Thesis for the Degree of Master of Engineering

Massive MIMO Using Full-Rate QOSTBC for Higher Capacity Wireless Transmission Systems

by

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고용량 무선전송시스템을 위한 완전비율 준직교 공간시간 블록보호 기반의대교모 MIMO

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List of Abbreviations

16QAM ················ Sixteen-Phase Quadrature Amplitude Modulation

3GPP ································· 3rd Generation Partnership Project

8PSK ··· Eight-Phase Shift Keying

A_r ···Number of Receive Antenna

A_t ··· Number of Transmit Antenna

AWGN······································ Additive White Gaussian Noise

BC ··· Broadcast Channel

BER ·· Bit Error Rate

BPSK··· Binary Phase Shift Keying

CSI·· Channel State Information

EVCM································· Equivalent Virtual Channel Matrix

i.i.d···························· Independent and Identically Distributed

LOS··· Line of Sight

LTE··· Long Term Evolution

MAC ···Multiple-Access Channel

Massive MIMO···················Massive Multiple Input Multiple Output

MIMO·· Multiple Input Multiple Output

MISO··· Multiple Input Single Output

ML··Maximum likelihood

MRC·· Maximum Ratio Combining

MU-MIMO······················Multi-user Multiple Input Multiple Output

NLOS ··· Non-Line of Sight

OFDM······················ Orthogonal Frequency Division Multiplexing

OSTBC······························ Orthogonal Space-Time Block Code

QOSTBC ······················ Quasi-Orthogonal Space-Time Block Code

QPSK — Quadrature Phase Shift Keying
Rx — Receiver
SIMO — Single Input Multiple Output
SISO — Single Input Single Output
SMUX — Spatial Multiplexing
SNR — Signal to Noise Ratio
STBC — Space-Time Block Code
STC — Space-Time Coding
T_c — Coherence Time
TV — Television
Tx — Transmitter
Wi-Fi — Wireless Fidelity
WiMAX — Worldwide Interoperability for Microwave Access
W-LAN — Wireless-Local Area Network

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Abstract

The wireless industry has recently been introduced with a technology known as massive Multiple-Input Multiple-Output (massive MIMO) to minimize errors, to maximize performance, energy and spectral efficiency, to increase robustness and link reliability and to enhance data rates. This is implemented by using massive number of multiple transmit and receive antennas, as well as by applying quasi-orthogonal space-time block code (QOSTBC) techniques.

The advanced research area in the field of wireless communication system is to place more and more antennas either at the base station or mobile station or both sides of the communication system in order to achieve huge spectral effectiveness comparable to the conventional MIMO systems. The conventional MIMO systems have certain limitations including comparatively low achievable data rates using the transmitter with a maximum of 4 antennas, low spectral effectiveness, and less potential for large spatial dimensions.

This thesis deals with massive MIMO system performance employing the QOSTBC scheme with multiple antennas up to 128×128 configuration. The QOSTBC scheme has many advantages in terms of the higher transmission rates and lower decoding complexity. It is an important transmit diversity scheme for more than 2 transmit antennas. The antenna array configurations are classified into 2×2, 4×4, 8×8, 16×16, 32×32, 64×64 and 128×128 massive MIMO systems, which directly affect the system performance. The channel vectors are quasi orthogonal, and the interference is then reduced significantly. The users of this technology can benefit from the improved data rates while using the same frequency

resource simultaneously. We present that the BER performance improves with increasing number of antennas.

Simulation results verify that the massive MIMO systems with QOSTBC can enhance performance to a full rate, as compared with other massive MIMO systems. We provide simulation results demonstrating the performance for up to 128 transmitter and receiver antennas with BPSK, QPSK, 8PSK and 16QAM modulation formats. The simulation results show how multiple transmit antennas with QOSTBC can lead to outstanding performance over additive white Gaussian noise (AWGN) and Rayleigh fading channels.

1. Introduction

1.1. Massive MIMO Communication

In the advanced mobile communication systems, greater transmission data rate, efficiency and reliability of transmission, and the equipment and methods for achieving the above mentioned goals have become an interesting area of research for many researchers nowadays. Recently, due to exponential increase in mobile users as well as increased demand for high speed internet, the role of multiple transmitter and receiver antennas is considered an important and urgent means for accomplishing these demands. The literature on information theory and communications indicates how the use of multiple transmitter and receiver antennas can effectively improve the wireless communication industry. According to the information-theory [1]-[3], smooth and reliable communication rates noticeably enhance the consistency of a wireless link. The communication link can be established using multiple antenna systems without any need of additional bandwidth and power. These links are technologically superior to the single antenna systems.

Multiple input multiple output (MIMO) systems operate employing multiple antennas on both the transmitter and receiver sides of wireless communication using the spatial dimension in order to accomplish higher data rates and performance. The current MIMO technology can be found in Long Term Evolution (LTE) with 3GPP standard [4], [5]. The releases of 3GPP standard have accepted the application of MIMO technology with different limits. An example is Release 10, which is recognized as LTE-Advanced. LTE-Advanced supports up to 8 independent spatial streams for spatial multiplexing. Additionally, users are permitted to have up to 4 antennas [5]. A new enhancement for the W-LAN standard IEEE 802.11ac also recommends the use of up to eight MIMO spatial streams. The requirement for the enhanced performance comes with the increased hardware complexity, energy consumption, and signal processing; all of which are essential at both ends of the transmission scheme.

Multi-user MIMO (MU-MIMO) is MIMO used to communicate with different terminals simultaneously. MU-MIMO has improved the data rates, enhanced transmission reliability, increased energy efficiency and reduced interference. However, MU-MIMO technology cannot achieve these benefits at the same time without further improvement.

Massive MIMO is a new model exceeding the capabilities of the conventional MIMO system. All the current advancements of MIMO and upgrades from massive MIMO can raise performance to a robust level. Wireless communication systems utilizing an array of transmitter and receiver antennas can be implemented to increase the channel capacity and/or energy efficiency. Authors in [6] present the concepts of massive MIMO. Their research demonstrates how multiple users can communicate at the same time from a base station using a large number of antennas over the single frequency. Full-dimensional MIMO systems, or massive MIMO systems, expand antenna use to between tens and hundreds of antennas. This is the dawn of an emerging field of research in mobile communication [7], [8].

In fact, massive MIMO technology is envisioned to be a core transmission technology for high speed wireless communications based on research findings of the performance capabilities on transmit diversity and spatial multiplexing [9]. The massive MIMO transmission of signal processing is performed in time and spatial dimensions by utilizing multiple, spatially distributed antennas. Space-time coding (STC) [10], [11] and spatial multiplexing (SMUX) [1] provide high diversity and achieve high data rates over massive MIMO channels respectively.

The most prominent space-time block codes (STBCs) are orthogonal STBCs (OSTBCs) and the most popular OSTBC is the full-rate Alamouti codes. This code is differentiated by its high transmission diversity, full rate, and a low complexity decoding algorithm at the receiver end while using two transmit antennas on the base station. Unfortunately, for more than 2 transmit antennas, the rate of the OSTBC, defined as the number of symbols transmitted divided by the number of time slots, cannot be greater than ¾ [12], [13]. An improvement for this limitation is the implementation of the MIMO system combined with quasi orthogonal space-time block code (QOSTBC) for full-rate with more than two transmitter antennas [14]. In two separate studies, QOSTBC can achieve a higher code rate than OSTBC and lower decoding complexity than non-orthogonal STBC [14]-[16]. A full-rate MIMO system with a large number of transmit antennas was not yet reported in the literature [15]-[17]. In [18] and [19], a full-rate MIMO with up to four antennas was presented. A thorough report on the potential use of the larger scale massive MIMO system with full rate is presented in this thesis.

This research thesis analyses a true massive MIMO system with up to 128 transmitter and receiver antennas. Comparative studies are undertaken to evaluate the performance of the different antenna configurations. The performance evaluation is presented employing BPSK, QPSK, 8PSK and 16QAM modulations over AWGN and Rayleigh flat-fading channel. The main idea of increasing antennas is to increase the capacity of the system. The increase in the number of antennas can provide higher transmission speed and high capacity. It may also improve the system by reducing bit-error rate (BER). Therefore, the main focus of this thesis is to present how the full-rate massive MIMO system can reduce the BER by using a greater number of antennas.

1.2. Motivations and Research Objectives

The aim of this thesis is to investigate the performance of the massive MIMO system using full-rate QOSTBC over AWGN and Rayleigh flat fading channel. A comparison of the BER performance of massive MIMO under different antenna configurations such as 1×1, 2×2, 4×4, 8×8, 16×16, 32×32, 64×64 and 128×128 antennas are presented in this research.

We demonstrate major motivations for the massive MIMO in wireless communication.

- To apply all the existing advantages of conventional MIMO in a much greater scale
- To increase the quality of wireless communication (i.e. reduce bit-error rate)
- To improve the throughput of the massive MIMO system for high-speed transmission.

1.3. Chapter Organization

In Chapter 2, we introduce the massive MIMO system, including the channel model with diagram. Different types of STBC, including quasi-orthogonal STBC, used in massive MIMO system are explained in Chapter 3. The experimental studies are declared in Chapter 4. The theoretical background of the research is first presented and the simulation results are then discussed. Finally, the concluding remarks are drawn out in Chapter 5.

2. Massive MIMO System Design

There are a number of different transmission configurations or formats that can be used in wireless communication system. These formats are termed as follows: Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO). Each format offers unique technological advantages but also contain limitations. The formats can be balanced to provide optimum configurations for any given application.

Antenna technology refers to single or multiple inputs and outputs. The input is provided from the transmitter antenna side which transmits into the link or signal path. The output is received at the receiver antenna station. It is at the output of the wireless link.

The different formats require specific numbers of antennas as well as each has its own level of complexity. Depending on the selected format, processing may be needed at one end of the link or the other.

The transmission formats are defined by single and multiple antennas below:

- SISO – Single Input Single Output system – 1 Tx antenna , 1 Rx antenna
- SIMO – Single Input Multiple Output system – 1 Tx antenna, A_r Rx antennas (A_r >1)
- MISO – Multiple Input Single Output system – A_t Tx antennas, 1 Rx antenna (A_t >1)
- MIMO – Multiple Input Multiple Output system – A_t Tx antennas, A_r Rx antennas (A_t , A_r >1)

The massive MIMO format, which is the main emphasis system in this thesis, and the MU-MIMO format are described in later section.

Four key factors to evaluate each format are expressed as gain. The four different types of gain are produced due to the use of multiple antennas and suitable transmit algorithms. They are:

1. Array gain.
2. Diversity gain
3. Spatial multiplexing gain, and
4. Interference reduction

While simple SIMO and MISO systems achieve all above mentioned gains, multiplexing gain, which is necessary to increase point-to-point throughput, is only supported by MIMO systems. We mainly focus on each of these features in this section, considering the system with multiple transmit and receive antennas [20], [21].

Array gain, simply known as power gain, is available through processing and systematic combining of various antenna signals at the transmitter and/or receiver ends, thus improving the average receive SNR due to the coherent combining effect. To achieve an array gain in most cases, usage of multiple antenna systems depends upon a perfect knowledge of the channel either at the receiver side, at the transmitter side, or at both sides.

Diversity gain is the increase in signal-to-interference ratio due to how much the transmission power is reduced when a diversity scheme is introduced. This leads to an improvement in link reliability obtained by receiving replicas of the information signal through independent fading links. Adding independent signal copies decreases the feasibility of encountering a deep fade at each signal. An important measure is the diversity order, defined as the number of independently fading propagation paths.

The $A_t.A_r$ is the maximum diversity order that can be achieved over a MIMO link, where A_t and A_r represents the number of transmitting and receiving antenna respectively. Without losing performance, an increase in signal-to-interference ratio can result from applying diversity scheme that reduces the effort of transmission power. Diversity gain is usually expressed in decibels, though sometimes it is expressed as a power ratio. The corresponding technique is called space-time coding (STC) [10], [12], [22]. STC is an efficient bandwidth coding scheme [10], which transmits a block of information symbols in complex orders to and from the different antennas.

Spatial multiplexing gain is achieved when a system is transmitting various streams of data through multiple antennas. Multiple data streams are sent and received over different antennas when the transmit power, time, and bandwidth expenditure remain unchanged. The spatial multiplexing gain is used to increase system capacity and to enhance the system throughput. Hence, this form of gain has created a large impact on the research and introduction of MIMO systems in wireless technology.

The capacity of the MIMO system is much higher than that of a single-antenna system because the channel capacity can be linearly increased in proportion to the number of antennas.

Interference reduction can be implemented at the transmitter, where the goal is to minimize the interference energy sent toward the co-channel users while delivering the signal to the desired user. Interference reduction allows aggressive frequency reuse and this leads to a multi-cell capacity improvement. In mobile cellular communications system, inter-cell interference is the frequency sharing and multiplexing challenge both within as well as between the cells. The interference signal consists of coloured noise which is different from white noise. When the expected signals are combined, the interference signals are suppressed through proper multi-antenna spatial weight at the receiving end. Thus, the average SNR at the receiving end is improved. This is the basis of the interference reduction combining feature which is a gain available to all configuration systems.

2.1. Single Input Single Output (SISO)

The single-input single-output (SISO) is the basic communication system out of all four systems by which the transmitter and receiver operate with one antenna [23]. SISO is used in personal wireless technologies (e.g. Wi-Fi, Bluetooth), radio broadcasting and TV.

It is commonly known that the channel capacity is a measurement of the maximum amount of information that can be transmitted over a channel and can be received with a negligible probability of error at the receiver. The SISO system capacity is calculated by using the well-known Shannon theorem giving the mathematical form as by

$$C = D\log_2\left(1+\frac{S}{N}\right) \text{ bit /s} \tag{2.1}$$

where C denotes the capacity and D represents the bandwidth of the systems. S/N is the signal to noise ratio. There is no diversity and no additional processing required. SISO is beneficial in terms of its simplicity and is cheap to implement. The SISO channel restricts in its performance, however. The data throughput of the system depends upon the channel bandwidth and signal to noise ratio. Interference and fading impact the SISO system more than a MIMO system which employs a more transmission diversity scheme. In addition, there may be reductions in data speed, increasingly more errors and packet loss owing to scattering and reflection on to many obstacles within the communication link. Finally, the results in degrading of the BER performances come as a consequence of receiver's lack of ability to recover the message information in the signal.

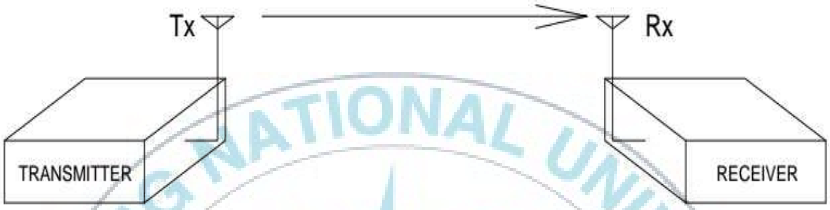

Figure 2.1. SISO system model block diagram.

In the next section, we define five cases of systems with multiple antennas; SIMO, MISO, conventional MIMO, MU-MIMO and Massive MIMO. Their names correspond to the multiple antennas involved on the transmitter sides, the receiver sides, or on both sides. The advantages of this system are increased numbers of users, range, security, bandwidth and reduced transmission interference.

2.2. Single Input Multiple Output (SIMO)

Single-input multiple-output (SIMO) is a system composed of a single transmitting antenna at the source and multiple receiving antennas (A_r) at the destination with the purpose of improving performance. This transmission scheme is also known as receiver diversity schemes in which multiple antennas are employed at the receiver leading to switched diversity and maximum ratio combining (MRC), since multipath components and signal copies arrive at receiver end.

In a switched diversity or selection diversity implementation, it identifies the strongest signal from the most efficient antenna and switches to that antenna. In a MRC implementation, it takes both signals and combines them from all available antennas in order to maximize the SNR. In this way, the signals from both antennas contribute to the overall signal. The SIMO system capacity [24] is

$$C = D \log_2\left(1 + A\frac{S}{N}\right) \text{ bit/s} \tag{2.2}$$

where A is the number of receiver antennas. SIMO is beneficial because it is relatively easy to implement despite having receiver processing requirements which can be have drawbacks. The SIMO systems are suitable in mobile devices manufactured with limited sizes, costs and battery performance. The diagram of the SIMO system is illustrated below.

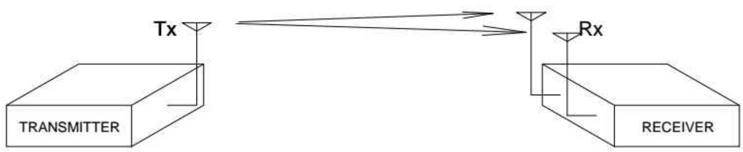

Figure 2.2. SIMO system model block diagram.

2.3. Multiple Input Single Output (MISO)

Multiple-input single-output (MISO) wireless communication system consists of multiple antennas at the transmitter and a single antenna at the receiver. The signals are transmitted from multiple transmitting antennas to single receiving antenna. This antenna technique is also called Alamouti STC which is employed at the source with two antennas. In this scenario, the same signal is transmitted redundantly from the two transmitter antennas at the different times consecutively.

The receiver is then able to receive the optimum signal which it can then use to extract the required data. It is used for improved data speed and reduces problems caused by multipath fading and minimize symbol error rate. The advantage of using MISO systems is that the redundancy coding has been transferred from the receiving end towards the transmitting end. In example of cell phone, less power and reducing the level of processing is needed at the receiver.

The only difference between MISO and SIMO mathematical expressions for capacity is that A is either the number of transmit antennas or receive antennas for MISO and SIMO system respectively.

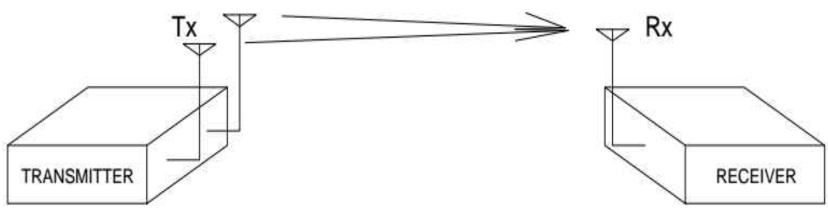

Figure 2.3. MISO system model block diagram.

2.4. Multiple Input Multiple Output (MIMO)

Multiple-input multiple-output (MIMO) wireless communication systems is deployed by multiple antennas on the receiver and transmitter to utilize the multi-path effects that always exist to transmit additional data, rather than causing interference. [25]. In recent times, MIMO systems have become popular since they provide a more reliable reception compared to its counterpart by means of the potential for achieving higher data rates.

MIMO technology has aroused interest in today's wireless communication technology, including 3GPP Long Term Evolution (LTE), 4G, WiMAX and IEEE802.11n (Wi-Fi) [26]. By using MIMO, we can achieve more spectral efficiency combined with improved link reliability, reduced fading and high data throughput without additional bandwidth or power. MIMO system with same amount of antennas at both the source and the destination is capable to multiply the system throughput linearly with every additional antenna. For instance, 2×2 MIMO will double the data transfer rate.

In wireless communication systems, fading may either be owing to multipath propagation or because of shadowing from obstacles. Diversity is a powerful technique to protect against deep fades, a choice to combat fading in wireless link. This is used for supplying the receiver with multiple versions of the same information signal. Accordingly, it provides a stabilize link, progresses performance and reducing error rate. Diversity techniques rely on transmitting the signal over multiple and independent fading paths (in time/ frequency/ space).

The following diversity modes supplying a number of advantages are available:

Time (temporal) diversity: Data representing the same information are sent over the same channel at different times. The separation between the transmit times should be greater than the coherence time, T_c. The time interval depends on the fading rate, and increases with the decrease in the rate of fading. Time diversity is often used over systems subject to burst error conditions, and at intervals adjusted to be longer than an error burst.

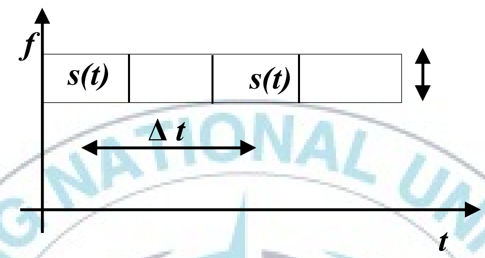

Figure 2.4. Time diversity.

Frequency diversity: The same information signal is transmitted on different carrier frequency, the frequency separation between them being at least the coherence bandwidth. Frequency diversity is sometimes employed in microwave systems and technologies such as OFDM modulation, spread spectrum.

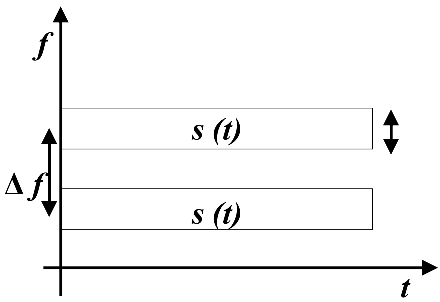

Figure 2.5. Frequency diversity.

Space diversity: This diversity technique uses multiple antennas at the transmitting and receiving side. The signal is transmitted over several different propagation paths. There are multiple receiving antennas placed at different spatial locations, resulting in different (possibly independent) received signals. Space diversity, used in the broadest sense of the definition, is used as the basis for MIMO.

With the use of MIMO technology, the additional paths available can be used for an advantage [27]. They can be used to provide additional robustness to the radio link by improving the SNR, or by increasing the data link capacity [28]. MIMO system capacity is described as below:

$$C = D\log_2\left(1 + A_t A_r \frac{S}{N}\right) \text{ bit/s} \tag{2.3}$$

The A_t and A_r are the number of transmitter antennas and receiver antennas respectively. However, the signal is coded using the technique called space-time coding. Data to be transmitted is divided into independent data streams. The number of streams S is always less than or equal to the number of antennas; in the case of asymmetrical antenna constellations, it is always smaller or equal the minimum number of antennas. For example, 4×4 system could be used to transmit four or fewer streams, while a 3×2 system could transmit two or fewer streams. Theoretically, the capacity C increases linearly with the number of streams S.

$$C = S\,D\log_2\left(1 + \frac{S}{N}\right) \text{ bit/s} \tag{2.4}$$

Apart from the antenna configurations, two main methods of transmitting data using MIMO configuration with respect to how data is transmitted across the given channel are described below:

Spatial diversity or simply diversity technique: The same data information is transmitted on multiple transmit antennas and hence this increases the diversity of the system. Diversity means that the same data has travelled through diverse paths to get to the receiver. This guarantees that at least one of the copies will suffer less fading compared to rest of the copies. Diversity increases the reliability of communications and improves the SNR.

Spatial multiplexing techniques: The transmitting antennas simultaneously transmit multiple different data streams to one receiver. The receiver receives parallel data streams on each of its antennas, thus increasing the throughput in wireless communication. If the scattering by the environment is rich enough, several independent sub-channels are created in the same allocated bandwidth. Hence, the multiplexing gain comes no additional cost on bandwidth or power.

By considering a MIMO system with the number of transmit antennas A_t and the number of receive antennas A_r [29], we can represent the MIMO channel at a given time instant as an $A_r \times A_t$. The received signal at the output of the receiving antennas in flat fading can be written in vector form as

$$r = \mathrm{M}n + e \tag{2.5}$$

where $\boldsymbol{n}$ is the A_t transmitted vector with complex components, and $\boldsymbol{e}$ is an A_r noise vector with zero-mean independent and identically distributed (i.i.d.) complex Gaussian entries with independent real and imaginary parts having equal variance, where σ_e is the standard deviation of the noise at that receiver, given by $\sigma_{\mathrm{e}} = \sqrt{(1/\mathrm{SNR})}$ for unit signal power. The SNR is defined as SNR=E_b/N_0 when BPSK is employed. The vectors $\boldsymbol{n}$ and $\boldsymbol{e}$ are assumed independent.

We assume that the perfect channel state information (CSI) is available at the receiver but unavailable at the transmitter, therefore transmit antennas operate with equal power. Moreover, we assume a quasi-static flat-fading channel, i.e. the channel coefficients are constant within one block of code transmission and independently realized from block to block. The channel matrix M whose entries are i.i.d. complex Gaussian can be defined as an $A_r \times A_t$ matrix.

$$M = \begin{bmatrix} M_{1,1} & M_{1,2} & \cdots & M_{1,A_t} \\ M_{2,1} & M_{2,2} & \cdots & M_{2,A_t} \\ \vdots & \vdots & \ddots & \vdots \\ M_{A_r,1} & M_{A_r,2} & \cdots & M_{A_r,A_t} \end{bmatrix} \tag{2.6}$$

Figure 2.6 illustrates the MIMO communication system with the multiple antennas at the transmitter and receiver side. Considering, that we have a transmission sequence ($\boldsymbol{v}_1$, $\boldsymbol{v}_2$,…, $\boldsymbol{v}_n$). In regular transmission, we send $\boldsymbol{v}_1$ in the first time slot, $\boldsymbol{v}_2$ in the second time slot and $\boldsymbol{v}_n$ in the n^{th} time slot.

Figure 2.6. MIMO system model block diagram.

2.5. Multi-User MIMO (MU-MIMO)

Multi-user MIMO or MU-MIMO is an enhanced form of MIMO technology where the available antennas are spread over a multiple independent access antenna points that is gaining acceptance. MU-MIMO enables multiple independent radio terminals to access a system enhancing the communication capabilities of each individual terminal. The difference between MIMO and MU-MIMO is that MU-MIMO allows a terminal to transmit/receive signals to and from multiple users in the same frequency band at the same time.

MU-MIMO enhances MIMO by arranging multiple users to be able to simultaneously access the same channel using the spatial degrees of freedom offered by MIMO. When using spatial multiplexing, MU-MIMO, adding more antennas for additional processing to accommodate the interference between the different users on the same channel, when enables the spatial separation of the different users.

MU-MIMO offers some significant advantages over other techniques such as allowing a direct gain from the multiple user multiplexing schemes, leasing effect of signal propagation issues and allowing the MIMO gain to be made at the base station, not at the terminal station. All of this is accomplished without the need for multiple antennas at the user's end. This results in lower manufacture costs for the production remote terminals because the intelligence and cost are included within the base station.

The advantages of using MU-MIMO come at the cost of additional antenna hardware and processing. MU-MIMO users must also obtain the channel state information which requires the use of the available bandwidth. Even though the technology is still in the early stages of development, it solves several issues which the simple MIMO format does not [30].

We evaluate capacity results for the two basic MU-MIMO channel models: the MIMO broadcast channel (BC or downlink) and the MIMO multiple-access channel (MAC or uplink). The MIMO BC consists of one multiple-antenna transmitter sending to many multiple-antenna receivers and the MIMO MAC consists of many multiple-antenna transmitters sending to a single multiple-antenna receiver.

In cellular-type architectures (e.g. cellular networks or wireless local-area networks), the MAC models the channel from mobile devices to the base-station, and the BC models the channel from the base-station to mobile devices. Depending on the user's device, a significant increase in total downlink throughput may result. Multi-user MIMO receivers are significantly more complex than single-user MIMO systems, since the signals from all users must be detected simultaneously.

Figure **2.7** demonstrates a multiuser MIMO system model. In a downlink scenario, we assume that K out of L mobile users are scheduled by higher layers scheme, where the base station broadcasts information to mobile users and each selected mobile user receives multiple data streams, while that station employs N_t transmit antennas and the k^{th} mobile user is equipped with n_k receiving antennas.

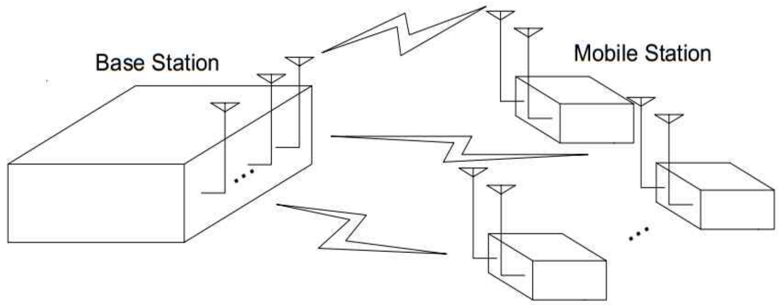

Figure 2.7. Multi-user MIMO system model block diagram.

The $H_k \in C^{M_k \times N_t}$ is signified as the downlink complex channel matrix between the base station and the k^{th} mobile terminal. The H_k, zero-mean circular symmetric complex Gaussian random variables, are appropriate for a narrow-band system operating in a non-Line-of-Sight (NLOS) rich scattering environment. The channel fading between the q^{th} transmitting antennas at the base station and the p^{th} receiving antenna at the k^{th} mobile characterize the user $(p, q)^{th}$ elements of H_k. It can be assumed that they experience independent fading since the mobile terminals are spatially separated.

The transmitted signal vector intended for the k^{th} mobile user is denoted as $x_k \in C^{N_t \times 1}$ and the zero-mean additive white Gaussian noise vector with variance σ_n^2, is denoted as $n_k \in C^{M_k \times 1}$ while the $M_k \times 1$ received signal vector at the k^{th} mobile terminal is given as [31]

$$y_k = H_k \sum_{k=1}^{K} x_k + n_k, \tag{2.7}$$

2.6. Massive MIMO System

MIMO communication systems achieve substantial gains in spectral, power, and energy efficiency compared to conventional SISO systems [32]. In fact, it has been shown that under ideal conditions the capacity of a point-to-point MIMO system with A_t transmit antennas and A_r receive antennas scales linearly with min $\{A_t, A_r\}$, which is referred to as the multiplexing gain in the literature [33]. However, traditional MIMO systems may have two or four, some may even have eight antennas, but this has been the limitation on early systems that have adopted MIMO.

Moreover, point-to-point MIMO systems have several disadvantages in practice. Firstly, the number of antennas that a mobile terminal such as a smart phone can accommodate is constrained to size, power consumption, and cost, which limits the multiplexing gain. Second, the multiplexing gain may disappear altogether in case of strong interference (i.e., at the cell edges), unfavourable channel conditions (e.g., insufficient scattering), and narrow antenna spacing mandated by the size constraints of mobile terminals.

The MU-MIMO systems emerge in order to overcome the weaknesses of point-to-point MIMO systems [34]. MU-MIMO offers big advantages over conventional point-to-point MIMO: it works with simple and low cost single-antenna terminals. It does not require a rich scattering environment and resource allocation is simplified because every active terminal utilizes all of the time-frequency bins. In MU-MIMO systems, a quantity of (mobile) users with a small number of antennas is served by a central node with numerous antennas (i.e. base station).

Therefore, the signal processing complexity at the mobile stations is low, particularly in case of single-antenna terminals. Additionally, the array and the channels of users can be assumed independent if they are spatially distributed over the entire cell; the angular separation of the terminals typically exceeds Rayleigh resolution. Nevertheless, the multiple users in the system introduce inter-user interference which has to be mitigated by appropriate processing at the transmitter and receiver for downlink and uplink transmission, respectively. Furthermore, multi-user MIMO, as originally proposed with roughly equal numbers of service-antennas and terminals and frequency division duplex operation, is not a scalable technology [30].

Massive MIMO (often referred to as very large MIMO, Full-dimension MIMO and large-scale antenna systems) consists of several antennas from tens to hundreds in the communication terminals [30]. The motivation for creating the massive MIMO is to upgrade all the specification of conventional MIMO, but in a much greater scale. Massive-MIMO technology has been primarily focused on improving frequency utilization efficiency by enabling spatial sharing between systems.

Hence this makes a clean break with current practice through the use of a large excess of service-antennas over active terminals and time division duplex operation. However, an increase in the number of antennas may create greater challenges for transceiver design and implementation; there are some interesting advantages for signal processing and communication [7]. The concept of massive MIMO systems is entering new areas of development due to its potential to offer some distinct advantages.

Adding extra antennas supports significant improvements in throughput and radiated energy efficiency by focusing energy into ever smaller regions of space. Other benefits of massive MIMO include the widespread use of inexpensive low-power components, reduced latency, simplification of the media access control (MAC) layer, and robustness to intentional jamming. The anticipated throughput depends on the propagation environment providing asymptotically orthogonal channels to the terminals, but so far experiments have not disclosed any limitations in this regard.

While massive MIMO solves many drawbacks of conventional MIMO system, it encounters new challenges that should be urgently focused on. Those areas include: making many low-cost low-precision components that work effectively together, acquisition and synchronization for newly-joined terminals, the exploitation of extra degrees of freedom provided by the excess of service-antennas, reducing internal power consumption to achieve total energy efficiency reductions, and finding new deployment scenarios.

When the base station antennas grow large, random impairments such as small-scale fading and noise are scattered [35]. Although massive MIMO communication systems have been first proposed in 2010 [6], they have attracted significant interest from both academia and industry in a very short time. In fact, it has been shown in [35] that if A_t grows large and all other system parameters are assumed constant, the transmit power per user in multi-user massive MIMO systems can be reduced proportionally to $1/A_t$ and $1/\sqrt{A_t}$ for known and unknown CSI knowledge at the base station, respectively, without affecting throughput and reliability.

Hence, massive MIMO systems offer a simple path to more energy efficient and "greener" communication networks. Considering the promising properties and great interest in massive MIMO systems, we expect them to become an essential part of future wireless communication systems. Even though a significant research effort has already been concentrated on massive MIMO systems, several important signal processing and signal design problems remain to be solved. Massive MIMO system with a large number of transmitter and receiver antennas is illustrated in Figure 2.8. Massive MIMO has many favorable capabilities to fulfill the future needs of the wireless communication systems and also promise to give throughput even more than that of today dominating LTE systems. In the next section, some of the massive MIMO signaling schemes are presented.

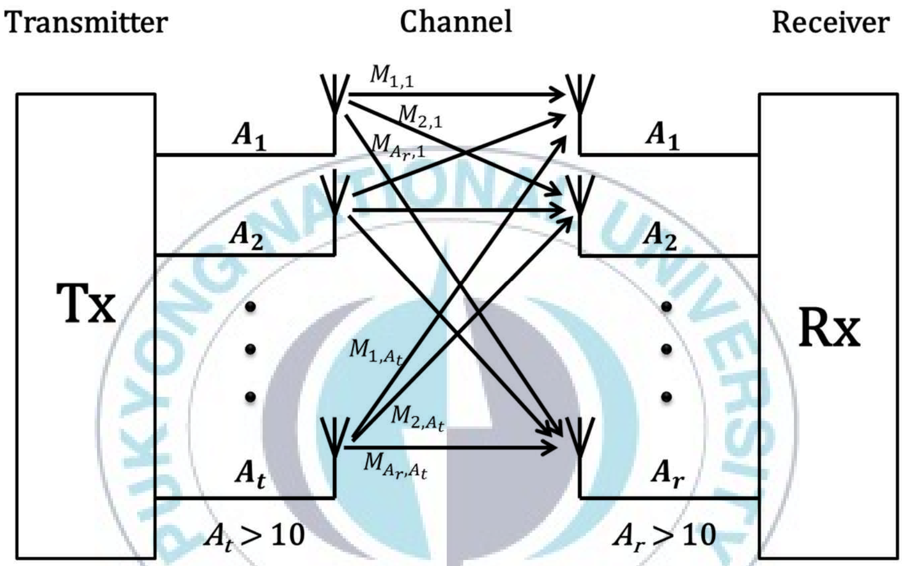

Figure 2.8. Massive MIMO system model diagram with antennas array up to tens to hundreds.

3. Quasi-Orthogonal Space-time Block Code

As described in the previous section, MIMO systems promise much higher spectral efficiency than SISO systems. MIMO systems can also be leveraged to improve the quality of transmission (reduce error rate). In this section, we will emphasis on MIMO signalling schemes that assume perfect knowledge of the channel at the receiver and no channel knowledge at the transmitter. Moreover, we will mainly present the algorithm how to make the 16×16 matrix using the quasi-orthogonal space-time block code (QOSTBC) in massive MIMO communication system.

3.1. Space-time Code (STC)

Space-time coding (STC) combines all the copies of the received signal in an optimal way to extract as much information from each of them as possible. STC is designed for the transmission of multiple copies of the data, also known as diversity, through the use of the multiple antennas. This helps to compensate for the channel problems such as fading and thermal noise. Although there is redundancy in the data, some copies may arrive less corrupted at the receiver.

A space-time encoder generates the different replicas of data sent for exploiting diversity. The space-time encoder coding is performed in both spatial and temporal domains to jointly modulate signals transmitted from several antennas at various time periods. The spatial-temporal modulation is used to exploit the MIMO channel fading and to minimize transmission errors at the receiver. Therefore, STC can achieve transmit diversity and power gain over spatially un-coded systems without sacrificing the bandwidth [36]. These are the functions of STC [12, 37].

Due to their decoding simplicity, the most dominant form of STC is space-time block code (STBC).

3.2. Space-time Block Code (STBC)

Space-time block coding (STBC) has recently emerged as a popular multi-antenna communication scheme, owing to its simple code construction and maximal diversity gain. The system using STBC as a coding technique has a significant impact on the overall performance of a wireless network [38].

STBC is used for MIMO systems to enable the transmission of multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer. STBC uses both spatial and temporal diversity and in this way enables significant gains to be made for MIMO systems.

When using STBC, the data stream is encoded in blocks prior to transmission. These data blocks are then distributed among the multiple antennas (which are spaced apart to decorrelate the transmission paths) and the data is also spaced across time. The STBC is usually denoted by a matrix. In the matrix below, each row signifies a time slot T and each column represents A_t transmit antennas.

Transmit antennas →

$$\begin{bmatrix} n_{11} & n_{12} & \cdots & n_{1A_t} \\ n_{21} & n_{22} & \cdots & n_{2A_t} \\ \vdots & \vdots & & \vdots \\ n_{T1} & n_{T2} & \cdots & n_{TA_t} \end{bmatrix} \downarrow \text{Time slots} \tag{3.1}$$

where $\boldsymbol{n}_{ij}$ symbolize the modulated symbol transmitted at time slot i from jth transmit antenna. The code rate of the STBC measures how many k symbols per time slot T and it transmits on average over the course of one block [39]. The rate of code is defined as R=k/T.

3.3. Orthogonal Space-time Block Code (OSTBC)

Orthogonal designs have been used as STBC for wireless communications with multiple transmit antennas (A_t). STBC is designed such that the vectors representing any pair of columns taken from the coding matrix are orthogonal. There are two types of orthogonal design theory: one for real numbers and other for complex numbers. For real or complex numbers, matrices satisfying the following equation are called orthogonal designs [36].

$$\boldsymbol{D}^H \boldsymbol{D} = (|n_1|^2 + |n_2|^2 + \ldots + |n_i|^2) \boldsymbol{I}, \tag{3.2}$$

where $\boldsymbol{D}^H$ is the Hermitian of the matrix $\boldsymbol{D}$, if $\boldsymbol{D}$ has complex numbers. $\boldsymbol{D}^H$ also represent the transpose of the matrix $\boldsymbol{D}$, if $\boldsymbol{D}$ has real numbers. In the real orthogonal designs, a $A_t \times A_t$ matrix is with real entries $\pm n_i,\ i = 1, \ldots., A_t$. In the complex orthogonal designs, an $A_t \times A_t$ matrix is with complex entries $\pm n_i, \pm n_i^*, \pm j n_i$, and $\pm j n_i^*,\ i = 1, \ldots, A_t$.

In complex orthogonal design, not only do the information symbols appear but also their conjugates. The i^{th} column of the code matrix can contain either the information symbols $n_1, \ldots, n_T$, or their conjugates $n_1^*, \ldots, n_T^*$ only.

The Alamouti code, one of the most well-known STBC, is designed for two transmit antennas [10]. This is a complex space-time diversity technique that can be used in 2x1 MISO model or in a 2x2 MIMO mode. The code is successfully integrated in 3G standards [40]. The Alamouti block code is the only complex block code that has full rate (i.e. data rate of 1) while achieving maximum diversity gain since it transmits 2 symbols every 2 time intervals. The Alamouti scheme encoding operation is given by

$$Q_2 = \begin{bmatrix} n_1 & n_2 \\ -n_2^* & n_1^* \end{bmatrix} \tag{3.3}$$

Concisely, two antennas are used, to send two symbols and their conjugate, in two time slots, which brings a diversity gain without compromising the data rate. The transmitted symbols will suffer from channel fading after transmission and their sum will be received at the receiver.

In this thesis, the rows of each coding scheme represents a different time instant, while the columns represent the transmitted symbol through each different antenna. In this case, the first and second rows represent the transmission at the first and second time instant respectively. At a time t, the symbol $\boldsymbol{n}_1$ and symbol $\boldsymbol{n}_2$ are transmitted from antenna 1 and antenna 2 respectively. Assuming that each symbol has duration T, then at time $t + T$, the symbols - $\boldsymbol{n}_2$* and $\boldsymbol{n}_1$*, where * represents the complex conjugate, are transmitted from antenna 1 and antenna 2 respectively.

r_1 and r_2 are the received signals at time t and $t+T$. Conjugating the signal r_2, the received signal can be expressed as [10]

$$\begin{aligned} r_1 &= m_1 n_1 + m_2 n_2 + \tilde{e}_1 \\ r_2^* &= -m_1^* n_2 + m_2^* n_1 + \tilde{e}_2 \,. \end{aligned} \tag{3.4}$$

Therefore, the equation (3.4) can be described as

$$\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} m_1 & m_2 \\ m_2^* & -m_1^* \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} + \begin{bmatrix} \tilde{e}_1 \\ \tilde{e}_2 \end{bmatrix} \tag{3.5}$$

or in short notation:

$$r = M\,n + \tilde{e}$$

(3.6)

where $\boldsymbol{r}=[r_1, \quad r_2^*]^{\mathrm{T}}$ represents the receive vector. $\boldsymbol{M}$ will be called the equivalent virtual MIMO channel matrix (EVCM) [41] of the Alamouti STBC scheme as the following:

$$M = \begin{bmatrix} m_1 & m_2 \\ m_2^* & -m_1^* \end{bmatrix}$$

(3.7)

The equivalent virtual MIMO channel matrix $\boldsymbol{M}$ is a matrix that satisfies $M^H M = \sum_1^N |m_i|^2 G$, where G is a sparse matrix with ones on its main diagonal, having at least $N^2/2$ zero entries at off diagonal positions and its remaining (self-interference) entries being bounded in magnitude by 1 [41]. For MIMO channel matrix, the rows and columns of the virtual channel matrix $\boldsymbol{M}$ of Alamouti STBC are orthogonal:

$$\boldsymbol{M}\,\boldsymbol{M}^{\mathrm{H}} = \boldsymbol{M}^{\mathrm{H}}\,\boldsymbol{M} = (|m_1|^2 + |m_2|^2)\,\boldsymbol{I}_2 = |m|^2\,\boldsymbol{I}_2,$$

(3.8)

where I_2 is the (2×2) identity matrix and m^2 is the power gain. It is certain that the EVCM depends on the structure of the code and the channel coefficients. The channel coefficients m_1 and m_2 can be used by the decoder as channel state information (CSI), if they can be absolutely estimated at the receiver. Assuming that all modulation constellation signals are equiprobable, a maximum likelihood (ML) detector decides for that pair of signals ($\hat{n}_1$, $\hat{n}_2$) from the signal modulation constellation that minimizes the decision metric

$$d^2(r_1, m_1 n_1 + m_2 n_2) + d^2(r_2, -m_1 n_2^* + m_2 n_1^*) =$$
$$|r_1 - m_1 n_1 - m_2 n_2|^2 + |r_2 + m_1 n_2^* - m_2 n_1^*|^2 ,$$
(3.9)

where $d(x_1, x_2) = |x_1 - x_2|$. The received signals r_1 and r_2 are combined by the signal combiner at the receiver by using a linear receiver.

$$n_1 = m_1^* r_1 + m_2 r_2^* = (|m_1|^2 + |m_2|^2) n_1 + m_1^* e_1 + m_2 e_2^*$$
$$\tilde{n}_2 = m_2^* r_1 - m_1 r_2^* = (|m_1|^2 + |m_2|^2) n_2 - m_1 e_2^* + m_2^* e_1 .$$
(3.10)

Therefore, $\tilde{n}_1$ and $\tilde{n}_2$ are two decisions statistics constructed by combining the received signals with coefficients derived from CSI.

Some authors apply the mathematical framework of orthogonal designs to construct both real and complex orthogonal codes that achieve full diversity [22]. For the case of real orthogonal codes, it has been shown that a full rate code can be constructed. However, for the case of complex orthogonal codes, it is unknown if a full rate and full diversity codes exist for $A_t > 2$ [29]. Among all types of space-time block codes (STBCs), quasi-orthogonal STBC (QOSTBC) is the major focus in this thesis.

3.4. Quasi-orthogonal Space-time Block Code (QOSTBC)

Since full transmission rate cannot be accomplished with complex orthogonal STBCs when more than two transmit antennas are used, the full-rate quasi-orthogonal STBC is employed. QOSTBC is a type of non-orthogonal STBC. Its transmission matrix is not entirely orthogonal but is partially orthogonal. QOSTBC is more suitable when using more than two antennas at the transmitter side in the wireless system. It provides the full rate matrix. Simple pair wise decoding can be performed and relatively better results can be achieved.

This QOSTBC designed code provides the transmission matrixes which do not separate transmitted symbols at the decoder by each other. In QOSTBC transmission matrix, the matrix columns are divided into the orthogonal groups where the columns within a group are not orthogonal to each other. Therefore, we called it as quasi-orthogonal STBC. The pairs of transmitted symbol can be decoded by using quasi-orthogonal STBC. This type of structure provides the higher transmission rate. For two transmit antennas, Alamouti *et al.* proposed the full rate orthogonal STBC for complex signal constellations [10]. Then, Jafarkhani proposed a QOSTBC which is an extension of the Alamouti matrix to (4×4) code matrix for improving the data rate [14] and can be given as:

$$Q_4 = \begin{bmatrix} n_1 & n_2 & n_3 & n_4 \\ -n_2^* & n_1^* & -n_4^* & n_3^* \\ -n_3^* & -n_4^* & n_1^* & n_2^* \\ n_4 & -n_3 & -n_2 & n_1 \end{bmatrix}$$

(3.11)

The ith column of above matrix is represented by a_i. Then, for any intermediate variable n_1, n_2, n_3, and n_4, we have

$$(a_1,a_2)=(a_1,a_3)=(a_2,a_4)=(a_3,a_4)=0 \tag{3.12}$$

where the parenthesis indicates inner product.

Although, Jafarkhani built the transmission matrix for 8 transmit antennas from 4 antennas, the 8x8 matrix cannot provide more than ¾ rate codes. We compare the transmission matrices of two quasi-orthogonal STBC with different rates, J_8 (R) = 3/4 and Q_8 (R) = 1 (full rate), for eight transmit antennas.

The QOSTBC for 8 transmit antennas (A_t) to send 6 information symbols (k) in the eight blocks which use T time slots is as shown in (3.13) [14]. The rate R of this QOSTBC code is, $R=\frac{k}{T}=\frac{6}{8}=\frac{3}{4}$.

$$J_8=\begin{bmatrix} n_1 & n_2 & n_3 & 0 & n_4 & n_5 & n_6 & 0 \\ -n_2^* & n_1^* & 0 & -n_3 & n_5^* & -n_4^* & 0 & n_6 \\ n_3^* & 0 & -n_1^* & -n_2 & -n_6^* & 0 & n_4^* & n_5 \\ 0 & -n_3^* & n_2^* & -n_1 & 0 & n_6^* & -n_5^* & n_4 \\ -n_4 & -n_5 & -n_6 & 0 & n_1 & n_2 & n_3 & 0 \\ -n_5^* & n_4^* & 0 & n_6 & -n_2^* & n_1^* & 0 & n_3 \\ n_6^* & 0 & -n_4^* & n_5 & n_3^* & 0 & -n_1^* & n_2 \\ 0 & n_6^* & -n_5^* & -n_4 & 0 & n_3^* & -n_2^* & -n_1 \end{bmatrix} \tag{3.13}$$

The proposed design of transmission matrix for 8 transmit antennas of size 8x8 is given in (3.14). This matrix is clearly a QOSTBC and sends k=8 information symbols in a block of T=8 uses. Therefore, the rate of this QOSTBC code is $R = \frac{k}{T} = \frac{8}{8} = 1$.

The QOSTBC designs we present in this chapter have a special structure. Each row has either only complex symbols or only conjugate complex symbols. This structure gives the flexibility to manipulate the complex number properties in order to demodulate the receiver signals. 8 transmit antennas with symbol transmission rate-1 QOSTBC is constructed by using the concept of the Alamouti scheme with the equivalent virtual MIMO channel matrix as shown in (3.14):

$$Q_8 = \begin{bmatrix} n_1 & n_2 & n_3 & n_4 & n_5 & n_6 & n_7 & n_8 \\ -n_2^* & n_1^* & -n_4^* & n_3^* & -n_6^* & n_5^* & -n_8^* & n_7^* \\ -n_3^* & -n_4^* & n_1^* & n_2^* & -n_7^* & -n_8^* & n_5^* & n_6^* \\ n_4 & -n_3 & -n_2 & n_1 & n_8 & -n_7 & -n_6 & n_5 \\ -n_5^* & -n_6^* & -n_7^* & -n_8^* & n_1^* & n_2^* & n_3^* & n_4^* \\ n_6 & -n_5 & n_8 & -n_7 & -n_2 & n_1 & -n_4 & n_3 \\ n_7 & n_8 & -n_5 & -n_6 & -n_3 & -n_4 & n_1 & n_2 \\ -n_8^* & n_7^* & n_6^* & -n_5^* & n_4^* & -n_3^* & -n_2^* & n_1^* \end{bmatrix} \quad (3.14)$$

Obviously, the new quasi-orthogonal design has a greater rate than the conventional code. Consequently, the new high rate orthogonal design can achieve larger diversity gain by transmitting additional two more information symbols.

In addition, the generation scheme is also proposed and is described for QOSTBC with up to 16 antennas below:

Step 1. Create a basic function *ArrayCreate* to form a QOSTBC matrix with only two input arguments. To create Q_2, use two symbols n_1 and n_2 as input arguments to *ArrayCreate*. Then, Q_2 is given by:

$$Q_2 = \begin{bmatrix} n_1 & n_2 \\ -n_2^* & n_1^* \end{bmatrix} \tag{3.15}$$

Step 2. To create Q_4, obtain Q_{21} whose elements are n_1, n_2 and Q_{22} whose elements are n_3, n_4 using the function *ArrayCreate*. Then, obtain Q_4 by calling the function *ArrayCreate* with input matrices Q_{21} and Q_{22}.

Step 3. To create Q_8, first create two 4×4 matrices Q_{41} with input elements n_1, n_2, n_3, n_4 and Q_{42} with input elements n_5, n_6, n_7, n_8. Q_8 is now created by calling the function *ArrayCreate* with input matrices Q_{41} and Q_{42}.

Step 4. Repeat Step 3 to obtain Q_{81} whose input elements are n_1, n_2, n_3,…, n_8 and Q_{82} whose input elements are n_9, n_{10}, n_{11}, …, n_{16}. The function *ArrayCreate* is called with input matrices Q_{81} and Q_{82} to create Q_{16}.

By using above algorithm, we expand from the 8 transmit antennas (3.14) to the 16 transmit antennas with full rate QOSTBC which is given in (3.16).

In this way, the QOSTBC for any number of antennas can readily be generated by extending the proposed scheme. In the next chapter, the BER performance in AWGN channel and Rayleigh flat fading channel are considered for massive MIMO system.

$$
Q_{16}=\begin{bmatrix}
n_1 & n_2 & n_3 & n_4 & n_5 & n_6 & n_7 & n_8 & n_9 & n_{10} & n_{11} & n_{12} & n_{13} & n_{14} & n_{15} & n_{16} \\
-n_2^* & n_1^* & -n_4^* & n_3^* & -n_6^* & n_5^* & -n_8^* & n_7^* & -n_{10}^* & n_9^* & -n_{12}^* & n_{11}^* & -n_{14}^* & n_{13}^* & -n_{16}^* & n_{15}^* \\
-n_3^* & -n_4^* & n_1^* & n_2^* & -n_7^* & -n_8^* & n_5^* & n_6^* & -n_{11}^* & -n_{12}^* & n_9^* & n_{10}^* & -n_{15}^* & -n_{16}^* & n_{13}^* & n_{14}^* \\
n_4 & -n_3 & -n_2 & n_1 & n_8 & -n_7 & -n_6 & n_5 & n_{12} & -n_{11} & -n_{10} & n_9 & n_{16} & -n_{15} & -n_{14} & n_{13} \\
-n_5^* & -n_6^* & -n_7^* & -n_8^* & n_1^* & n_2^* & n_3^* & n_4^* & -n_{13}^* & -n_{14}^* & -n_{15}^* & -n_{16}^* & n_9^* & n_{10}^* & n_{11}^* & n_{12}^* \\
n_6 & -n_5 & n_8 & -n_7 & -n_2 & n_1 & -n_4 & n_3 & n_{14} & -n_{13} & n_{16} & -n_{15} & -n_{10} & n_9 & -n_{12} & n_{11} \\
n_7 & n_8 & -n_5 & -n_6 & -n_3 & -n_4 & n_1 & n_2 & n_{15} & n_{16} & -n_{13} & -n_{14} & -n_{11} & -n_{12} & n_9 & n_{10} \\
-n_8^* & n_7^* & n_6^* & -n_5^* & n_4^* & -n_3^* & -n_2^* & n_1^* & -n_{16}^* & n_{15}^* & n_{14}^* & -n_{13}^* & n_{12}^* & -n_{11}^* & -n_{10}^* & n_9^* \\
-n_9^* & -n_{10}^* & -n_{11}^* & -n_{12}^* & -n_{13}^* & -n_{14}^* & -n_{15}^* & -n_{16}^* & n_1^* & n_2^* & n_3^* & n_4^* & n_5^* & n_6^* & n_7^* & n_8^* \\
n_{10} & -n_9 & n_{12} & -n_{11} & n_{14} & -n_{13} & n_{16} & -n_{15} & -n_2 & n_1 & -n_4 & n_3 & -n_6 & n_5 & -n_8 & n_7 \\
n_{11} & n_{12} & -n_9 & -n_{10} & n_{15} & n_{16} & -n_{13} & -n_{14} & -n_3 & -n_4 & n_1 & n_2 & -n_7 & -n_8 & n_5 & n_6 \\
-n_{12}^* & n_{11}^* & n_{10}^* & -n_9^* & -n_{16}^* & n_{15}^* & n_{14}^* & -n_{13}^* & n_4^* & -n_3^* & -n_2^* & n_1^* & n_8^* & -n_7^* & -n_6^* & n_5^* \\
n_{13} & n_{14} & n_{15} & n_{16} & -n_9 & -n_{10} & -n_{11} & -n_{12} & -n_5 & -n_6 & -n_7 & -n_8 & n_1 & n_2 & n_3 & n_4 \\
-n_{14}^* & n_{13}^* & -n_{16}^* & n_{15}^* & n_{10}^* & -n_9^* & n_{12}^* & -n_{11}^* & n_6^* & -n_5^* & n_8^* & -n_7^* & -n_2^* & n_1^* & -n_4^* & n_3^* \\
-n_{15}^* & -n_{16}^* & n_{13}^* & n_{14}^* & n_{11}^* & n_{12}^* & -n_9^* & -n_{10}^* & n_7^* & n_8^* & -n_5^* & -n_6^* & -n_3^* & -n_4^* & n_1^* & n_2^* \\
n_{16} & -n_{15} & -n_{14} & n_{13} & -n_{12} & n_{11} & n_{10} & -n_9 & -n_8 & n_7 & n_6 & -n_5 & n_4 & -n_3 & -n_2 & n_1
\end{bmatrix}
\quad (3.16)
$$

4. Performance Analysis of Massive MIMO System

As described in Chapter 1, the target of this study is to develop a full-rate massive MIMO system which will fulfil the given objectives. In order to materialize the objectives, several experiments were performed on the massive MIMO system by using QOSTBC described in Chapter 3. In this chapter, we present the simulation results to verify the theoretical analysis for massive MIMO system using QOSTBC. For comparison and readability purposes we plot all the corresponding BER curves for massive MIMO according to the large number of transmitter and receiver antennas by using the simulation parameters from Table 4.1 for simulations over AWGN channel and from Table 4.2 for simulations over Rayleigh flat fading channel. The bit-error rate performances were calculated while performing simulations with different modulations namely QPSK, BPSK, 8PSK and 16QAM by varying SNR and by using different antenna configurations up to 128 transmitter and receiver antennas.

4.1. Additive White Gaussian Noise (AWGN) Channel

In an AWGN channel, bits transmitted from antenna on the transmitter side arrive at the receiver with addition of noise and phase rotation. AWGN channel does not take either frequency selective fading or flat fading or interference into account. The amplitude of AWGN noise is Gaussian distributed with mean, $\mu = 0$ and variance σ^2, where $\sigma^2 = \frac{N}{2}$.

Antenna system model for an AWGN channel can be defined as

$$y = Ms + n \tag{4.1}$$

where $\boldsymbol{y}$ is the received vector, $\boldsymbol{n}$ is AWGN, $\boldsymbol{s}$ is a transmitted vector and M is a complex matrix [42].

The simulated linear AWGN channel has a bandwidth greater than that of the message signal. The noise $\boldsymbol{n}$ is a complex Gaussian-distributed stationary random process with zero mean and is generated as a vector with the same number of elements as the message to be transmitted. The noise power is calculated as the ratio of signal power to SNR. This noise is added to the message vector $\boldsymbol{c}$ to obtain the received signal $\boldsymbol{r}$ [43].

$$\boldsymbol{r} = \boldsymbol{c} + \boldsymbol{n} \tag{4.2}$$

The description of the matrix dimension for various multiple antenna configurations is given in the following subsection:

4.1.1. SIMO

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{A_r} \end{bmatrix} = \begin{bmatrix} M_{1,1} \\ M_{2,1} \\ \vdots \\ M_{A_r,1} \end{bmatrix} s + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{A_r} \end{bmatrix} \tag{4.3}$$

In (4.3), the SIMO model is represented. When compared to the SISO model in (4.1), SIMO model gives $\boldsymbol{y}$ and $\boldsymbol{n}$ having dimension A_r×1 and $\boldsymbol{s}$ has dimension A_t×1, M is a complex column matrix of dimension A_t×1. There is only single input corresponding to single transmitted antenna.

4.1.2. MISO

$$y = \begin{bmatrix} M_{1,1} & M_{1,2} & \cdots & M_{1,A_t} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_{A_t} \end{bmatrix} + n$$

(4.4)

In (4.4), the MISO model is represented. When compared to the SISO model in (4.1), MISO model gives ***s*** having dimensions of $A_t \times 1$ and ***y*** and ***n*** having dimension $A_r \times 1$, M is a row matrix having a dimension of $1 \times A_t$. There is only single output corresponding to single received antenna.

4.1.3. MIMO

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{A_r} \end{bmatrix} = \begin{bmatrix} M_{1,1} & M_{1,2} & \cdots & M_{1,A_t} \\ M_{2,1} & M_{2,2} & \cdots & M_{2,A_t} \\ \vdots & \vdots & \ddots & \vdots \\ M_{A_r,1} & M_{A_r,2} & \cdots & M_{A_r,A_t} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_{A_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{A_r} \end{bmatrix}$$

(4.5)

In (4.5), the MIMO model is represented. When compared to the SISO model in (4.1), MIMO model gives ***s*** having dimensions of $A_t \times 1$, ***y*** and ***n*** having dimension of $A_r \times 1$. M has the dimension of $A_r \times A_t$.

4.2. Simulation Results over AWGN Channel

The simulations were conducted to investigate the BER versus SNR for different antenna configurations such as 1×1, 2×2, 4×4, 8×8, 16×16, 32×32, 64×64 and 128×128 over AWGN channel in this section. The transmission using QOSTBC for massive MIMO system is performed using various modulations such as QPSK, BPSK, 8PSK and 16QAM. As shown in the following figures, the higher the value of SNR, the lower the number of errors.

The results are observed with the assumption that channel state information is perfectly known to the receiver. We increase the size of QOSTBC matrix while performing our simulation. We then evaluated the BER performance according to the matrix size (i.e. the number of antennas). During simulation, we increased the number of antennas one by one up to 128, by designing the QOSTBC code to get the matrix of size 128x128. Table 4.1 summarizes the simulation parameters for simulation under AWGN channel.

Table 4.1. Simulation Parameters for AWGN channel

Parameters	Specifications
Number of transmitter antennas	1, 2, 4, 8, 16, 32, 64, 128
Number of receiver antennas	1, 2, 4, 8, 16, 32, 64, 128
Data Length	1024 bits
Number of packets	100
Modulation technique	QPSK, BPSK, 8PSK, 16QAM
Channel	AWGN channel

Through simulations, we first analyse the BER performance of massive MIMO system up to 64 antenna configurations employing BPSK modulation. For comparison and reliability purposes, we also plot all the BER curves for all the aforementioned various antenna configurations using the proposed QOSTBC, as shown in Figure 4.1. We can see that the performance of the 64×64 configuration achieve a BER of about 10^{-5} at the SNR values of -6dB as the greatest performance among 1×1, 2×2, 4×4, 8×8, 16×16, 32×32, and 64×64 antennas.

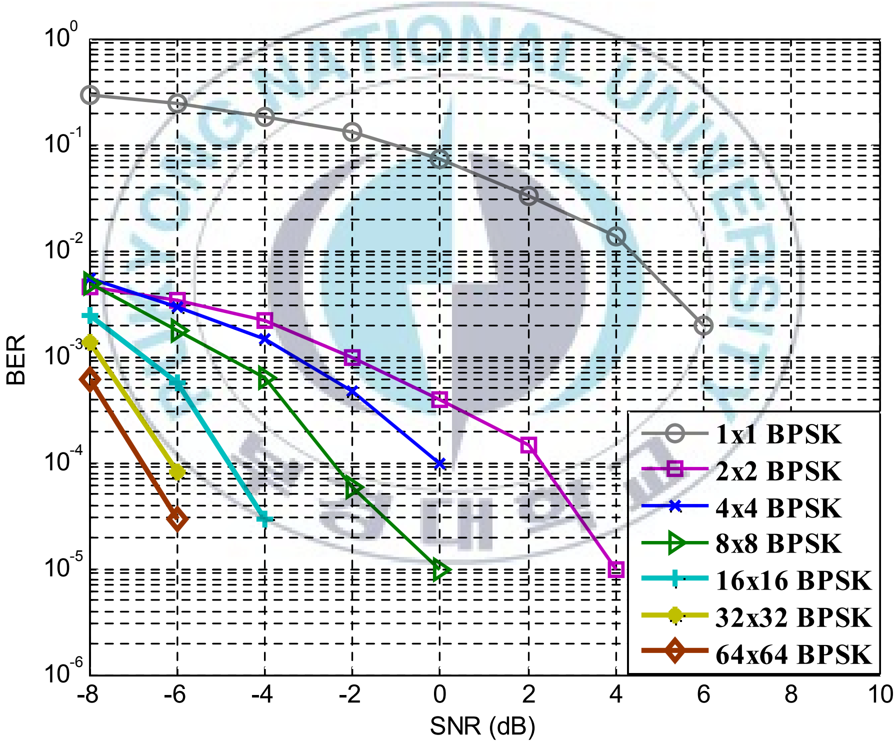

Figure 4.1. Massive MIMO system performance using QOSTBC with up to 64×64 number of transmit and receive antennas with BPSK over AWGN.

After that we performed simulations for up to 128 antennas using the proposed QOSTBC by employing QPSK modulation. Figure 4.2 shows the BER performance results of massive MIMO with up to 128×128 number of transmit and receive antennas. In case of higher SNR, BER drops for every configuration. By increasing the number of antennas, the BER performance is significantly improved. Therefore, it is clearly observed from Figure 4.2 that the best performance is predictably achieved with 128×128 antennas of massive MIMO system when compared to the other different antennas.

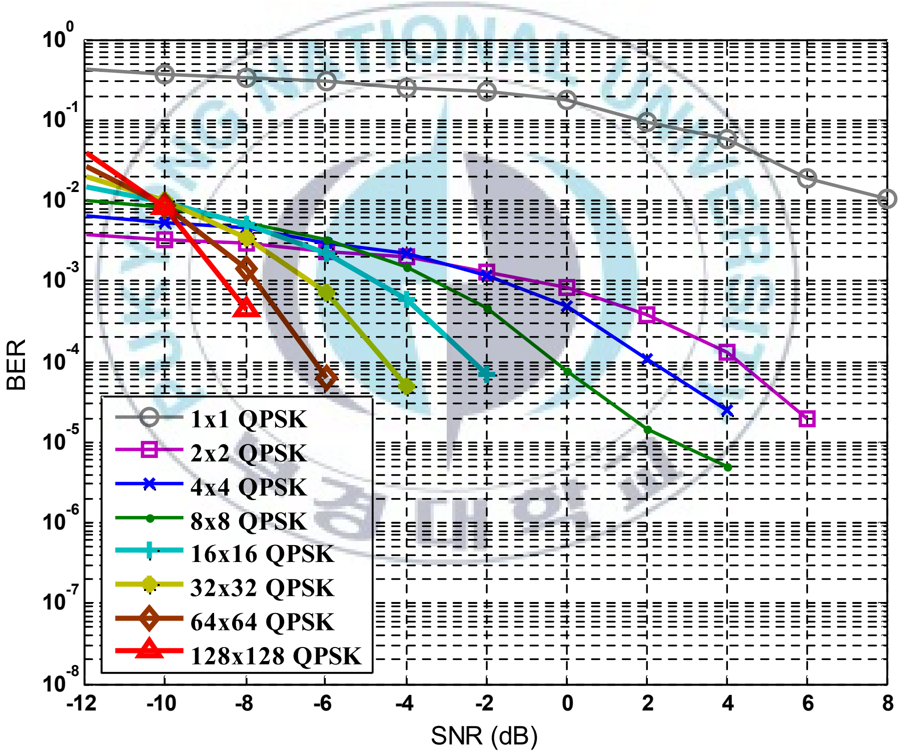

Figure 4.2. Up to 128×128 antenna configuration performances of massive MIMO system using QOSTBC employing QPSK over AWGN.

In order to evaluate the effectiveness of the proposed QOSTBC for Massive MIMO using 8PSK modulation, we calculated BER performance and is shown in Figure 4.3. Figure 4.3 plots error performances with increasing number of transmit and receive antennas for massive MIMO. We performed simulations for up to 16 antennas. As we can see from comparison of the BER performance for different antenna configurations, the best BER performance is achieved with the 16×16 configuration as expected. This performance can become more effective by increasing the number of antennas.

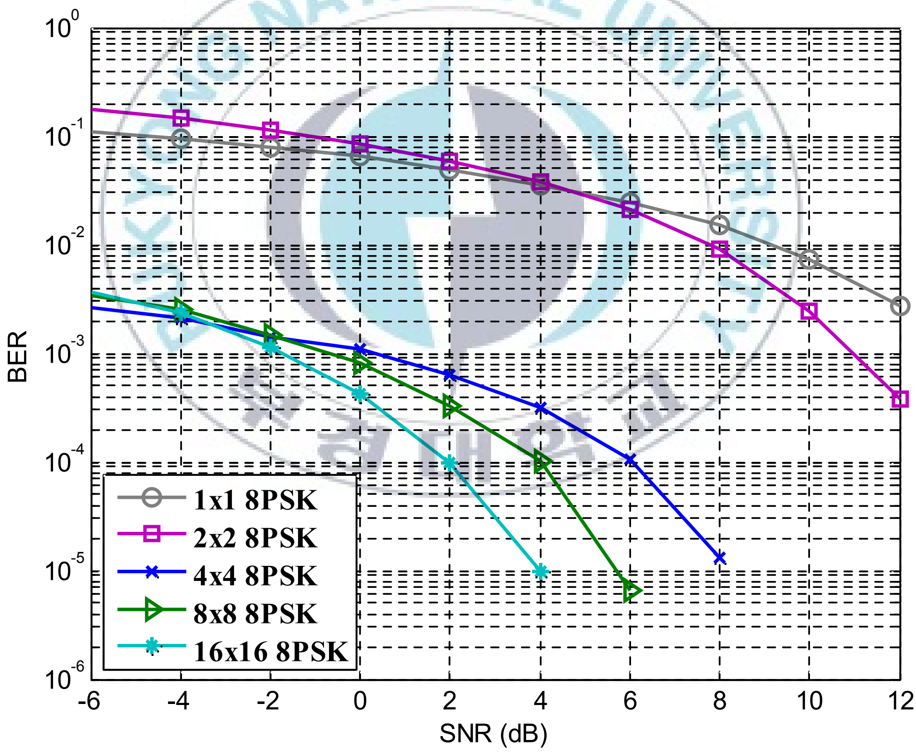

Figure 4.3. Massive MIMO system performances using QOSTBC with up to 16 number of antennas employing 8PSK over AWGN.

We also conducted performance evaluation by employing 16QAM modulation using QOSTBC with 1×1, 2×2, 4×4, 8×8, and 16×16 number of transmit and receive antennas. We assumed that the total transmit signal power was equally divided by the number of transmit antennas. The SNR vs BER results for 16QAM modulation technique with various antenna configurations are plotted in Figure 4.4. The higher the number of transmit and receive antennas, the better the BER performance of massive MIMO system. Therefore, it is clearly observed from the Figure 4.4 that the greatest BER performance of 10^{-5} is achieved at SNR value of 6dB in 16x16 configuration.

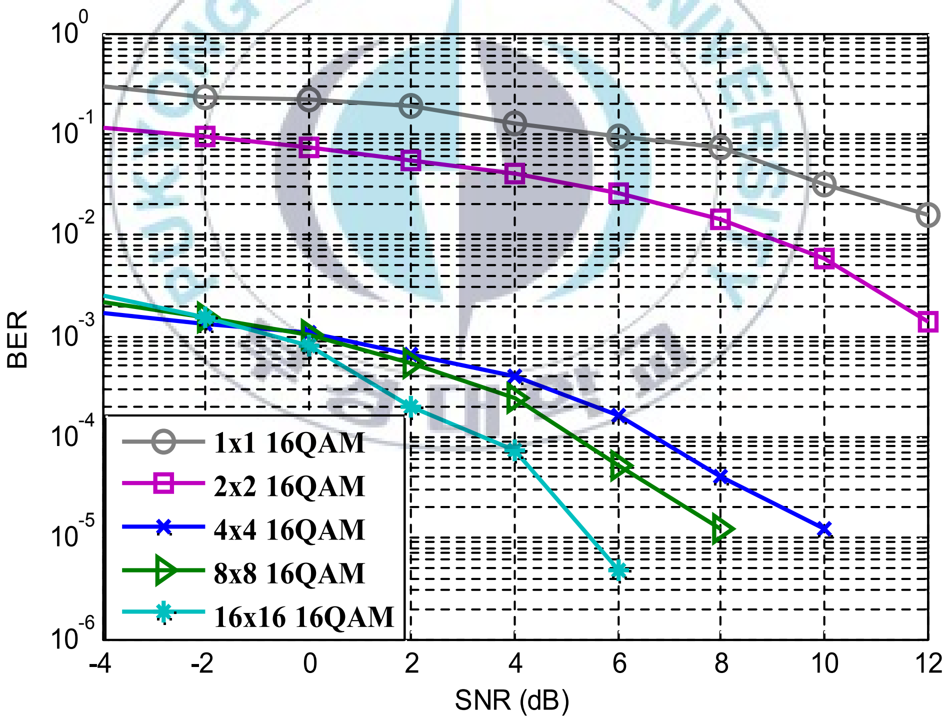

Figure 4.4. Performances of massive MIMO system using QOSTBC with up to 16×16 antenna configuration employing 16QAM over AWGN.

4.3. Rayleigh Fading Channel

Among the fading models, the Rayleigh Fading channel is one of the most commonly used fading model. Rayleigh fading assumes that there is no Line of Sight (LOS) communication path, which means when there will be no direct path between transmitter and receiver, various components from multiple path will be received by the receiver. Thus represents the worst case fading scenario. The phase and the amplitude in Rayleigh fading are independent of one another. Rayleigh fading is the most commonly used model as most practical scenarios (especially urban) do not have an LOS component.

Rayleigh fading is a statistical model for the strong influence of a propagation environment on a radio signal, used by wireless communication devices [44]. When there are large numbers of paths, each path can be modelled as circularly symmetric complex Gaussian random variable with time as the variable. When the waves of multipath signals are out of phase, reduction in signal strength can occur; such a type of fading is called Rayleigh fading in wireless communications [45]. This can be caused by multipath with or without the Doppler Effect.

In Rayleigh fading channel, the transmitted bits arrive at the receiver with some attenuation and also with phase rotation because of the multiplicative factor introduced in the channel. This multiplicative factor is a channel amplitude gain and is a Gaussian distributed complex random variable.

Rayleigh fading is mostly applied in situations when there is less or no dominant propagation along a line of sight between the transmitter and receiver. According to the central limit theorem, if there is sufficiently too much scattering, the impulse response of the channel can be modelled well as a Gaussian process, not bothering about the distribution of the individual components. Antenna system model for Rayleigh channel can be mathematically represented similar to (4.1) with the only difference in the channel matrix M replaced by M_{Ray} suggesting Rayleigh channel.

$$y = M_{Ray} s + n \tag{4.6}$$

A circularly symmetric complex Gaussian random variable is of the form,

$$M_{Ray} = M_{RayI} + jM_{RayQ} \tag{4.7}$$

where, real M_{RayI} and imaginary jM_{RayQ} parts of the channel response are zero mean independent and identically distributed Gaussian random variables. For a circularly symmetric complex random variable,

$$E[h] = E[e^{j\theta} h] = e^{j\theta} E[h] \tag{4.8}$$

The statistics of a circularly symmetric complex Gaussian random variable is completely specified by the variance,

$$\sigma^2 = E[h^2] \tag{4.9}$$

Rayleigh random variable has a probability density function as shown in (4.10).

$$P(z) = \frac{2z}{\sigma^2} e^{-\frac{z^2}{\sigma^2}}, z \geq 0 \tag{4.10}$$

The received signal in a Rayleigh fading channel is

$$y = hx + n \tag{4.11}$$

where, $\boldsymbol{y}$ and $\boldsymbol{x}$ are the received and transmitted signals, respectively. $\boldsymbol{h}$ is the Rayleigh fading channel response and $\boldsymbol{n}$ is the Additive White Gaussian

Noise. When the mobile station moves, the frequency shift of each reflected signal component that arises from the Doppler Effect also has an influence on the fading. Very often, the gain and phase elements of a channel's distortion are represented as a complex number for mathematical convenience. The channel is randomly varying in time, so each transmitted signal gets multiplied by a random varying complex number **h**. Since **h** is modeled as Rayleigh fading channel, the real and imaginary parts of Gaussian distributed have mean 0 and variance ½.

When the coherence bandwidth of the channel is much greater than the bandwidth of the signal being transmitted, the Rayleigh flat fading occurs. In the time domain, the flat fading channels in which the signal symbol period is larger than the multi-path delay spread. As a result the channel response is composed of a constant gain and a linear phase. Flat fading results in a decreased SNR at the receiver.

4.4. Simulation Results over Rayleigh Fading Channel

The following graphs illustrates the simulation results of the BER performance of the massive MIMO using the proposed QOSTBC for 1×1, 2×2, 4×4, 8×8, and 16×16 number of transmit and receive antennas configuration. In the simulation, quasi-static flat fading channels are assumed. The results employing QPSK, BPSK, 8PSK and 16 QAM modulation techniques are plotted for BER with increasing value of SNR. The simulation parameters used throughout this work are listed in Table 4.2.

Table 4.2. Simulation Parameters for Rayleigh fading channel

Parameters	Specifications
Number of transmitter antennas	1, 2, 4, 8, 16
Number of receiver antennas	1, 2, 4, 8, 16
Data Length	1024 bits
Number of packets	100
Modulation method	QPSK, BPSK, 8PSK, 16QAM
Channel	Rayleigh flat fading channel

The BER performance of massive MIMO QOSTBC system with configurations of up to 16 antennas are plotted by employing QPSK and BPSK constellation in Figure 4.5 and Figure 4.6 respectively. When the number of antennas increases, the BER of the system dramatically progress. It is clearly observed that the 16×16 antennas massive MIMO QOSTBC system with BPSK modulation technique form Figure 4.6 gives better performance when compared to that system with QPSK from Figure 4.5. Simulations are carried out for evaluating performances with different SNR values. Figure 4.5 and Figure 4.6 illustrate a significant performance improvement when the number of transmit and receive antennas increases. Moreover, a greater performance improvement is observed with increased SNR.

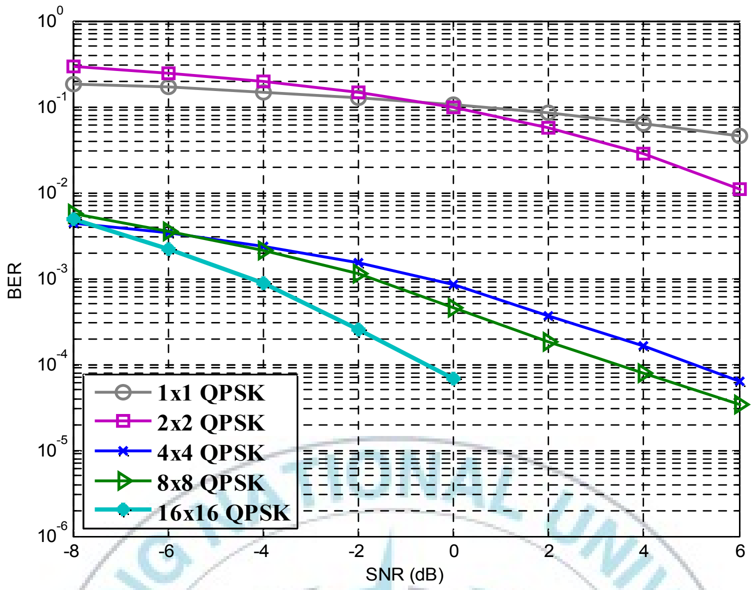

Figure 4.5. BER performances of the massive MIMO QOSTBC system with up to 16 antenna configuration using QPSK over Rayleigh flat fading.

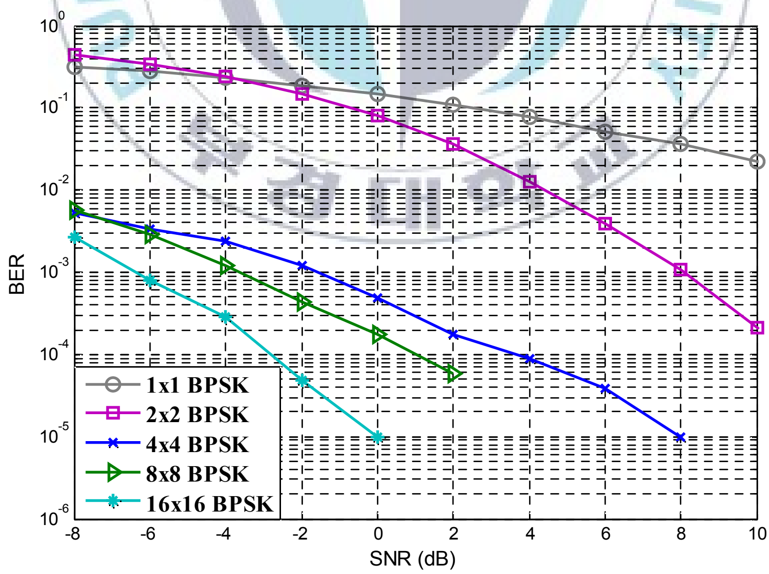

Figure 4.6. BER performances of the Rayleigh flat fading massive MIMO QOSTBC system with up to 16 antenna configuration using BPSK.

According to Figure 4.7 and Figure 4.8, increasing the number of antennas results in significant BER performance. We can see the comparison of the BER performance of the massive MIMO QOSTBC system as shown in Figure 4.7 and Figure 4.8. The following graphs demonstrate simulation results employing 8PSK and 16QAM modulation technique are designed for BER versus SNR. Based on the analysis and simulations, it is noticeably observed that the 16×16 antennas Rayleigh flat fading massive MIMO QOSTBC system with 8PSK constellation form Figure 4.7 provides better performance when compared to that system with 16QAM from Figure 4.8.

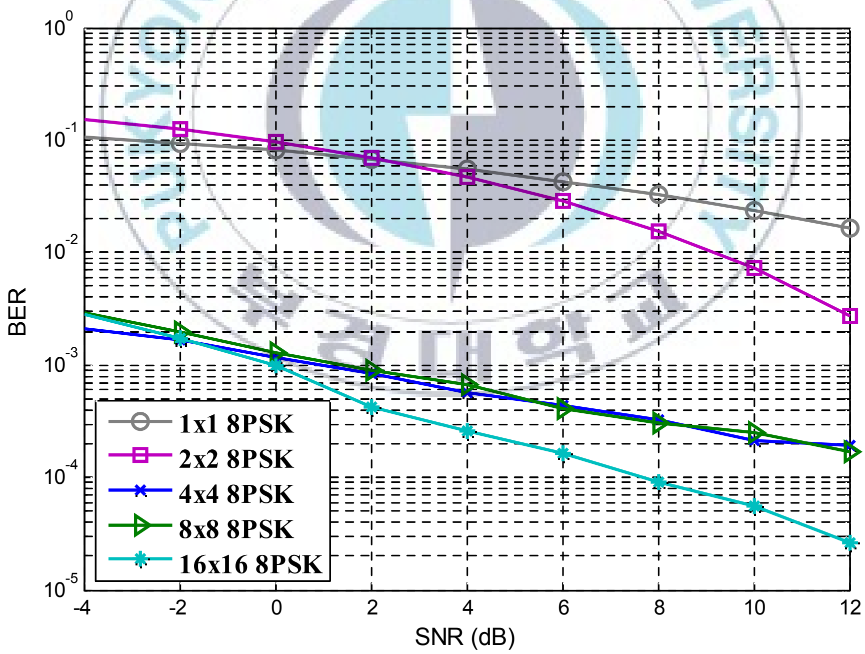

Figure 4.7. Rayleigh flat fading massive MIMO QOSTBC system performances with different antenna configurations employing 8PSK.

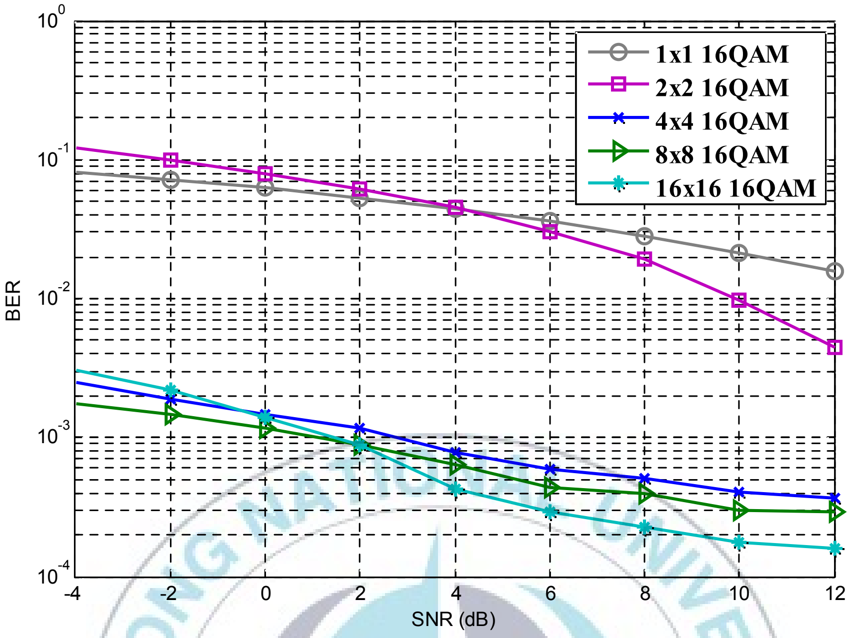

Figure 4.8. Rayleigh flat fading massive MIMO QOSTBC system performances with different antenna configurations employing 16QAM.

The comparisons of BER performances between the aforementioned modulation techniques for the 16x16 number of transmit and receive antennas under Rayleigh flat fading channel are illustrated in Figure 4.9. They are used the simplified full rate QOSTBC signaling scheme of massive MIMO system. Among them, 16×16 antenna array configuration employing the BPSK constellation provides the best performance. It achieved a BER of 10^{-5} at the SNR 0dB.

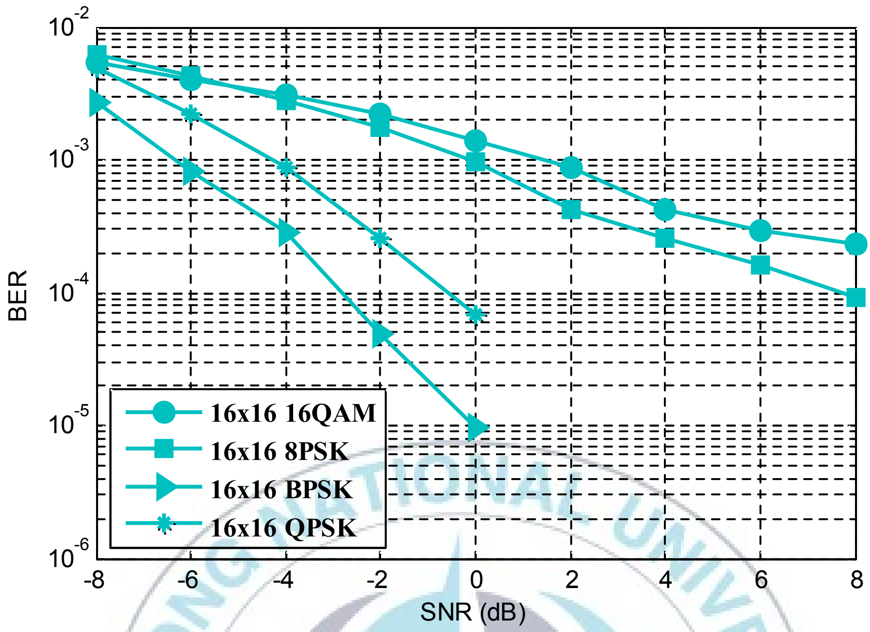

Figure 4.9. Comparisons between different modulation techniques of 16×16 number of transmit and receive antenna of massive MIMO system over Rayleigh flat fading.

Massive MIMO model has been developed by using the proposed QOSTBC scheme with 1×1, 2×2, 4×4, 8×8, 16×16, 32×32, 64×64 and 128×128 antennas configurations. We have analysed the BER performance of massive MIMO system over AWGN channel and Rayleigh flat fading channel employing different constellations.

5. Conclusions

The single and multiple antenna system classifications such as SISO, SIMO, MISO, conventional MIMO, Multi-user (MU-MIMO), and massive MIMO functions have been presented. This thesis is more focus on massive MIMO systems as a key enabling technology for future wireless communication system.

Massive MIMO provides the significant increase in data throughput and link range when bandwidth or transmit power remain unchanged. The use of massive MIMO enables higher data transmission rates by a factor proportional to the number of streams.

The STBC can be classified into two major categories: orthogonal STBC and quasi-orthogonal STBC. Under OSTBC, Alamouti code and its equivalent virtual MIMO channel matrix have been described. The performance analysis and optimization of QOSTBC massive MIMO system have been discussed in this thesis.

QOSTBC scheme is mainly used to analyze the theoretical performance of massive MIMO due to its dramatic increase in speed of data transmissions. The result of the algorithm used in this thesis is to achieve the full rate QOSTBC matrix for massive number of antennas. This thesis has proved that 16×16 QOSTBC matrix achieve full code rate, the proposed 16×16 QOSTBC matrix is presented.

Through our work, we investigated and demonstrated that significant BER performance of massive MIMO using simplified full-rate QOSTBC is achievable by increasing the number of transmitter and receiver antennas. Then we presented the performance results of up to 128×128 antenna configurations employing QPSK constellation over AWGN channel.

We have further investigated the simplified scheme of quasi-orthogonal space-time block code for up to 128×128 massive MIMO over AWGN channel and up to 16×16 massive MIMO over Rayleigh flat fading channel. The results of research demonstrated how the bit-error rate (BER) performed with the QOSTBC scheme and the results produced a significant difference in terms of energy efficiency, spectral efficiency, robustness and reliability as the number of transmitter and receiver antennas increased. The research model is a basic for a realistic massive MIMO system with up to 128 transmit and receive antennas.

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List of Publications

International Journals

[1] Khin Zar Chi Winn, Phyu Phyu Han, Kasun Bandara and Yeon-Ho Chung, “On the Performance of Quasi-Orthogonal Space Time Block Coded Massive MIMO with up to 16 Antennas,” Lecture Note in Electrical Engineering (SCOPUS), Dec. 2014.

[2] Khin Zar Chi Winn, Phyu Phyu Han, Atul Sewaiwar and Yeon-Ho Chung, “Simplified Full-Rate Quasi-Orthogonal STBC for 16x16 Massive MIMO in Rayleigh Fading Channels” The Institute of Electronics, Information and Communication Engineers (SCI), (in review)

[3] Khin Zar Chi Winn and Yeon-Ho Chung, “32×32 Full-Rate Massive MIMO Using Quasi-Orthogonal Space-Time Block Code (QOSTBC),” Journal of the Korea Institute of Information and Communication Engineering (JKIICE), (in review)

International Conferences

[4] Khin Zar Chi Winn, Phyu Phyu Han, Kasun Bandara and Yeon-Ho Chung, "On the Performance of Quasi-Orthogonal Space Time Block Coded Massive MIMO with up to 16 Antennas," The 2nd FTRA International Conference on Ubiquitous Computing Application and Wireless Sensor Network (UCAWSN-14), Jeju, South Korea, July, 2014.

[5] Khin Zar Chi Winn, Phyu Phyu Han, Atul Sewaiwar and Yeon-Ho Chung, "Quasi-Orthogonal Space-time Block Code (QOSTBC) for Full-Rate Massive MIMO with up to 32 antennas" The 2014 FTRA International Symposium on Ubiquitous Green IT Systems (U-GIT-2014), Jeju, South Korea, July, 2014.

Domestic Conferences

[6] Phyu Phyu Han, Khin Zar Chi Winn, Kasun Bandara and Yeon-Ho Chung, "QOSTBC based Massive MIMO with MMSE Channel Estimation" The Korean Institute of Communications and Information Sciences (KICS), pp. 57-60, Busan, South Korea, Dec 2013.

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