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & x_2 \\ -x_4 & -x_3 & x_2 & x_1 \end{pmatrix} \tag{2.25}$$

And for complex symbols with $R_s = 1/2$ *S/Ts*

$$\boldsymbol{G}_4 = \begin{pmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{pmatrix} \tag{2.26}$$

This thesis studies an 4 × 4 MIMO system but in [8] it has been proven that:

Theorem*:* A complex orthogonal design of size 4 × 4 does not exist [8].

They (in [8]) do not know any other generalized design of dimensions greater than 4 × 4 with rate greater than 0.5 *S/Ts* for a complex orthogonal design. They believe that the construction of complex generalized designs with rate greater than 0.5 S/Ts is difficult. Recently in 2001, H. Jafarkhani in [9] develops a new full rate ($R_s = 1$ *S/Ts*) complex Quasi-Orthogonal STBC (QOSTBC) for four transmit antennas as shown below:

$$\boldsymbol{G}_4 = \begin{pmatrix} \boldsymbol{G}_{12} & \boldsymbol{G}_{34} \\ -\boldsymbol{G}_{34}^* & \boldsymbol{G}_{12}^* \end{pmatrix} = \begin{pmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & -x_4^* & x_1^* & x_2^* \\ x_4 & -x_3 & -x_2 & x_1 \end{pmatrix} \tag{2.27}$$

where $\boldsymbol{G}_{12} = \boldsymbol{G}_2 = \begin{pmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{pmatrix}$ is the Alamouti encoding scheme like eq. (11) and the subscript '12' is included to denote that the matrix contains symbols x_1 and x_2, also the subscript '34' to denote the matrix which contains symbols x_3 and x_4.

From eq.(2.1) with 4 × 4 MIMO system and similar to Alamouti analysis eq.(2.12-2.15) with four time slots assuming a flat fading channel and by letting $\boldsymbol{x} = \boldsymbol{G}_4^T$.

$$\boldsymbol{H}_{4x4} = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{pmatrix} = \begin{pmatrix} \boldsymbol{h}_1 & \boldsymbol{h}_2 & \boldsymbol{h}_3 & \boldsymbol{h}_4 \end{pmatrix} \tag{2.28}$$

Where $\boldsymbol{h}_n = \begin{pmatrix} h_{1n} & h_{2n} & h_{3n} & h_{4n} \end{pmatrix}^T$ or by other words $\boldsymbol{h}_n$ is the n^{th} column vector of $\boldsymbol{H}_{4\times4}$.

$$\begin{pmatrix} \boldsymbol{r}_1 \\ \boldsymbol{r}_2^* \\ \boldsymbol{r}_3^* \\ \boldsymbol{r}_4 \end{pmatrix} = \begin{pmatrix} \boldsymbol{h}_1 & \boldsymbol{h}_2 & \boldsymbol{h}_3 & \boldsymbol{h}_4 \\ \boldsymbol{h}_2^* & -\boldsymbol{h}_1^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_3^* \\ \boldsymbol{h}_3^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_1^* & -\boldsymbol{h}_2^* \\ \boldsymbol{h}_4 & \boldsymbol{h}_3 & -\boldsymbol{h}_2 & -\boldsymbol{h}_1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} \boldsymbol{n}_1 \\ \boldsymbol{n}_2^* \\ \boldsymbol{n}_3^* \\ \boldsymbol{n}_4 \end{pmatrix} \tag{2.29}$$

where $\boldsymbol{r}_p = \begin{pmatrix} r_{1p} & r_{2p} & r_{3p} & r_{4p} \end{pmatrix}^T$ and $\boldsymbol{n}_p = \begin{pmatrix} n_{1p} & n_{2p} & n_{3p} & n_{4p} \end{pmatrix}^T$ is the P^{th} time slot received signal and AWGN vectors, respectively.

The virtual channel matrix of 4 transmit time slots is of size 16 × 4 and given by

$$\boldsymbol{H}_{4,QOSTBC} = \begin{pmatrix} \boldsymbol{H}_{4x4} \\ \boldsymbol{H}_{4x4}^* \\ \boldsymbol{H}_{4x4}^* \\ \boldsymbol{H}_{4x4} \end{pmatrix}_{16x4} = \begin{pmatrix} \boldsymbol{h}_1 & \boldsymbol{h}_2 & \boldsymbol{h}_3 & \boldsymbol{h}_4 \\ \boldsymbol{h}_2^* & -\boldsymbol{h}_1^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_3^* \\ \boldsymbol{h}_3^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_1^* & -\boldsymbol{h}_2^* \\ \boldsymbol{h}_4 & \boldsymbol{h}_3 & -\boldsymbol{h}_2 & -\boldsymbol{h}_1 \end{pmatrix}_{16x4}, \tag{2.30}$$

Where $\boldsymbol{h}_n$ is the n^{th} column vector of $\boldsymbol{H}_{4\times4}$ of length 4.

At the receiver side, the decoding process must be done to estimate the transmitted. symbols like Alamouti decoding scheme in eq.(2.17)

$$\tilde{\boldsymbol{r}} = \boldsymbol{H}_{4,QOSTBC}^H \boldsymbol{r} = \boldsymbol{H}_{4,QOSTBC}^H \boldsymbol{H}_{4,QOSTBC} \boldsymbol{x} + \boldsymbol{H}_{4,QOSTBC}^H \boldsymbol{n} \tag{2.31}$$

$$\tilde{\boldsymbol{r}} = \Delta \boldsymbol{x} + \tilde{\boldsymbol{n}} \tag{2.32}$$

The noise term is still white since the noise terms are (i.i.d.). For an orthogonal block code, Δ is 4 × 4 diagonal matrix but for a quasi-orthogonal block code Δ will have some non-zero terms other than diagonal elements that reduce the diversity gain of the code and it will have the form [9]

$$\Delta = \left(\boldsymbol{H}_{4,QOSTBC}^{H}\right)_{\boldsymbol{4x16}} \left(\boldsymbol{H}_{4,QOSTBC}\right)_{16x4} = \begin{pmatrix} \gamma & 0 & 0 & \alpha \\ 0 & \gamma & -\alpha & 0 \\ 0 & -\alpha & \gamma & 0 \\ \alpha & 0 & 0 & \gamma \end{pmatrix}_{4x4} \tag{2.33}$$

where $\gamma = \sum_{k=1}^{4} \left| \boldsymbol{h}_k^H \boldsymbol{h}_k \right|$, and $\alpha = Re\left\{ \boldsymbol{h}_1^H \boldsymbol{h}_4 - \boldsymbol{h}_2^H \boldsymbol{h}_3 \right\}$ [9].

$$\begin{pmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \\ \tilde{x}_4 \end{pmatrix} = \underset{x \in A^S}{arg\ min} \begin{pmatrix} (\left|\boldsymbol{h}_1^H \boldsymbol{h}_1\right| + \left|\boldsymbol{h}_2^H \boldsymbol{h}_2\right| + \left|\boldsymbol{h}_3^H \boldsymbol{h}_3\right| + \left|\boldsymbol{h}_4^H \boldsymbol{h}_4\right|) x_1 \\ (\left|\boldsymbol{h}_1^H \boldsymbol{h}_1\right| + \left|\boldsymbol{h}_2^H \boldsymbol{h}_2\right| + \left|\boldsymbol{h}_3^H \boldsymbol{h}_3\right| + \left|\boldsymbol{h}_4^H \boldsymbol{h}_4\right|) x_2 \\ (\left|\boldsymbol{h}_1^H \boldsymbol{h}_1\right| + \left|\boldsymbol{h}_2^H \boldsymbol{h}_2\right| + \left|\boldsymbol{h}_3^H \boldsymbol{h}_3\right| + \left|\boldsymbol{h}_4^H \boldsymbol{h}_4\right|) x_3 \\ (\left|\boldsymbol{h}_1^H \boldsymbol{h}_1\right| + \left|\boldsymbol{h}_2^H \boldsymbol{h}_2\right| + \left|\boldsymbol{h}_3^H \boldsymbol{h}_3\right| + \left|\boldsymbol{h}_4^H \boldsymbol{h}_4\right|) x_4 \end{pmatrix} + \begin{pmatrix} \boldsymbol{n}_1' \\ \boldsymbol{n}_2' \\ \boldsymbol{n}_3' \\ \boldsymbol{n}_4' \end{pmatrix} \tag{2.34}$$

The effective bandwidth of the STBC system must be divided by P to compensate $\tilde{\boldsymbol{r}}$ in eq.(2.33) since it must be measured over P-(time slots) consecutive symbol periods [56]. The resulting capacity equations are:

$$C_{4,QOSTBC} = \frac{1}{4} log_2 (det \mid \boldsymbol{I}_N + \frac{\gamma}{M} \boldsymbol{H}_{4,QOSTBC}^{H} \boldsymbol{H}_{4,QOSTBC} \mid) \tag{2.35}$$

$$C_{4,OSTBC} = \frac{1}{8} log_2 (det \mid \boldsymbol{I}_N + \frac{\gamma}{M} \boldsymbol{H}_{4,OSTBC}^{H} \boldsymbol{H}_{4,OSTBC} \mid) \tag{2.36}$$

The bit error rate and the capacity of 4 × 4 MIMO system with no coding , full rate QOSTBC of eq. (2.27) and half rate OSTBC of eq. (2.26) are simulated and the results shown in Fig. 2.12 and 2.13.

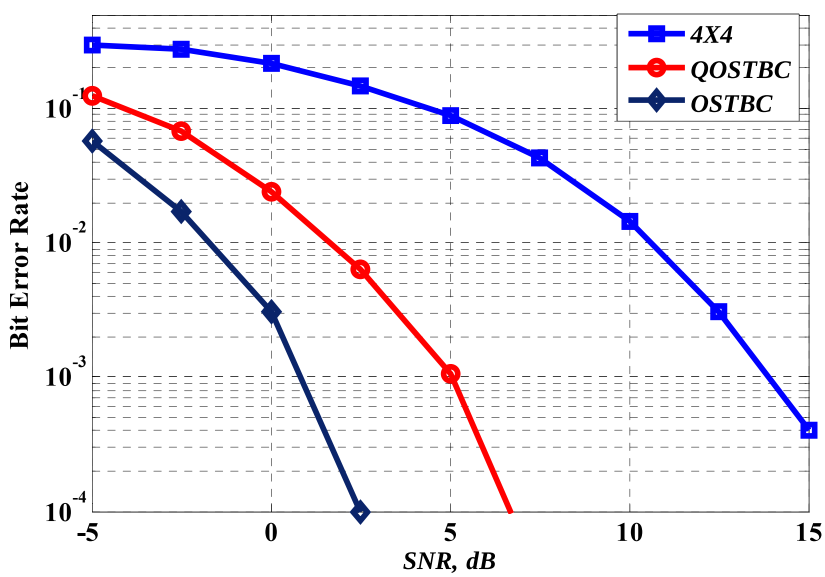


Fig. 2.12 4 × 4, QOSTBC, OSTBC MIMO System Performance Comparison.

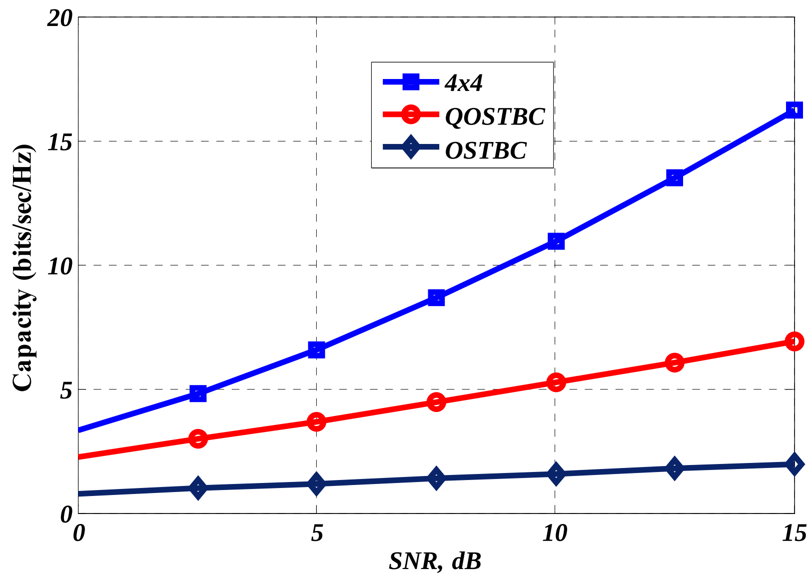


Fig. 2.13 4 × 4, QOSTBC, OSTBC MIMO System Capacity Comparison.

as it was expected 4 × 4 V-BLAST has the best spectral efficiency but with the worst BER performance opposite to OSTBC which has the worst throughput with best BER performance.

2.6 Summary

This chapter gave an overview of the MIMO channel model, MIMO capacity and the basic open loop MIMO communication system. It covered Vertical and Diagonal Bell Labs Space Time (VBLAST and DBLAST) architectures and Space Time Block Codes (Alamouti, QOSTBC and General Orthogonal STBC) systems.

In MIMO technology, system performance was improved using spatial diversity techniques. But with spatial multiplexing the channel capacity was linearly increased as independent data streams were transmitted from the multiple transmit antennas and received by multiple antennas at the receiver.

Transmit diversity was used in order to combat the fading of the channel. Generally, STBC leads to signal-reliability improvement. So that even when one or more of the paths were in a fade, it is still possible to obtain an error-free signal. Using spatial diversity, however, reduced the number of independent paths, which leads to a decreased maximum possible rate (capacity) at the transmitter.

CHAPTER 3
HYBRID BLAST STBC SYSTEM

3.1 Introduction

In BLAST systems, spatial multiplexing is used where independent signals are transmitted simultaneously via different antennas. This gives good results in increasing the capacity of the channel. This well known system is designed to maximize the spectral efficiency [57]. However, in some environments, the independent links of BLAST system may suffer from a considerable fading which causes decreasing in the total data rate.

Space-time codes can mitigate this problem in BLAST system but it decreases the capacity since it uses a minimum of two antennas to transmit one symbol (Alamouti). So combining spatial multiplexing and STBC can provide a tradeoff between the throughput and diversity.

Recently, there are several proposals to combine space-time block coding (STBC) and spatial multiplexing (SM) to obtain transmit diversity and spatial multiplexing gain simultaneously in a system called Hybrid BLAST-STBC (or Hybrid BLAST-STBC) MIMO system [58]. This idea emerged in a Multi-User (MU) systems, if each user has a STBC encoder then by letting all users considered as one user having multilayer STBC scheme (every layer has a STBC encoder) then this user enjoys a high spectral efficiency and transmit diversity benefits.

As MU-STBC system and the hybrid BLAST-STBC system are equivalent, symbol detection schemes for MU-STBC systems could be applied to the case of the hybrid BLAST-STBC system [58].

There are tow types of hybrid systems, the first type [14] is called hybrid STBC-BLAST system, this system has a dedicated number of antennas for BLAST transmission and for STBC transmission or by other words it is a BLAST system with STBC encoders in the lower layers. The second type is called hybrid BLAST-STBC system or it is referred to as Multi-Layered STBC (MLSTBC) system, and more details about these types will be discussed in the next sections.

3.2 Hybrid STBC-VBLAST System

The first study on this system was in 2005 [14] when Tianyu Mao and Mehul Motani complete their Technical Report at National University of Singapore (NUS) in 2004. In their study, they introduced a new STBC-VBLAST scheme. By letting J to be the number of STBC layers and each layer has n transmit antennas, the new system integrates J orthogonal $n \times p$ STBC into the lower layers of VBLAST systems with a total M transmit and N receive antennas.

The remaining higher layers transmit independent data streams (VBLAST). This structure is called in [59] the Hybrid MIMO Transmission Schemes (HMTS) and it also aims to achieve diversity and multiplexing gains at the same time [60]. Fig. 3.1 shows the block diagram for the Hybrid STBC-VBLAST system.

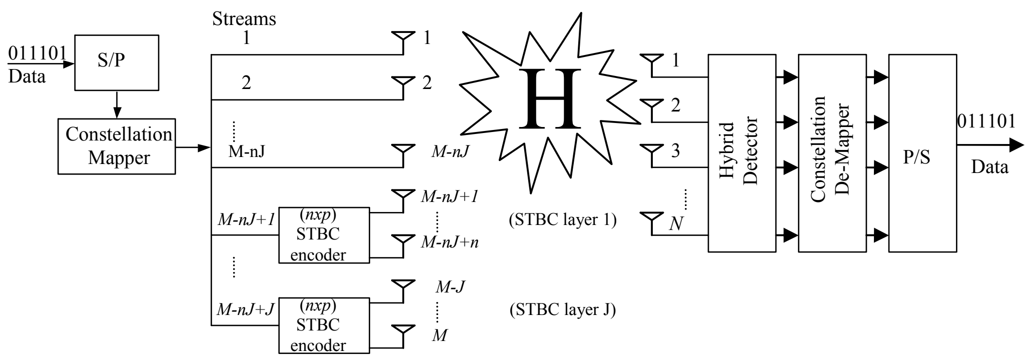


Fig. 3.1 Block Diagram for Hybrid STBC-VBLAST Transmitter

The information symbol sequence is divided into $M-(n-1)J$ streams. Streams 1 to $M-nJ$ are transmitted on the first $M-nJ$ antennas. But the other J streams are passed through J-STBC encoders (STBC Layers) and they are transmitted on nJ antennas.

Furthermore, each group of n antennas is used to transmit an $n \times p$ STBC symbols, denoted by $\boldsymbol{G}_n$, where n and p indicate the number of transmit antennas for each encoder and symbol intervals occupied by the STBC, respectively. We call each of the J STBC encoded streams a STBC layer and the system a (n, p, J) STBC-VBLAST system [14] and ($G_n + 1 + 1\ldots$) in [61] where that ones refer to number of transmit antennas appointed to V-BLAST transmission. The transmitted signal can be expressed in matrix form as

$$\boldsymbol{x} = \begin{pmatrix} \boldsymbol{x}_{spa} \\ \boldsymbol{G}_n \end{pmatrix}, \tag{3.1}$$

where $\boldsymbol{x}_{spa}$ contains the independent symbols (VBLAST)

$$x_{spa} = \begin{pmatrix} x_1^1 & x_1^2 & \cdots & x_1^p \\ x_2^1 & x_2^2 & \cdots & x_2^p \\ \vdots & \vdots & \ddots & \vdots \\ x_{M-nJ}^1 & x_{M-nJ}^2 & \cdots & x_{M-nJ}^p \end{pmatrix}, \tag{3.2}$$

and $\boldsymbol{G}_n$ is the transpose of one of encoding matrices of STBC ($\boldsymbol{G}_2, \boldsymbol{G}_3, \boldsymbol{G}_4$....etc) like in eq. (2.11) or (2.26).

An efficient encoder and decoder were proposed in [15]. The system aims to send symbols and their negative conjugates in the second time slot excepts that of the Alamouti encoded layers, then eq.(3.1) will be

$$\boldsymbol{x} = \begin{pmatrix} \boldsymbol{x}_{spa} \\ \boldsymbol{G}_2 \end{pmatrix}, \tag{3.3}$$

where $\boldsymbol{G}_2$ is the Alamouti encoder matrix of eq.(2.11) of $p = 2$ and eq.(3.2) will be

$$x_{spa} = \begin{pmatrix} x_1 & -x_2^* \\ x_3 & -x_4^* \\ \vdots & \vdots \\ x_{2(M-nJ)-1} & -x_{2(M-nJ)}^* \end{pmatrix}, \tag{3.4}$$

and eq.(2.1) will be

$$(\boldsymbol{r}) = (\boldsymbol{H})\begin{pmatrix} \boldsymbol{x}_{spa} \\ \boldsymbol{G}_2 \end{pmatrix} + (\boldsymbol{n}). \tag{3.5}$$

After arranging eq.(3.5) it will have the form:

$$\begin{pmatrix} r_1 \\ r_2^* \\ \vdots \\ r_{N-1} \\ r_N^* \end{pmatrix} = \begin{pmatrix} \boldsymbol{H}_{spa} & \boldsymbol{H}_{A} \end{pmatrix} \boldsymbol{x} + \begin{pmatrix} n_1 \\ n_2^* \\ \vdots \\ n_{N-1} \\ n_N^* \end{pmatrix} \tag{3.6}$$

where $\boldsymbol{H}_{\boldsymbol{A}}$ is the Alamouti channel matrix for groups of two and it has the form of

$$\boldsymbol{H}_{\boldsymbol{A}} = \begin{pmatrix} \boldsymbol{H}_{1,1}^{A} & \boldsymbol{H}_{1,2}^{A} & \cdots & \boldsymbol{H}_{1,J}^{A} \\ \boldsymbol{H}_{2,1}^{A} & \boldsymbol{H}_{2,2}^{A} & \cdots & \boldsymbol{H}_{2,J}^{A} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{H}_{N,1}^{A} & \boldsymbol{H}_{N,2}^{A} & \cdots & \boldsymbol{H}_{N,J}^{A} \end{pmatrix} \tag{3.7}$$

where every element of eq.(3.7) is given by:

$$\boldsymbol{H}_{\boldsymbol{a,b}}^{\boldsymbol{A}} = \begin{pmatrix} h_{a,2b+M-nJ-1} & h_{a,2b+M-nJ} \\ h_{a,2b+M-nJ}^{*} & -h_{a,2b+M-nJ-1}^{*} \end{pmatrix} \tag{3.8}$$

For $a = 1, 2, \ldots, N$ and $b = 1, 2, \ldots, J$ and $\boldsymbol{H}_{\boldsymbol{spa}}$ is

$$\boldsymbol{H}_{\boldsymbol{spa}} = \begin{pmatrix} \boldsymbol{H}_{1,1}^{spa} & \boldsymbol{H}_{1,2}^{spa} & \cdots & \boldsymbol{H}_{1,M-nJ}^{spa} \\ \boldsymbol{H}_{2,1}^{spa} & \boldsymbol{H}_{2,2}^{spa} & \cdots & \boldsymbol{H}_{2,M-nJ}^{spa} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{H}_{N,1}^{spa} & \boldsymbol{H}_{N,2}^{spa} & \cdots & \boldsymbol{H}_{N,M-nJ}^{spa} \end{pmatrix} \tag{3.9}$$

where every element of eq.(3.9) is given by:

$$\boldsymbol{H}_{\boldsymbol{i,j}}^{\boldsymbol{spa}} = \begin{pmatrix} h_{i,j} & 0 \\ 0 & -h_{i,j}^{*} \end{pmatrix} \tag{3.10}$$

For $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, M\text{-}nJ$.

Now for 4 × 4 MIMO system, Alamouti scheme can be used so $M = 4$, $J = 1$, $n = 2$ and $p = 2$.

According to eq.(3.1) and $\boldsymbol{G}_2$ then

$$x = \begin{pmatrix} x_1 & -x_2^{*} \\ x_3 & -x_4^{*} \\ x_5 & -x_6^{*} \\ x_6 & x_5^{*} \end{pmatrix} \tag{3.11}$$

and for the channel matrix in eq.(2.1) and eq.(2.28) and also according to the criteria in eq.(2.12) to eq.(2.20) the channel matrix will be

$$\boldsymbol{H}_{Hibrid} = \begin{pmatrix} \boldsymbol{H}_{4x6} \\ \boldsymbol{H}^*_{4x6} \end{pmatrix}_{8x6} = \begin{pmatrix} \boldsymbol{h}_1 & 0 & \boldsymbol{h}_2 & 0 & \boldsymbol{h}_3 & \boldsymbol{h}_4 \\ 0 & -\boldsymbol{h}_1^* & 0 & -\boldsymbol{h}_2^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_3^* \end{pmatrix}_{8x6}, \quad (3.12)$$

where $\boldsymbol{h}_n$ is the n^{th} column vector of $\boldsymbol{H}_{4\times 4}$.

$$\begin{pmatrix} \boldsymbol{r}_1 \\ \boldsymbol{r}_2^* \end{pmatrix} = \begin{pmatrix} \boldsymbol{h}_1 & 0 & \boldsymbol{h}_2 & 0 & \boldsymbol{h}_3 & \boldsymbol{h}_4 \\ 0 & -\boldsymbol{h}_1^* & 0 & -\boldsymbol{h}_2^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_3^* \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{pmatrix} + \begin{pmatrix} \boldsymbol{n}_1 \\ \boldsymbol{n}_2^* \end{pmatrix}, \quad (3.13)$$

$$\tilde{\boldsymbol{r}} = \boldsymbol{H}^H_{Hibrid}\boldsymbol{r} = \boldsymbol{H}^H_{Hibrid}\boldsymbol{H}_{Hibrid}\boldsymbol{x} + \boldsymbol{H}^H_{Hibrid}\boldsymbol{n}, \quad (3.14)$$

$\boldsymbol{H}^H_{Hibrid}\boldsymbol{H}_{Hibrid}$ will be a 6 × 6 matrix where any decoding scheme can be applied.

The same criteria can be done for 3 × 4 MIMO system, eq.(3.11) can be like

$$x = \begin{pmatrix} x_1 & -x_2^* \\ x_3 & -x_4^* \\ x_4 & x_3^* \end{pmatrix} \quad (3.15)$$

The channel matrix will be

$$\boldsymbol{H}_{Hibrid} = \begin{pmatrix} \boldsymbol{H}_{3x4} \\ \boldsymbol{H}^*_{3x4} \end{pmatrix}_{6x4} = \begin{pmatrix} \boldsymbol{h}_1 & 0 & \boldsymbol{h}_2 & \boldsymbol{h}_3 \\ 0 & -\boldsymbol{h}_1^* & \boldsymbol{h}_3^* & -\boldsymbol{h}_2^* \end{pmatrix}_{6x4}, \quad (3.16)$$

and

$$\begin{pmatrix} \boldsymbol{r}_1 \\ \boldsymbol{r}_2^* \end{pmatrix} = \begin{pmatrix} \boldsymbol{h}_1 & 0 & \boldsymbol{h}_2 & \boldsymbol{h}_3 \\ 0 & -\boldsymbol{h}_1^* & \boldsymbol{h}_3^* & -\boldsymbol{h}_2^* \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} \boldsymbol{n}_1 \\ \boldsymbol{n}_2^* \end{pmatrix} . \quad (3.17)$$

As eq.(3.14) shows, $\boldsymbol{H}^H_{Hibrid}\boldsymbol{H}_{Hibrid}$ will be a 4 × 4 matrix so any decoding scheme can be applied.

PERFORMANCE ANALYSIS

It is clear that the hybrid system has much higher diversity than VBLAST systems. Let the diversity d of the system as the minimum diversity among all the layers, the following theorem gives an exact result for the diversity of hybrid system.

***Theorem 3.1**:* [14] For an (n, p, J) STBC-VBLAST system having M transmit and N receive antennas, the diversity is the minimum of $n(N-M) + n^2$ and $N-M+Jn+1$. Since the minimum diversity among all the layers is enhanced, the error propagation is suppressed efficiently. For example, a STBC-VBLAST with one layer of 2×2 STBC and $N = M$ has a diversity of three, compared to one for VBLAST systems.

Table 3.1 [14] illustrates the comparison between hybrid and VBLAST systems.

Table 3.1 Summary of diversity and spectral efficiency for STBC-VBLAST and VBLAST

Schemes	Hybrid system	Uncoded VBLAST
Diversity (d)	$\min \begin{cases} n(N-M) + n^2 \\ N-M+Jn+1 \end{cases}$	N-M+1
Spectral efficiency (η)	$K(M-nJ+JRs)$	KM

PERFORMANCE AND SPECTRAL EFFICIENCY TRADEOFF

For a BLAST system, the spectral efficiency can be expressed as

$$\eta = K.M \quad \text{bits/s/Hz}, \tag{3.18}$$

where K is the number of bits in a modulated symbol. For a (n, p, J) STBC-VBLAST system

$$\eta = K(M-nJ+JR_s) \quad \text{bits/s/Hz}, \tag{3.19}$$

where R_s is the code rate for STBC of eq.(2.17). The problem is how to choose n and J to obtain best tradeoff between performance and spectral efficiency.

***Theorem 3.2**:* [14] For an (n, p, J) STBC-VBLAST system having M transmit and N receive antennas, in order to use the bandwidth efficiently, J should be chosen such that

$$J \leq n+(N-M)-\left\lfloor \frac{N-M+1}{n} \right\rfloor, \tag{3.20}$$

where $\lfloor(\cdot)\rfloor$ indicates the largest integer which is smaller than (.).

3.3 Hybrid BLAST STBC System (Layered Space-Time Codes)

This is the second type of hybrid system, combining BLAST and STBC performance in a layered architecture with transmit diversity in each layer. This is called a Multi-Layered STBC (MLSTBC) system [10], [62]. It is called in some references a hybrid BLAST-STBC system [56], it may be called a combined STBC and BLAST or combined STBC and SM system [63]. This architecture was first considered in [10] but with space time trellis codes (STTC). One advantage of using STBC over STTC is that the orthogonal structure and the short code length can be exploited at the receiver to reduce the minimum required number of receive antennas [6]. For MLSTTC, the number of receive antennas should be at least equal to the total number of transmit antennas. However, for MLSTBC, the number of receive antennas is equal to the number of layers. In [64], [65] horizontally layered space time (HLST) codes and diagonally layered space-time (DLST) codes were proposed, HLST considers a VBLAST layering technique and DLST considers a DBLAST layering technique with channel coding then moving them through space and time through these layers. Fig. 3.2 shows the architecture of the Hybrid BLAST STBC system.

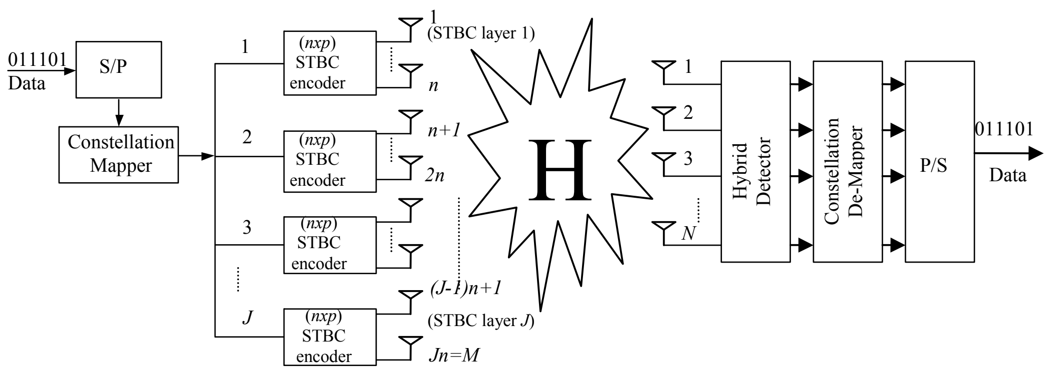
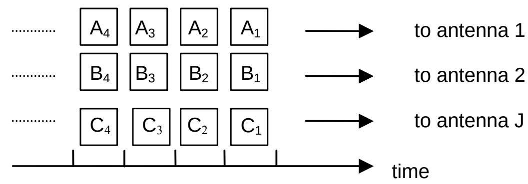
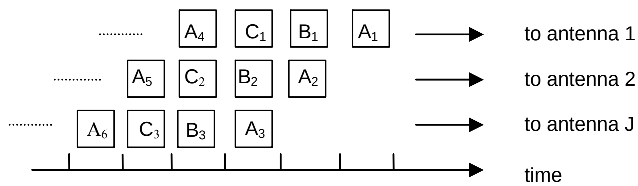


Fig. 3.2 Architecture of the Hybrid BLAST STBC System

Consider a system with M transmit and N receive antennas, the idea of this system is to de-multiplex single user's data into parallel J layers then each layer is encoded by STBC encoder. Furthermore, each group of n antennas is used to transmit an $n \times p$ STBC symbols, denoted by $\boldsymbol{G}_n$, where n and p indicate the number of transmit antennas for each encoder and symbol intervals occupied by the STBC, respectively and $M = nJ$. Fig. 3.3 illustrates the Layered Space Time (LST) code encoding process for both of HLST and DLST [64], [65].



A) HLST



B) DLST

Fig. 3.3 LST Code Encoding Process. (A) In HLST, the coded symbols from encoder *m* are transmitted by antenna *m*. (B) In DLST, the coded symbols from encoders are rotating on all *M* transmitting antennas.

In general, the transmitted signals of this system can be expressed in matrix form as

$$\boldsymbol{x} = \begin{pmatrix} \boldsymbol{G_n^1} \\ \boldsymbol{G_n^2} \\ \vdots \\ \boldsymbol{G_n^J} \end{pmatrix}, \tag{3.21}$$

where $\boldsymbol{G_n}$ is the transpose of one of encoding matrices of STBC ($\boldsymbol{G_2}$,$\boldsymbol{G_3}$,$\boldsymbol{G_4}$....etc) like in eq. (2.11) or (2.26).

For $\boldsymbol{G_2}$, Alamouti encoder matrix of eq.(2.11), eq.(3.21) will be

$$x_{spa} = \begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \\ \vdots & \vdots \\ x_J & x_{J-1}^* \end{pmatrix}, \tag{3.22}$$

and eq.(2.1) will be

$$(\boldsymbol{r}) = (\boldsymbol{H})\begin{pmatrix} \boldsymbol{G_n^1} \\ \boldsymbol{G_n^2} \\ \vdots \\ \boldsymbol{G_n^J} \end{pmatrix} + (\boldsymbol{n}). \tag{3.23}$$

After arranging eq.(3.23) it will has the form of

$$\begin{pmatrix} r_1 \\ r_2^* \\ \vdots \\ r_{N-1} \\ r_N^* \end{pmatrix} = \begin{pmatrix} \boldsymbol{H}_{\boldsymbol{A}}^{\boldsymbol{1}} & \boldsymbol{H}_{\boldsymbol{A}}^{\boldsymbol{2}} & \cdots & \boldsymbol{H}_{\boldsymbol{A}}^{\boldsymbol{J}} \end{pmatrix} \boldsymbol{x} + \begin{pmatrix} n_1 \\ n_2^* \\ \vdots \\ n_{N-1} \\ n_N^* \end{pmatrix}, \tag{3.24}$$

where $\boldsymbol{H}_A$ is the Alamouti channel matrix for groups of two as eq.(2.16)

Now for 4 × 4 MIMO system, Alamouti scheme can be used so $M = 4$, $J = 2$, $n = 2$ and $p = 2$.

According to eq.(3.21) and $\boldsymbol{G}_2$ then

$$\boldsymbol{x} = \begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \\ x_3 & -x_4^* \\ x_4 & x_3^* \end{pmatrix}, \tag{3.25}$$

and for the channel matrix in eq.(2.1) and eq.(2.28) eq.(3.21) will be

$$\begin{pmatrix} r_1 \\ r_2^* \end{pmatrix} = \begin{pmatrix} \boldsymbol{H}_{\boldsymbol{A}}^{\boldsymbol{1}} & \boldsymbol{H}_{\boldsymbol{A}}^{\boldsymbol{2}} \end{pmatrix} \boldsymbol{x} + \begin{pmatrix} n_1 \\ n_2^* \end{pmatrix}. \tag{3.26}$$

And according to the criteria in eq.(2.12) to eq.(2.20) the channel matrix will be

$$\boldsymbol{H}_{Hibrid} = \begin{pmatrix} \boldsymbol{H}_{\boldsymbol{A}}^{\boldsymbol{1}} & \boldsymbol{H}_{\boldsymbol{A}}^{\boldsymbol{2}} \end{pmatrix} = \begin{pmatrix} \boldsymbol{H}_{\boldsymbol{4x4}} \\ \boldsymbol{H}_{\boldsymbol{4x4}}^* \end{pmatrix}_{8x4} = \begin{pmatrix} \boldsymbol{h}_1 & \boldsymbol{h}_2 & \boldsymbol{h}_3 & \boldsymbol{h}_4 \\ \boldsymbol{h}_2^* & -\boldsymbol{h}_1^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_3^* \end{pmatrix}_{8x4}, \tag{3.27}$$

where $\boldsymbol{h}_n$ is the n^{th} column vector of $\boldsymbol{H}_{4x4}$.

$$\begin{pmatrix} \boldsymbol{r}_1 \\ \boldsymbol{r}_2^* \end{pmatrix} = \begin{pmatrix} \boldsymbol{h}_1 & \boldsymbol{h}_2 & \boldsymbol{h}_3 & \boldsymbol{h}_4 \\ \boldsymbol{h}_2^* & -\boldsymbol{h}_1^* & \boldsymbol{h}_4^* & -\boldsymbol{h}_3^* \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} \boldsymbol{n}_1 \\ \boldsymbol{n}_2^* \end{pmatrix}. \tag{3.28}$$

$$\tilde{\boldsymbol{r}} = \boldsymbol{H}_{Hibrid}^H \boldsymbol{r} = \boldsymbol{H}_{Hibrid}^H \boldsymbol{H}_{Hibrid} \boldsymbol{x} + \boldsymbol{H}_{Hibrid}^H \boldsymbol{n}. \tag{3.29}$$

$\boldsymbol{H}_{Hibrid}^H \boldsymbol{H}_{Hibrid}$ will be a 4 × 4 matrix where any detecting scheme can be applied.

Again the capacity of the Hybrid BLAST-STBC system may be obtained by the same general form as eq.(2.4). The bandwidth must be scaled by factor of p for a compensation of $\tilde{\boldsymbol{r}}$ to be measured over p consecutive symbol periods. The general formula for the capacity of the Hybrid BLAST-STBC system for any STBC scheme is

$$C_{Hibrid} = \frac{1}{p} log_2 (det \mid \boldsymbol{I}_N + \frac{\gamma}{M} \boldsymbol{H}^H_{Hibrid} \boldsymbol{H}_{Hibrid} \mid) \qquad bps/Hz \qquad (3.30)$$

As with the Alamouti scheme, the bandwidth must be scaled by factor of two consecutive symbol periods. This time, the resulting capacity equation is

$$C_{Hibrid} = \frac{1}{2} log_2 (det \mid \boldsymbol{I}_4 + \frac{\gamma}{4} \boldsymbol{H}^H_{Hibrid} \boldsymbol{H}_{Hibrid} \mid) \qquad bps/Hz. \qquad (3.31)$$

3.4 summary

Combining spatial multiplexing and STBC can provide both increased throughput and diversity. Occasionally it mitigated the problem of deep fading in some independent links of a BLAST system in some environments, but it decreased the overall capacity since it reduced the multiplexing rate that it needed one more antenna to use Alamouti encoder at least.

Hybrid BLAST-STBC (or Hybrid STBC-BLAST) MIMO system [58] is proposed and studied widely. Hybrid STBC-BLAST system [14], HMTS [59], Multi-Layered STBC (MLSTBC) [10] [62], combined STBC and BLAST or combined STBC-SM system [63], HLST and DLST [64] [65] and hybrid BLAST-STBC [64] were introduced, its structure referred as $G_n + G_n + \ldots + 1 + 1 + \ldots$ according to the number of G_n $(n \times p)$ STBC encoders used and the remaining multiplexing layers.

It was clear that the hybrid systems had much higher diversity than VBLAST systems then the overall performance of the system was improved significantly with respect to the same multiplexing rate system with same transmit power. It was shown that the number of the G_n encoders should not be greater than a threshold in order to use the bandwidth efficiently. Although a part of the spectral efficiency was lost because of the STBC, it could been compensated for by using a higher modulation scheme.

CHAPTER 4

PERFORMANCE AND CAPACITY COMPARISON BETWEEN HYBRID BLAST-STBC, VBLAST AND STBC SYSTEMS

4.1 Introduction

This chapter compares the BER performance and the capacity of Hybrid BLAST-STBC (G2 + 1 + 1) and (G2 + 1), MLSTBC (G2 + G2), V-BLAST, QOSTBC and G4-OSTBC. In addition, we provide performance comparison between the Hybrid BLAST-STBC and MLSTBC and the former systems and investigate the advantages of the Hybrid system.

One of the main differences between MLSTBC and V-BLAST at the same number of transmit/receive antennas is that MLSTBC has more transmit diversity than V-BLAST while V-BLAST has more layers. For example, with a 4 × 4 MIMO system, hybrid system has at least one layer with a transmit diversity of two with receive diversity of four with ML detector at the receiver. On the other hand, V-BLAST has four layers and no transmit diversity with the same receive diversity. The concerned systems in the current simulation are V-BLAST, Hybrid G2 + 1 + 1, Hybrid G2 + G2, Hybrid G2 + 1, QOSTBC and OSTBC systems.

Throughout this thesis, a 4 × 4 MIMO system is considered as a case study in MIMO communication systems using the same constellation of QPSK modulation by each transmitter. Alamouti code [7] is used for a certain layer in hybrid system. The capacity and BER performance of different systems is estimated by generating random complex AWGN channel realizations and averaged over more than 10000 random (i.i.d) Rayleigh distributed flat fading channel, the channel elements are complex numbers, with both real and imaginary parts drawn from zero mean, Gaussian distributions assuming a full channel estimation at the receiver side.

The simulation is done using MATLAB software where the total transmitting power normalized to one, thus a power transmitted by each transmitter is proportional to $1/M$. The system signal-to-noise ratio (SNR) is a given parameter. Hence, the power of the white noise is adjusted in accordance with the SNR. The purpose of normalizing the transmit power is to make the results independent of transmitted power. All the detections are done using optimal receiver (ML) as eq.(2.10). Although ML detector is a complex ,it is used to get an optimum detection for making a fair comparison.

4.2 Comparing VBLAST systems and Receive Diversity

As Fig. 2.7 in chapter 2, a 1 × 1, 2 × 2, 3 × 3 and 4 × 4 VBLAST performances and channel capacities must be simulated and compared to 1 × 4, 2 × 4 and 3 × 4 VBLAST performances and channel capacities. Fig. 4.1 and Fig. 4.2 shows this comparison.

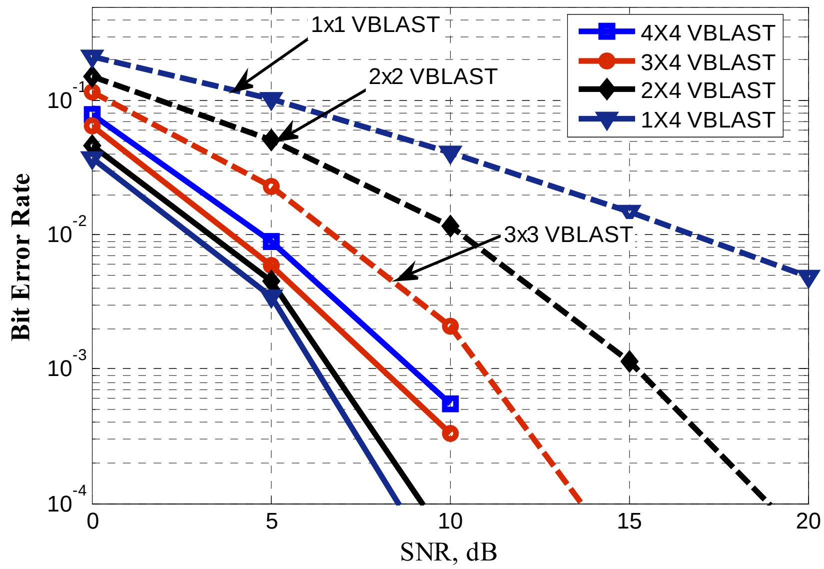


Fig. 4.1 Comparing $M \times M$ and $M \times 4$ VBLAST Performance.

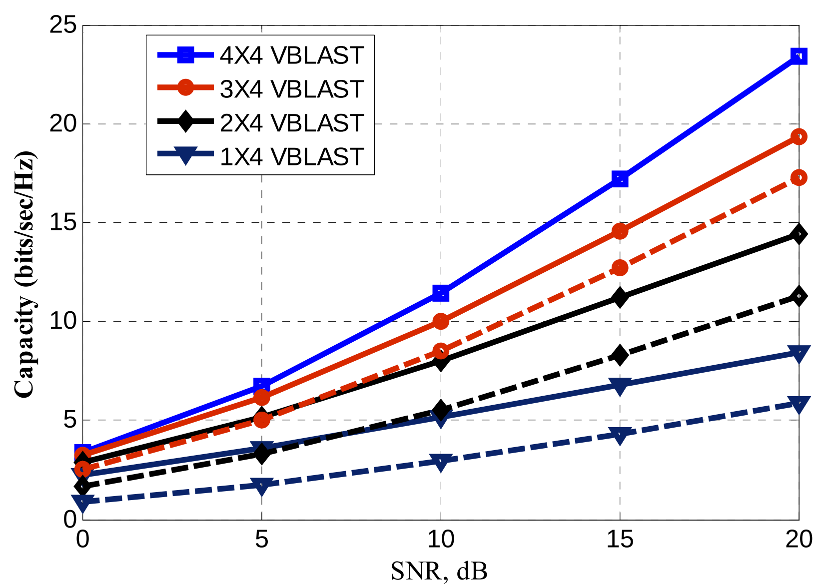


Fig. 4.2 Comparing $M \times M$ and $M \times 4$ VBLAST Capacity.

It is clear from the Fig. 4.1 and 4.2 that $M \times M$ VBLAST performances are worse than $M \times 4$ system excepts that 1 × 1 case due to less interferences appeared from other transmitting antennas compared to 2 × 2, 3 × 3 and 4 × 4 cases, but there is an important results in the previous figures that $M \times 4$ system has greater capacity than its higher order VBLAST system. In contrast, at SNR equals 8 dB 2×4 system has the same channel capacity as 3×3 system. Likely, 1×4 system has a greater capacity than 2×2 system for SNR less than 8 dB because of receive diversity. Finally it can be concluded that $M \times 4$ system have better performance and greater capacity.

4.3 Comparing Hybrid G2 + 1 + 1, G2 + G2 and G2 + 1 systems

After introducing $M \times 4$ and $M \times M$ system, it is important to see the hybrid system's performances and capacities which are depicted on Fig. 4.3 and Fig. 4.4.

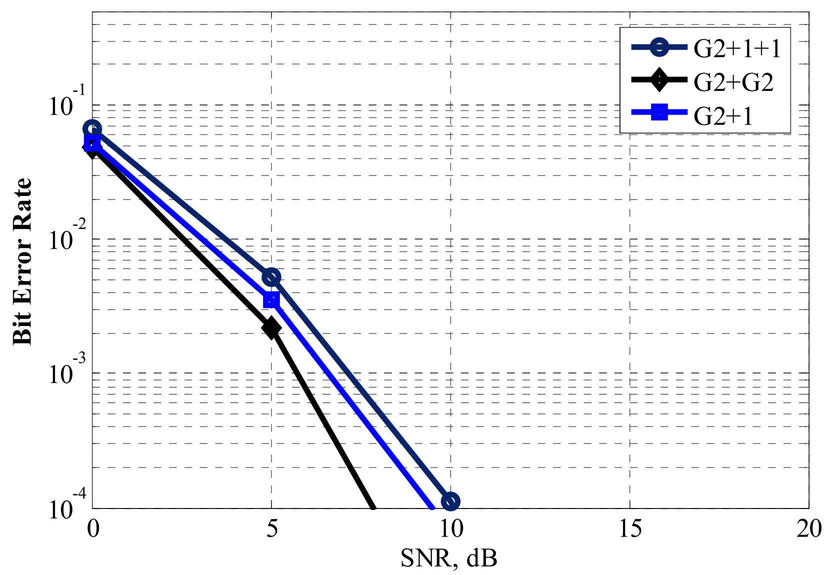


Fig. 4.3 BER of Hybrid systems G2 + 1 + 1, G2 + G2 and G2 + 1.

The hybrid system G2 + G2 in Fig. 3.2 presents the best BER performance compared to others since it has two transmit diversity (one for each layer). Conversely, the hybrid system G2 + 1 + 1 of Fig 3.1 with $M = 4$ and $J = 1$ Alamouti encoder has the worst performance because it has two pure spatial multiplexing layers with additional layer which having a transmit diversity of Alamuoti [7], but its ergodic capacity according to eq.(3.30) is the best since it has 6 bit/sec/Hz eq.(3.19) spectral efficiency at QPSK modulated signals. Regarding to hybrid system G2 + 1 of Fig 3.1 with $M = 3$ and $J = 1$ Alamouti encoder, it has worse performance than G2 + G2 by about 14×10^{-4} BER at 5 dB-SNR or 1 dB in SNR at 10^{-3} BER and better than G2 + 1 + 1 by about 16×10^{-4} BER at 5 dB SNR or better 0.75 dB in SNR at 10^{-3} BER, at 10^{-3} BER there is about 0.75 dB improvement in SNR between G2 + 1 + 1 and G2 + 1. Both of G2 + G2 and G2 + 1 hybrid systems has a spectral efficiency of 4 bit/sec/Hz eq.(3.19) but the upper bound Shannon capacity of G2 + G2 is better by about 0.25 bit/sec/Hz since it has one more transmit diversity layer.

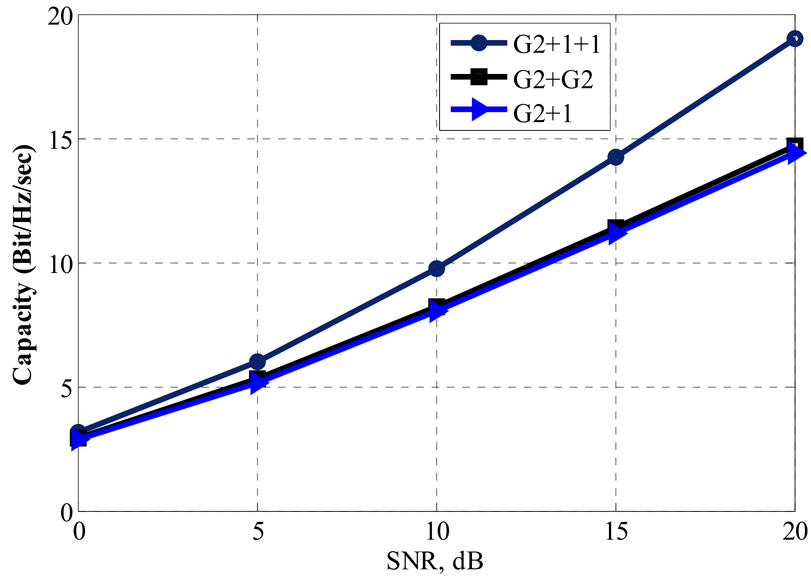


Fig. 4.4 Capacity of Hybrid systems G2 + 1 + 1, G2 + G2 and G2 + 1.

4.4 Comparing 3 × 3, 3 × 4, 4 × 4 VBLAST and Hybrid G2 + 1 + 1 systems

It is expected that G2 + 1 + 1 hybrid system has better performance than pure spatial multiplexing scheme.

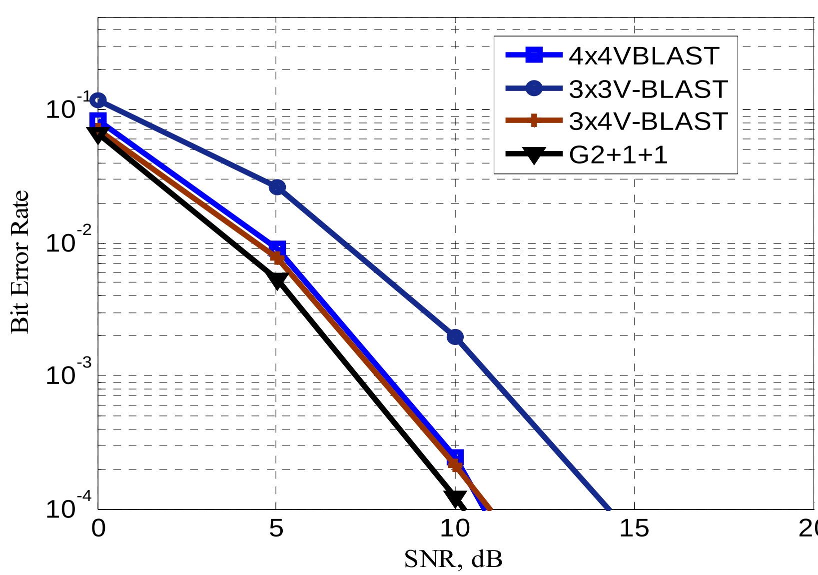


Fig. 4.5 Performance comparison for 3 × 3, 4 × 4, 3 × 4 and G2 + 1 + 1 systems.

By logical inference, both of them have 4-Tx and 4-Rx antennas with the same symbol power and the same receive diversity. So only one thing is varied, it is the last two layers of the transmitter in which it is replaced by an Alamouti encoder which is considered as a third layer with transmit diversity. Unfortunately, transmitting over two time slots causes a decrease in spectral efficiency or average channel capacity since 4 × 4 MIMO loses one transmitting layer, Fig. 4.5 and Fig. 4.6 show the results.

As expected the BER performance of G2 + 1 + 1 hybrid system is better than pure 4 × 4 and 3 × 3 VBLAST system due to transmit diversity benefit of Alamouti in the last layer. An 4 × 4 blast system has 4 layers to be transmitted and 3×3 BLAST system has 3 layers as 3 × 4 BLAST system with receive diversity of 4 but with no transmit diversity. A hybrid system G2 + 1 + 1 has 3 layers, two of them are pure uncoded layers and one of them has Alamouti encoder with receive diversity of 4 using ML detector.

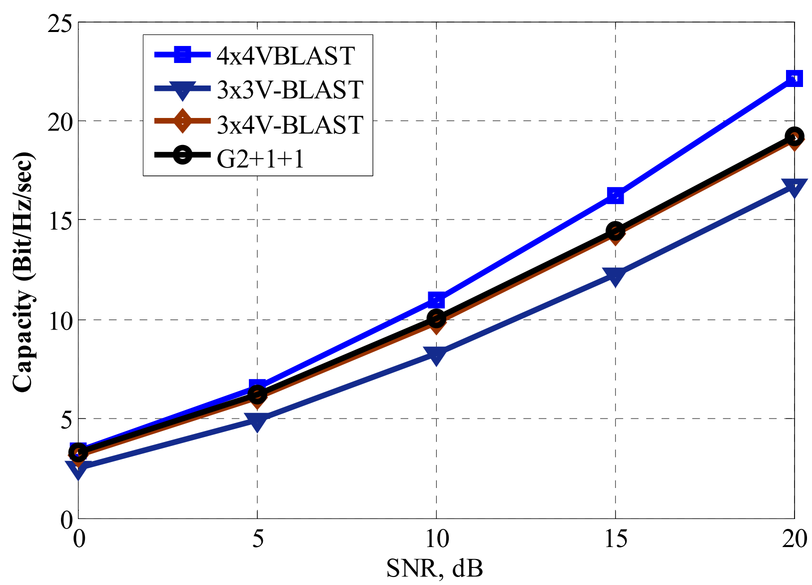


Fig. 4.6 Capacity comparison for 3 × 3, 4 × 4, 3 × 4 and G2 + 1 + 1 systems.

4 × 4 BLAST system has a 8 bps/Hz spectral efficiency with the greatest upper bound Shannon capacity and 3 × 3 and 3 × 4 and G2 + 1 + 1 system has 6 bps/Hz with lower bound of Shannon capacities. However, G2 + 1 + 1 hybrid system has better capacity than both of 3 × 3 and 3 × 4 BLAST systems. Finally, the results give a conclusion that G2 + 1 + 1 hybrid system has a better performance and capacity than switching off one transmit antenna or one receive antenna.

4.5 Comparing 2 × 2, 2 × 4 VBLAST, Hybrid G2 + G2 and G2 + 1 systems

2 × 2, 2 × 4, G2 + G2 and G2 + 1 systems have the same spectral efficiency of 4 bps/Hz, Fig. 4.7 presents the performance results of them.

2 × 4 , G2 + G2 in Fig. 3.2 and G2 + 1 in Fig. 3.1 have the same number of receive antenna but they have different number of transmit antennas 2, 3, and 4, respectively, they have another different thing, it is a transmit diversity layers. A 2 × 2 and 2 × 4 in Fig. 2.1 have no transmit diversity layers while G2 + 1 has one transmit diversity layer and G2 + G2 has two transmit diversity layers. The benefits of hybridizing scheme is clearly appeared in Fig. 4.7. Even though all these scheme have the same transmit signal power of 2*Es* at each time slot, it can be seen that at 10^{-3} BER there is about 1 dB improvement in SNR respect to G2 + 1 and 2 × 4 and 11 dB improvement in SNR respect to 2 × 2 VBLAST.

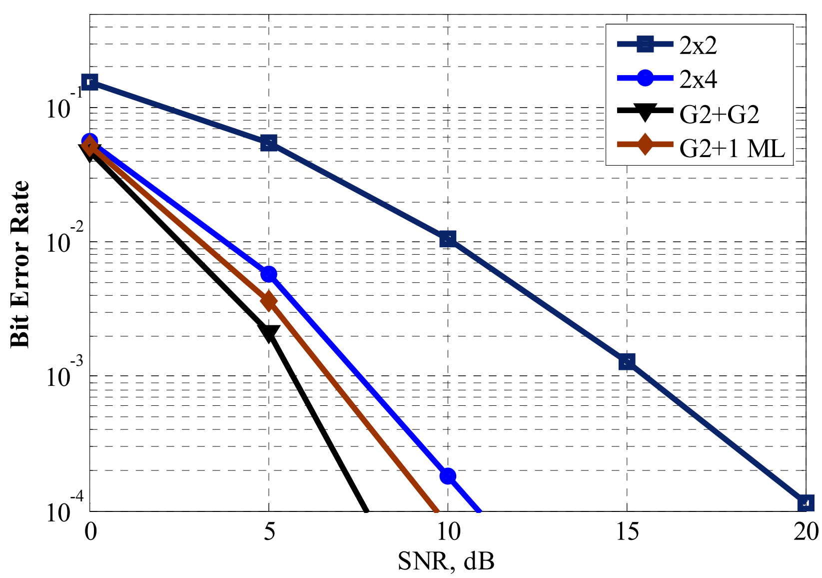


Fig. 4.7 Performance comparison for 2 × 2, 2 × 4, G2 + G2 and G2 + 1 systems

Accordingly, these systems have the same spectral efficiency of 4 bps/Hz and there is no large difference in Shannon capacities as illustrated in Fig. 4.8 below

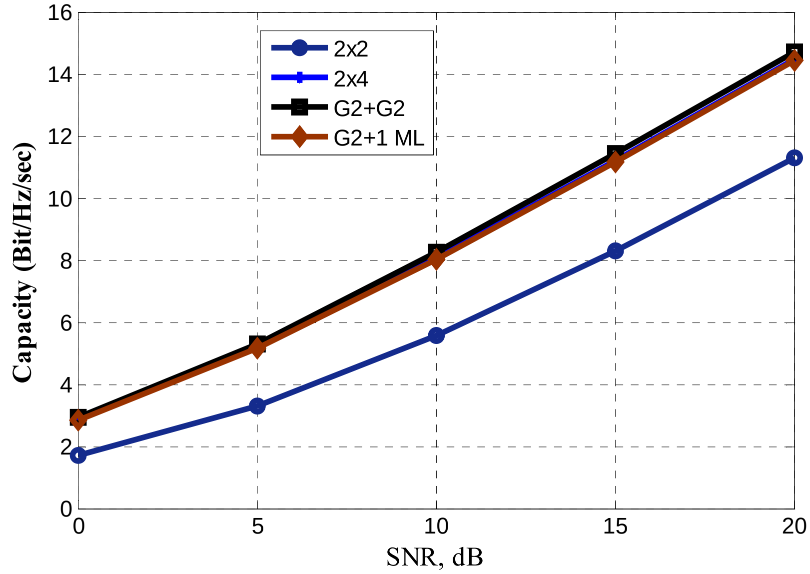


Fig. 4.8 Capacity comparison for 2 × 2, 2 × 4, G2 + G2 and G2 + 1 systems.

As seen in Fig. 4.8, there is slight difference between hybrid systems and receive diversity technique about 0.25 dB in SNR but high for 2 × 2 VBLAST about additional 5 dB improvement in SNR to reach 11 bps/Hz. G2 + G2 hybrid structure has the best performance and capacity with equal transmit power and spectral efficiency respect to pure 2 × 2 VBLAST system, switching off two transmit antenna of 4 × 4 system to be 2 × 4 VBLAST or switching off one transmit antenna of 4 × 4 system and hybridizing it with Alamouti encoder applied to one layer to be G2 + 1 hybrid system.

4.6 Comparing 1 × 1, 1 × 4 VBLAST, G4-OSTBC, G2-OSTBC and QOSTBC systems

An 1 × 1 system has no diversity benefits while 1 × 4 structure has four receive diversity order when using ML detector. G4-OSTBC, G2-OSTBC (Alamouti) and QOSTBC have both transmit and receive diversity benefits. Fig. 4.9 shows the performance results in a comparable way. Clearly, it is in Fig. 4.9 seen that at 10^{-3} BER QOSTBC scheme needs more 4 dB improvement in SNR, 6 dB for 1 × 4 system, 9 dB for 2 × 2 Alamouti system and more than 20 dB for 1 × 1 VBLAST system to reach G4-OSTBC performance with the same transmit power. All these system have a spectral efficiency of 2 bps/Hz except G4-OSTBC system which has a 1 bps/Hz and half transmitted power of them. Fig. 4.10 shows the Shannon capacity of them in a comparable way.

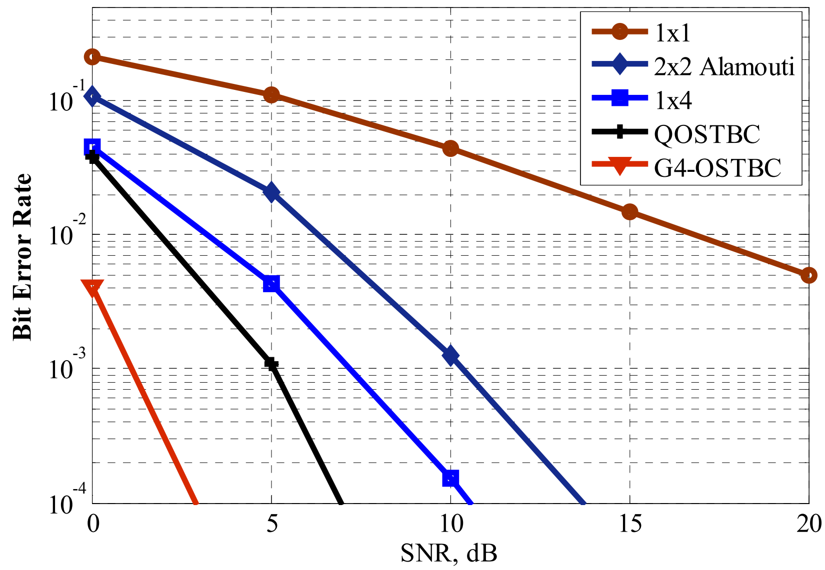


Fig. 4.9 Performance comparison for 1 × 1, 1 × 4, 2 × 2 Alamouti, QOSTBC and G4-OSTBC systems

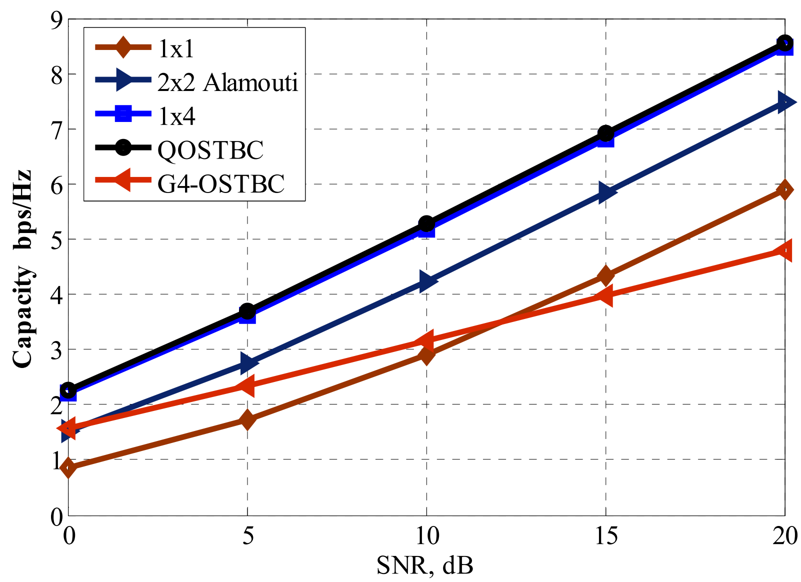


Fig. 4.10 Capacity comparison for 1 × 1, 1 × 4, 2 × 2 Alamouti, QOSTBC and G4-OSTBC systems

G4-OSTBC system has better capacity than 1 × 1 VBLAST for SNR below than 12 dB since it enjoys both transmit diversity on 4 transmit antennas and receive diversity benefits of 4 receive antennas but both of them have lower capacity than other systems. QOSTBC scheme [9] in Fig. 2.9 achieves better capacity than others with the same transmit power. For example to achieve 4 bps/Hz 1 × 4 system needs more about 0.25 dB improvement in SNR, 3.25 dB for 2 × 2 Alamouti system, 8 dB for 1 × 1 system and 9.5 dB for G4-OSTBC system to reach the bound of QOSTBC system.

Finally, QOSTBC had a very good performance compared to other systems with the best capacity for the same transmit power.

4.7 Comparing 4 × 4 VBLAST, Hybrid G2 + 1 + 1, G2 + G2 and QOSTBC systems

Now a comparison of the best performances and capacities of the above case or for cases of the same transmit power must be introduced. Fig. 4.11 and Fig. 4.12 show the compared performances and capacities of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems.

Form Fig. 4.11 and Fig. 4.12 a good comparison could be done that a 4 × 4 VBLAST system needs 3.75 dB improvement in received SNR to reach the BER performance of QOSTBC system of 10^{-3}. Conversely, a 6 dB improvement in SNR is needed for QOSTBC system to reach the capacity of 4 × 4 system of 5 bps/Hz. Also a 2.5 dB improvement in SNR needed for 4 × 4 system to achieve 10^{-3} BER performance's of G2 + G2 system, but G2 + G2 need 2 dB improvement in SNR to reach the capacity of 4 × 4 system of 5 bps/Hz. Finally, G2 + 1 + 1 needs more 0.75 dB in SNR to reach a 4 × 4 capacity bound of 5 bps/Hz, but 4 × 4 system needs 1 dB improvement in SNR to achieve G2 + 1 + 1 performance of 10^{-3} BER.

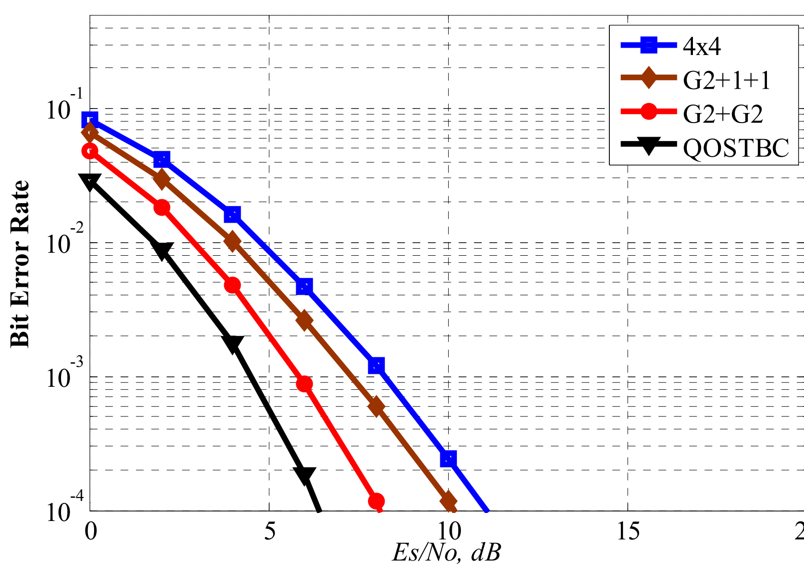


Fig. 4.11 Performance comparison for 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems.

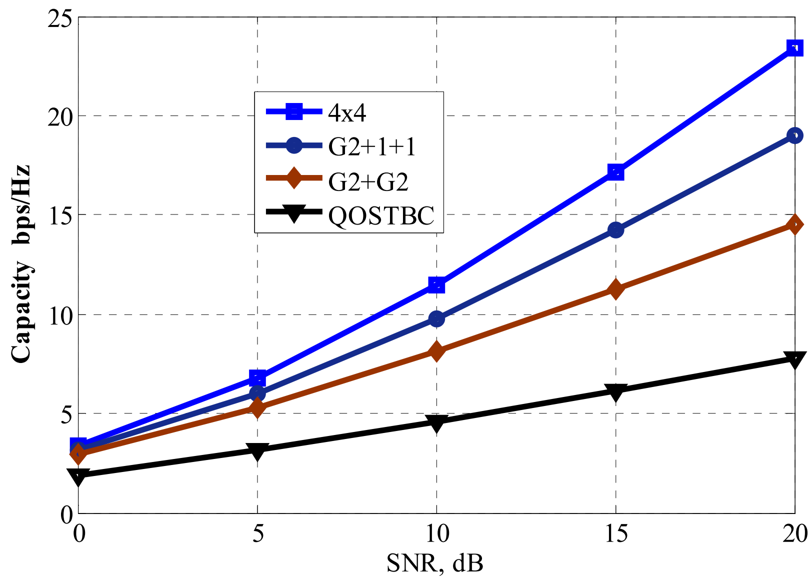


Fig. 4.12 Capacity comparison for 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems.

4.8 Summary

A comparison for the BER performances and the capacity of V-BLAST, QOSTBC, G4-OSTBC and Hybrid systems G2 + 1 + 1, G2 + 1 and G2 + G2 were carried using simulation. In addition, it was shown that the Hybrid systems was better than pure VBLAST in both BER and capacity. At the same transmit power and spectral efficiency the hybrid system G2 + G2 presented better performance and capacity than G2 + 1 system since it has two transmit diversity layers. It has also better performance than G2 + 1 + 1 system, but not for the capacity with different transmitting power and spectral efficiency at QPSK modulated signals. $M \times 4$ systems (for $M = 1, 2, 3$ or 4) have better performance and greater capacity than $M \times M$ systems. The results showed that G2 + 1 + 1 hybrid system have a better performance and capacity than switching off one transmit antenna. G2 + G2 hybrid structure have better performance and capacity than switching off two transmit antennas of 4 × 4 system or switching off one transmit antenna of 4 × 4 system and hybridizing it with Alamouti encoder applied to one layer to be G2 + 1 hybrid system. The QOSTBC have a very good performance and the best capacity than switching off three transmitting antennas of 4 × 4 system. Finally, a comparison between 4 × 4 VBLAST, hybrid G2 + 1 + 1, hybrid G2 + G2 and QOSTBC was made to see the best cases at several spectral efficiencies.

CHAPTER 5
ADAPTIVE SWITCHING HYBRID BLAST-STBC SYSTEM

5.1 Introduction

Fading is a wireless channel impairment [18]. Wireless communications occur in the public space, where signal transmission suffers from many factors such as path loss, shadowing, fading, etc. As a result, the wireless channel has time-varying condition and capacity. Thus, transmission techniques such as adaptive transmission, will play an important role in increasing the throughput. Adaptive transmission is one of the key enabling techniques in the new generation standards for wireless systems that has been developed to achieve high spectral efficiency on fading channels [19]. Adaptive modulation, antenna subset selection and switching systems are considered as common adaptive schemes for MIMO communication systems in high data rate next generation.

Throughput is a key measure of the quality of a wireless data link. It is defined as the number of information bits received without error per second and this is required to be as high as possible [17].

This chapter will study the effect of transmit antenna multipath channel deep fading on the effective received SNR, BER, capacity and throughput of 4 × 4 MIMO system for several transmit fading scenarios. A new way to represent 4 × 4 MIMO systems will be studied, in which the transmission process is carried out in an adaptive manner for both 4 × 4 SM system and transmit diversity of QOSTBC, Hybrid systems G2 + 1 + 1 and G2 + G2 according to the transmit link state in order to save the total transmitted power, get the maximum throughput and the best performance under certain level which keep overall performance robustness and efficient capacity. An adaptive switching transmission scheme by the strategy of measuring the transmit links fading is investigated as well. The simulated results are obtained in an environment as same as the previously described simulation environment in chapter 4 with more ideal conditions are assumed for adaptive switching transmission such as no channel estimation errors, no feedback transmission errors, no channel state feedback delay, a very low capacity feedback transmission and no peak power constraints, etc. It is also assumed that all management and control frames are transmitted correctly and in time.

5.2 Transmit Link Deep Fade

In last chapters, a full study of 4 × 4 VBLAST system was introduced regarding to the performance and Shannon capacity. Now the questions is what will happen to BER, Capacity and throughput of this system if one or more transmit links suffers from a considerable fading.

In addition, what is the best choice to do if the system is under deep fade condition to maintain a certain level of BER or received SNR which achieving the best capacity and throughput without additional transmit power.

Throughput can be computed as [63],

$$T = R\ (1\text{-}BER), \tag{5.1}$$

where *R* is the data rate, the capacity of wireless channel is *C*, but the data that wanted to be sent on that channel is with rate *R* where $R \leq C$. Now data rate *R* can be equal or less than the capacity of the channel. *C* is the upper bound capacity of the channel and data rate *R* is the actual data that is being sent/received on that particular channel.

The data rate can be equal or less than the capacity according to the application. To give a specific example, the ISDN telephone line which normally offer 128 Kbps. If this ISDN line is used for just single telephone and not for any data purpose, then only 64 Kbps is used while its capacity is still 128 Kbps but only 64 Kbps is used. So in this sense capacity and data rate may differ from each other and can be treated as different terms, but usually they considered the same.

Since fading will decrease the Shannon bound then letting *R* to be at the maximum bound of Shannon $R = C$ will give a good test in this system.

$$T = C\ (1\text{-}BER) \tag{5.2}$$

The effective average received SNR of 4 × 4 MIMO system is equal to [66]

$$SNR_{eff} = \frac{E_s \|H\|_F^2}{MN_o} = SNR\|H\|_F^2\ , \tag{5.3}$$

where $\| \ \|_F^2$ is the Frobenius norm [67] which is equal to

$$\|H\|_F = \sqrt{\sum_{j=1}^{N}\sum_{i=1}^{M} h_{ij}^2} \tag{5.4}$$

The individual contribution of each receive antenna to the effective SNR is through the contribution of $\|H\|_F^2$ [68].

5.2.1 Deep Fade of Transmit Link 4

The first case that will be studied and simulated is that if transmit link 4 of 4 × 4 VBLAST system under deep fading condition. This means that the 4th column of channel matrix has lower overall gain than the other columns. Then all symbols transmitted from this antenna will be received with high error probability which will increase the overall BER of the system as well as the capacity of the system will decreased until it reaches the capacity of a 3 × 4 system. In other words, the faded Tx link will look like as switched off. Fig. 5.1, 5.2, 5.3, 5.4 and 5.5 show their effect on the effective SNR, BER, capacity and the overall throughput.

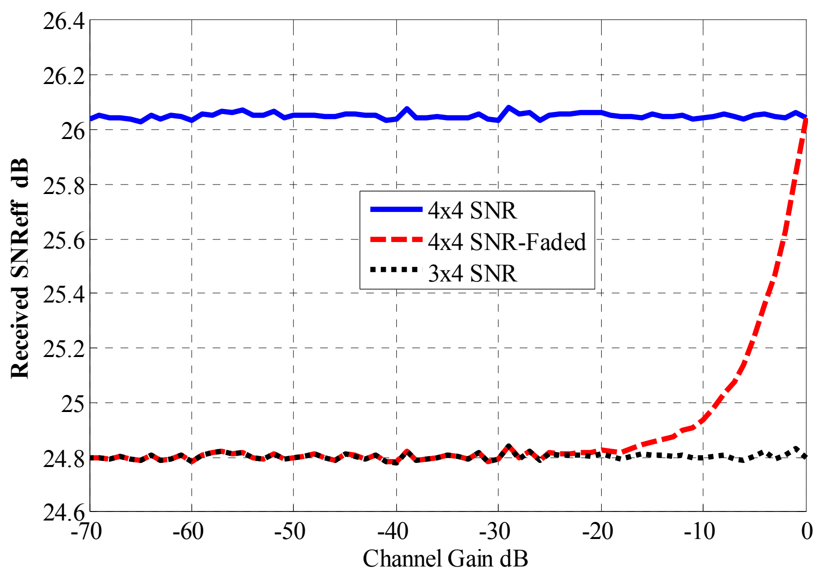


Fig. 5.1 Effect of 4th Tx link fading on SNR_{eff} for SNR = 14 dB.

It seen from Fig. 5.1 that a 4 × 4 VBLAST SNR_{eff} decreases as the channel gain decreases until it reaches a 3 × 4 VBLAST at fading lower than -20 dB, the maximum decreasing of SNR_{eff} of 4th Tx link fading at 14 dB SNR is about 1.2 dB. Since 4 × 4 Rayleigh Channel with variance 1 so eq. (5.4) states that the average Frobenius norm of H is 16, so the effective SNR of 4 × 4 MIMO channel is 16 times the received SNR for one receive link then is SNR=14dB then SNR_{eff} = 14 +10log$_{10}$16 = 26.02 dB on average. But the average Frobenius norm of 3 × 4 channel is 12 then SNR_{eff} = 14 +10×log$_{10}$12 = 24.8 dB on average. As a result, 3 × 4 channel and 4 × 3 channel have the same effect on SNR_{eff} since the average Frobenius norm of 3 × 4 and 4 × 3 channel is the same. It can be inferred that a deep fading of one Tx link or one Rx link have the same effect on SNR_{eff} and average capacity.

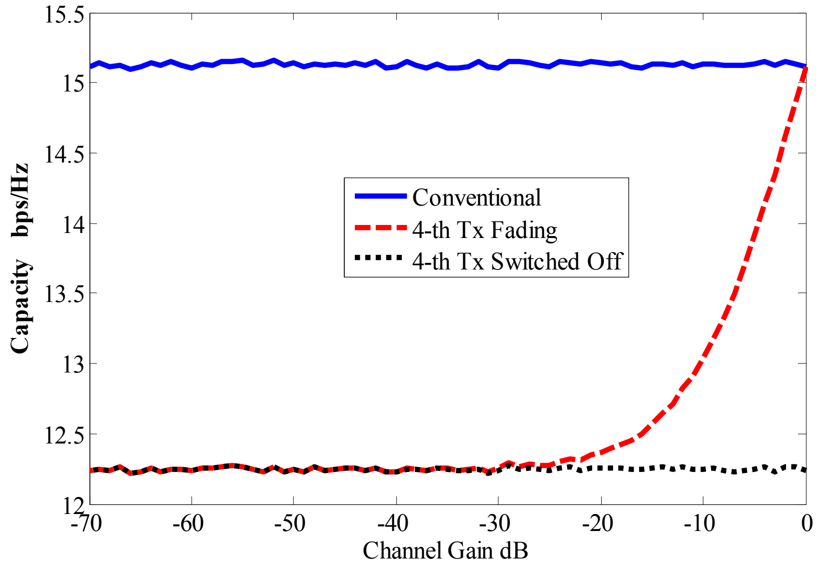


Fig. 5.2 Effect of 4th Tx link fading on average capacity for SNR = 14 dB.

When the channel gain is lower than -30 dB then there is a loss in capacity of 4.35 bps/Hz as shown in Fig. 5.2.

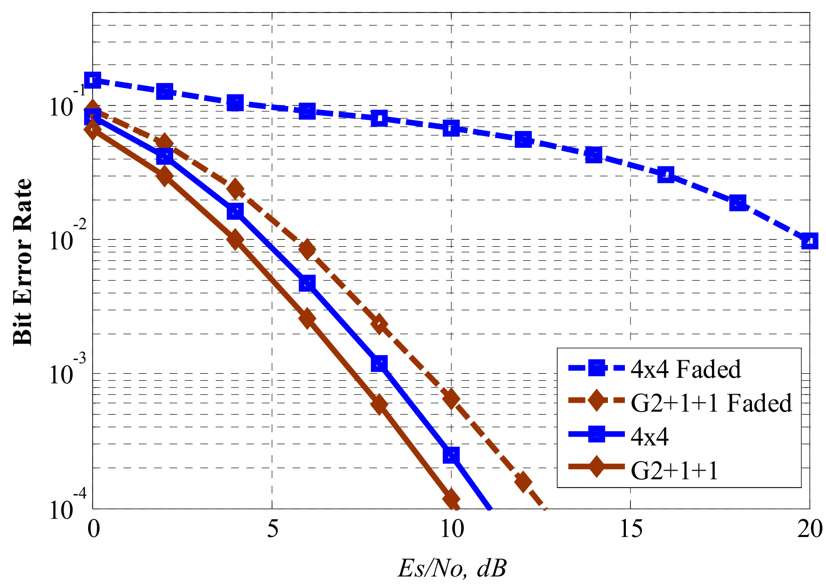


Fig. 5.3 BER of 4 × 4 and G2 + 1 + 1 if 4th Tx link faded to -20 dB.

Now the BER performance when 4th Tx link faded to -20 dB then the 4th layer will suffer of high errors which causes a very bad BER. However, if Alamouti encoder is used for the last two layers with the same transmitted power for every symbol (G2 + 1 + 1 system), an improvement in BER can be noticed. The difference between conventional G2 + 1 + 1 system and the faded one is only about 2 dB . Fig. 5.3 shows that an improvement by 14 dB is needed for 4 × 4 system to achieve the BER performance of G2 + 1 + 1 under a deep fading condition. The capacity of both of them is approximately the same as seen below in Fig. 5.4.

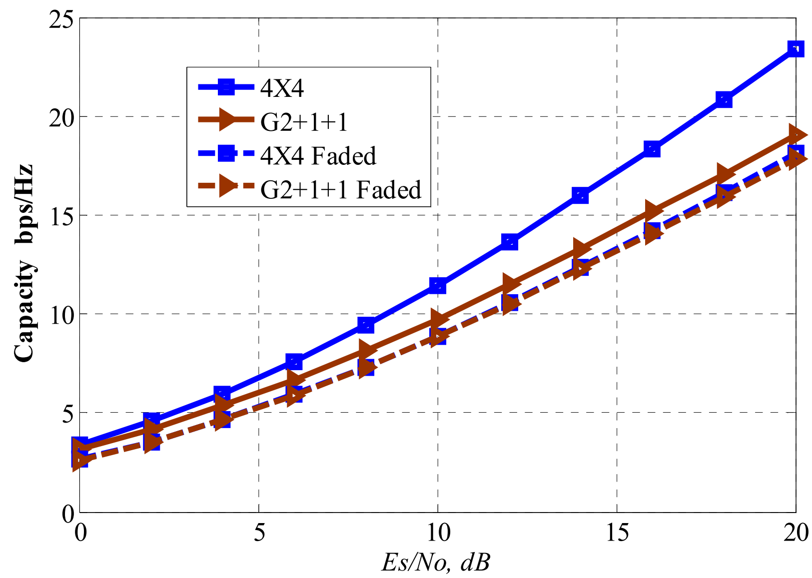


Fig. 5.4 Average Capacity of 4 × 4 and G2 + 1 + 1 if 4th Tx link faded to -20 dB.

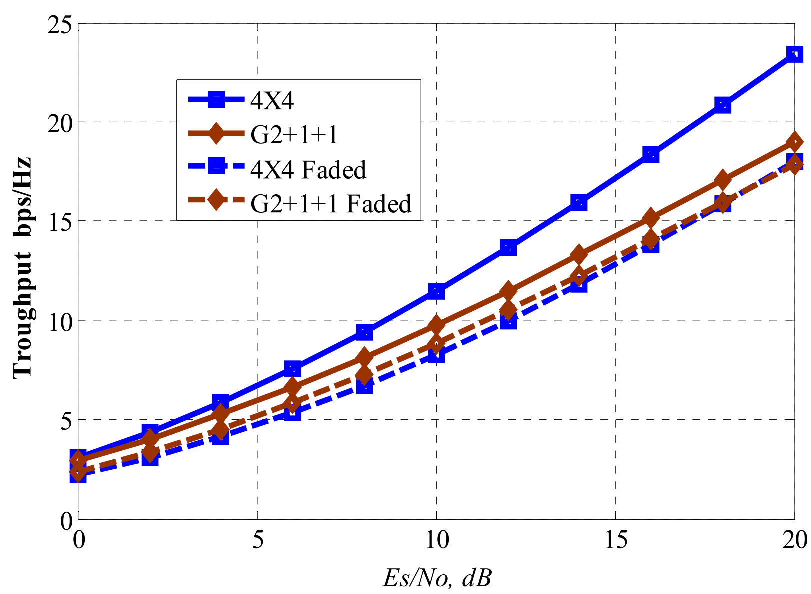


Fig. 5.5 Throughput of 4 × 4 and G2 + 1 + 1 if 4th Tx link faded to -20 dB.

Normally, G2 + 1 + 1 system has lower BER at the same capacity of deeply faded 4 × 4 system so from eq. (5.2) G2 + 1 + 1 system will have higher throughput until getting high SNR about 20 dB as seen in Fig.5.5 .

5.2.2 Deep Fade of Transmit Links 3&4

The third and fourth columns of channel matrix have lower overall gain at deep fading condition. All symbols transmitted from these antennas will be received with a high error probability which make the overall BER of the system so bad. Moreover, the capacity of the system will decrease until it reaches a 2×4 system. In other words the faded Tx links will look like as switched off.

Fig. 5.6, 5.7, 5.8, 5.9 and 5.10 will their effect on the effective SNR, BER, capacity and the overall throughput.

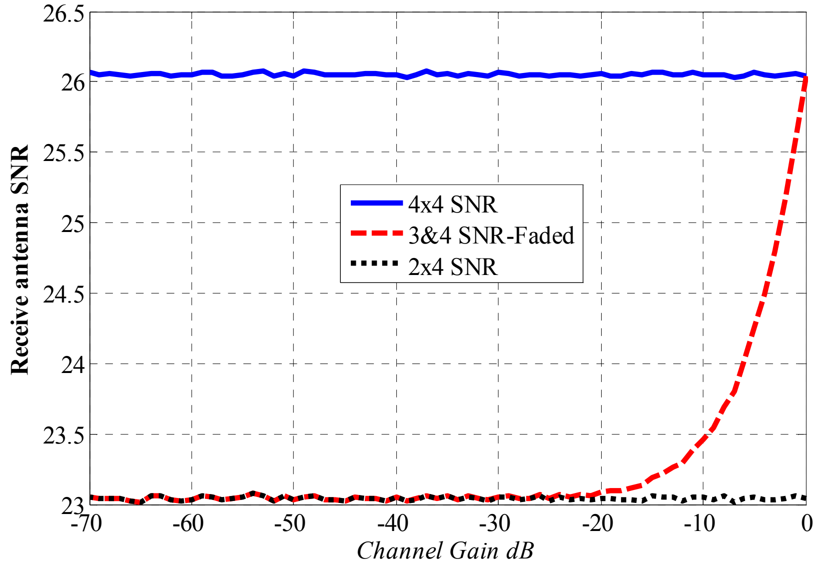


Fig. 5.6 Effect of 3rd & 4th Tx links fading on SNR_{eff} for SNR = 14 dB.

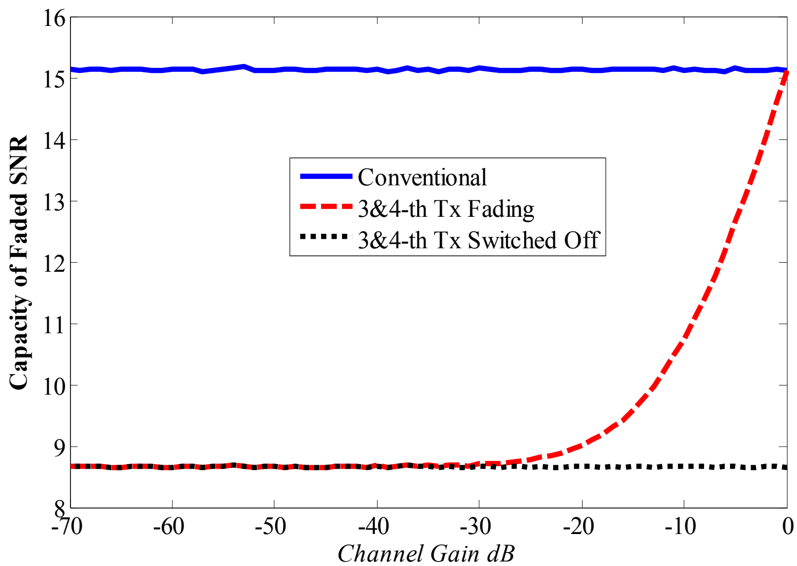


Fig. 5.7 Effect of 3rd & 4th Tx links fading on Average Capacity for SNR = 14 dB.

It can be seen from Fig. 5.6 that a 4 × 4 VBLAST SNR_{eff} decreases as the channel gain decreases until it reaches the SNR_{eff} of 2 × 4 VBLAST at fading lower than -20 dB. The maximum decreasing of SNR_{eff} of 3rd & 4th Tx links fading at 14 dB SNR is about 3 dB. On the other hand, Fig. 5.7 shows that there is a loss in capacity of 6.3 bps/Hz when the fading gain of 3rd & 4th Tx links is lower than -30 dB.

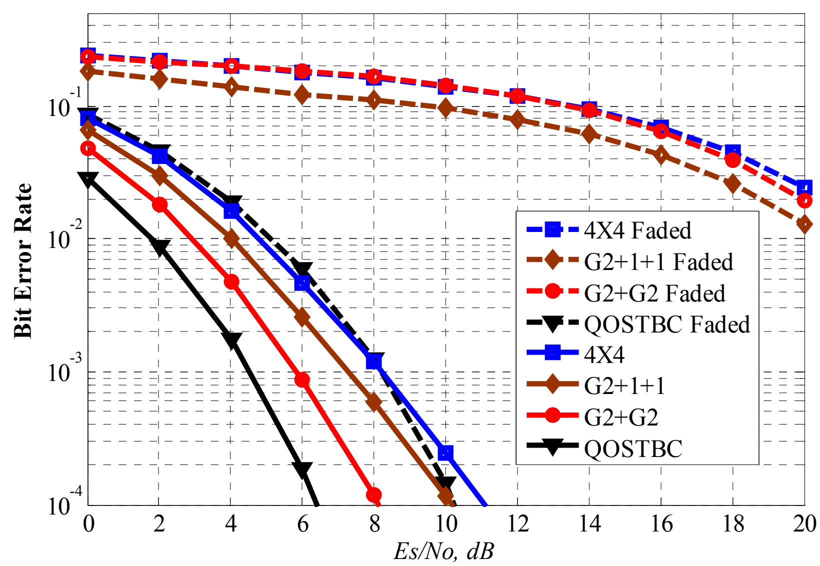


Fig. 5.8 BER of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 3rd & 4th Tx links faded to -20 dB.

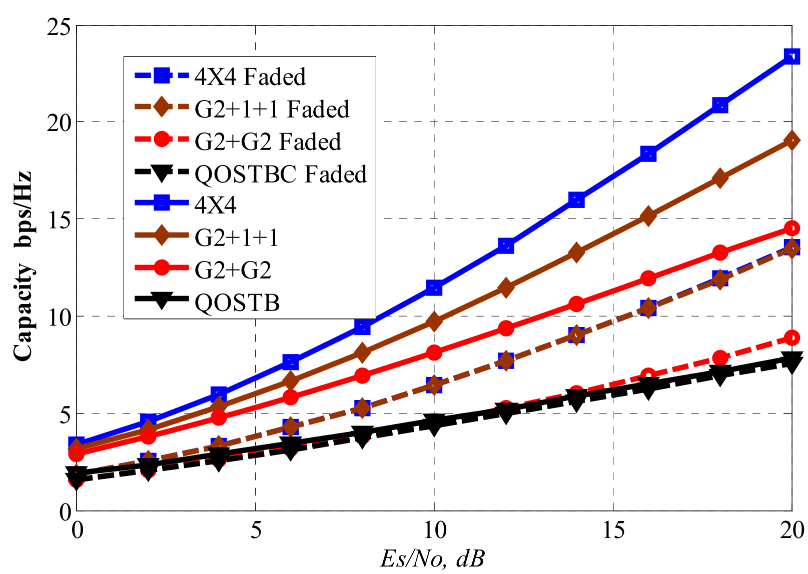


Fig. 5.9 Average Capacity of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 3rd & 4th Tx links faded to -20 dB.

In Fig. 5.8, it is clear that the BER of 4 × 4, G2 + 1 + 1 and G2 + G2 systems for 3rd & 4th Tx links faded to -20 dB are bad enough. However, QOSTBC system has the best BER performance but with much lower capacity as in Fig. 5.9 which make its throughput to be lower than other as seen in Fig. 5.10. Additionally, Fig. 5.10 states that G2 + 1 + 1 system has the best throughput. So using Alamouti encoder for 3rd & 4th fading layers and leave the first two layers to be transmitted directly as a pure spatial multiplexing transmission will give the best throughput.

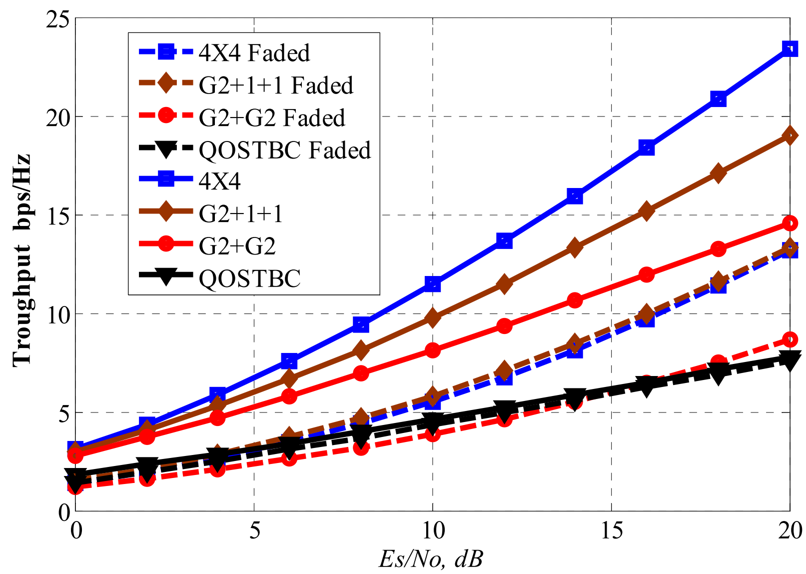


Fig. 5.10 Throughput of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 3rd & 4th Tx links faded to -20 dB.

5.2.3 Deep Fade of Transmit Links 2&4

Now if 2nd & 4th transmit links have been faded deeply then the effect on the received SNR_{eff} and the average capacity is as same as the effect of deeply fading of 3rd & 4th transmit links but not for BER, average capacity and overall throughput.

It is clear from in Fig. 5.11 that the BER of 4 × 4 and G2 + 1 + 1 systems for 2nd & 4th Tx links faded to -20 dB are bad enough. However, G2 + G2 and QOSTBC systems have a very good BER performance with lower capacity as in Fig. 5.12. Additionally, Fig. 5.13 states that G2 + G2 system has the best throughput. So using two Alamouti encoder for the first two layers which include the 2nd deeply faded Tx link and the last two layers which include the 4th deeply faded Tx link gives the best throughput. At 10^{-2} BER, there is loss of more than 16 dB in SNR due to deep fading for 4 × 4 and G2 + 1 + 1 systems but only 4 dB loss for G2 + G2 and 3 dB for QOSTBC systems as shown in Fig. 5.11.

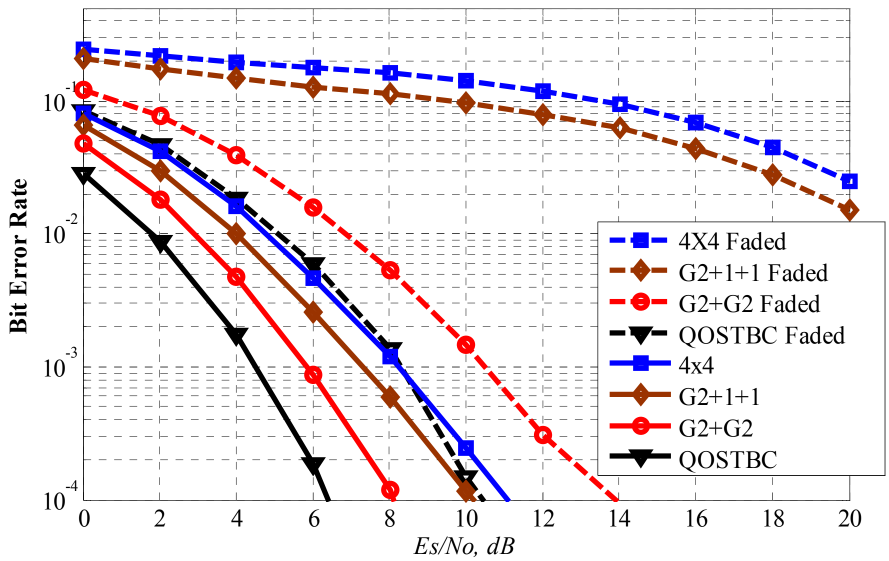


Fig. 5.11 BER of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 2nd & 4th Tx links faded to -20 dB.

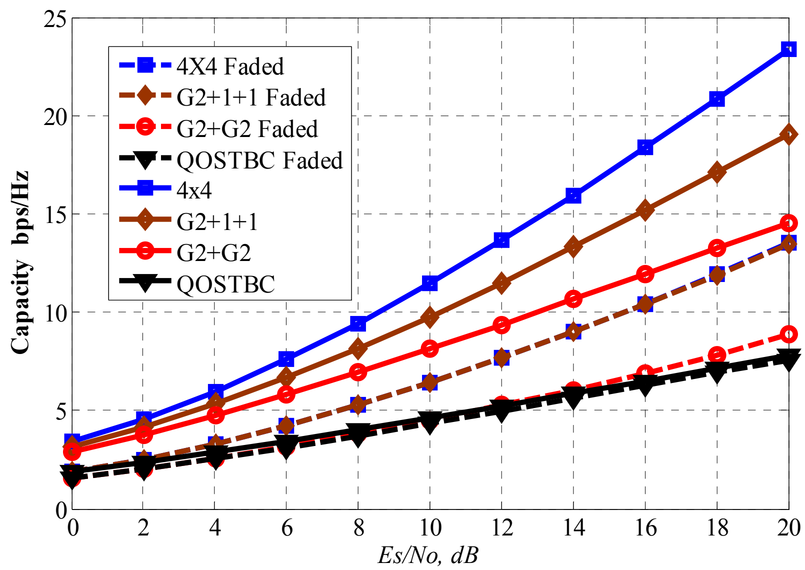


Fig. 5.12 Average Capacity of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 2nd & 4th Tx links faded to -20 dB.

Also Fig. 5.12 shows a 6 dB loss due to deep fading of 2nd & 4th Tx links for 4 × 4 and G2 + 1 + 1 systems, 8 dB loss for G2 + G2 system and no loss for QOSTBC system at 5 bps/Hz. Finally, Fig. 5.13 shows that G2 + G2 system has the best throughput until improving in SNR to be more than 17 dB then 4 × 4 VBLAST system will be the best. Notice that the best throughput is achieved without additional power nor additional bandwidth.

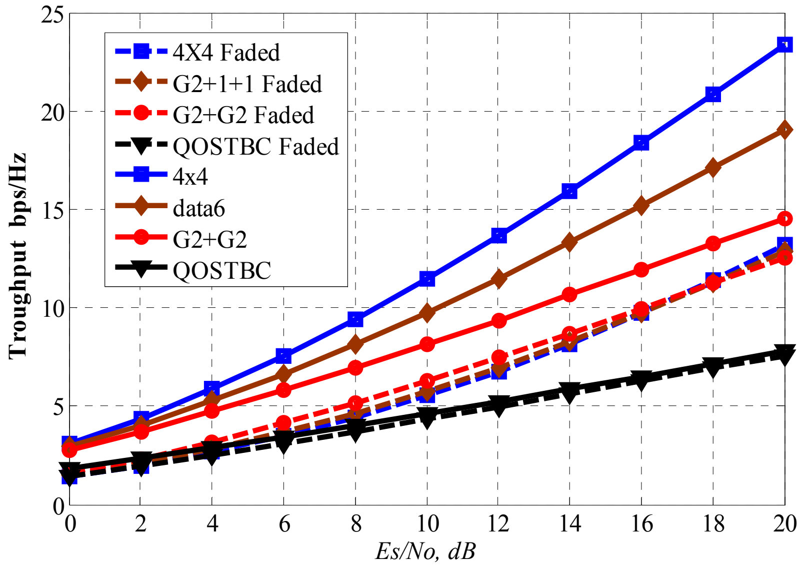


Fig. 5.13 Throughput of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 2nd & 4th Tx links faded to -20 dB.

5.2.4 Deep Fade of Transmit Links 2nd & 3rd & 4th

At -20 dB fading of 2nd & 3rd &4th Tx links, then all symbols transmitted from 2&3&4th Tx antennas will be received with high error probability. Then the overall BER of the 4 × 4 system is so bad also its capacity until it reaches the capacity of a 1 × 4 system. In other words, the faded Tx links will be switched off. Fig. 5.14, 5.15, 5.16, 5.17 and 5.18 show their effect on the effective SNR, BER, capacity and the overall throughput.

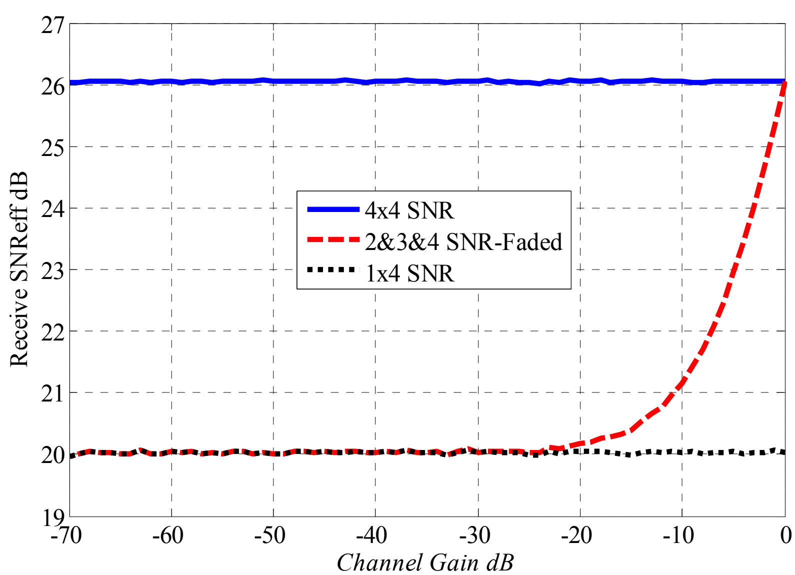


Fig. 5.14 Effect of 2nd & 3rd & 4th Tx links fading on SNR_{eff} for SNR = 14 dB.

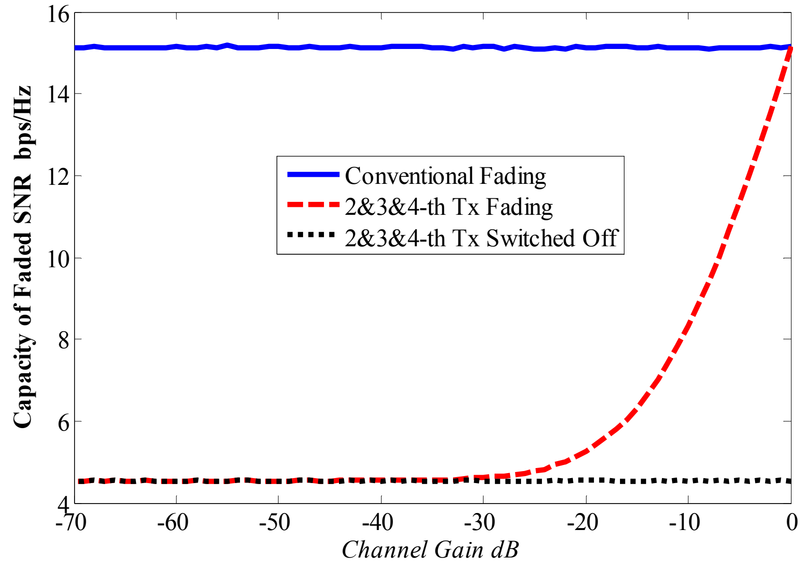


Fig. 5.15 Effect of 2nd & 3rd & 4th Tx links fading on average capacity for SNR = 14 dB.

It can seen from Fig. 5.14 that a 4 × 4 VBLAST SNR_{eff} decreases as the fading gain decreases until it reaches a -20 dB, the SNR_{eff} of 1 × 4 VBLAST at fading lower than -20 dB. The maximum decrease of SNR_{eff} of 2nd & 3rd & 4th Tx links fading at 14 dB SNR is about 6 dB.

On the other hand, Fig. 5.15 shows that there is a loss in capacity of 10.5 bps/Hz, when the fading gain of 2nd & 3rd & 4th Tx links is lower than -30 dB.

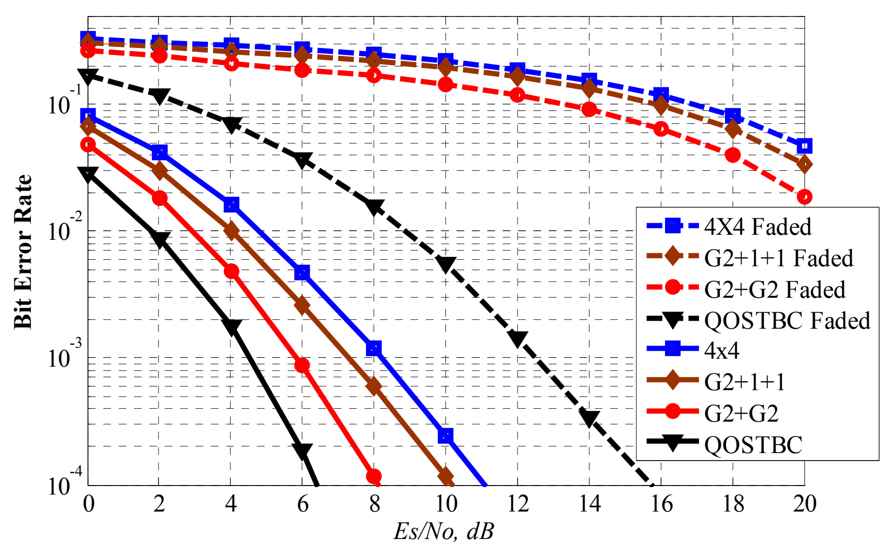


Fig. 5.16 BER of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 2nd & 3rd & 4th Tx links faded to -20 dB.

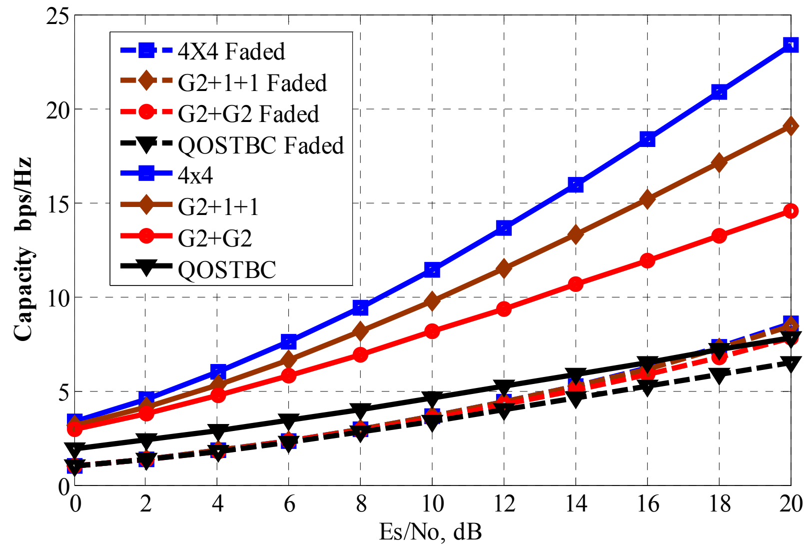


Fig. 5.17 Average Capacity of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 2nd & 3rd & 4th Tx links faded to -20 dB.

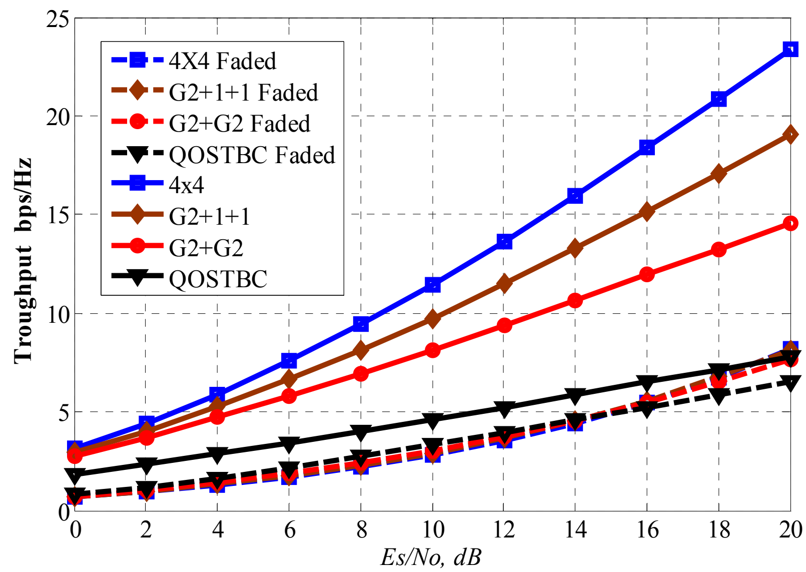


Fig. 5.18 Throughput of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for 2nd & 3rd & 4th Tx links faded to -20 dB.

Additionally, Fig. 5.18 states that QOSTBC system has the best throughput until SNR is equal to 15 dB then the throughput of G2 + 1 + 1 system gives better performance until the SNR is equal to 20 dB.

Hence 4 × 4 system reacquire its advantages of increasing the capacity with acceptable BER performance and yields the best throughput. At 10^{-2} BER there is loss of more than

16 dB in SNR due to deep fading for 4 × 4 G2 + 1 + 1 and G2 + G2 systems but only 7 dB loss for QOSTBC system as shown in Fig. 5.16.

Also Fig. 5.17 shows more than 10 dB loss due to deep fading of 2^{nd} & 3^{rd} & 4^{th} Tx links for 4 × 4, G2 + 1 + 1 and G2 + G2 system and only 4 dB loss for QOSTBC system at 5 bps/Hz. Notice that the best throughput is achieved without additional power nor additional bandwidth.

5.2.5 Deep Fade of All Transmit Links

If all Tx links suffer from deep fading then all entries of the channel matrix will be at low gain then SNR_{eff} will decreases more and more as the channel gain decrease as seen in Fig. 5.19.

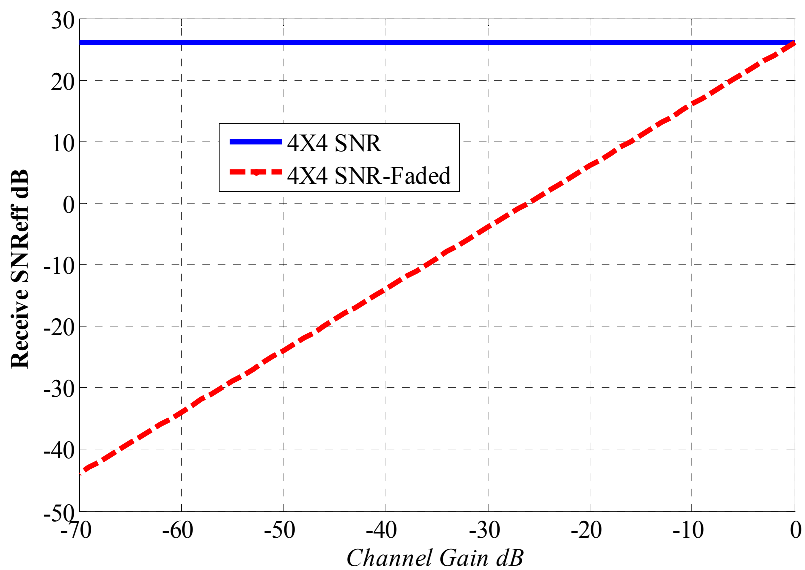


Fig. 5.19 Effect of all Tx links fading on SNR_{eff} for SNR = 14 dB.

Also the capacity will decrease more and more until it reaches 0 bps/Hz which means that it is equivalent to switching off all Tx antennas. Fig. 5.20 shows the effect of deep fading of all Tx links. In addition, Fig. 5.21 shows the BER performance of these systems. This case of fading makes all BER performances very bad and a great loss of power occurred, a great loss of capacity occurred too and all systems capacities approximately the same as seen in Fig. 5.22 until 14 dB SNR. Some improvements on BERs and capacities of these systems are noticed at SNR higher than 15 dB.

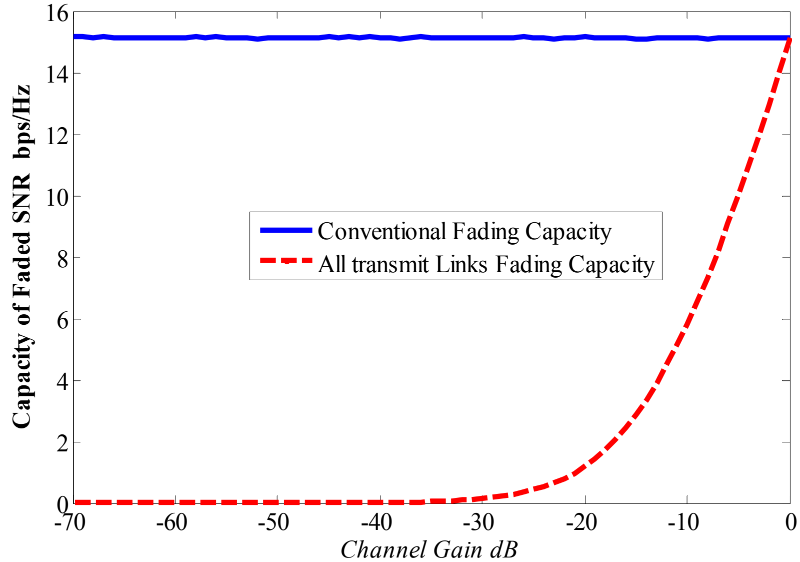


Fig. 5.20 Effect of all Tx links fading on average capacity for SNR = 14 dB.

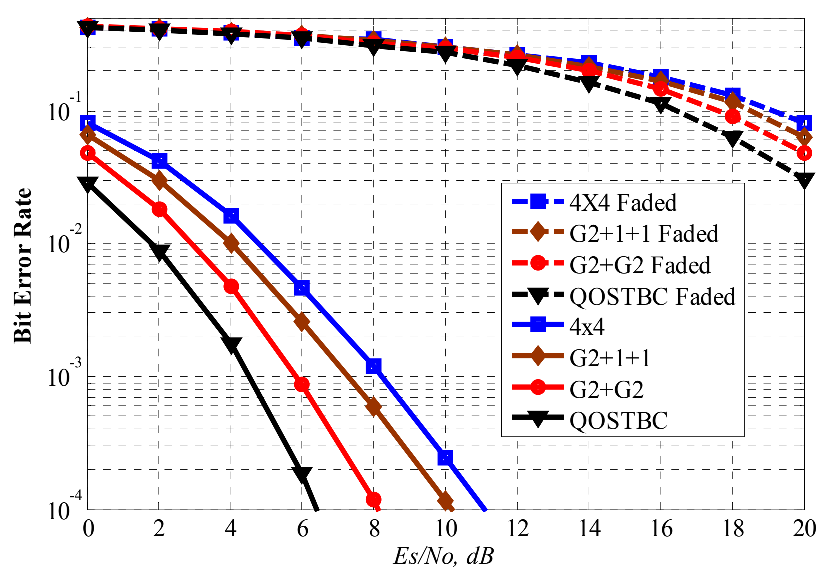


Fig. 5.21 BER of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC Systems for all Tx links faded to -20 dB.

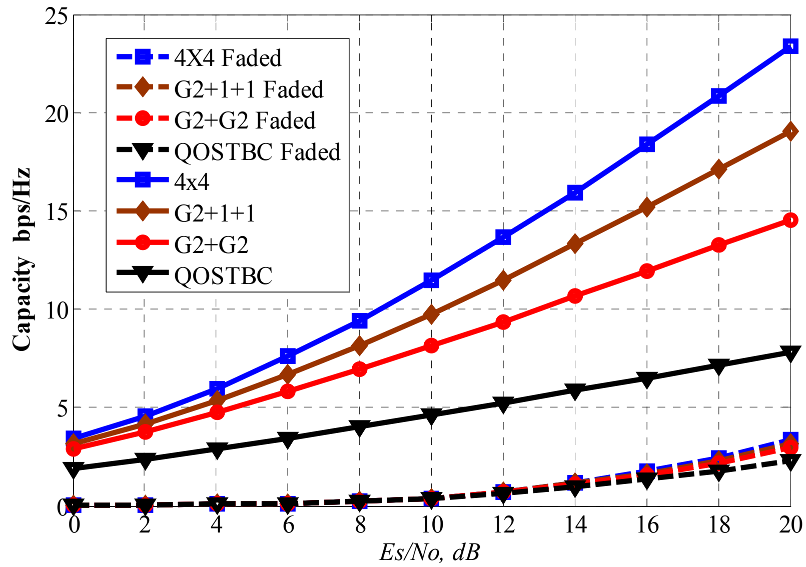


Fig. 5.22 Average Capacity of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for all Tx links faded to -20 dB.

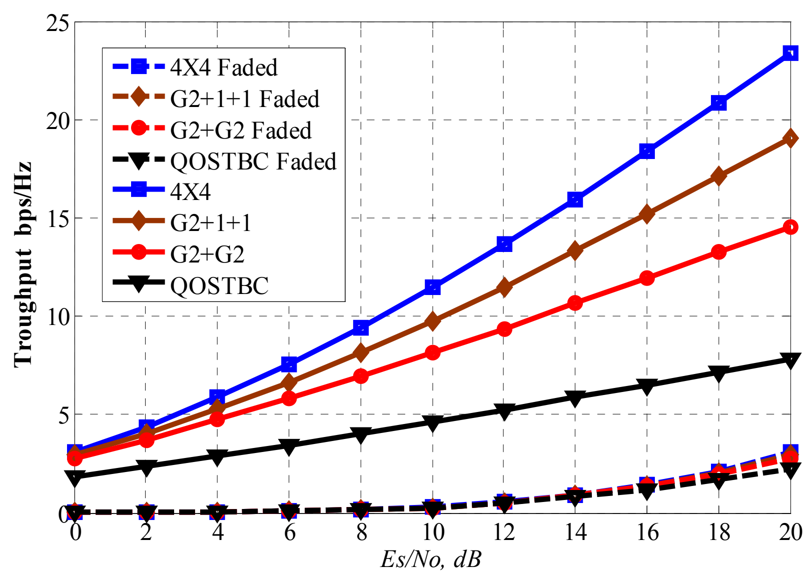


Fig. 5.23 Throughput of 4 × 4, G2 + 1 + 1, G2 + G2 and QOSTBC systems for all Tx links faded to -20 dB.

It is seen from Fig. 5.23 that the system's throughput is not good since this channel is so bad but some bps could be saved for a given bandwidth, 4 × 4 system has better throughput for all cases.

5.3 Proposed Adaptive Switching between VBLAST, Hybrid G2+1+1, Hybrid G2+G2 and QOSTBC Systems

In 4 × 4 MIMO system, there are two antenna selection methods to improve the effective SNR, transmit antenna selection and receive antenna selection [67], [68]. This thesis considers only the first way, every way has a base to select on, it may be based on SNR threshold, BER threshold, bandwidth efficiency or channel norm threshold [69] [70], [71], [72]. The proposed adaptive switching hybrid system (ASHS) will be switched in order to maximizing the throughput in all cases through sending a training sequence of every scheme for every ±2 dB change of received SNR and computing the throughput of all transmitted schemes.

Since the wireless channel condition is always changing and the signal quality is unpredictable [19], ASHS always chooses the best transmission scheme based on the Channel State Information (CSI) obtained from the receiver. The throughput maximizing-based ASHS is implemented.
The basic procedure for ASHS follows:

- The receiver constantly measures and estimates current SNR and CSI.
- If ±2 dB change in SNR has happened then the receiver send a request of training sequence.
- The transmitter sends a training sequence of every system without error correcting codes.
- The BER and Capacity for each transmission scheme is estimated.
- Based on the highest data rate, select a transmission scheme that yields a maximum throughput.
- The receiver sends the decision of transmission scheme back to the transmitter via control channel or management frames. Both the receiver and the transmitter switch to the new transmission scheme.

ASHS can track the channel fading gain and adapt the transmission to be the best one for any change in the effective SNR but it takes a small time to transmit the training sequence, compute the best throughput and feed back the selected transmission mode to the transmitter. Fig. 5.24 illustrate this proposed system.

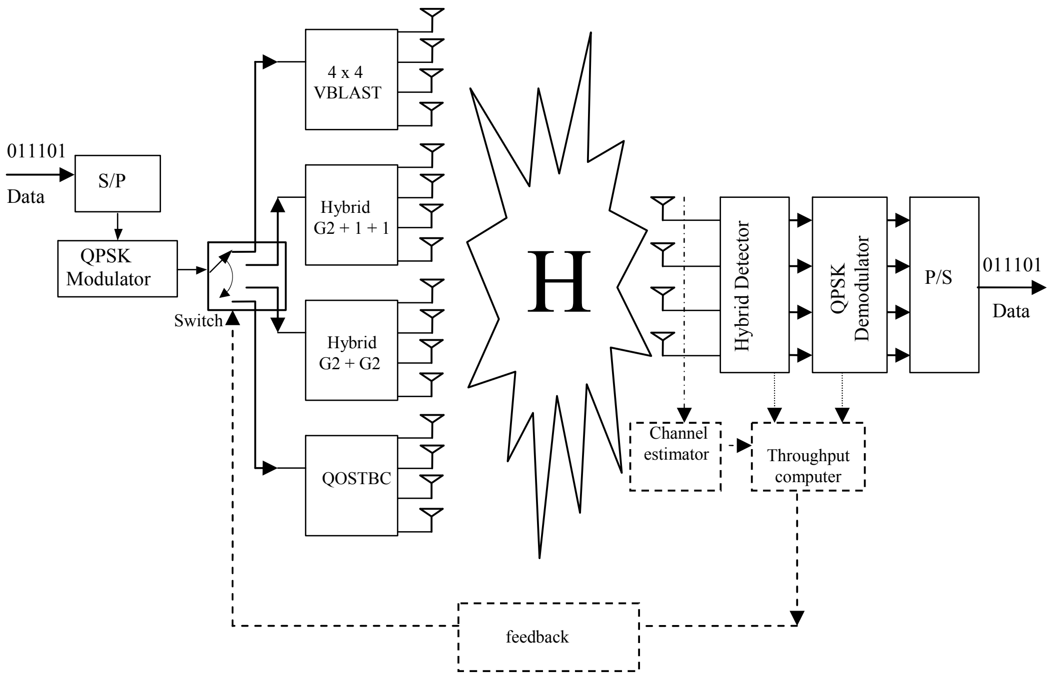


Fig.5.24 Proposed Adaptive Switching Hybrid System.

The ASHS system of Fig. 5.24 works well in the case of transmit link fading or receive link fading as well. Since it computes the overall throughput regardless of the source of fading. Sending a training sequence is the better than making a threshold-base selection.

Additionally, the effect of receive link fading on the effective SNR and the average capacity is as same as transmit link fading due to the effect of cancelling one column or more for transmit link fading and one row or more for receive link fading as stated in section 5.2.1. Now a test for this system will be done for all cases of deep fading studies in the previous sections.

5.3.1 Adaptive Switching Hybrid System for 4th Tx. Deep Fading

The BER performances, capacities and the throughputs of these systems are shown in the figures 5.25, 5.26 and 5.27 in addition to ASHS BER, Capacity and throughput.

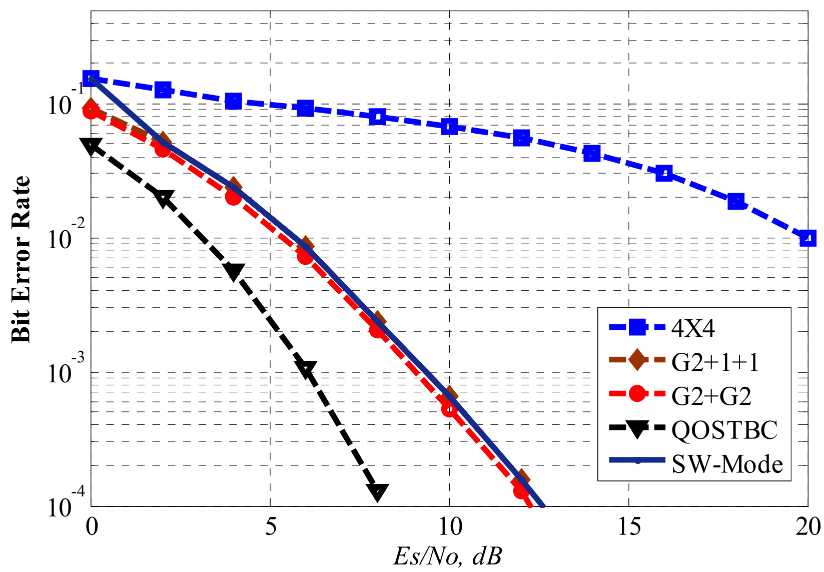


Fig. 5.25 BER of ASHS for 4th Tx link faded to -20 dB.

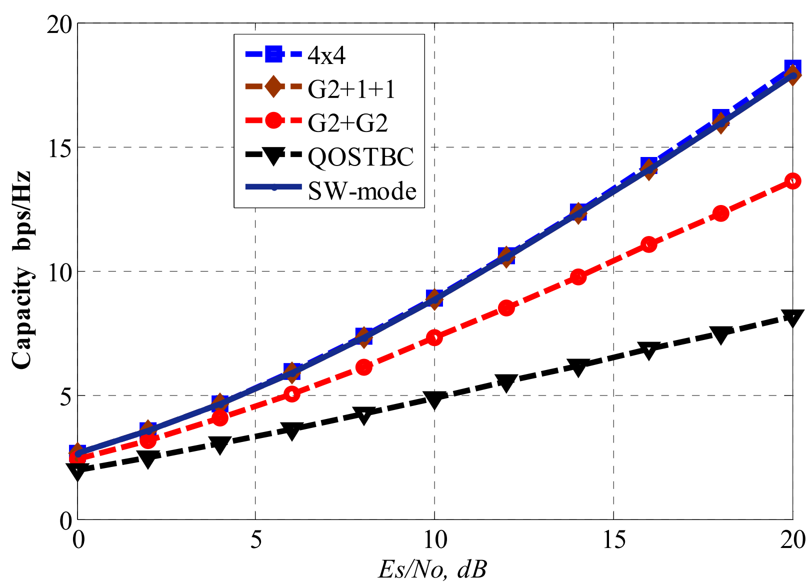


Fig. 5.26 Capacity of ASHS for 4th Tx link faded to -20 dB.

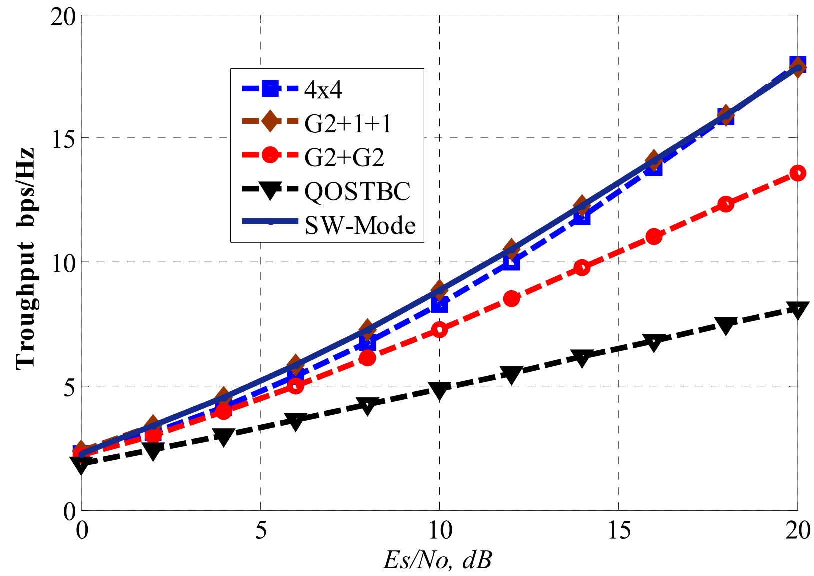


Fig. 5.27 Throughput of ASHS for 4th Tx link faded to -20 dB.

By default, ASHS system transmission was done by 4 × 4 VBLAST system until a request to send training sequence (TS) is coming from the receiver as shown in Fig. 5.25. Let us assume that the received SNR is -2 dB and there is an improvement of 2 dB in SNR so the improved SNR is equal to 0 dB and the transmission scheme was a 4 × 4 VBLAST then the receiver sending a request of TS to compute the BER, capacity and the throughput of all systems.

After sending the TS and computing the throughput the decision is G2 + 1 + 1 system, then ASHS switches to this decision as in Fig. 5.25, 5.26 and 5.27 and keeps using it until a 20 dB. At that point, SNR is measured then it will switch again to 4 × 4 VBLAST system and leep using it for SNR higher than 20 dB.

5.3.2 Adaptive Switching Hybrid System for 3rd & 4th Tx. Deep Fading

Fig. 5.28 shows that ASHS system will switch to G2 + 1 + 1 system for a change of ±2 dB in SNR. Although its BER is not so good, the throughput is the best until a 20 dB SNR is measured or higher, then ASHS system will switch to 4 × 4 VBLAST system. Fig. 5.29 shows that 4 × 4 VBLAST and G2 + 1 + 1 systems are at the same capacity bound and G2 + G2 system has a worse capacity and finally QOSTBC system has the worst capacity but its throughput better than G2 + G2 system for SNR less than 16 dB as seen from Fig. 5.30.

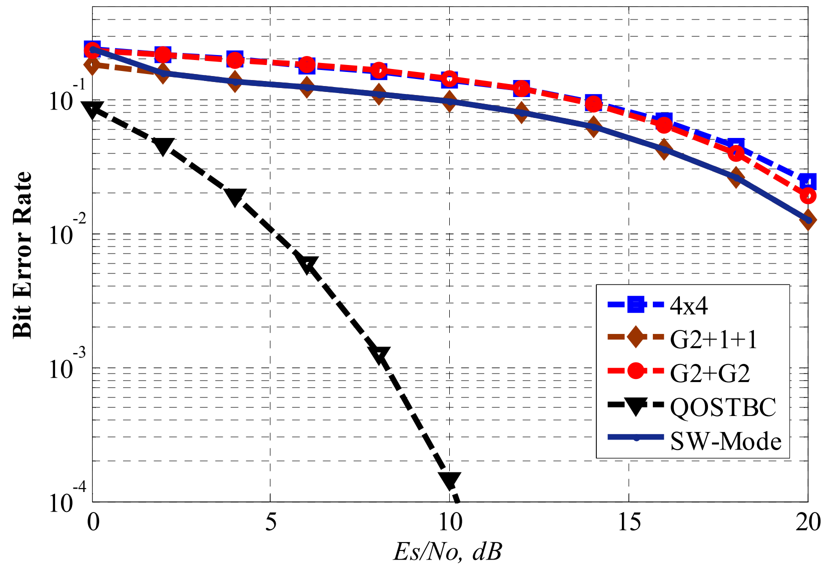


Fig. 5.28 BER of ASHS for 3rd & 4th Tx links faded to -20 dB.

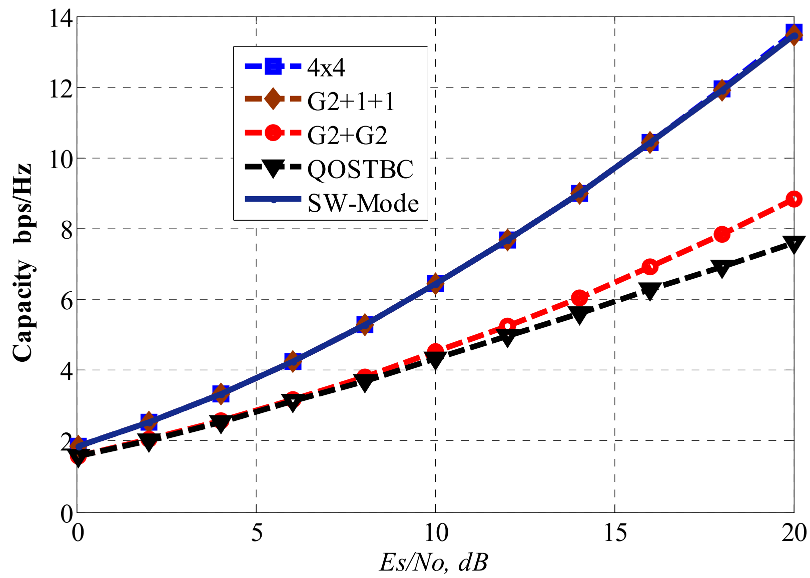


Fig. 5.29 Capacity of ASHS for 3rd & 4th Tx links faded to -20 dB.

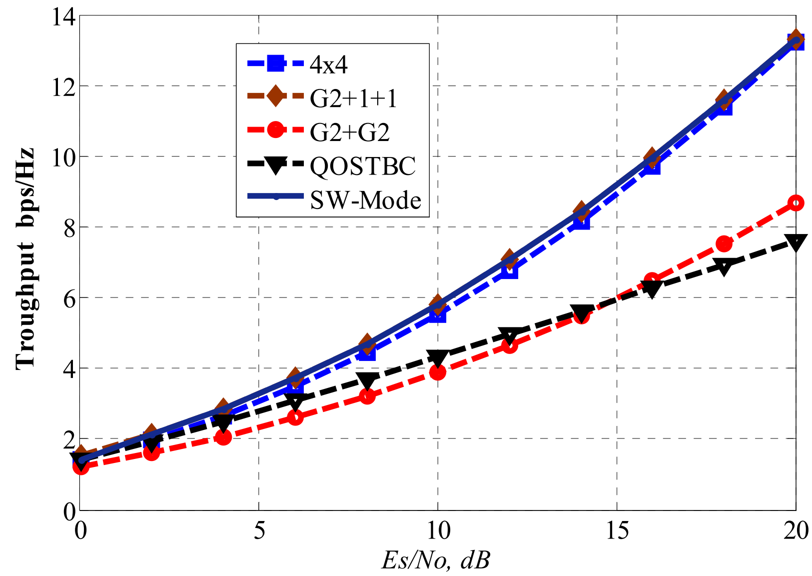


Fig. 5.30 Throughput of ASHS for 3rd & 4th Tx links faded to -20 dB.

5.3.3 Adaptive Switching Hybrid System for 2nd & 4th Tx. Deep Fading

Fig. 5.31 shows that ASHS system will switch to G2 + G2 system for a change of ±2 dB in SNR and its BER is very good opposite to the BER performance of 4 × 4 VBLAST and G2 + 1 + 1 systems. The QOSTBC system shows also a very good BER performance but with the worst capacity and throughput as seen in Fig. 5.32 and 5.33. In Fig. 5.33, the throughput of G2 + G2 system is the best until higher than 17 dB SNR is measured then it will switch to 4 × 4 VBLAST system.

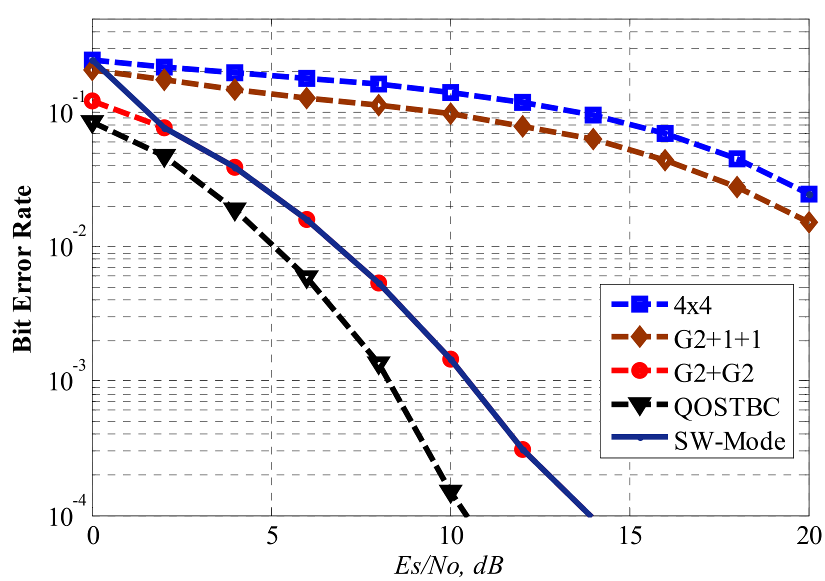


Fig. 5.31 BER of ASHS for 2nd & 4th Tx links faded to -20 dB.

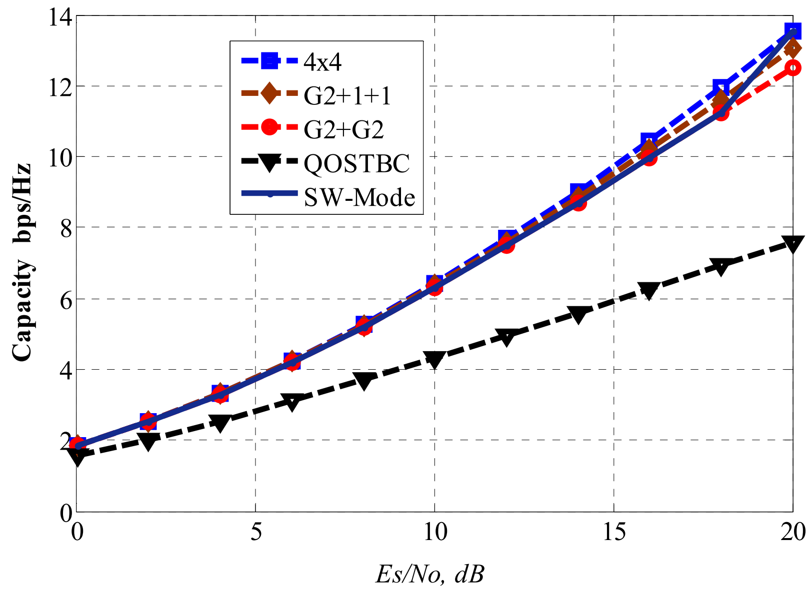


Fig. 5.32 Capacity of ASHS for 2nd & 4th Tx links faded to -20 dB.

Fig. 5.32 shows that 4 × 4 VBLAST, G2 + 1 + 1 and G2 + G2 systems are at the same capacity bound.

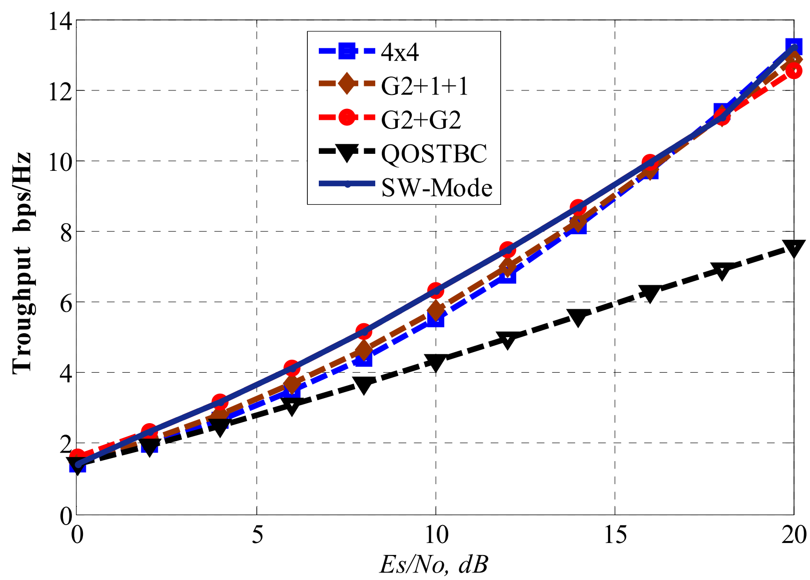


Fig. 5.33 Throughput of ASHS for 2nd & 4th Tx links faded to -20 dB.

5.3.4 Adaptive Switching Hybrid System for 2nd & 3rd & 4th Tx. Deep Fading

Fig. 5.34 shows that ASHS system will switch to QOSTBC system for a change of ±2 dB in SNR and its BER is very good opposite to the bad BER performances of 4 × 4 VBLAST, G2 + 1 + 1 and G2 + G2 systems for SNR lower than 15 dB.

The ASHS system will switch to G2 + 1 + 1 system for SNR higher than 15 dB and lower than 20 dB. After 20 dB, the SNR is measured and the ASHS system will switch to 4 × 4 VBLAST system as seen in Fig. 5.34.

Fig. 5.35 shows that 4 × 4 VBLAST, G2 + 1 + 1, G2 + G2 and QOSTBC systems have the same capacity bound for SNR lower than 15 dB and there is some difference between them for higher SNR.

In Fig. 5.36, the throughput of QOSTBC system is the best until the measured SNR is above 15 dB then it switches to G2 + 1 + 1 . The throughput of 4 × 4 VBLAST system is better for more than 20 dB SNR.

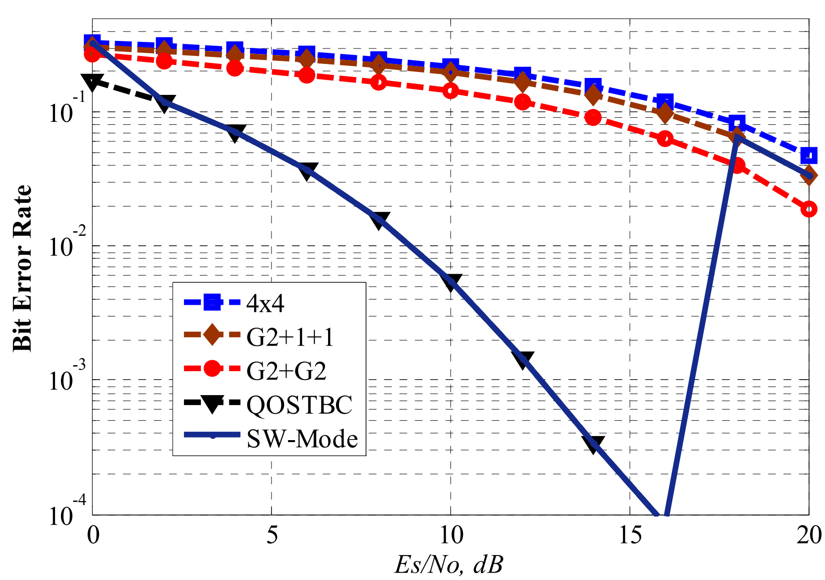


Fig. 5.34 BER of ASHS for 2nd & 3rd & 4th Tx links faded to -20 dB.

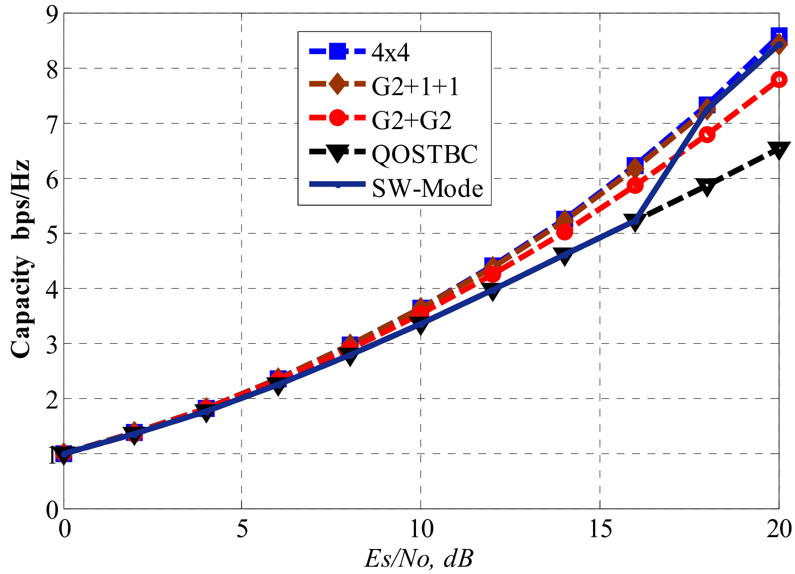


Fig. 5.35 Capacity of ASHS for 2nd & 3rd & 4th Tx links faded to -20 dB.

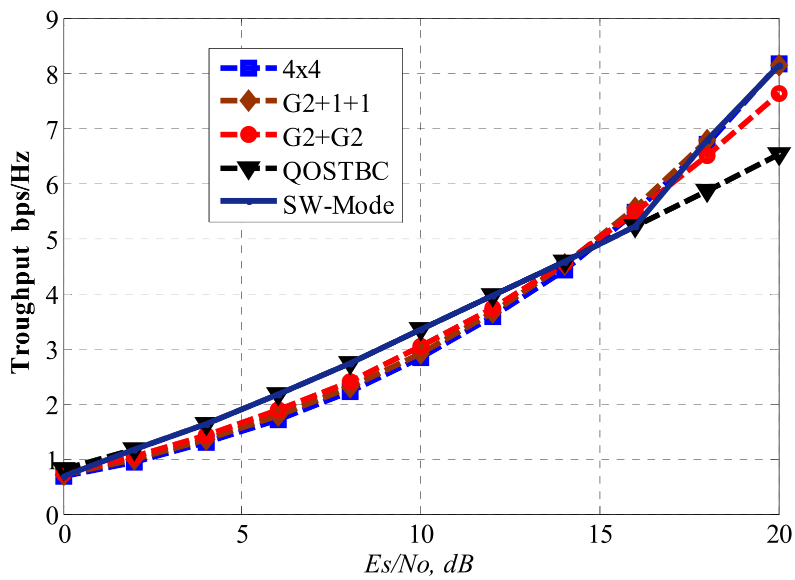


Fig. 5.36 Throughput of ASHS for 2nd & 3rd & 4th Tx links faded to -20 dB.

5.3.5 Adaptive Switching Hybrid System all Tx. Deep Fading

As stated in section 5.2.4 this is the worst case of deep fading cases, this channel is inefficient. Fig. 5.37 shows the BER performance of these systems, this case of fading make all BER performances very bad and a great loss of data occurred.

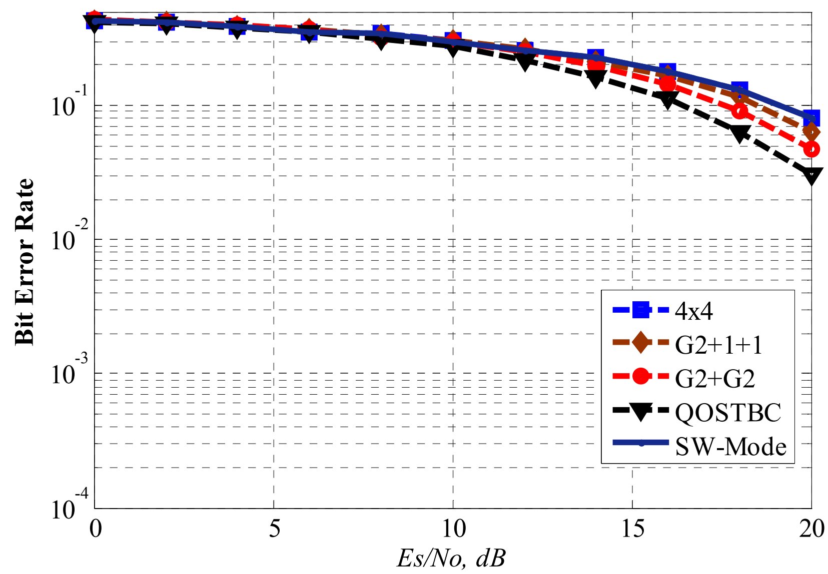


Fig. 5.37 BER of ASHS for all Tx links faded to -20 dB.

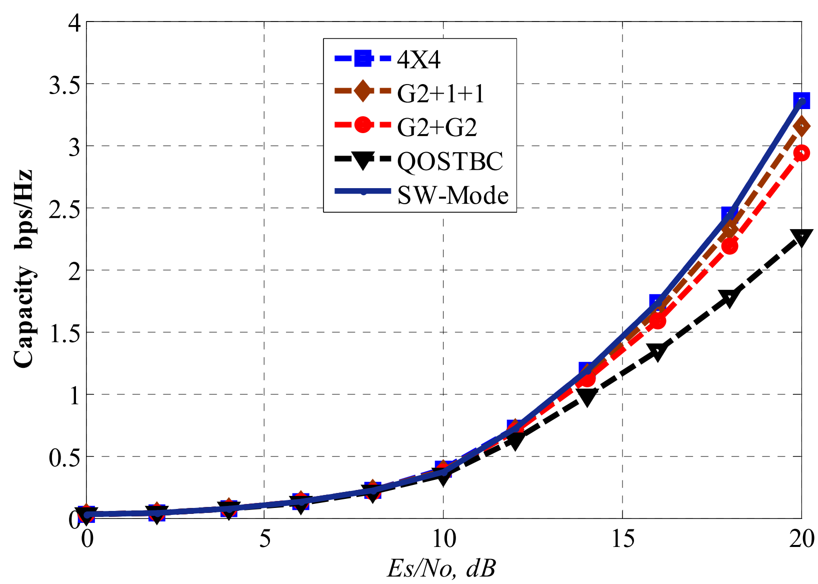


Fig. 5.38 Capacity of ASHS for all Tx links faded to -20 dB.

A low capacity bound is obtained and all systems capacities approximately the same as seen in Fig. 5.38 until measured SNR is equal to 14 dB, some improvements on BER performances and capacities of these systems could be gained for SNR higher than 15 dB.

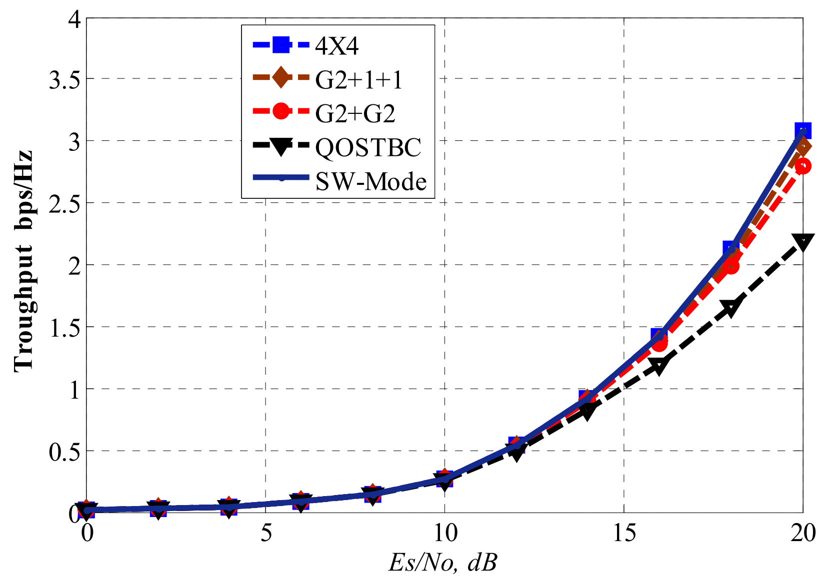


Fig. 5.39 Throughput of ASHS for all Tx links faded to -20 dB.

The ASHS will transmit over VBLAST system for most of time however its throughput is the best but it is not practical.

5.3.6 Adaptive Switching Hybrid System for Random Tx. Deep Fading

Finally, ASHS system must be tested for a random deep fading of all cases previously studied Fig. 5.40 shows the performance of these system with 2×10^5 random deep fading simulation scenarios in addition to ASHS performance. For SNR lower than 8 dB G2 + G2 system is selected because it has the highest throughput. If SNR higher than 8 dB 4×4 VBLAST system has the maximum throughput so ASHS is switched to 4×4 VBLAST system and continue to working on it as seen from Fig. 5.41 and 5.42.

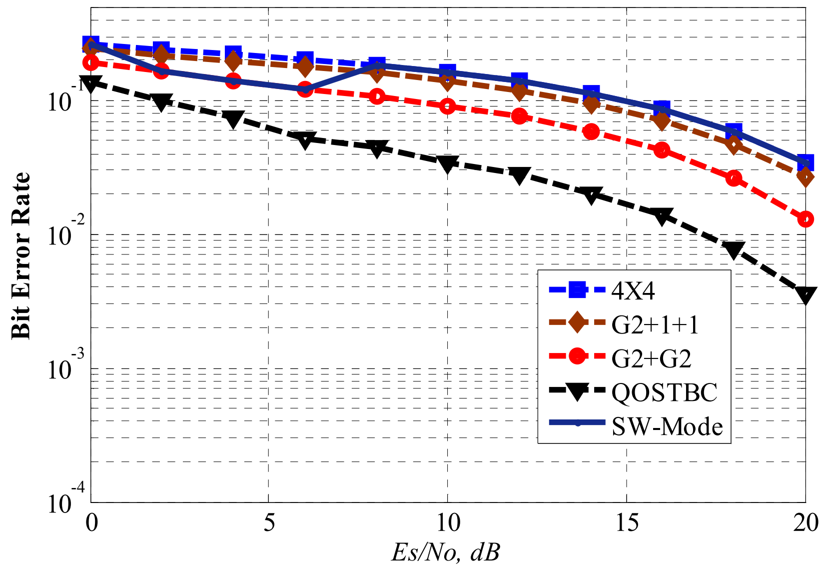


Fig. 5.40 BER of ASHS for random Tx links faded to -20 dB.

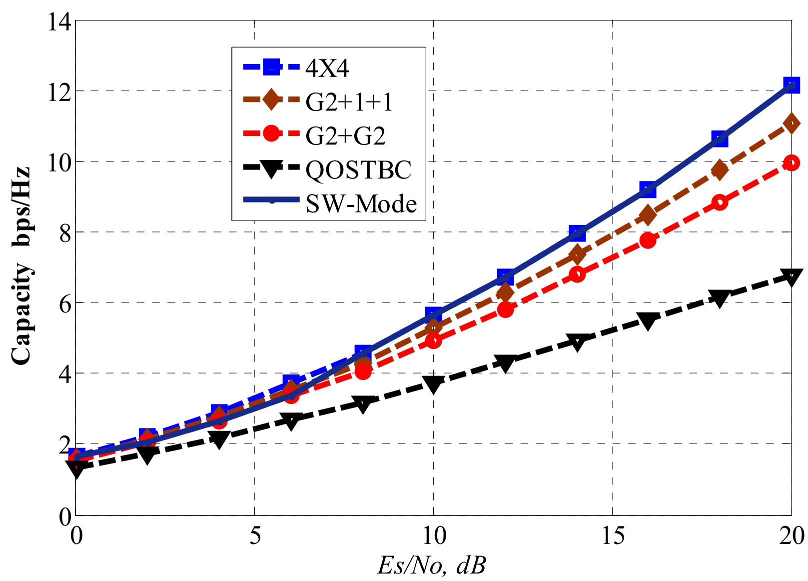


Fig. 5.41 Capacity of ASHS for random Tx links faded to -20 dB.

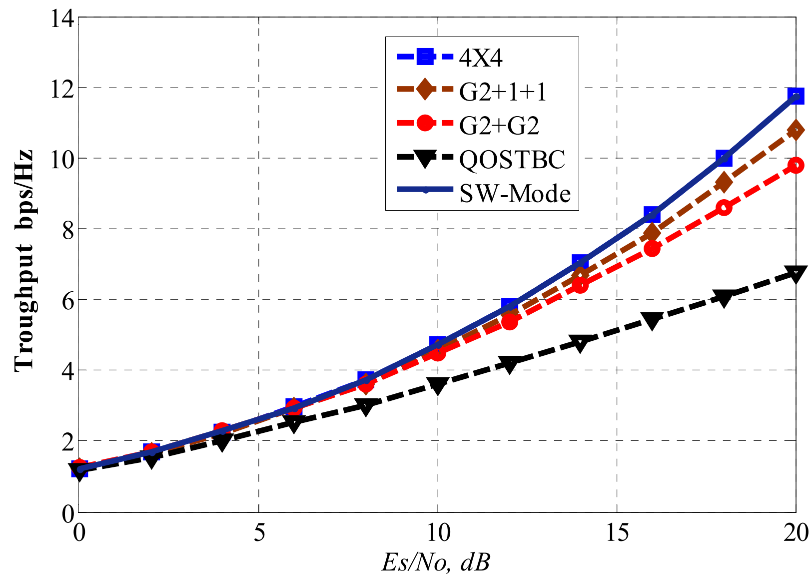


Fig. 5.42 Throughput of ASHS for random Tx links faded to -20 dB.

5.4 Summary

In this chapter, the effect of deep fading on different transmit links were simulated and analyzed. It had been realized that the transmit link deep fading had the same effect on the effective SNR and the average capacity as the case of receive link deep fading. Also a decision was made for the best throughput system in each case.

A 4 × 4 VBLAST had the best throughput at high SNR in all cases and G2 + 1 + 1 system proves itself for the case of deep fading of 3rd, 4th or 3rd & 4th Tx links, and G2 + G2 system was the best in case of deep fading of 2nd & 4th, 1st & 4th, 1st & 3rd or 2nd & 3rd Tx links. The QOSTBC system gave a very good BER and saved a lot of bps/Hz if any of the three transmit links were suffering from deep fading. At the case of deep fading of all transmit links there was no valuable solution. However, for a range of SNR from 0 – 20 dB it could save from 0 – 2 bps/Hz.

ASHS system was switched in order to maximize the throughput in all cases through sending a training sequence of every scheme for every ±2 dB change of the measured SNR at the receiver, and decision was made based on the maximum throughput transmission scheme. The decision was fed back to the transmitter. ASHS showed a lot of benefits such as a higher throughput, no additional transmit power and no additional bandwidth needed but it suffered from a higher complexity degree and switching effect.

CHAPTER 6
CONCLUSION AND FUTURE WORK

6.1 Conclusion

BLAST MIMO system is one of current promising techniques that could realize Giga bps high-speed wireless transmission for future communications networks. STBC system can improve the performance much better but with a reduction of data rate. So by hybridizing BLAST and STBC systems into one hybrid BLAST-STBC system was considered as the optimal tradeoff between increasing data rate and getting better performance with same transmit power. Study and analysis of hybrid BLAST-STBC system were done for only Alamouti scheme (G_2 encoder).

4 × 4 MIMO communication systems were studied. A comparison for the performances and the capacity of V-BLAST, QOSTBC, G4-OSTBC and Hybrid systems G2 + 1 + 1, G2 + 1 and G2 + G2 were carried out through using simulation results. In addition, it was shown that the Hybrid system was better than pure VBLAST in both BER and capacity, QOSTBC and OSTBC capacities that was neither QOSTBC nor OSTBC BER performance.

The simulation results showed for 4 × 4 system, the hybrid systems G2 + 1 + 1 and G2 + G2 and QOSTBC had better performances and capacities than switching off one, two or three transmit antennas respectively.

It had been realized from the deep fading effect study that the transmit link deep fading had the same effect on the effective SNR and the average capacity as the case of receive link deep fading. A 4 × 4 VBLAST had the best throughput at high SNR in all cases and G2 + 1 + 1 system was better if one or two adjacent Tx links are deeply faded, G2 + G2 system was the best in case of deep fading of two nonadjacent Tx links and QOSTBC system gave a very good BER and saved a lot of bps/Hz if any of the three transmit links were suffering from deep fading.

This thesis proposed and analyzed a MIMO communication system that switches between spatial multiplexing, Hybrid BLAST-STBC and QOSTBC systems

based on instantaneous channel state information. The adaptive switching criteria were based on the result performance of a training sequence sent on receiver request.
Throughput performance results under different channel conditions showed that the hybrid algorithm could provide enhanced performance relative to a standard spatial multiplexing approach.

Training sequence was requested if the received SNR changed by about ±2 dB. The adaptive switching architecture was presented and described specifically for flat fading Rayleigh MIMO channels. It was clear, that for frequency selective fading Rayleigh MIMO channels OFDM could be applied to get a flat fading for every tone.

The simulation results proved that the proposed ASHS system could track the best throughput scheme and kept the BER performance robust over deeply fading MIMO channels. Based on the results, the proposed ASHS system appeared to be an effective feasible solution for improving the throughput in the next generation of mobile communication systems or for general MIMO systems suffered from a deep fading without additional transmit power, bandwidth nor number of antennas.

6.2 Future Work

This thesis considered the ML detection where corresponding metrics were generated for all possible transmitted symbols, and the vector with the least ML Euclidian distance was considered as an estimation of the transmitted vector. Although ML achieves the best performance and diversity order, it required an exhaustive search which is exponential in the number of transmit antennas and constellation set size. Thus, for high modulation order ML becomes infeasible from a hardware implementation perspective.

- Reimplementing this work by applying other low complexity detection scheme.
- Using Space Time Trilles Coding instead of STBC and see the performance and throughput behavior.
- Study the effect of receive antenna deep fading hence apply adaptive switching scheme to the receiver antennas in order to choose the best set of antennas which achieve the highest throughput.
- A work on studying the empirical results could be studied and simulated for choosing the SNR threshold for adaptive switching instead of applying a training sequence to test the channel for both transmit and receive antenna switching to reach the optimum throughput with lower complexity or applying any other threshold-based switching schemes.
- A fuzzy rules could be applied to the proposed system instead of studying the empirical results for optimization.
- ASHS system can make an improvement to WiMAX technology [74] if an adaptive modulation scheme applied to it.
- For simplicity, adaptive switching technique can be applied to a pure BLAST system for both transmit and receive antennas with ability to apply adaptive modulation scheme to compensate the decreasing in data rate when switching to lower order BLAST systems like 3×3 or 2×2 VBLAST.
- A complexity analysis of ASHS system can be studied as well.
- A complexity reduction of ASHS could be farther studied and some ideas could be proposed to reduce the system's complexity.
- Applying the DLST technique of Fig. 3.3B instead of vertical scheme with different detection schemes could be applied and studied.

7. References

1. *J. H. Winters, "On the Capacity of Radio Communication Systems with Diversity in a Rayleigh Fading Environment," IEEE J. Select. Areas Commun., vol. JSAC-5(5), pp. 871-878, June 1987.*
2. *L. Hanlen, "Channel Modelling and Capacity Analysis for Multi-input Multi-output, Wireless Communication Systems ," University of Newcastle, PhD Thesis, Australia, 2003.*
3. *L. Zheng and D. Tse, "Diversity and Multiplexing: A fundamental Tradeoff in Multiple Antenna Channels," IEEE Trans. Inf. Theory, vol. 49, pp. 1073-1096, 2003.*
4. *H. Yao, " Effcient Signal, Code, and Receiver Designs for MIMO Communication Systems ," Massachusetts Institute of Technology, PhD Thesis, 2003.*
5. *G. J. Foschini, "Layered Space-Time Architecture for Wireless Communication in A Fading Environment When Using Multi-element Antennas," Bell Labs Tech. J., vol. 1, no. 2, pp. 41-59, 1996.*
6. *S. Al-Ghadhban "Multi-layered Space Frequency Time Codes" Blacksburg, Virginia PhD Dissertation, 2005.*
7. *S. M. Alamouti. "A Simple Transmit Diversity Technique for Wireless Communications" IEEE Select. Areas in Comm., vol 16, no. 8, pp. 1451-1458, 1998.*
8. *V. Tarokh, H. Jafarkhami, and A. R. Calderbank. "Space-Time Block Codes from Orthogonal Designs," IEEE Trans. Inform. Theory, vol. 45, no. 5, pp. 1456-1467, July 1999.*
9. *H. Jafarkhani, "A Quasi-Orthogonal Space-Time Block Code," IEEE Trans. Commun., vo1.49, pp.1-4, Jan. 2001.*
10. *V. Tarok, A. Naquib, N. Seshadri, and A. R. Calderbank, "Combined Array Processing and Space-Time Coding," IEEE Trans. Inform. Theory, vol. 45, no. 4, pp.1121-1128, May, 1999.*
11. *S. Baro, G. Bauch, A. Pavlic, and A. Semmler, "Improving BLAST Performance Using Space-Time Block Codes and Turbo Decoding," IEEE Global Telecommu. Conference, GLOBECOM, vol. 2, pp. 1067-1071, USA, Nov. 2000.*
12. *M. Tao and R. S. K. Cheng, "Low Complexity Post-Ordered Iterative Decoding for Generalized Layered Space-Time Coding Systems," IEEE Intern. Conference on Comm., vol 4, pp. 1137-1141, 2001.*

13. *M. Mohammad, S. Al-Ghadhban, B. Woerner, and W. Tranter, " Comparing Decoding Algorithms for Multi-Layer Space-Time Block Codes," IEEE Southeast Con Proceedings, pp.147-152 , 2004.*

14. *T Mao, M Motani, "STBC-VBLAST for MIMO Wireless Communication Systems, " IEEE intern. Conference on Communications vol. 4, pp. 2266 – 2270, 2005.*

15. *J. Cortez, M. Bazdresch, A. Garcia, J. Campoy and A. Pizarro "An Efficient Detector for STBC-VBLAST Space-Time Code for MIMO Wireless Communications," IEEE Electronics, Robotics and Automotive Mechanics Conference pp. 44, 2009.*

16. *T. Yoo, R. Lavery, A. Goldsmith, and D. Goodman," Throughput Optimization Using Adaptive Techniques," Wireless Systems Lab, Stanford University, CA, USA, Tech. Rep., 2004.*

17. *R. Lavery, "Throughput Optimization for Wireless Data Transmission," MCs Thesis, Polytechnic University, June 2001.*

18. *W.C.Y. Lee "Mobile Communication Engineering: Theory & Application," 2nd Edition, McGraw-Hill International, 1998.*

19. *X. Dong "Effect of Slow Fading and Adaptive Modulation on TCP/UDP Performance of High-Speed Packet Wireless Networks" Technical Report No. UCB/EECS-2006-109, University of California at Berkeley, 2006.*

20. *J. Huang, S. Signell, "Adaptive MIMO Systems in 2 × 2 Uncorrelated Rayleigh Fading Channel," IEEE Wireless Communications and Networking Conference WCNC, Issue Date: 11-15 March 2007, pp 1114 - 1118.*

21. *R. Heath and A. Paulraj, " Switching Between Diversity and Multiplexing in MIMO Systems," IEEE Transactions on Comm., vol. 53, no. 6, pp 962- 968,June, 2005.*

22. *Forenza, M. McKay, I. Collings, and R. Heath, "Switching Between OSTBC and Spatial Multiplexing with Linear Receivers in Spatially Correlated MIMO Channels," In Vehicular Technology Conference, VTC 2006-Spring. IEEE 63rd, volume 3, pages 1387-1391, May 2006.*

23. *Phelps, "Adaptation for Multi-Antenna Systems," MSc Thesis, Faculty of Virginia Polytechnic Institute, 2009.*

24. *M. Moustafa, " Switched-Mode BLAST Technique for MIMO Communications ," 11th International Conference on Advanced Communication Technology, Issue*

Date: 15-18 Feb, vol. 3, pp 1491 – 1491, 2009.

25. *J. Lee and M. Ahmed, " A-BLAST: A Novel Approach to Adaptive Layered Space-Time Processing," ACM 1-59593-306-9/06/0007, IWCMC Proceedings of the Intern. Conf. on Wireless Comm. and Mobile Computing, NY, USA 2006 .*
26. *A. Molisch, M. Win, and J. Winters, "Capacity of MIMO Systems With Antenna Selection," IEEE Int. Conf. Commun. Proc., pp. 570–574, June 2001.*
27. *D. Gore, R. Nabar, and A. Paulraj, "Selecting An Optimal Set Of Transmit Antennas For A Low Rank Matrix Channel," IEEE ICASSP Proc., pp. 2785–2788, June 2000.*
28. *S. Sandhu, R. Nabar, D. Gore, and A. Paulraj, "Near-Optimal Selection Of Transmit Antennas For A MIMO Channel Based On Shannon Capacity," Proc. Asilomar Conf. Signals, Syst., Comput., Pacific Grove, pp. 567–571 Nov. 2000.*
29. *D. Gore and A. Paulraj, "Space Time Block Coding With Optimal Antenna Selection," IEEE ICASSP Proc., pp. 2441–2444, May 2001.*
30. *D. Gore and A. Paulraj, "MIMO Antenna Subset Selection With Space-Time Coding," IEEE Trans. Signal Processing, vol. 50, pp. 2580–2588, Oct. 2002.*
31. *A. Gorokhov, "Antenna Selection Algorithms for MEA Transmission Systems," IEEE ICASSP Proc., pp. 2857–2860, May 2002.*
32. *Z. Chen, J. Yuan, B. Vucetic, and Z. Zhou, "Performance of Alamouti Scheme with Transmit Antenna Selection," IEEE Electronic Letter, vol. 39, no. 23, pp. 1666-1668, Nov. 2003.*
33. *S. Thoen, L. Perre, B. Gyselinckx and M. Engels, "Performance Analysis of Combined Transmit –SC/ Receive-MRC," IEEE Trans. Commun., vol. 49 no. 1, pp. 5-8, Jan. 2001.*
34. *H. Bocskei and A. J. Paulraj, "Multiple-Input Multiple-Output (MIMO) Wireless Systems" Cambridge University Press, 2003.*
35. *Wikipedia MIMO in wireless communications, http://en.wikipedia.org/wiki/MIMO.*
36. *L. Guzman, "A Study on MIMO Mobile-To-Mobile Wireless Fading Channel Models," MSc, Thesis, Heriot Watt University, 2008.*
37. *T. M. Cover and J. A. Thomas, "Elements of Information Theory," Wiley, 1st edition, 1991.*
38. *D. Gesbert, M. Shafi, D. Shiu, P. Smith, and A. Naguib " From Theory to Practice: An Overview of MIMO Space-Time Coded Wireless Systems," IEEE Journal on*

Selected Areas in Communications, vol. 21, pp. 281-302, 2003.

39. *A. Paulraj and T. Kailath, "Increasing Capacity in Wireless Broadcast Systems Using Distributed Transmission/Directional Reception," Tech. Rep. U. S. Patent no. 5345599, 1994.*
40. *G. Foschini. and M. Gans, "On the Limits of Wireless Communication in a Fading Environment When Using Multiple Antennas," Wireless Personal Communications, vol. 6, no. 3, pp. 311-355, 1998.*
41. *J. Andrews, A. Ghosh, R. Mohamed, "Fundamentals of WiMAX: Understanding Broadband Wireless Networking," Prentice Hall, 2007 .*
42. *M. Sellathurai and S. Haykin "Space-Time Layered Information Processing for Wireless Communications" John Wiley & Sons, Inc , 1st edition, 2009.*
43. *G. D. Golden, J. G. Foschini, R. A. Valenzuela, and P. W. Wolniansky, "Detection Algorithm and Initial Laboratory Results Using V-BLAST Space-Time Communication Architecture," Electronics Letters, vol. 35, no. 1, pp. 14–15, Jan. 1999.*
44. *I. Berenguer and X. Wang, "Coding and Signal Processing for MIMO Communications," IEEE Journal of Computer Science and Technology, vol. 18, issue 6, pp. 689-702, November 2003.*
45. *A. Elshokry, "Complexity and Performance Evaluation of Detection Schemes for Spatial Multiplexing MIMO Systems" MSc Thesis, Islamic University - Gaza ,January 2010 .*
46. *J. Boccuzzi " Signal Processing for Wireless Communications" The McGraw-Hill Companies, Inc,1st edition, 2008.*
47. *C. Schlegel and Z. Bagley "MIMO Channels and Space-Time Coding" IASTED Tutorial, WOC, Banff, Alberta, CANADA, July 18, 2002.*
48. *A. Goldsmith "Wireless Communications " Cambridge University Press, 2005.*
49. *V. Kuhn, " Wireless Communications Over MIMO Channels" Wiley & Sons, 1st edition, 2006.*
50. *M. Jankiraman " Space-Time Codes and MIMO Systems," Artech House ,Inc., 1st edition, 2004.*
51. *V. Tarokh, N. Seshadri, and A. Calderbank. "Space-Time Codes for High Data Rate Wireless Communications: Performance Criterion and Code Construction," IEEE*

Trans. Inform. Theory, vol. 44, no. 2, pp. 744-765, Mar. 1998.

52. *J. G. Proakis, "Digital Communications," 4th ed. Boston: McGraw-Hill, 2000.*
53. *3GPP, "Group Services and System Aspects; 3GPP Systems to Wireless Local Area Network (WLAN) Interworking; System Description (R. 6)," TS 23.234. v1.10.0, 2003.*
54. *Signal Processing for Communication http://www.dsplog.com/.*
55. *V. Tarokh, H. Jafarkhami, and A. R. Calderbank " Space-Time Block Coding for Wireless Communications: Performance Results" IEEE J. Select. Areas in Commun., vol. 17, no. 3, pp. 451-460, Mar. 1999.*
56. *N. Sinha, S. Chakraborty and A. Bera, "Capacity Enhancement of 4G- MIMO Using Hybrid Blast STBC Systems" Journal of Telecommunications, vol. 3, issue 1, pp. 115-124, June 2010.*
57. *R. Nory, " Performance Analysis of Space-Time Coded Modulation Techniques Using GBSB-MIMO Channel Models, " MSc Thesis, Blacksburg University, Virginia, June 2002.*
58. *X. Tran, H. Ho, T. Fujino and Y. Karasawa, " Performance of Detectors for Combined STBC-SM Systems," Intern. Symp. Antennas Propagation (ISAP2007), pp.1362-1365, Japan, 2007.*
59. *W. Freitas Jr., "Performance of MIMO Antenna Systems with Hybrids of Transmit Diversity and Spatial Multiplexing Using Soft-Output Decoding" Lecture Notes in Computer Science, Springer-Verlag Heidelberg, v.3124, p.28–37, Aug. 2004.*
60. *W. Freitas Jr., F. Cavalcanti and R. Lopes, "Hybrid MIMO Transceiver Scheme With Antenna Allocation and Partial CSI at Transmitter Side," IEEE 17th Annual Intern. Symp. on Personal, Indoor and Mobile Radio Commu., pp. 1-5, 2006.*
61. *W. Freitas, F. Cavalcanti and R. Lopes, " Hybrid Transceiver Schemes for Spatial Multiplexing and Diversity in MIMO Systems, " IEEE Journal of Commu. and Inform. Systems, vol. 20, no. 3, pp. 63–76, 2005.*
62. *N. Sinha, P. Sutradhar, S. Chakraborty, R. Bera and M. Mitra, " Hybrid Multilayer Schemes for Achieving The Maximum Possible Diversity Gain," International Journal of Research and Reviews in Applied Sciences, vol. 2, issue 3, March 2010 .*
63. *A. Doufexi, A. Nix and M. Beach "Combined Spatial Multiplexing and STBC to Provide Throughput Enhancements to Next Generation WLANs" IST Mobile and*

Wireless Communications Summit, Germany, 2005.

64. *D. Shiu and J. Kahn, " Layered Space-Time Codes for Wireless Communications Using Multiple Transmit Antennas," IEEE International Conference on Communications, , vol. 1, pp. 436-440, 1999.*
65. *M. Tao and R. Cheng " Generalized Layered Space–Time Codes for High Data Rate Wireless Communications," IEEE transactions on wireless communications, vol. 3, no. 4, pp. 1067 – 1075, july 2004.*
66. *S. Sandhu and A. Paulraj, " Space-Time Block Codes: A Capacity Perspective," IEEE Comm. Letter, vol. 4, no. 14, pp 384-386, 2000.*
67. *S. Sanayei and A. Nosratinia, "Antenna Selection in MIMO Systems," IEEE Communications Magazine, pp 68-73, 2004.*
68. *G. Alkhansari and A. Gershman, " Fast Antenna Subset Selection in MIMO Systems," IEEE Transactions on Signal Processing, vol. 52, no. 2, pp 339-347, 2004.*
69. *J. Liu, J. Sun and S. Lv, "A Novel Throughput Optimization Approach in Wireless Systems," IEEE ICCT2010, Intern. Conf. on Commu. Technology, China, vol. 32, no. 6 , Nov. 2010.*
70. *D. Song and C. Chen, " Novel Layered Scalable Video Coding Transmission over MIMO Wireless Systems with Partial CSI and Adaptive Channel Selection," Proceedings of SPIE Conf. on Multimedia on Mobile Devices, January 2007, San Jose, CA.*
71. *H. Nguyen, J. Andersen and G. Pedersen, " On the Performance of Link Adaptation Techniques in MIMO Systems," Wireless Personal Communications Journal, vol. 42, no. 4, pp. 543-561, September 2007.*
72. *P. Vieira, P. Queluz and A. Rodrigues, " Improving MIMO Spectral Efficiency in 4G Macro-Cellular Networks," Lisbon Polytechnic Institute, ANACOM Portugal, October 2008, http://www.anacom.pt/render.jsp?categoryId=2.*
73. *S. Gaur and M.A. Ingram, "Transmit/Receive Antenna Selection for MIMO Systems to Improve Error Performance of Linear Receivers," Proc. of the International ITG/IEEE Workshop on Smart Antennas, Duisburg-Essen, Germany, April , 2005.*
74. *R. Wang, " MIMO: from Theory to Reality," CodioLink Enabling Mobile Broadband Internet White Paper, July 2009.*