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Performance Evaluation of LTE Downlink with MIMO Techniques

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ABSTRACT

Long Term Evolution (LTE) of the Universal Mobile Telecommunication System (UMTS) also known as the Evolved Packet System (EPS) is a transilient move in the field of mobile communications. Such a revolution is necessitated by the unceasing increase in demand for high speed connections on networks, low latency and delay, low error rates and resilience because modern users and network applications have become increasingly dependent on these requirements for efficient functionality and performance. Third Generation Partnership Project Long Term Evolution (3GPP LTE) promises high peak data rates for both uplink and downlink transmission, spectral efficiency, low delay and latency, low bit error rates, to mention but a few. These functional and performance targets of 3GPP LTE are laudable and can be met with a great measure of certainty, but then a vital question emerges: What are the prime drivers or enablers for these technology standard requirements to be met? LTE leverages on a number of technologies namely Multi Input Multiple Output (MIMO) antennas, Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiplexing Access (OFDMA) at the downlink, Single Carrier Frequency Division Multiple Access (SCFDMA) at the uplink, support for Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (16QAM), and 64QAM.

This thesis work evaluates the performance of LTE downlink with MIMO techniques. MIMO technology involves the use of multiple antennas at the transmitter, receiver or both. There are different combinations of array configuration and polarization, transmission and detection schemes that can be implemented to achieve different purposes in functional and performance terms. In terms of array configuration and polarization, there exists single polarized array and cross polarized array (which could be compact or detached); transmission schemes include diversity schemes particularly transmit diversity and spatial multiplexing; detection schemes such as Zero Forcing (ZF) and Soft Sphere Decoding (SSD). The performance metrics considered are throughput and BER and these are used to evaluate the performance of LTE in flat-fading and International Telecommunications Union B (ITU-B) Pedestrian channel with zero forcing and soft sphere decoding for Single Input Single Output (SISO), transmit diversity and spatial multiplexing. The granular analysis and evaluation of the performance 3GPP LTE is imperative and this thesis implements this on the downlink side. A thorough analysis and performance evaluation of the LTE downlink with MIMO antennas is thus the focal point and the results demonstrate that the design goals and requirements of 3GPP LTE can be met with a great deal of reliability and certainty. The simulations show that the performance of MIMO is better than SISO in both channel models particularly when SSD is employed. When high order modulation is utilized, performance in the flat-fading channel model is better than ITU pedestrian B channel at low SNR regions. Spatial multiplexing is ideal for achieving very high peak rates, while transmit diversity is a valuable scheme to minimize the rate of bit error occurrence thereby improving signal quality.

Keywords: 3GPP LTE, 16QAM, 64QAM, EPS, ITU-B, MIMO, OFDM, OFDMA, SCFDMA, SSD, UMTS, ZF

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Mengistu and Yinka

DEDICATION

We dedicate this thesis to Almighty God for his love, blessings and protection over us from the day we made entry into this world until this very moment. We thank and give Him praise for our successes, accomplishments and achievements in life which includes this noble piece.

Mengistu & Yinka

I dedicate this noble piece to:

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Yinka

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Acronyms and Notation Description

3GPP	Third Generation Partnership Project
ADC	Analog to Digital Converter
AMC	Adaptive Modulation and Coding
AN	Access Network
ARQ	Automatic repeat request
BER	Bit Error Rate
CCPCH	Common Control Physical Channel
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CN	Core Network
DAC	Digital to Analog Converter
DFE	Decision Feedback Equalizer
DFT	Discrete Fourier Transform
DL	Downlink
DL – SCH	Downlink Shared Channel
E-UMTS	Evolved Universal Mobile Telecommunication Systems
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
eNB	Evolved Node-B
EPA	Extended pedestrian A
EPC	Evolved Packet Core
ETU	Extended TU
EVA	Extended Vehicular A
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FDMA	Frequency division multiple access
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Intersymbol Interference
ITU	International Telecommunications Union
HARQ	Hybrid ARQ
HSPA	High Speed Packet Access
LPDC	Low density Parity Check
LOS	Line of sight
LTE	Long-Term Evolution
MBMS	Multimedia Broadcast and Multicast Service
MCH	Multicast Channel
MIMO	Multiple input, multiple output

ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MISO	Multiple-Input Single-Output
MU-MIMO	Multi-User MIMO
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
OLSM	Open loop spatial multiplexing
PAPR	Peak-to-average power ratio
PBCH	Physical broadcast channel
PCFICH	Physical control format indicator channel
PCH	Paging Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHY	Physical layer
PL	Path loss
PMCH	Physical multicast channel
PRB	Physical Resource block
PSTN	Public Switched Telephone Networks
PUSCH	Physical uplink shared channel
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RE	Resource Element
RRC	Radio resource control
RRM	Radio resource management
S/P	Serial – Parallel Converter
SAE	System Architecture Evolution
SCM	Spatial Channel Modeling
SCME	Spatial Channel Modeling Extended
SD	Sphere Decoding
SIMO	Single-Input Multiple-Output
SINR	Signal-to-noise and interference ratio
SNR	Signal-to-noise ratio
SSD	Soft Sphere Decoder
SU-MIMO	Single-User MIMO
TDD	Time division duplex
TDM	Time division multiplexing
TDMA	Time division multiple access

UE	User equipment
UL	Uplink
UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunication Systems
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
ZF	Zero Forcing

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Chapter 1

Introduction

1.1 Background and general overview

The demand for high speed and widespread network access in mobile communications increases everyday as the number of users' increases and applications are constantly developed with greater demand for network resources. As a result of this trend, mobile communications has experienced significant developments within the last two decades which is the result of tremendous research that have been carried out.

The 3GPP Long Term Evolution (LTE) is the system that marks the evolutionary move from third generation of mobile communication (UMTS) to fourth generation mobile technology. The first work on LTE began in release 7 of the 3GPP UMTS specifications involving the completion of its feasibility studies. This release also included further improvements on High Speed Packet Access (HSPA). Specification of LTE and SAE (System Architecture Evolution) constitutes the main work done in release 8 of the 3GPP UMTS specifications. As at the time of writing, work is currently in progress for the enhancement of LTE which is featured in release 10 of the 3GPP Universal Mobile Telecommunications System (UMTS) specifications and named LTE-Advanced (LTE-A). A comprehensive summary of the evolutionary trend of the 3GPP UMTS is given in Table 1-1 [7].

Release	**Functional freeze**	**Main UMTS feature of release**
Rel-99	March 2000	Basic 3.84 Mcps W-CDMA (FDD & TDD)
Rel-4	March 2001	1.28 Mcps TDD (aka TD-SCDMA)
Rel-5	June 2002	HSDPA
Rel-6	March 2005	HSUPA (E-DCH)
Rel-7	December 2007	HSPA+ (64QAM downlink, MIMO, 16QAM uplink) LTE and SAE feasibility study
Rel-8	December 2008	LTE work item – OFDMA/SC-FDMA air interface SAE work item – new IP core network Further HSPA improvements

Table 1-1 Evolution of the UMTS Specifications [9]

Under the 3G/UTRAN (Universal Terrestrial Radio Access Network) evolution study item, LTE was initially referred to as the Evolved UTRAN access network in 3GPP reports, documents, and specifications. On the Core Network side (CN), the evolution towards the Evolved Packet Core (EPC) is known as the SAE (System Architecture Evolution). The Evolved UMTS is thus the combination of the E-UTRAN access network and the EPC Core Network, known as 3GPP UMTS in standard documents [16].

1.2 Overview of the Evolved UMTS and main concepts.

The main requirements and basic concepts will be briefly evaluated in this section, from the radio interface and overall network architecture perspective [16].

1.2.1 Evolved UMTS Concepts

An all-IP Architecture/Network

The aim of this is to integrate all applications over a simplified and common architecture. The first major component of the E-UMTS, the E-UTRAN, is a packet optimized Access Network which can efficiently support IP-based non real-time services as well as circuit-like services that requires constant delay and constant bit rate transmission. The second major component, the Core Network, is composed of only one packet domain, supporting all packet system services and co-operative interoperability with traditional Public Switched Telephone Networks (PSTN) [16].

A Shared Radio Interface

Efficient radio transmission schemes for packet data imperative as the CN approaches an all-IP architecture. Thus, a fine and specific radio resource management scheme is an unavoidable requirement. Radio resource sharing and allocation in E-UTRAN is achieved by combining all radio bearers on a sort of shared high rate radio pipe. This implies that all services are supported over a shared radio resource [16].

1.2.2 Design goals for Long Term Evolution

The Evolved UTRAN Access Network (LTE) requirements include

- Radio interface throughput
- latency in data transmission
- Terminal state transition requirements
- Mobility requirements
- Flexibility in spectrum usage
- Mobility requirements for compatibility between systems

The design goals for LTE is to provide downlink peak rates of 100Mbps and uplink of 50Mbps, to exhibit spectral efficiency and flexibility by supporting scalable bandwidth which enhances the provision of more data and voice services over a given bandwidth. In addition, it should provide low latency, specifically, for the control plane: 50 – 100msec to establish the U-plane and for the User Plane: less than 10msec from the user equipment (UE) to server. In terms of mobility, LTE is designed to be optimized for low speeds of about 15km/hr, provide high performance at speeds up to 120km/hr and to maintain the link at speeds up to 350km/hr. With respect to coverage area it is expected that full performance will be achieved up to 5km [1, 8].

Other design objectives include

- Support for seamless inter-working with existing 3G systems and interoperability non-3GPP specified systems.
- Moderate level of system and terminal complexity, economical cost and judicious power consumption.
- Efficient support for various types of services particularly from the packet switching domain such as Voice over IP, Presence, Video streaming and Image sharing, etc.

In terms of Terminal State Transition also known as control plane latency, there are three defined STATES namely IDLE, STANDY and ACTIVE as explained in [16]. The requirements for these are:

(i) the transition from IDLE to ACTIVE state shall be less than 100ms.

(ii) the transition between ACTIVE and STANDBY states shall be less than 50ms.

1.3 Enabling technologies for LTE

The design goals or targets for the LTE standard can be met with a great deal of certainty and reliability because this standard leverages on certain technologies that enable it to meet and possibly surpass the above mentioned targets. Some of the enabling technologies are briefly described below:

a) Orthogonal Frequency Division Multiplexing (OFDM): LTE employs OFDM for downlink data transmission, the available bandwidth is divided into many narrower subcarriers and the data is transmitted in parallel streams. Varying levels of QAM modulation (e.g. QPSK, 16QAM, 64QAM) is employed for the modulation of each of the subcarriers. There are two remarkable advantages of OFDM: First, it eliminates ISI by preceding each OFDM symbol by a cyclic prefix. Second, it efficiently utilizes bandwidth because there are tight spacings between its subcarriers and yet there is virtually no interference among adjacent subcarriers [1].

b) Single Carrier Frequency Division Multiple Access (SCFDMA): SCFDMA as its name implies utilizes single carrier modulation, Discrete Fourier Transform (DFT) spread orthogonal frequency multiplexing, and frequency domain equalization. It has been adopted as the uplink multiple access scheme for 3GPP LTE. The main advantage of SC-FDMA is the low peak-average-power ratio (PAPR) of the transmit signal which enhances the performance of the power amplifier of the user terminal thereby resulting in higher efficiency. Furthermore SC-FDMA still possesses similar performance and complexity as OFDMA [2].

c) Multiple input Multiple output (MIMO) Antennas: This is a very important technology that the LTE system leverages on to achieve its design goals. MIMO technologies use multiple antennas at both the transmitter and receiver to improve communication performance by offering significant increases in data throughput and link range without additional bandwidth or transmit power.

1.4 Thesis Motivation

The 3GPP LTE is a new standard with laudable performance targets, therefore it is imperative to evaluate the performance and stability of this new system at an early stage in order to promote its smooth and cost-efficient introduction and deployment.

This thesis work therefore aims at evaluating the performance of LTE under varying channel conditions. This evaluation will be based on performance metrics such as BER vs. SNR, Throughput vs. SNR for different MIMO antenna transmission schemes.

1.5 Thesis Outline

This thesis work is organized according to the following structure:

Chapter one provides some background information and general overview of the 3GPP LTE technology standard which includes its design goals and enabling technologies. Chapter two gives a comprehensive explanation of the 3GPP physical layer and air interface, as well as the parameters and technologies employed. Chapter three presents the radio wave propagation environment and channel modeling in LTE. Chapter four explores MIMO antennas and its application in the LTE system. Chapter five focuses on the simulation results and evaluates the performance of LTE based on the metrics. Chapter six gives the conclusion of this thesis work and presents the future work that can be undertaken in this research area.

Chapter 2

The 3GPP LTE Physical Layer and Air Interface

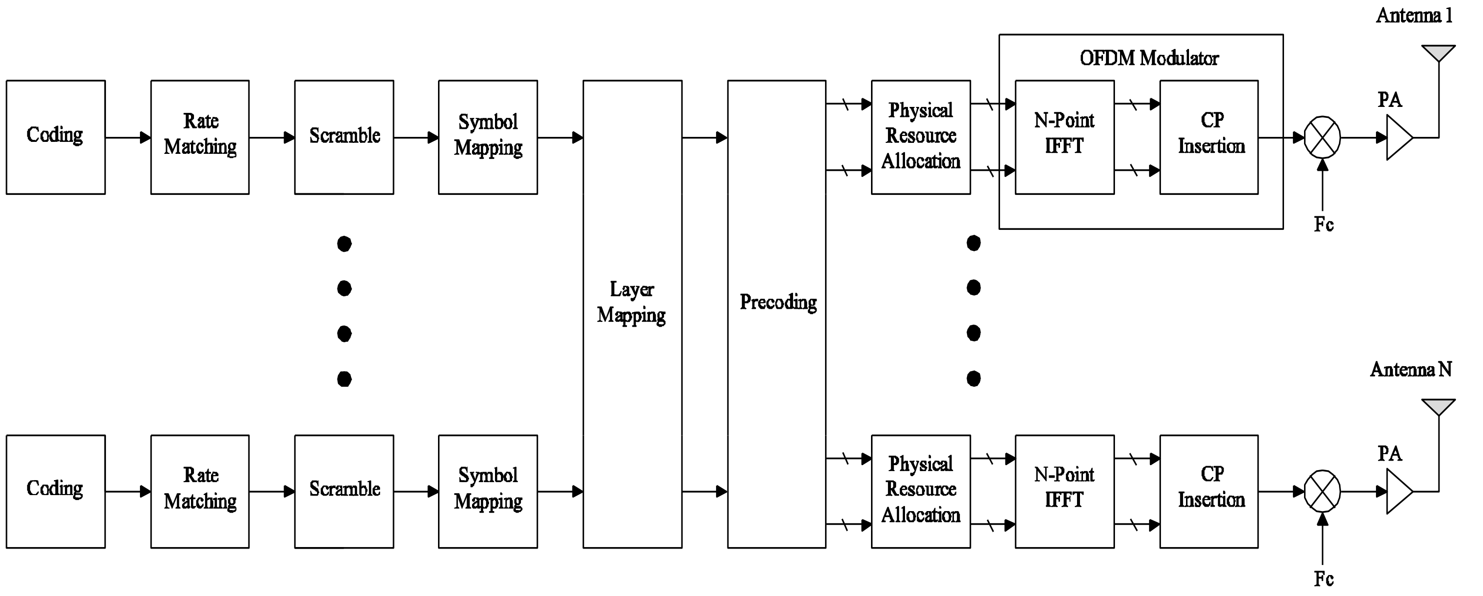
2.1 Basic Concepts

The main role of the LTE physical layer is to translate data into reliable signal for transmission across a radio interface between the eNodeB (enhanced NodeB) and the user equipment. It involves basic modulation, protection against transmission errors (using cyclic redundancy checks), multiplexing schemes as well as the antenna technology that are utilized. Multiplexing is a technique for sending multiple signals or streams of information on a carrier at the same time. The antenna technology involves the different configurations, schemes and techniques that can be incorporated into antenna systems to fulfill recommended requirements or to achieve desired goals

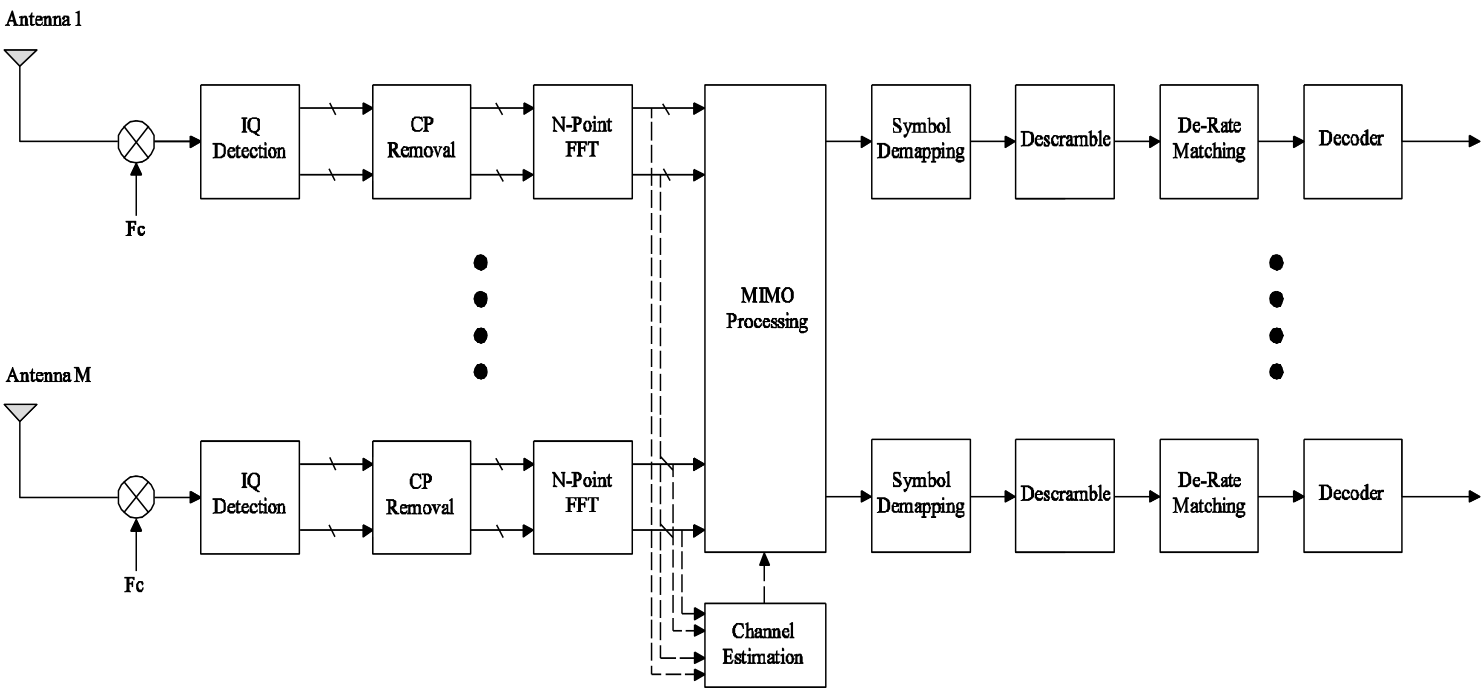
SC-FDMA is the multiplexing scheme used for uplink transmission in LTE as already explained in Chapter one and OFDMA has been discovered to be a beneficial multiplexing scheme for LTE downlink with many advantages such as improved spectral efficiency, less complex equalization at the receiver, flexible bandwidth adaptation, etc. With respect to antenna technology, MIMO antennas play a significant role in the attainment of the performance goals of 3GPP LTE.

The LTE air interface consists of physical channels and signals. Physical channels carry data from higher layers including control, scheduling and user payload (data) while the physical signals are used for system cell identification, radio channel estimation and system synchronization. The LTE air interface is designed for deployment in paired (FDD Mode) and unpaired (TDD mode) spectrum bands [3]. This thesis work is targeted or primarily based on LTE downlink transmission, therefore the bulk of the work is on the physical layer with focus on OFDMA and MIMO. The next section provides further details about these technologies.

2.2 The 3GPP LTE System Description



(A) LTE eNodeB Transmitter



(B) LTE eNodeB Receiver

Fig. 2 - 1. LTE eNodeB Transmitter and Receiver signal chain [18, 22]

2.3 3GPP LTE Air Interface Technologies

2.3.1 Orthogonal Frequency Division Multiplexing

In OFDM systems, the available bandwidth is broken into many narrower subcarriers and the data is divided into parallel streams, one for each subcarrier each of which is then modulated using varying levels of QAM modulation e.g. QPSK, 16QAM, 64QAM or higher orders as required by the desired signal quality. The linear combination of the instantaneous signals on each of the subcarriers constitutes the OFDM symbols. The spectrum of OFDM is depicted in fig.2-2. Each of the OFDM symbol is preceded by a cyclic prefix (CP) which is effectively used to eliminate Intersymbol Interference (ISI) and the subcarriers are also very tightly spaced for efficient utilization of the available bandwidth [1].

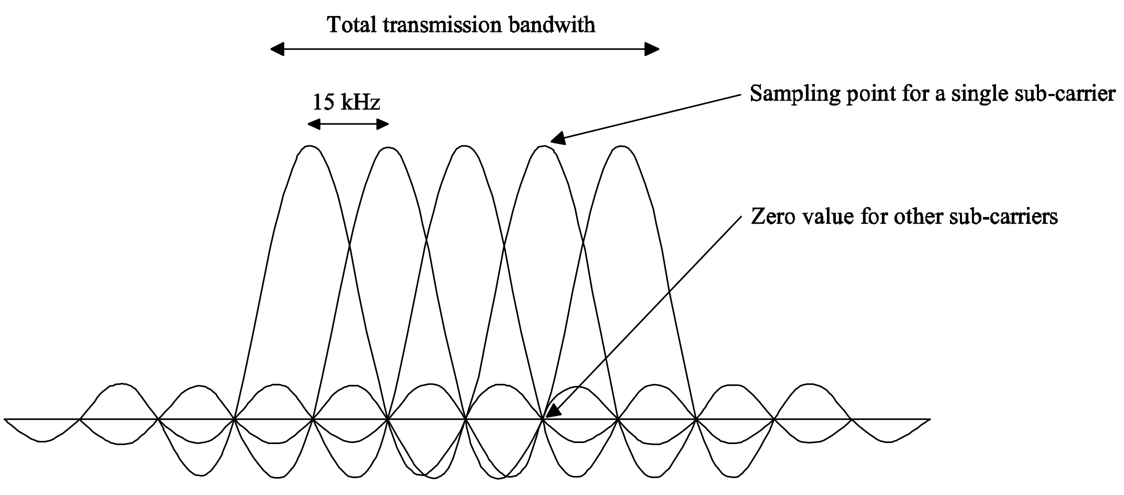


Fig. 2 - 2. OFDM Spectrum [33]

2.3.2 Orthogonal Frequency Division Multiple Access

Based on the various advantages that have been mentioned in the preceding sections, OFDMA is considered as an excellent multiple access scheme for the 3GPP LTE downlink. OFDMA uses multiple orthogonal subcarriers each of which is modulated separately. OFDMA distributes subcarriers to different users at the same time so that multiple users can be scheduled to receive data simultaneously; each of these is referred to as a physical resource block (PRB) in the LTE specification [4].

2.3.3 Multiple in Multiple out (MIMO) Antennas

MIMO antenna technology is one of the key technologies leveraged on by LTE. It is a technology in which multiple antennas are used at both the transmitter and at the receiver for enhanced communication: The use of additional antenna elements at either the base station (eNodeB) or User Equipment side (on the uplink and/or downlink) opens an extra spatial dimension to signal precoding and detection. Depending on the availability of these antennas at the transmitter and/or receiver, the following classifications exist [4]:

Single-Input Multiple-Output (SIMO): A simple scenario of this is an uplink transmission whereby a multi-antenna base station (eNodeB) communicates with a single antenna User Equipment (UE).

Multiple-Input Single-Output (MISO): A downlink transmission whereby a multi-antenna base station communicates with a single antenna User Equipment (UE) is a scenario.

Single-User MIMO (SU-MIMO): This is a point-to-point multiple antenna link between a base station and one UE.

Multi-User MIMO (MU-MIMO): This features several UE's communicating simultaneously with a common base station using the same frequency- and time-domain resources.

As a result of the requirements on coverage, capacity and data rates, integration of MIMO as part of the LTE physical layer is highly imperative since it necessitates the incorporation of transmission schemes like transmit diversity, spatial multiplexing and beam forming.

2.4 Physical Layer Parameters for LTE

In the downlink of LTE, a normal subcarrier spacing of 15 kHz is used with a normal cyclic prefix (CP) length of 5μs. This value of the subcarrier spacing suitably allows for high mobility and avoidance of the need for closed-loop frequency adjustments. The CP can also be extended to a length of 17 μs which ensures that the delay spread is accommodated within the CP even in large urban and rural cells. A compatible sampling frequency for the above parameterizations is 30.72 MHz, therefore in LTE specifications, the basic unit of time is T_s = 1/30.72μs, and all other time periods are multiples of this value. The number of Fast Fourier Transform (FFT) points varies with the bandwidth, for example, a 20MHz system bandwidth can employ 2048 FFT points for efficient operation. The table gives detailed information about the physical layer parameters and their corresponding values [1, 28].

Transmission bandwidth	1.25MHz	2.5 MHz	5MHz	10MHz	15MHz	20MHz
Sub-frame duration	0.5ms					
Sub-carrier spacing	15KHz					
Sampling Frequency	192MHz (1/2 x 3.84 MHz)	3.84MHz	7.68 MHz (2 x 3.84MHz)	15.36 MHZ (4 x 3.84 MHz)	23.04 MHz (6 x 3.84 MHz)	30.72 MHz (8 x 3.84 MHz)
FFT Size	128	256	512	1024	1536	2048
OFDM symbol per slot (short/long CP)	7/6					
CP length (μsec/samples) SHORT	(4.69/9) X 6 (5.21/10) X 1	(4.69/18) x 6 (5.21/20) x 1	(4.69/36) x 6 (5.21/40) x 1	(4.69/72) x 6 (5.21/80) x 1	(4.69/108) x 6 (5.21/120) x 1	(4.69/144) x 6 (5.21/160) x 1
LONG	(16.67/32)	(16.67/64)	(16.67/128)	(16.67/256)	(16.67/384)	(16.67/512)

Table 2-1 LTE Downlink Physical Parameters [1]

2.5 Modulation

One of the main design goals of LTE is to achieve high peak rates, and many multiple methods are employed in order to meet this goal, a sophisticated way is by utilizing adaptive modulation. This is the ability to adjust modulation schemes based on signal quality. Adaptive modulation provides a tradeoff between delivered bit rate and the robustness of the digital encoding, so as to balance throughput with error resilience. In 3GPP LTE, QPSK, 16QAM and 64QAM are supported modulation schemes. High order modulation like 64QAM work best with strong signals which is usually achieved near the base station while low order modulation like QPSK possess better signal recovery in poor signal quality areas. Adaptive modulation is therefore essential in LTE because it provides benefits to users on both high and low signal strength areas. [12]

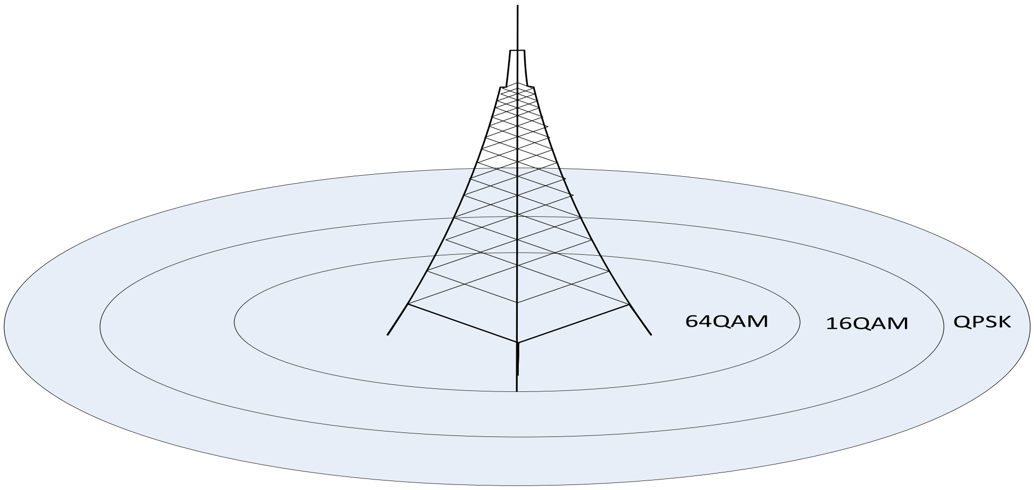


Fig. 2 - 3. High order modulation techniques work best near the base station [12]

2.6 Channel Coding

The current 3G systems use turbo coding scheme, but due to the high peak data rates supported by LTE [29], it becomes imperative to know if this same turbo coding scheme can scale to high data rates while maintaining reasonable decoding complexity. It is currently debated that turbo coding has a particular drawback that it is not amenable to parallel implementations which limit the achievable decoding speeds. The underlying reason behind this issue is the contention for memory resources among parallel processors which occurs as a result of the turbo code internal interleaver. On the other hand, it is argued that turbo codes can also employ parallel implementations if turbo internal interleavers can be made contention-free.

A coding scheme that possesses inherent parallelism and therefore offers high decoding speeds is the Low density Parity Check (LPDC) code which is currently increasing in availability. LPDC potential offers opportunities to achieve very high throughput which is made possible as a result of its inherent parallelism of the decoding algorithm while maintaining good error-correcting performance and low decoding complexity.

2.6.1 Channel Coding in LTE

The preferred channel coding for LTE is turbo coding. This selection in favor of turbo coding is based on few reasons:

- UMTS release 6 HSPA also uses turbo code.
- For backward compatibility reasons, dual-mode LTE terminals will need to implement turbo code therefore some decoding hardware can be reused.
- To avoid increased implementation complexity as the terminals have to support two different coding schemes.

There are some major channel coding schemes used in the LTE system [29]:

- Turbo coding: chiefly used for large data packets which common occurrence in downlink and uplink data transmission, paging and broadcast multicast (MBMS) transmissions. In other words, for Uplink shared channel (UL-SCH), downlink shared channel (DL-SCH), Paging Channel (PCH) and Multicast Channel MCH [9, 23].
- Rate 1/3 tail biting convolutional coding mainly used for downlink control and uplink control as well as broadcast control channel [9].

Chapter 3

Radio Propagation Environment and Channel Modeling

3.1 Introduction

The radio propagation environment is a critical aspect in the evaluation of the performance of LTE because of the sensitivity of the physical channels and signals to the nature of the radio environment. A realistic channel modeling is essential for accurate evaluation of link-level and system-level performance of LTE, and secondarily for the network planning phase of LTE deployment.

Standardized MIMO radio channel models must be investigated and the correlation between the signals of the different antenna branches must also be modeled accurately because the preferred spatial transmission mode and its performance are largely determined by it.

Furthermore, the ultimate limit of the theoretical channel capacity is defined by the spatial correlation properties of the MIMO radio channel. The applied channel should reflect all the instantaneous space-time-frequency characteristics which affect the configuration of diversity, beam forming, and spatial multiplexing techniques [4].

3.2 The Radio Propagation Environment

Some radio propagation environments include dense urban, sub-urban and rural environments. Various objects such as buildings, trees, rocks, and people within these environments have an impact on the propagation of signals in constructive or destructive ways. This situation introduces a phenomenon known as fading, which has presented a very challenging technical problem to communications engineering [4].

3.2.1 Fading

Fading is a term that refers to the time variation of received signal power caused by changes in the transmission medium or path(s) [10]. Fading could be caused by atmospheric conditions and location of obstacles within the propagation environment from the transmitter to the receiver. When the latter of these two occurs, it results in what is known as multipath.

Multipath occurs when a signal is reflected by obstacles along the path so that multiple copies of the signal with varying delays arrive at the receiver as shown in the simple illustration below.

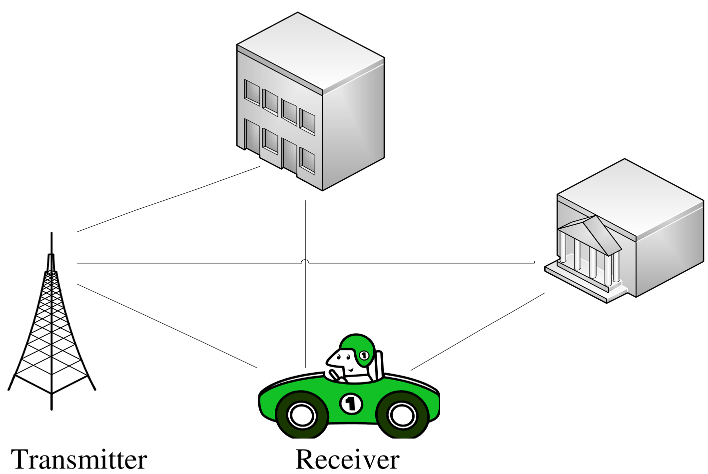


Fig.3 - 1. Multipath propagation

3.2.2 Multipath Propagation

The effects of multipath include diffraction, reflection and scattering.

Diffraction: This is the apparent bending or deviation of waves around obstacles and dispersion of waves past small openings.

Reflection: this occurs when a radio wave propagating in one medium impinges upon another medium with different electromagnetic properties.

Scattering: occurs when a radio signal strikes a rough surface or a size much smaller than or on the order of the signal wavelength [11].

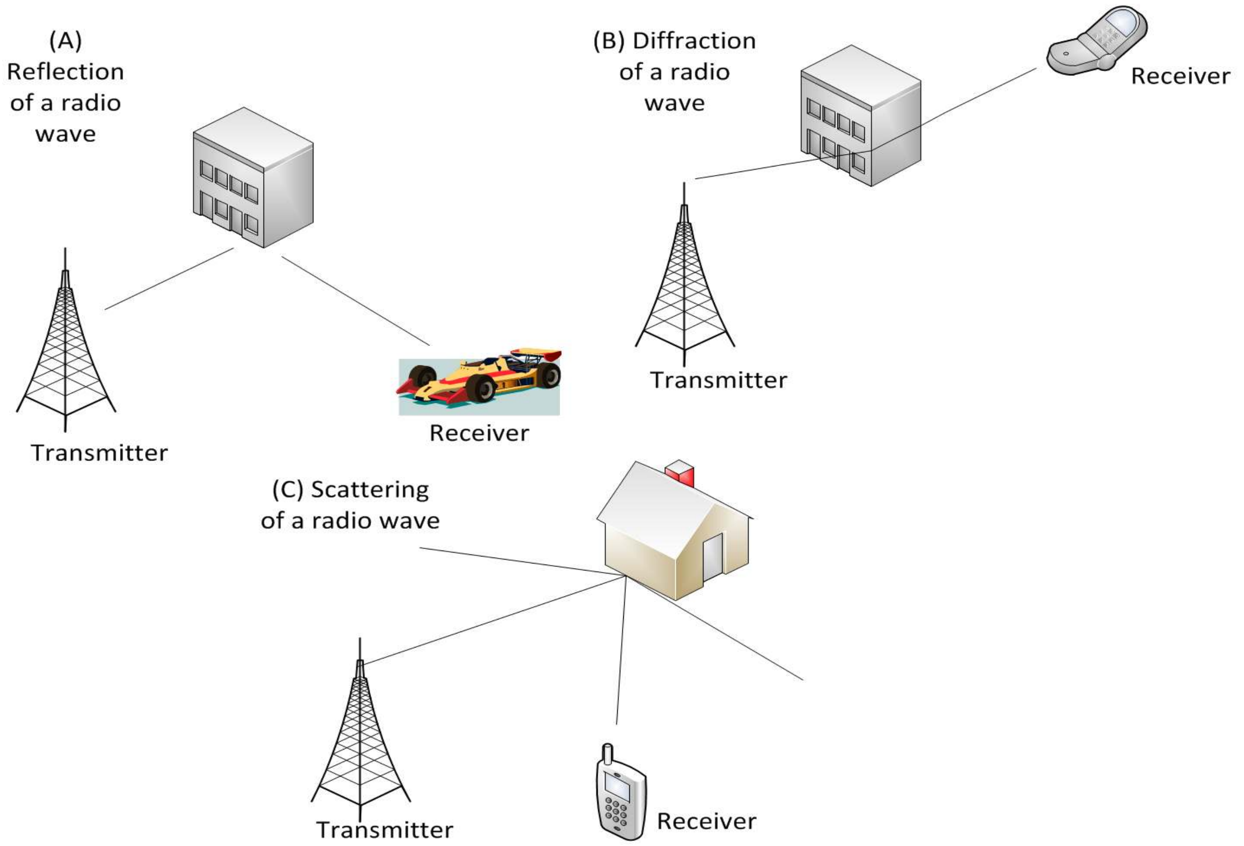


Fig.3 - 2. Scattering, reflection and diffraction of radio waves

3.3 Rayleigh Fading Channel model

This is a statistical channel model that relies on the presupposition that when a signal passes through a communications channel, its magnitude varies randomly or fades according to a Rayleigh distribution. The random variation and fades are as a result of multiple paths created due to reflections from objects in the radio channel which can be manifested in different ways in communication receivers based on the degree of path difference relative to the signaling rate, also relative to the wavelength of propagation, and the relative motion between the transmitter and receiver. Due to the central-limits type effects, which is based on the central-limit theorem that holds that, if the occurrence of scatter is adequate, the channel impulse response will be well-modeled as a Gaussian process (complex random variable) irrespective of the distribution of the individual components but if there's no dominant component to the scatter, then such a process will have a zero mean and phase evenly distributed between 0 and 2Π radians. The channel response will therefore have random amplitude whose envelope will follow a Rayleigh distribution [24]. This random variable can be denoted by R, and its probability density function can be given as

$$PR(r) = \frac{2\mathrm{r}}{\Omega} e^{-r^2/\Omega}, \; r \geq 0 \qquad (3\text{-}1)$$

where $\Omega = E(R^2)$.

3.4 ITU Channel Model

The ITU channel models were mainly used in the development of 3G 'IMT-2000' radio access systems. The key scenarios include indoor office, outdoor-to-indoor, pedestrian and vehicular radio environments. The key parameters for the description of each propagation model include time delay spread and its statistical variability, path-loss and shadow fading characteristics, multipath fading characteristics, and operating radio frequency [4].

The ITU have proposed multipath channel models which are used to select essential multipath conditions in typical environments under which the average energy per bit to noise density ratio (E_b/N_o) or SNR requirements of various services for certain performance levels are stipulated.

For performance evaluation and analysis of UMTS systems, three different test environments have been proposed by the ITU and are documented in the ITU-R M.1225 Recommendation [13]:

1) Indoor office test environment: features of this environment include small cells, low transmit power and indoor location of base stations and pedestrian users.
2) Outdoor to indoor and pedestrian test environment: this is also characterized by small cells and low transmit power, base stations with low antenna heights are located outdoors whereas pedestrian users are located on streets and inside buildings, Doppler rate is set by walking speeds with occasional higher rates due to vehicular reflections.
3) Vehicular test environment: this environment is characterized by large cells, high transmit power and fast moving terminals.

The propagation conditions for multipath fading in the ITU models are shown in Table 3-1.

	ITU Pedestrian A		ITU Pedestrian B		ITU Vehicular A	
Tap number	Relative delay (ns)	Relative mean power (dB)	Relative delay (ns)	Relative mean power (dB)	Relative delay (ns)	Relative mean power (dB)
1	0	0	0	0	0	0
2	110	−9.7	200	−0.9	310	−1.0
3	190	−19.2	800	−4.9	710	−9.0
4	410	−22.8	1200	−8.0	1090	−10.0
5			2300	−7.8	1730	−15.0
6			3700	−23.9	2510	−20.0

Table 3-1 Propagation conditions for multipath fading in the ITU models [4]

3.5 MIMO Channel

From the foregoing, MIMO systems utilize multiple antennas at the transmitter or receiver or at both, it is important to consider the channel and signal model in this system. For a system with M_T transmit antennas and M_R receive antennas, assuming frequency-flat fading over the bandwidth of interest, the MIMO channel at a given time may be represented as an M_R x M_T matrix.

$$H = \begin{pmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,M_T} \\ h_{2,1} & h_{2,2} & & h_{2,M_T} \\ \vdots & \ddots & & \vdots \\ h_{M_R,1} & \cdots & & h_{M_R,M_T} \end{pmatrix} \quad (3\text{-}2)$$

where $h_{m,n}$ is the single-input single-output channel gain between the m^{th} receive and n^{th} transmit antenna pair. The n^{th} column of H is often referred to as the spatial signature of the transmit antenna across the receive antenna array. The relative geometry of the M_T spatial signature determines the distinguishability of the signals launched from the transmit antennas at a receiver.

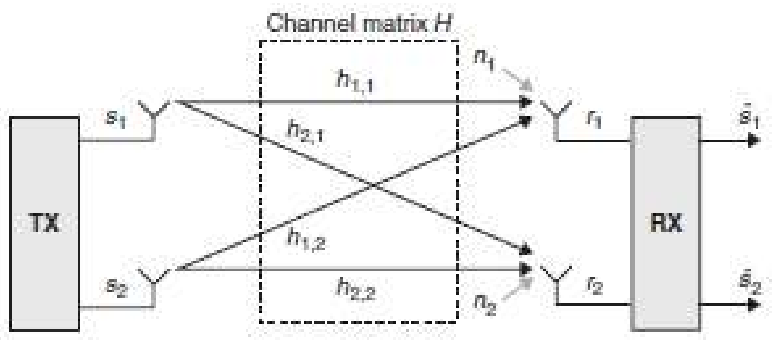


Fig.3 - 3. Simplified 2 x 2 MIMO antenna configuration [33]

In analyzing the MIMO signal model, we consider a matrix **Y** of size M_T x *t* denoting the set of signals being transmitted from M_T distinct antennas over *t* symbol durations (*t* subcarriers for frequency domain systems). Thus the n^{th} row of **Y** corresponds to the signal emitted from the n^{th} transmit antenna. **H** denotes the M_T x M_R channel matrix modeling the propagation effects from each of the M_T transmit antenna to any of the M_R receive antennas over a subcarrier. The M_T x M_R signal R received over *t* symbol durations over this subcarrier can be expressed as

$$\mathbf{R = HY + N} \quad (3\text{-}3)$$

where N is the additive noise matrix.

There are two types of MIMO channel model that are used for LTE namely:

- **Correlation matrix based channel models**: these include extended ITU models Extended pedestrian A, Extended Vehicular A, Extended TU (EPA, EVA, and ETU).
- **Geometry-based channel models**: the 3GPP Spatial Channel Model (SCM), Spatial Channel Model – Extension (SCME) and IST-WINNER model fall in this category [14].

3.6 Physical Channels

The LTE air interface comprises of physical channels and physical signals. The physical signals are created in Layer 1 and they are used for system synchronization, cell identification, and radio channel estimation. The physical channels are used to carry data form higher layer including control, scheduling, and user payload [31].

A. LTE Downlink Physical Signals

- Primary Synchronization Signal: this signal used for cell search and identification by the user equipment (UE). It carries a part of the cell ID.
- Secondary Synchronization Signal: performs the same function as the primary but carries the remainder of the cell ID.
- Reference Signal: Used for downlink channel estimation.

B. LTE Downlink Channels

- Physical Downlink Shared Channel (PDSCH): this channel is transports data and multimedia (payload) hence it is designed for very high data rates. QPSK, 16QAM and 64 QAM are suitable modulation techniques that can be employed in this channel.
- Physical Downlink Control Channel (PDCCH): this channel carries control information that is UE-specific e.g. scheduling, ACK/NACK. Understandably, robustness is therefore of main interest than maximum data rate. QPSK is the only available modulation format.
- Common Control Physical Channel (CCPCH): this channel conveys cell-wide control information. The CCPCH is transmitted as close to the centre frequency as possible.
- Physical broadcast channel (PBCH): carries cell-specific/system information.
- Physical multicast channel (PMCH): a downlink physical channel that carries the multicast/broadcast information.
- Physical control format indicator channel (PCFICH): defines number of PDCCH OFDMA symbols per sub-frame [9].

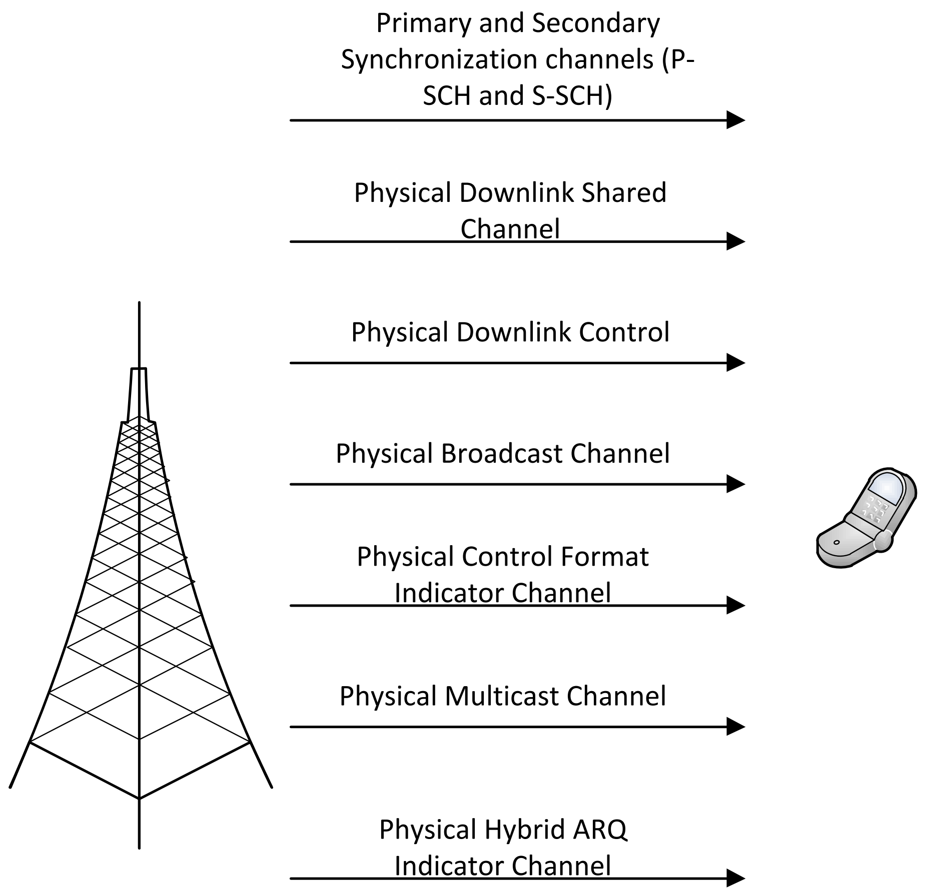


Fig.3 - 4. The Physical downlink channels [16]

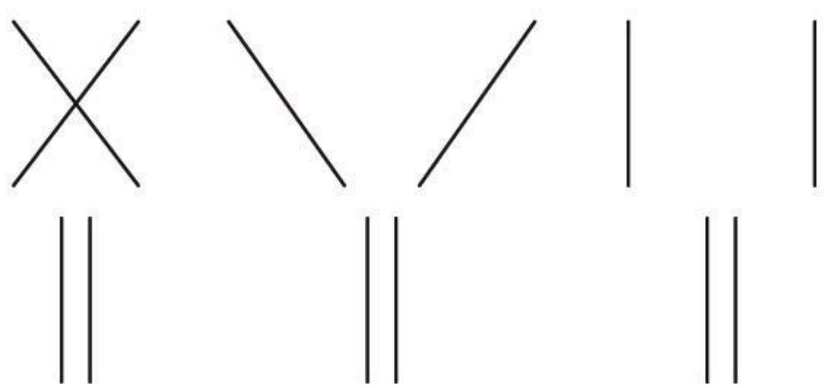
Chapter 4

MIMO and OFDM in LTE

4.1 MIMO Antenna Array/Configuration

In mobile communication systems there are antenna arrays with different antenna number and antenna configuration. There exist different arrays such as the single polarized array, unitary linear array (ULA), compact cross polarized array and detached cross polarized array [5]. The configuration considered for this thesis is a 2 x 2 MIMO system briefly explained below, comprehensive explanations for the other available configurations are found in [5]:

1) 2 x 2 MIMO with Two antennas at the eNode B (eNB)
   - 2 x 2 MIMO system with compact cross polarized array at eNB, and the ULA (Unitary Linear Array) with half-wavelength spacing at the User Equipment (UE) shown in fig.4-1 (a).
   - 2x2 MIMO system with detached cross polarized array at eNB and ULA with half-wavelength spacing at UE shown in fig.4-1(b)
   - 2x2 MIMO system with detached linear array at eNB and the ULA with half-wavelength spacing at UE shown in fig.4-1(c)



(a) (b) (c)

Fig. 4 - 1. Three antenna array configurations for 2 x 2 MIMO [5]

4.2 MIMO Transmission Schemes

MIMO technology consists of different transmission schemes each with its own peculiar features, advantages and drawbacks. The transmission schemes for consideration in this thesis are diversity schemes and spatial multiplexing.

4.2.1 Diversity Schemes

There are various diversity schemes that can be used which include time-diversity, frequency-diversity, receive diversity and transmit diversity. Transmit diversity is the focus of this thesis. It provides a means of averaging out the channel variation for operation at higher UE speeds or for delay sensitive services at both low and high UE speeds. Transmit diversity can be further sub-divided into Block-codes-based, Cyclic delay diversity, Frequency shift transmit diversity, and Time shift transmit diversity.

This thesis considers a very popular technique under block-codes-based category called the space block time codes (SBTC). A very simple way of realizing this for a 2 Tx –antenna system was developed by Alamouti and is popularly known as the Alamouti scheme [20, 30]. In this technique, typically the same user data is sent on both transmit channels with a slight modification to the data stream for improving the probability of successfully recovering the desired data. A simplified example is shown below. During the first symbol period, the first symbol in a sequence. S_o, is transmitted from the upper antenna while the second symbol, S_1, is simultaneously transmitted from the lower antenna. During next symbol period, the complex conjugate of the same two symbols, $-S_1^*$ and S_0^*, are transmitted form the upper and lower antennas [6, 27]. This symbol repetition and transmission improves the total system performance by giving the receiver two opportunities to recover each data symbol [6, 21]. Complex valued STBC's can be described by the matrix

$$\mathbf{B} = \begin{pmatrix} \boldsymbol{b_{0,0}} & \cdots & \boldsymbol{b_{0,s-1}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{b_{n-1,0}} & \cdots & \boldsymbol{b_{n-1,s-1}} \end{pmatrix} \qquad \text{(4-1)}$$

where *n* is the STBC length and *s* is the number of transmit antennas.

The well-known Alamouti code can therefore be represented by an STBC matrix **B** shown below

$$\mathbf{B} = \begin{pmatrix} S_0 & S_1 \\ -S_1^* & S_0^* \end{pmatrix} \qquad \text{(4-2)}$$

where S_0, S_1 are the information symbols and S_0^*, S_1^* are their complex conjugates [30].

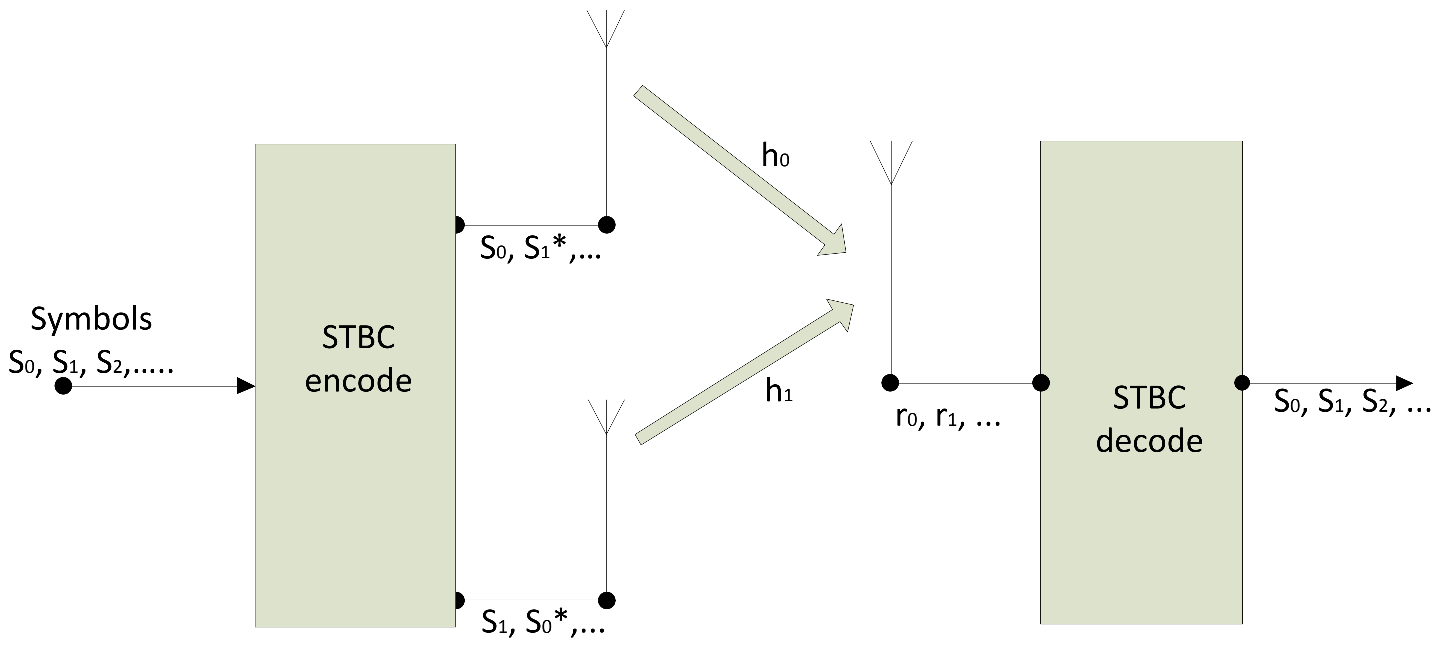


Fig. 4 - 2. Simplified Transmit Diversity scheme (Alamouti Space Time Block Coding)

Cyclic Delay Diversity is yet another type of STBC which can be applied with an arbitrary number of Tx-antennas without requiring modification at the receiver. The application of this scheme to OFDM system operates in such a way that delayed versions of the same OFDM symbol are transmitted from multiple antennas as illustrated in fig.4-3 where *S* arbitrary antennas are assumed. If the sequence of modulation symbols at the input of the IFFT are x_0, x_1,….., $x_{(N-1)}$, then the sequence of samples at the output of the IFFT can be z_0,z_1, …. , $z_{(N-1)}$, and can therefore be mathematically expressed as

$$z_n = \frac{1}{N} \sum_{k=0}^{(N-1)} x_k \ e^{-\frac{j2\prod kn}{N}} \qquad n = 0, 1, \dots, (N-1) \qquad (4\text{-}3)$$

The sequence of samples at the output of the IFFT z_0, z_1, …. , $z_{(N-1)}$ is cyclically shifted before transmission from different antennas. Cyclic delays of 0, 1, 2… (S – 1) samples from transmissions on antenna 0, 1, 2… (S – 1) are added respectively and they are added before the cyclic prefix (CP) as depicted in fig. 4-3. This minimizes the impact of multipath on the transmitted signal.

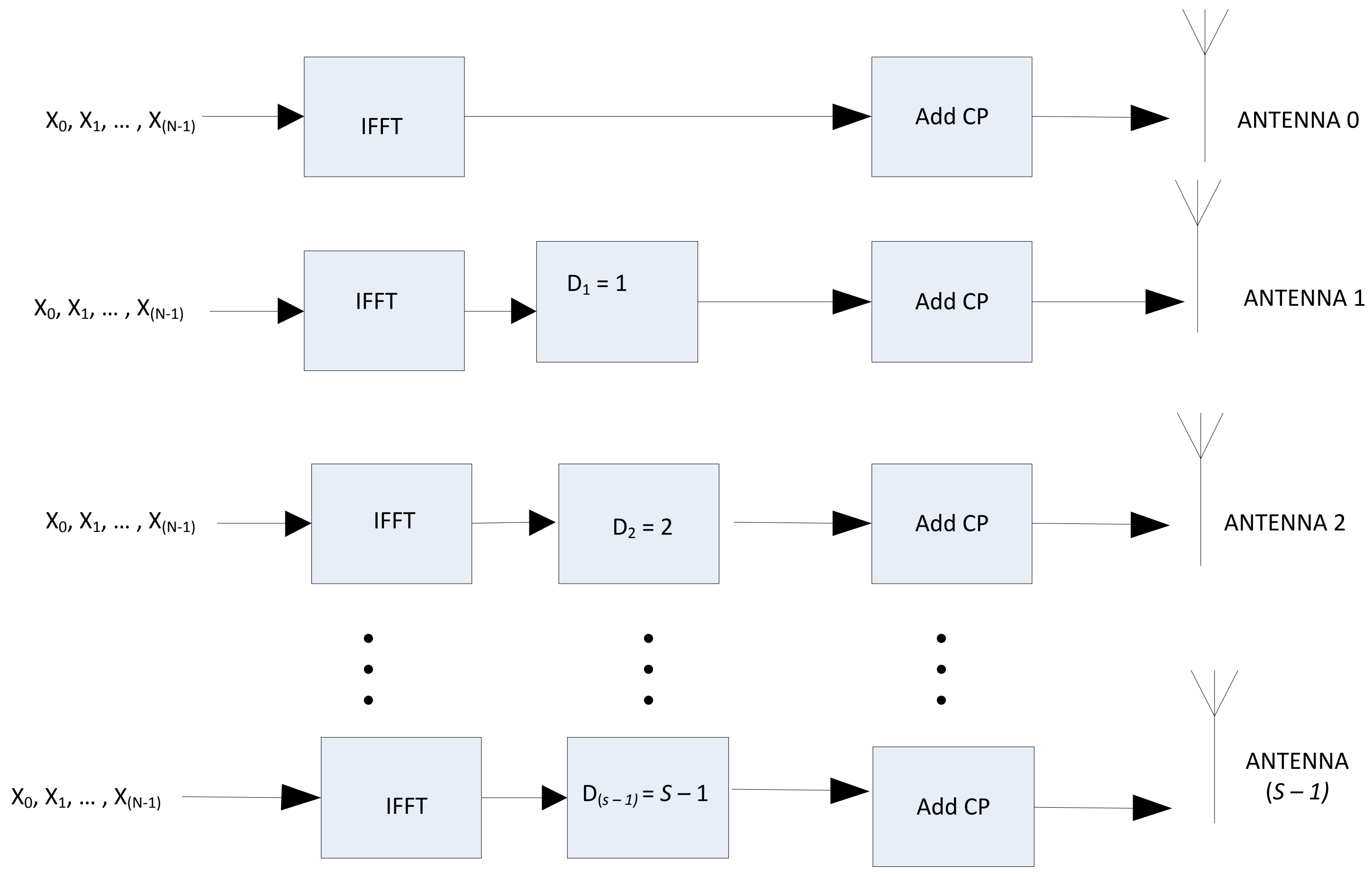


Fig. 4 - 3. Cyclic Delay Diversity (CDD) scheme [32]

4.2.2 Spatial Multiplexing

This scheme can provide a linear increase in data transmission rate with the same bandwidth and power by transmitting multiple independent data streams unlike transmission diversity where a single data stream is always transmitted independently [6, 19]. There exist a linear relation between the number of transmit/receive antenna pairs in a MIMO and the theoretical increase in capacity.

The concept of the operation of spatial multiplexing system is explained with the aid of fig. 4-4.

During the first symbol time, the first data symbol, S_o , is transmitted from the upper transmit antenna, T_{x0}, and the second data symbol, s_1, is transmitted from the lower transmit antenna, T_{x1}, this occurs simultaneously. The data rate is therefore doubled as alternate symbols are transmitted from each antenna and each symbol is only transmitted once unlike STBC where redundant data symbols are sent to give the receiver a fair chance of recovering the transmitted data.

The transmission of the signal from the transmit antenna T_{x0} to the receive antennas R_{x0} and R_{x1} takes place over wireless channels with a complex coefficients h_{00} and h_{10}. Similarly, there exist wireless channels with complex coefficients h_{01} and h_{11} between the transmit antenna T_{x1} to the two receive antennas, R_{x0} and R_{x1}. With proper placement of these antennas it can be assumed that these channel coefficients are potentially unique [6].

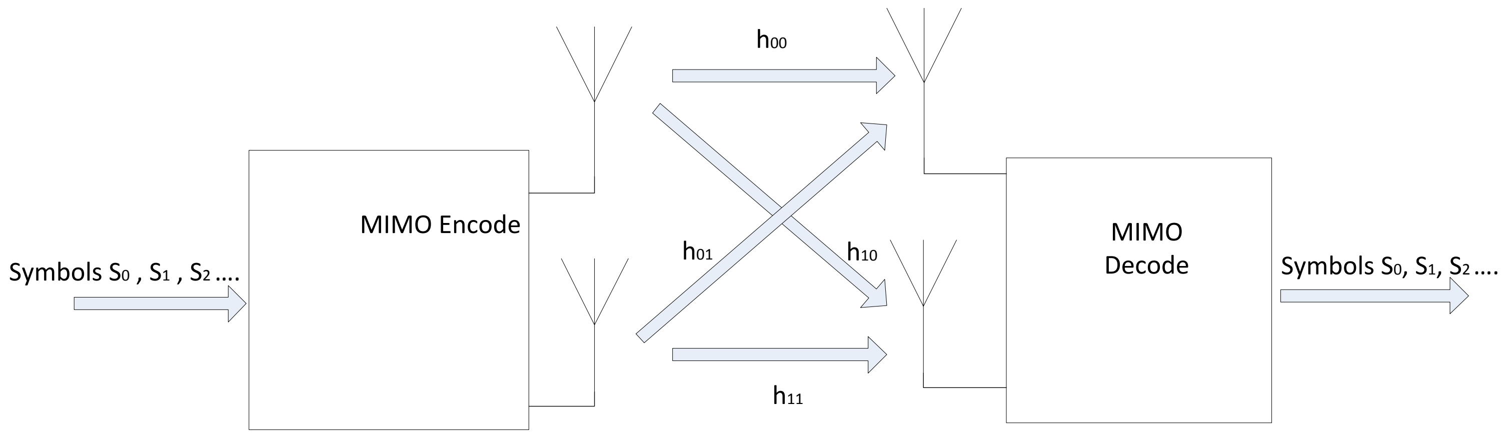


Fig. 4 - 4. Operation of spatial multiplexing

At the receiving end of the transmission, the received signal at the upper receive antenna, R_{x0}, denoted by r_0, as measured by the receiver as a combination of the s_0 and s_1 including channel effects, h_{00} and h_{01}. Similarly, the received signal at the lower antenna, R_{x1}, denoted by r_1, is measured by the receiver as a combination of s_0 and s_1 modified by the channel effects, h_{10} and h_{11} respectively.

The following therefore adequately represents equations for r_0 and r_1, respectively:

$$r_0 = h_{00}s_0 + h_{01}s_1 \quad (4\text{-}4)$$

$$r_1 = h_{10}s_0 + h_{11}s_1. \quad (4\text{-}5)$$

Spatial multiplexing transforms the disadvantage of multipath effects into an advantage. In fact, spatial multiplexing can only increase transmission rates when the wireless environment is very rich in multipath since this situation results in low correlations between the channels enabling the efficient recovery of transmitted data at the receiver. On the other hand, when the correlation between the channels is high then there is a rapid degradation of the performance of spatial multiplexing.

Mathematically, equation (4-4) and (4-5) can be re-expressed in matrix form as

$$\begin{bmatrix} r_0 \\ r_1 \end{bmatrix} = \begin{bmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} \quad (4\text{-}6)$$

$$[R] = [H]\,[S] \quad (4\text{-}7)$$

For accurate recovery of the data symbols, s_0 and s_1, we can perform inverse matrix mathematics as expressed in equation (4-8)

$$[S] = [H]^{-1}\,[R] \quad (4\text{-}8)$$

In a situation whereby the channel coefficients are highly correlated, it becomes difficult to perform the inversion of the channel coefficient matrix [H]; when this happens the matrix is said to be "ill-conditioned".

4.3 OFDM

The downlink of LTE system is OFDM based and this is so for good reason. OFDM possesses a remarkable characteristic of being able to be adapted in a straightforward manner to operate in different channel bandwidths according to spectrum availability. Another advantage of OFDM is the low complexity in the design of the receiver [25].

By the principle of operation of OFDM system, a high-rate stream of data symbols in first serial-to-parallel converted for modulation onto M parallel subcarriers as shown in fig.4-5.

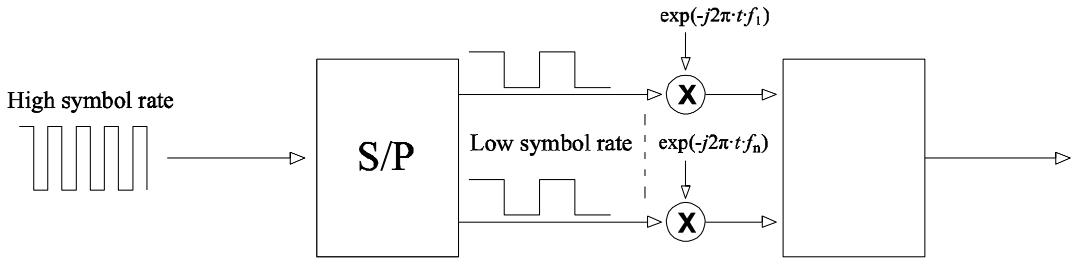


Fig. 4 - 5. Serial-to-parallel conversion of OFDM [4]

The signal to be transmitted is defined in the frequency domain, a serial-to-parallel (S/P) converter collects serial data symbols into a data block S_k of dimension M. S_k is given as

$$S_k = [\ S_k\,[0],\ \ S_k\,[1],\ \ldots..\ \ S_k\,[M\text{-}1]\ ]^T \qquad (4\text{-}9)$$

The subscript k is an index for the OFDM symbol, with ranging values based on the number of subcarriers, M. Each of the M parallel data streams are modulated independently using different modulations like QPSK, 16QAM, 64QAM on each carrier which results in complex vector $X_{k.}$ X_k [0] is given as

$$X_k\,[0] = [\ X_k\,[0],\ \ X_k\,[1],\ \ldots..,\ X_k\,[M - 1]\ ]^T \qquad (4\text{-}10)$$

This vector of data symbols X_k passes through an Inverse FFT (IFFT) which results in a set of N complex time-domain of samples given as

$$x_k\,[0] = [\ x_k\,[0],\ \ldots\ldots, x_k\,[N\ \text{-}1]\ ]^T \qquad (4\text{-}11)$$

Next, a cyclic prefix is added at the beginning of the symbol x_k to eliminate the impact of intersymbol interference (ISI) caused by multipath in the propagation environment. Then, a time domain OFDM symbol is generated

$$x_k\,[N - G],\ldots,\ x_k\,[N - 1],\ x_k\,[0],\ldots,\ x_k\,[0],\ldots\ x_k\,[N - 1]]^T \qquad (4\text{-}12)$$

where G = CP length.

In order to demodulate the OFDM signal at the receiver end, the CP is removed and all the above operations in the generation of the OFDM signal are performed in reverse.

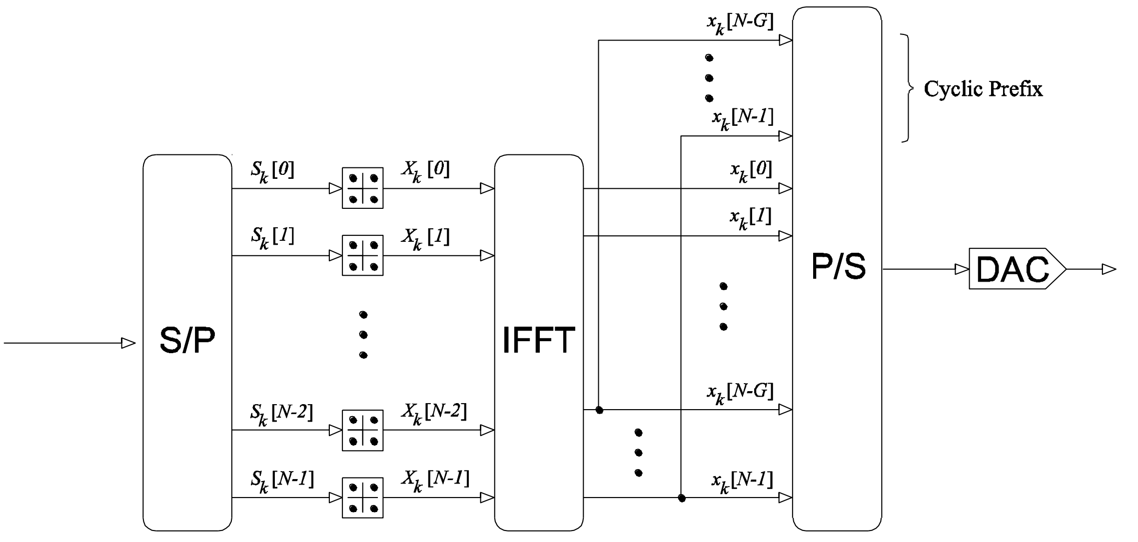


Fig. 4 - 6. OFDM Transmitter [4]

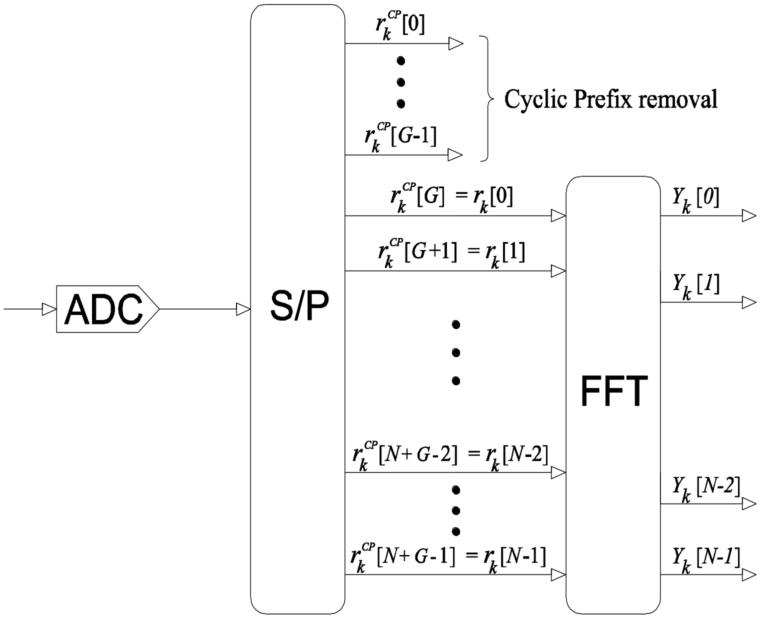


Fig. 4 - 7. OFDM Receiver [4]

4.4 OFDMA

OFDM is not a multiple access technique in itself but it can be a mixed with Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) systems to generate a multiuser system [25]. The combination of FDMA with OFDM produces OFDMA, which is a very useful approach in mobile communication systems. The subcarriers in each OFDM symbol are orthogonally divided among multiple users and users are dynamically assigned to subcarriers. This approach makes a whole lot of sense in realistic circumstances since users in the same cell may experience different signal reception conditions and thus have different signal-to-noise and interference ratios (SINRs), therefore it would be more efficient to allow multiple users to select their own subset of subcarriers with better channel conditions instead of selecting a single user that uses all the subcarriers at the same time, this is referred to as multiuser diversity gain. Thus, OFDMA is capable of supporting many users with different applications, quality of service and data rates requirements [25].

4.4.1 Resource Allocation

The number of subcarriers to be assigned to each user is scheduled by the system, hence, scheduling algorithms (time and frequency) are implemented into OFDMA which enhances the delivery of optimum services to users. This is resultant from the fact that efficient and dynamic bandwidth allocation can be achieved when multiplexing operation is performed in the digital domain before the Inverse FFT operation. A subchannel is a set of subcarriers, defined to enhance a basic unit of resource allocation in OFDMA. These subcarriers can be allocated in different ways to construct each subchannel, and this acts as the basis for classification of resource allocation methods. Therefore, the following resource allocation methods exist with variance in their distribution of the subcarriers.

i) Block type: This method is also known as cluster type, localized type or band type. A set of adjacent subcarriers make up the subchannels, as shown in fig. 4-8. This method of resource allocation is often utilized in environment of low mobility and stable channel conditions. This method permits link adaptation by an adaptive modulation and coding (AMC) scheme for different subchannels, subject to their own instantaneous channel conditions. The concept of multiuser diversity gain of OFDMA is also incorporated in this method, thus users are permitted to select their own preferred subchannels thereby improving average system throughput.
In this method, each block is constructed within the coherence bandwidth, thus simplifying channel estimation.

Diversity gain can still be introduced despite the fact that the allocation of subcarriers in block type subchannels is contiguous by performing frequency hopping of the subchannels throughout the entire frequency band [25].

Fig. 4 - 8. Block type

ii) Comb type: In this method, a set of equally spaced subcarriers make up a subchannel. It is also referred to as the interleaved type and diversity is sought by distributing the subcarriers over the whole band [25].

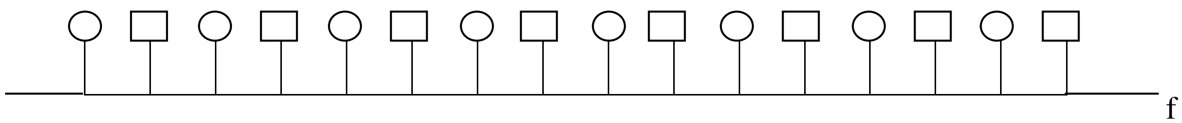


Fig. 4 - 9. Comb type

iii) Random type: Here, the subcarriers within a subchannel are randomly distributed over the whole frequency band. An OFDMA system using this type of resource allocation is also known as distributed OFDMA and can definitely achieve interference averaging effects and diversity gain. The random distribution of the subcarriers is useful for reducing the co-channel interference in such a way that the probability of subcarrier collision among adjacent cells is minimal [25].

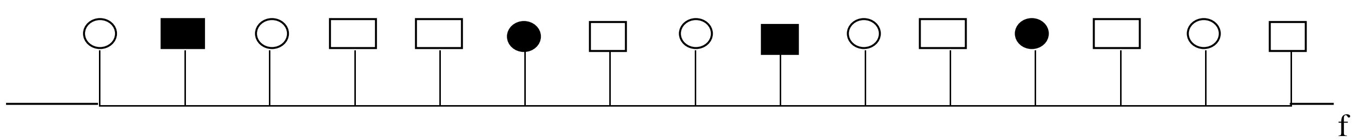


Fig. 4 - 10. Random type

High performance of OFDMA is enabled by two main principles namely

a) Multiuser diversity: This principle is based on the concept of describing the gains available from selecting a user from a subset of users that have “good” conditions.
b) Adaptive modulation: this principle aims at increasing data rates by exploiting good channels.

The time-frequency resources in LTE downlink have the following structure:

The largest unit of time is the 10ms radio frame (fig.4-11), this frame is further divided into 10 sub-frames each with duration of 1ms, each 1ms sub-frame is split into two 0.5ms slots.

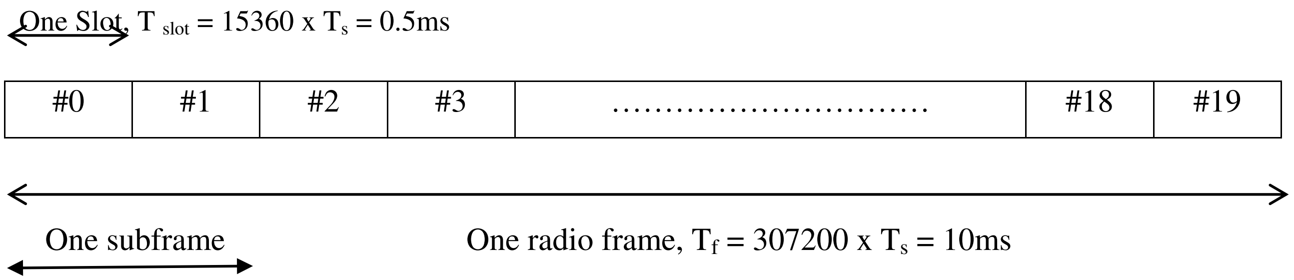


Fig. 4 - 11. Structure of the LTE radio frame [31]

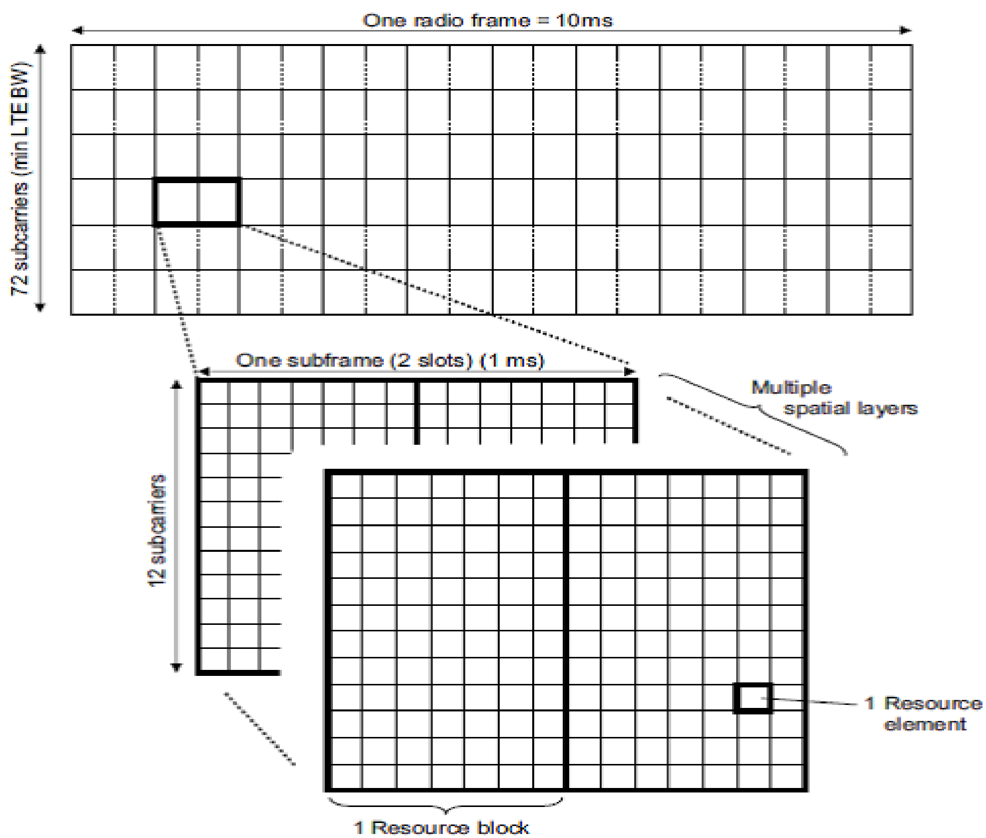


Fig. 4 - 12. Structure of time-frequency resources [1]

Each slot contains 7 OFDM symbols for a normal cyclic prefix length case or 6 OFDM symbols for the extended cyclic prefix case. In the frequency domain, each physical resource block (PRB) is a unit 12 of subcarriers for duration of one slot (0.5ms). A resource element (RE) is the smallest unit of resource which comprises of one sub-carrier for the duration of one OFDM symbol. Therefore, a resource block comprises of 84 resource elements for a normal cyclic prefix length and 72 resource elements for the extended cyclic prefix.

4.5 MIMO Detection Schemes

Detection in MIMO systems is an important subject for consideration on the basis of the principle of operation of MIMO technology. MIMO systems split a data stream into multiple distinct data streams, subsequently each data stream is individually or independently modulated and transmitted through a separate radio-antenna chain at the same time through the same frequency channel. When these data streams arrive at the receiver they are separated using MIMO algorithms that depend on estimates of all channels between the transmitter and each receiver.

There are different models that have been designed for MIMO detection, the Maximum Likelihood (ML) detector has been determined to be the optimal model for minimization of the joint probability error of detecting all symbols simultaneously. The ML detection is executed using a brute-force search over all of the possible transmitted vectors or by employing more efficient search algorithm such as the Sphere decoder. The computational complexities of optimal models are generally exponential and impractical. For a constellation size of M and k users, ML decoding will involve searching and evaluating over M^k possible vector candidates, for example if there are k users with 16-QAM, the number of vectors to be evaluated is 16^k. This drawback has sparked interest in the implementation of sub-optimal detection algorithms. Some common types are the linear receivers such as the matched filter (MF), the decorrelator or zero forcing (ZF), the minimum mean-squared error (MMSE) detectors, decision feedback equalization (DFE) and the semi definite relaxation (SDR) detector. Two of the detection schemes will be considered namely Zero Forcing and Sphere Decoding.

4.5.1 Zero Forcing

In this approach, the receiver with the ZF detector uses the estimated channel matrix to detect the transmitted signal as described by the following equation:

$$\hat{S} = (H^H H)^{-1} \; H^H \mathbf{y} = H^+ \mathbf{y} \qquad (4\text{-}13)$$

where H^H is the Hermitian conjugate and H^+ is the pseudo inverse respectively. Each element of $\hat{S}$ is moved to the nearest constellation point. The output of the ZF filter is thus only a function of the symbol to be detected and the noise, this output is then fed into a ML decoder which estimates the transmitted symbol. In the attempt to invert the channel completely, zero forcing receivers amplify noise greatly at frequencies f where the channel response $H(j2\pi f)$ has a small magnitude (i.e. near zeroes of the channel) and this action reduces the SNR. Thus, ZF receiver eliminates interference but enhances noise, this characteristic of interference elimination may not be significant at high SNR but it is significant at low SNR [15].

4.5.2 Sphere Decoding (SD)

The SD is one of the search algorithms used in ML detection scheme. As mentioned in the introductory part of this section, the problem with ML detection is the complexity involved searching through all possible vector candidates even though many of these are most probably not the correct candidate. This is attributable to the effect of the Gaussian distribution of noise, which makes codewords that are far away from the received vector much less probable than codewords close to the received vector. The idea behind the operation of SD is to limit the search among possible candidates to those that are located within a sphere of radius, σ, with the centre on the received vector as shown in fig.4-13. The sphere decoder proposes a very efficient method of identifying candidates inside the sphere as explained in [26].

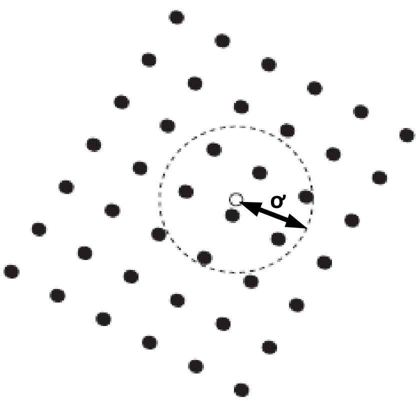


Fig. 4 - 13. The sphere of radius σ, centered at the received vector [34]

Chapter 5

Simulation Model and Results

5.1 System Model Layout

In this thesis, the performance of LTE Downlink with MIMO techniques is studied in terms of the Bit Error Rate (BER) and Throughput for two major LTE channel models namely the flat-fading channel and the ITU Pedestrian B channel. The OFDMA-based LTE Downlink is modeled and simulated using MATLAB for different MIMO techniques. A brief description of the designed simulation models is provided in the following subsection. The scenario includes one flat-fading channel and one multipath channel (ITU Pedestrian B).The flat-fading channel is generated randomly whereas the ITU pedestrian B channel is tabulated below.

Tap number	1	2	3	4	5	6
Relative delay(ns)	0	200	800	1200	2300	3700
Relative mean power (dB)	0	-0.9	-4.9	-8	-7.8	-23.9

Table 5-1 ITU Channel Model for Outdoor to Indoor and Pedestrian Test Environment

Bandwidth	5MHz
Modulation	QPSK, 16QAM, 64QAM
Cyclic prefix	Normal
IFFT size	512
Channel estimation	Perfect
Channel type	✓ Flat-fading ✓ ITU Pedestrian B
Receiver decoder type	ZF, SSD
Channel coding	Turbo
Number of iterations	1000
No. of Rx antenna	2
No. of Tx antenna	2
No. of users	1
Transmission modes	SISO/Transmit diversity/Open loop spatial multiplexing

Table 5-2 Simulation Parameters

5.2 Results and Analysis

According to the simulation scenario described in section 5.1, the simulation results will be presented and analyzed in this section. Our approach for this presentation and analysis is to investigate the performance of two MIMO techniques: Spatial Multiplexing (SM) and Transmit Diversity and compare the results with traditional SISO technique

- for three different orders of modulation, QPSK, 16QAM and 64QAM and coding rates corresponding to Channel Quality Indicator (CQI) values of 3, 8, and 13.
- with respect to two performance metrics, Throughput and Bit Error Rate (BER).
- for a flat-fading channel and ITU Pedestrian B channel.
- Using Soft Sphere and Zero Forcing Detection at the receiver.

5.2.1 Performance Analysis and Comparism of Flat-Fading vs. ITU Pedestrian B Channel with SSD and ZF detection.

5.2.1.1 Flat-Fading Channel vs. ITU Pedestrian B Channel with Soft Sphere Detection

A. QPSK

From Fig. 5-1, the performance metric under investigation is throughput. As hypothesized, the open loop spatial multiplexing clearly out performs transmit diversity and SISO in both channels with a peak data rate of 2.8Mbps from about 5dB SNR and above. Apparently, the performance of SM in the ITU Pedestrian B channel proves to be better than in the flat-fading channel between 0 – 5dB SNR values.

The transmit diversity scheme outperforms SISO for the low SNR values specifically between 0 – 10dB, interestingly, there happens to be increase in SISO's throughput performance above that of transmit diversity after the 2dB mark in the ITU Pedestrian B channel and at the10dB mark in the Flat-fading Channel, after which a peak rate of approximately 1.5Mbps is sustained as can be observed in fig. 5-1.

Following this simple analysis based on these channels, modulation and detection settings, it can be recommended that SISO be utilized for high SNR values, i.e. areas or regions near or around the base station, while transmit diversity can be utilized for low SNR values in areas farther away where the signal must have experienced significant fades and distortions due to obstructions or obstacles. These recommendations are based on the premise that transmit diversity is robust against multipath fading and its mode of operation is such that it sends the same signal from multiple antennas with some coding in order to exploit the gains from independent fading between the antennas, whereas spatial multiplexing operates by sending signals from two different antennas with different data streams, which increases the data rate by a factor of the minimum of the number of receiver or transmit antennas, i.e. min (n_{Tx}, n_{Rx}).

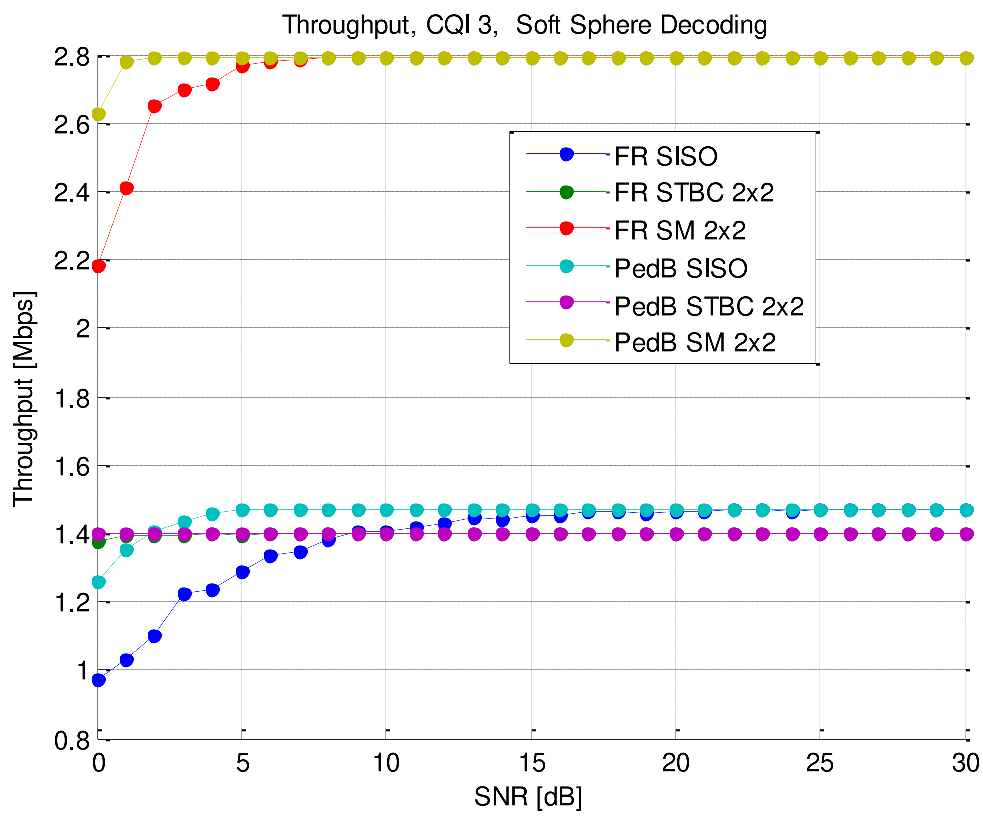


Fig.5 - 1. Throughput graph for SISO vs. 2 x 2 SM and 2 x 2 STBC (QPSK mod., Flat-fading vs. ITU Pedestrian B with SSD)

In fig. 5-2, the performance metric under consideration is the Bit Error Rate (BER) and from the figure it is observed that the transmit diversity scheme outperforms SISO and SM at low SNR values for both channel (Flat-fading and ITU Pedestrian B) scenarios. For instance, at 0dB the BER values are $2x10^{-3}$, $3.5x10^{-1}$, 10^{-1} for transmit diversity, spatial multiplexing and SISO respectively in the flat-fading channel. It's important to take note of the distinctive performance of transmit diversity by observing the relatively wide margin between transmit diversity curve and that of SM and SISO in the flat-fading channel scenario.

The open loop spatial multiplexing also exhibits a very good performance in the ITU Pedestrian B considering the fast rate of decay of its curve as compared to its performance in the flat-fading channel. Another alluring observation in this figure is the good performance of SISO in a ITU Pedestrian B channel unlike the poor performance obtained in a flat-fading channel meaning that SISO will experience low error rates, in high SNR areas, such as near the base station in a ITU Pedestrian B channel as observed in fig 5-2.

As an example, to attain a BER value of 10^{-2}, a SNR value of 2dB is required for spatial multiplexing while 11dB is required for SISO in the context of a flat-fading channel, resulting in a difference of 9dB which is significantly substantial. It is therefore suggested that transmit diversity be utilized whenever channel conditions deteriorates or in a scenario where the signal is bound to experience deep fading and distortion.

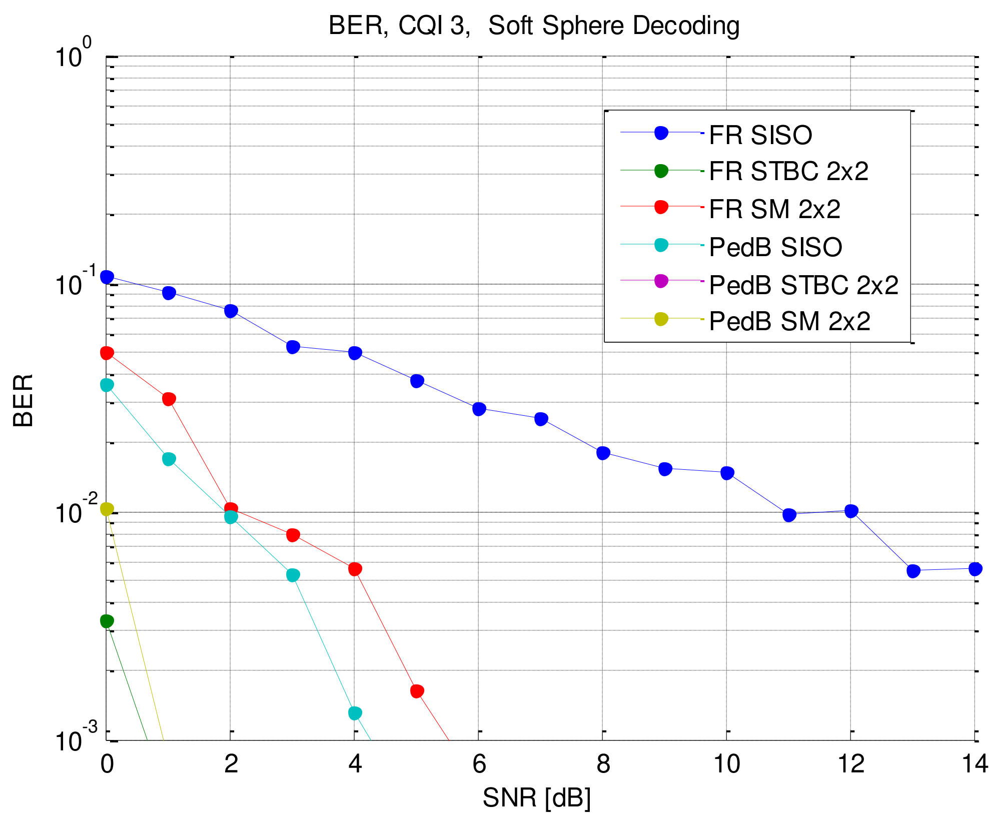


Fig.5 - 2. BER graphs for SISO vs. 2 x 2 SM and 2 x 2 STBC (QPSK mod., Flat-fading vs. ITU Pedestrian B with SSD)

B. 16QAM

Fig. 5-3 displays the throughput curves when 16QAM modulation is employed. As expected, the throughput performance exhibits marked improvement in all three techniques under consideration as compared with the QPSK case above. This is understandably so since the order of modulation has increased with each symbol now being represented by 4bits. Open loop spatial multiplexing peaks with an impressive value of about14Mbps although at a cost of high SNR values from approximately13dB in ITU Pedestrian B channel and between 20 – 25 dB in the flat-fading channel. Transmit diversity peaks at approximately 7Mbps and SISO peaks a little above that value, say 7.5Mbps within the same SNR range i.e. 20 – 25dB in the flat-fading channel. Transmit diversity delivers better performance than SM and SISO schemes between 0 – 10dB under both channel contexts after which SM exceeds it, but transmit diversity continues outperforming SISO up to an SNR value of 20dB when SISO achieves a slightly better performance and sustains it. It is noteworthy to observe that SISO actually exhibits better performance than open loop spatial multiplexing up to around the 8dB mark before open loop spatial multiplexing transcends considering the flat-fading channel instance.

A notable observation in this figure is that the performance of these antenna techniques for low SNR values between 0 – 5dB is better in the flat-fading channel than in ITU Pedestrian B channel but after the 5dB mark, throughput performance in the ITU Pedestrian B channel improves and transcends that achieved in the flat-fading channel but performance in both channels begins to streamline from the 10dB point onward. This suggests that at low SNRs, throughput performance is slightly better in flat-fading channels.

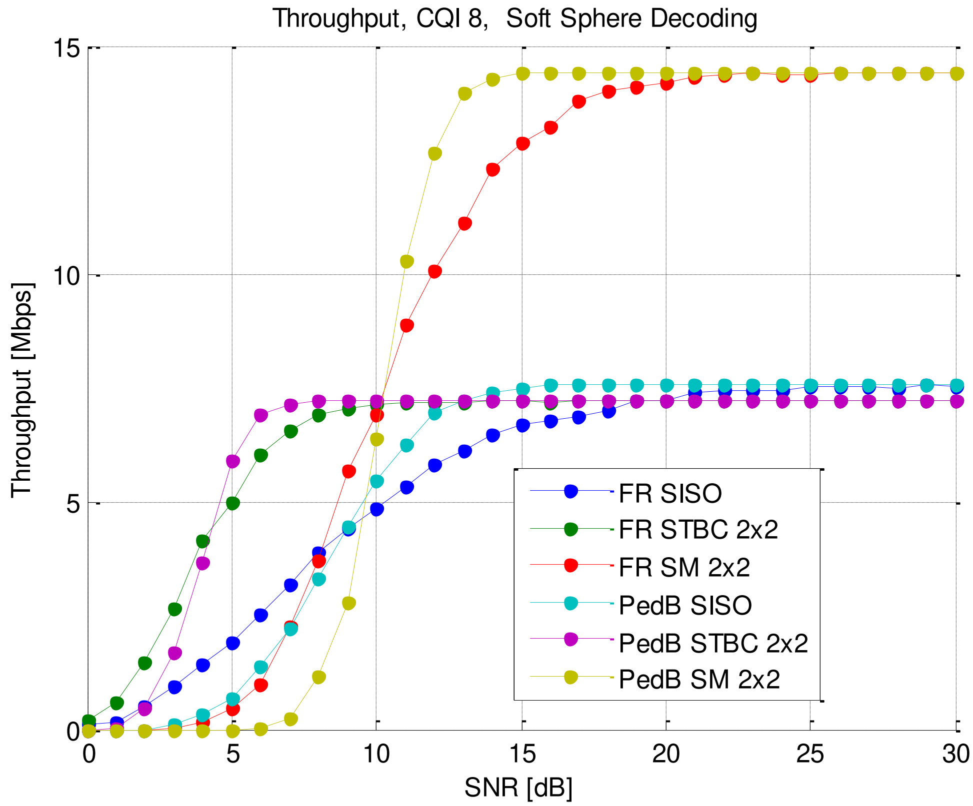


Fig.5 - 3. Throughput graphs for SISO vs. 2 x 2 SM and 2 x 2 STBC (16 QAM mod., Flat-fading vs. ITU Pedestrian B with SSD)

As shown in fig 5-4 transmit diversity performs best for the lower SNR values and it's curve has a fast decay or roll-off compared to the other two transmission modes. An appealing observation here is that performance in the ITU Pedestrian B channel is better than in the flat-fading channel; for instance, to attain a bit error rate value of 10^{-2}, approximately 5.5dB SNR is required when employing transmit diversity, 12.2dB for SM and 12.4dB for SISO in the ITU Pedestrian B channel as compared to 7dB, 17dB and 21dB for transmit diversity, SM and SISO respectively in a flat-fading channel which gives marginal SNR differences of 1.5dB, 4.8dB, and 8.6dB for each case respectively. One can also note that SISO has slightly better BER value than open loop spatial multiplexing up to an SNR value of 12dB after which open loop spatial multiplexing exhibits gradually better error rate performance as seen in the gradual widening of the margin between the two curves in the flat-fading channel. Finally, higher SNR values are required than in the preceding QPSK scenario and this can be attributed to the additional modulation bits incurred from the increase in order of modulation i.e. 4bits per symbol.

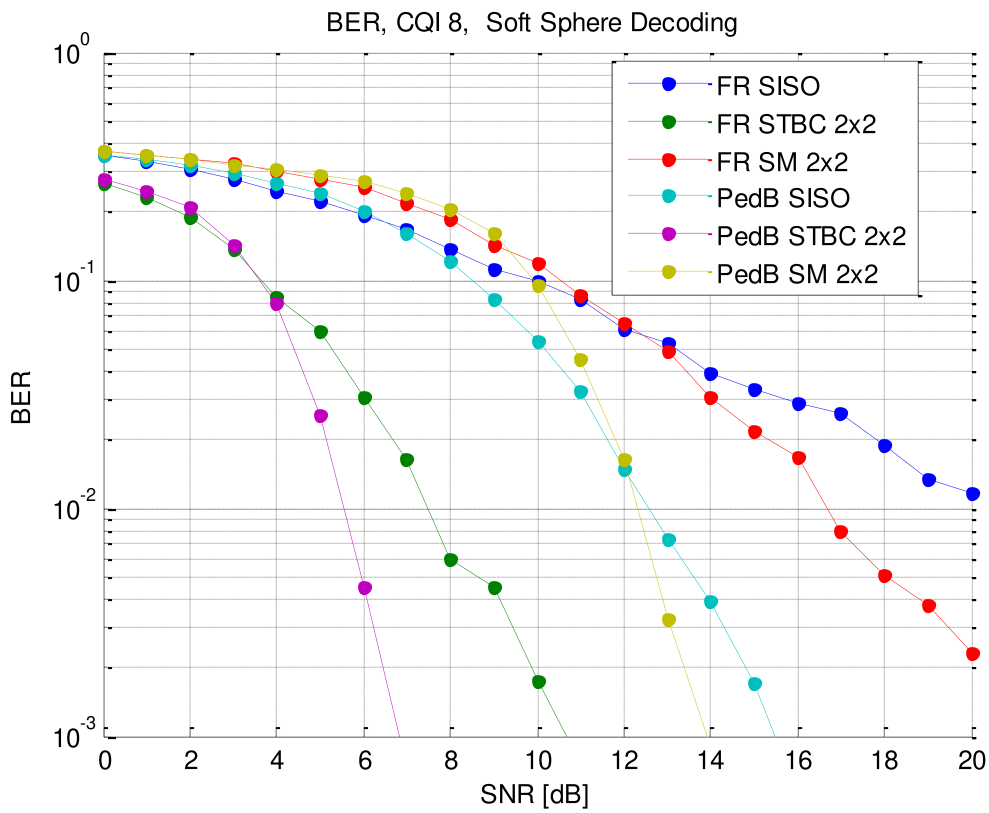


Fig.5 - 4. BER graphs for SISO vs. 2 x 2 SM and 2 x 2 STBC (16QAM, Flat-fading vs. ITU Pedestrian B with SSD)

C. 64 QAM

Fig 5-5 depicts the throughput of the different transmission modes. Here it clear that by increasing the order of modulation, all three transmission modes experience some sort of slow starting phase in the low SNR values (usually between (0 – 10dB) where the value of the throughput is essentially 0Mbps under both channel conditions(ITU Pedestrian B & Rayleigh). Above 10dB, a similar trend as obtained in 16QAM occurs. Since the order of modulation has increased (now 6 bits per symbols), all three modes have gained a throughput nearly double that which was obtained in 16QAM for the high SNR values. Open loop spatial multiplexing peaks at a whooping rate of 34Mbps, while SISO and transmit diversity are sustained about 17Mbps peak rates. Throughput of SM in the ITU Pedestrian B channel is slightly better than flat-fading between 23dB and SNR 25dB, but the same peak rate value is eventually sustained in both channel conditions.

The crossing point for the transmit diversity and SISO also occurs around the same SNR values (10dB) from that of 16QAM to 30dB.

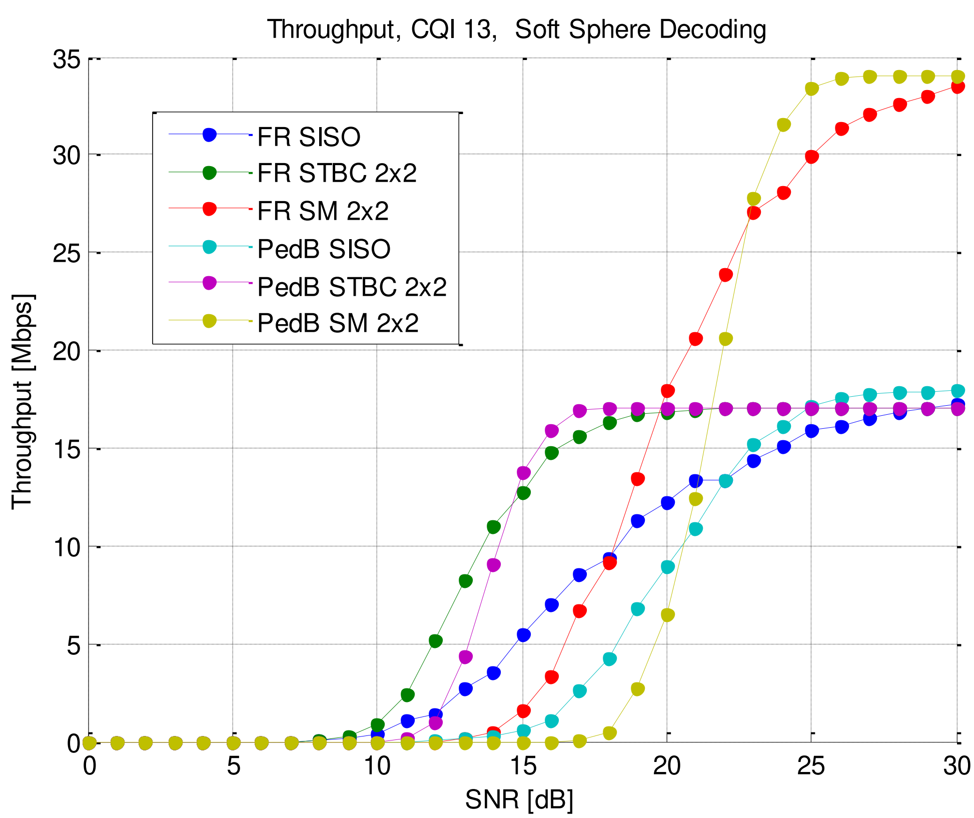


Fig.5 - 5. Throughput curves for SISO vs. 2 x 2 SM, and 2 x 2 STBC (64QAM, Flat-fading vs. ITU Pedestrian B with SSD)

In fig.5-6, it is clearly obvious that when there is need of transmitting more bits, extra SNR is required. Here in 64QAM, in a similar way just as obtained in 16QAM, transmit diversity has the lowest BER for any given SNR point and its roll-off margin with SISO and open loop spatial multiplexing widens as the SNR value increases due to fast decay rate of the transmit diversity in the range of 10 -20 dB. Following in the same trend, open loop spatial multiplexing (SM) performs better than SISO at high SNR values up to the 23dB mark after which SM gradually starts to exhibit an increasingly better performance. These observations are for both channel conditions (ITU Pedestrian B and flat-fading)

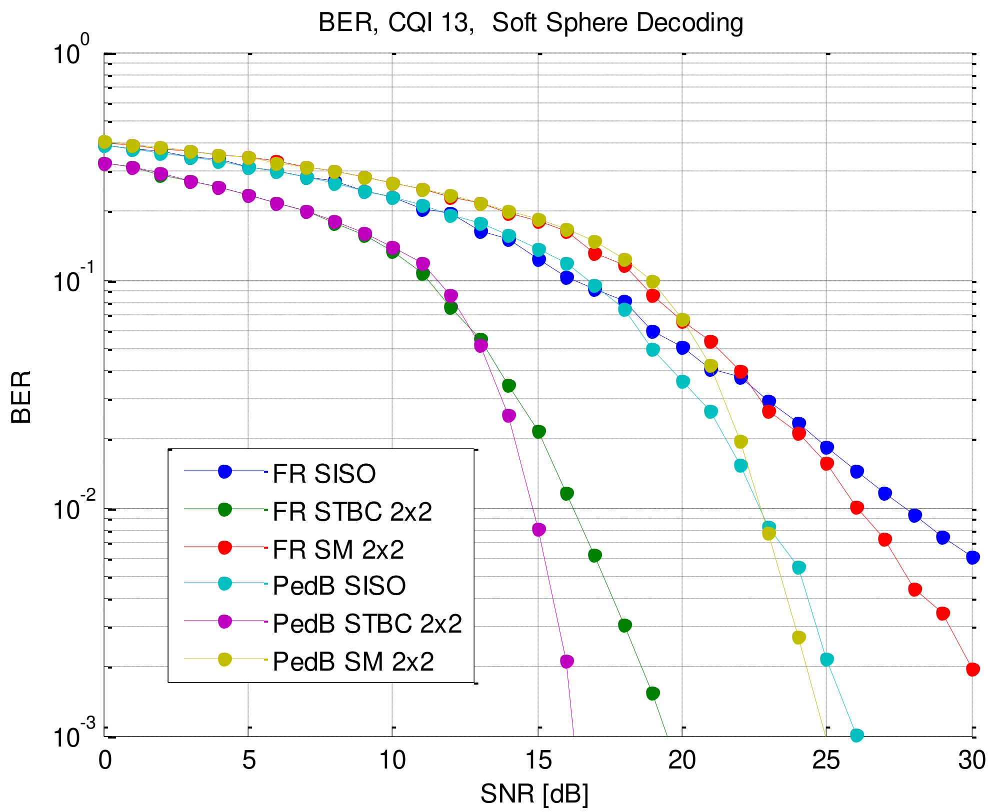


Fig.5 - 6. BER performance of SISO vs. 2 x 2 SM and 2 x 2 STBC (64QAM, Flat-fading vs. ITU Pedestrian B with SSD)

5.2.1.2 Flat-Fading Channel vs. ITU Pedestrian B Channel with Zero Forcing Detection

This section analyses performance of SISO, transmit diversity, and SM in flat-fading channel vs. ITU Pedestrian B channel using zero forcing detection.

A. QPSK

In Fig. 5-7, the instantaneous throughput value at 0dB for SM is observed to be much lower here as compared to the same scenario employing SSD (fig. 5-1) though the same peak value of 2.8Mbps is eventually attained with better throughput performance observed in ITU Pedestrian B as against the flat-fading channel. The transmit diversity performance in flat-fading and ITU Pedestrian B channel has almost the same performance. From the analysis of the performance of SM, SSD can be recommended as suitable for utilization or adoption in low SNR areas over ZF.

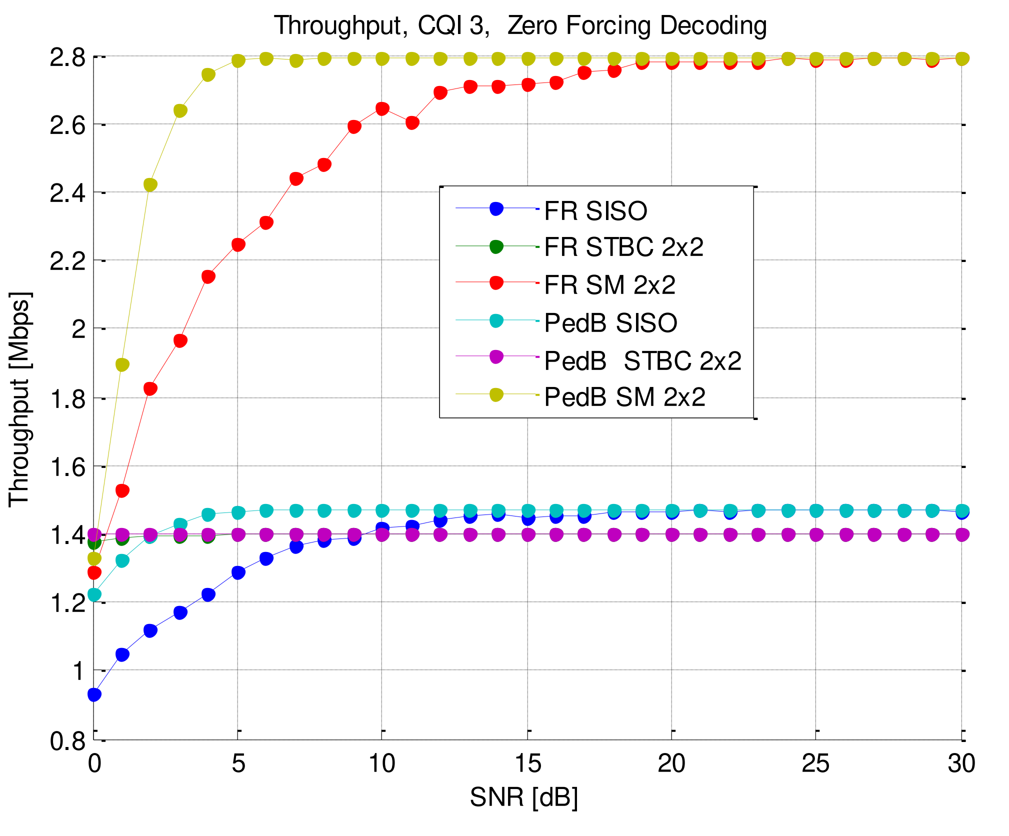


Fig.5 - 7. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (QPSK, Flat-fading vs. ITU Pedestrian B with ZF detection)

In fig. 5-8, transmit diversity gives the lowest BER performance. SM in flat-fading channel has a poor BER values though with better performance in the ITU Pedestrian B channel. Based on this inference from the analysis, SM is highly recommended for use in the ITU Pedestrian B channel because it exhibits an impressive performance with respect to throughput and BER.

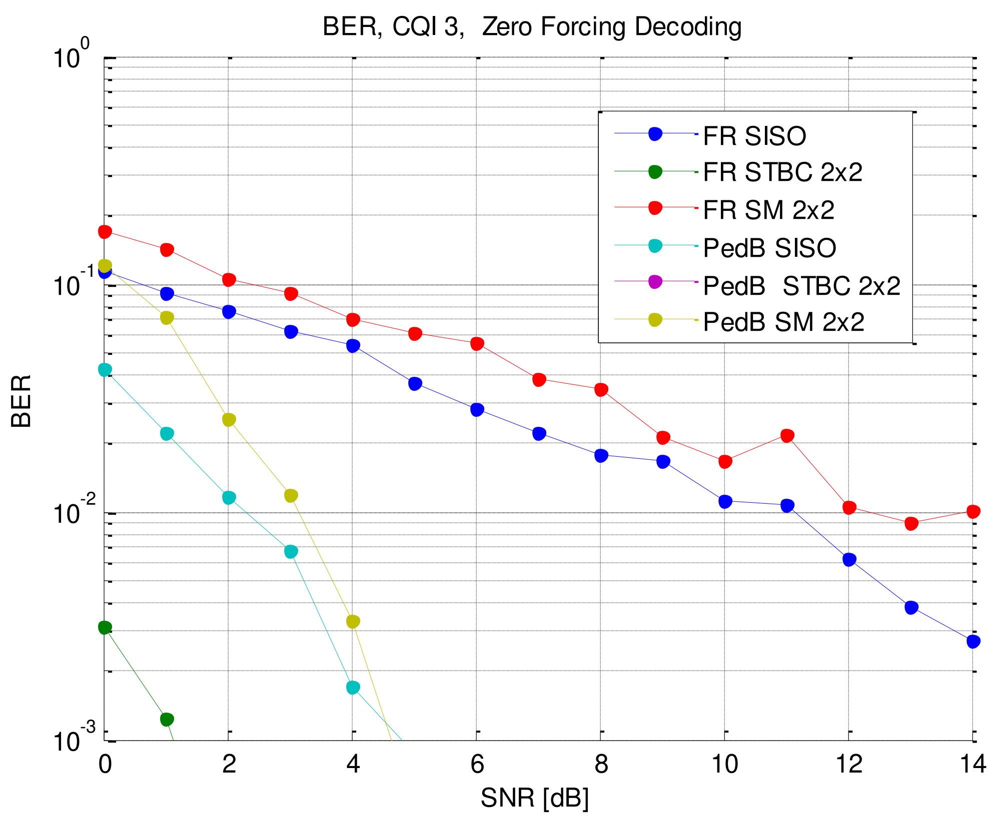


Fig.5 - 8. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (QPSK, Flat-fading vs. ITU pedestrian B with ZF detection)

B. 16 QAM

In fig.5-9, throughput performance in each of the schemes i.e. SISO, SM and transmit diversity is observed to be better at low SNRs in the flat-fading channel but at high SNRs throughput is better enhanced in the ITU Pedestrian B channel. The performance when Zero Forcing detection is utilized is also slightly reduced than that obtained when soft sphere decoding is employed as shown in fig. 5-3. It is also interesting that SISO can perform roughly the same or even a little better than the transmit diversity MIMO technique with respect to throughput, but in terms of bit of error performance SISO is totally displaced by transmit diversity, this is clearly seen in the next figure, fig.5-10.

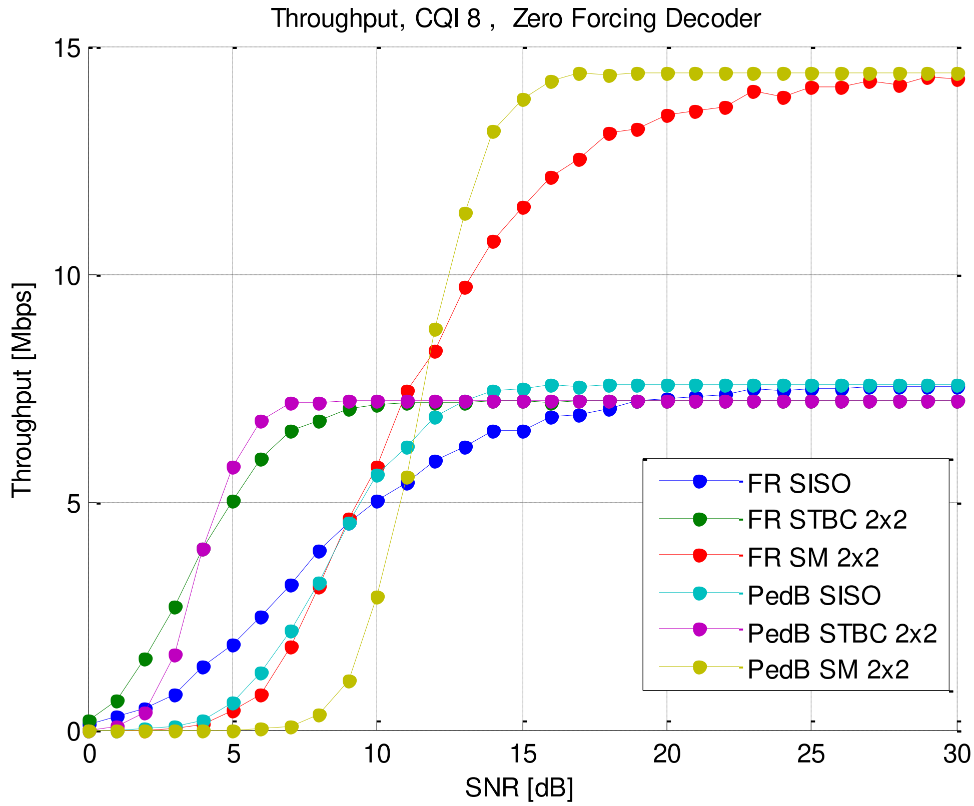


Fig.5 - 9. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, Flat-fading vs. ITU pedestrian B with ZF detection)

Fig-5-10 displays the bit error rate curves, in line with the theory of MIMO antennas, transmit diversity exhibits very low bit error rates with the lowest error rates occuring in the ITU Pedestrian B channel. Spatial multiplexing (SM) in the flat-fading channel has the worst bit error rate, while its performanc in a ITU Pedestrian B channel is fair. Considering this observation, spatial multiplexing can be utilized in the ITU Pedestrian B channel to achieve high throughput with minimal bit error rates.

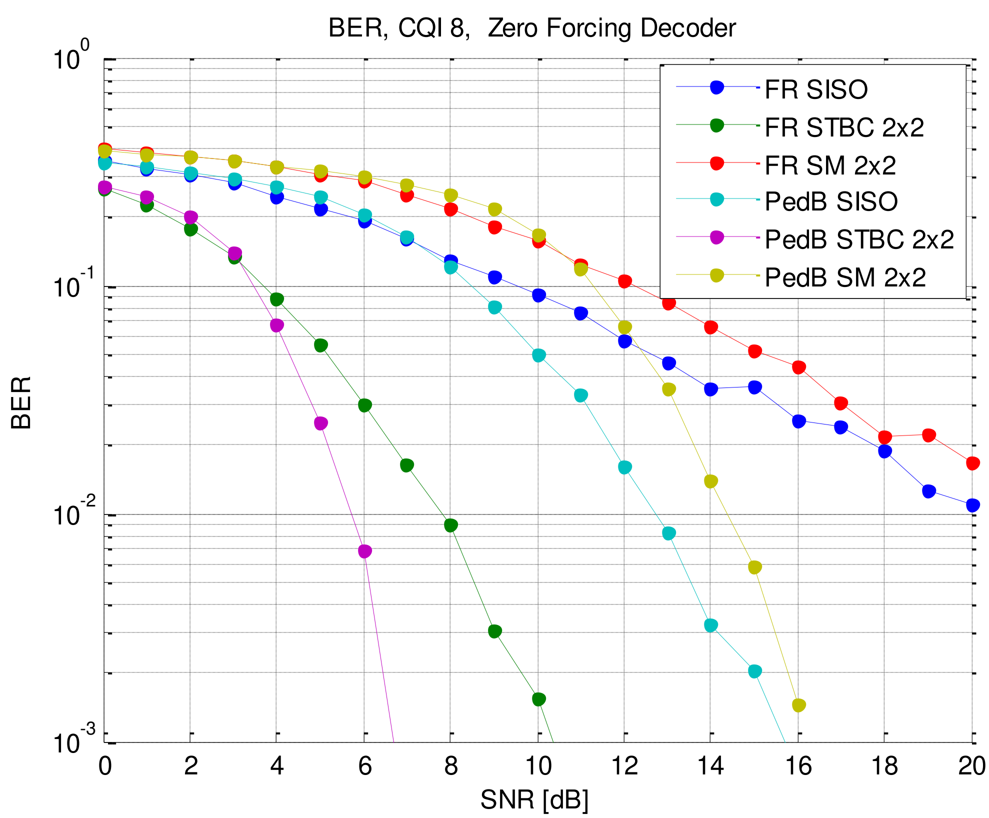


Fig.5 - 10. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, Flat-fading vs. ITU Pedestrian B with ZF detection)

C. 64 QAM

Fig.5-11 shows the throughput results when utilizing zero forcing detection. A similar trend with the preceding figures can be observed; that is, throughput is slightly better in low SNR region in the flat-fading channel than in ITU Pedestrian B channel. In this figure, considering the throughput curves in flat-fading and ITU Pedestrian B channel for SM for example, it is clear that the throughput was higher in the flat-fading channel than ITU Pedestrian B channel until just about 25dB SNR where the performance in the ITU Pedestrian B improves and exceeds that obtained in the flat-fading channel.

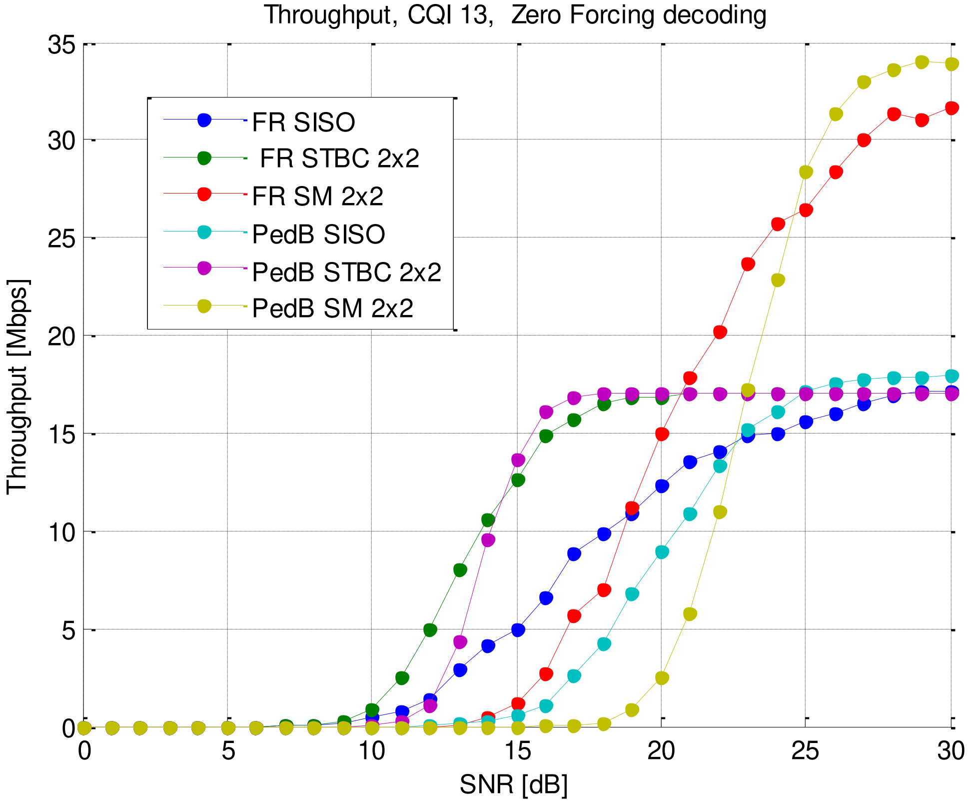


Fig.5 - 11. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, Flat-fading vs. ITU pedestrian B with ZF detection)

In Fig. 5-12, the order of modulation has increased to 64QAM, therefore more SNR is required to achieve low bit error rates as evidenced in fig.5-12. For instance, in the ITU Pedestrian B channel, in order to achieve a bit error rate of 10^{-3}, an approximate value of 17dB SNR is required when employing transmit diversity scheme.

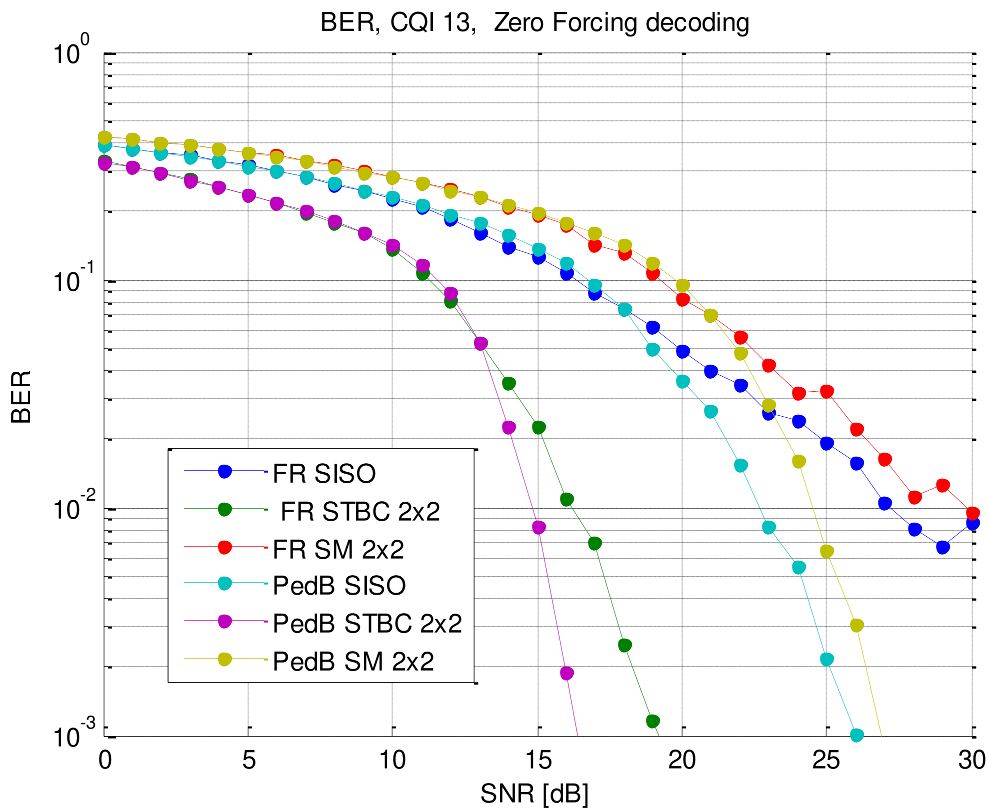


Fig.5 - 12. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, Flat-fading vs. ITU pedestrian B with ZF detection)

5.2.2 Performance Analysis and Comparism of SSD vs. ZF detection in Flat-Fading and ITU Pedestrian B Channels

5.2.2.1 SSD vs. ZF Detection in a Flat-fading Channel

A. QPSK

Fig 5-11 shows the maximum attainable throughput is around 2.8Mb/s. SSD decoding outperforms the ZF decoder in the low SNR regions; this difference is particularly visible in spatial multiplexing which requires additional SNR values for same values of throughput up to 20 dB .Transmit diversity has the same performance irrespective of the detection methods. The curves reveal that transmit diversity attains low bit error rate with SSD followed by ZF. The SSD spatial multiplexing follows the transmit diversity in low SNR region.

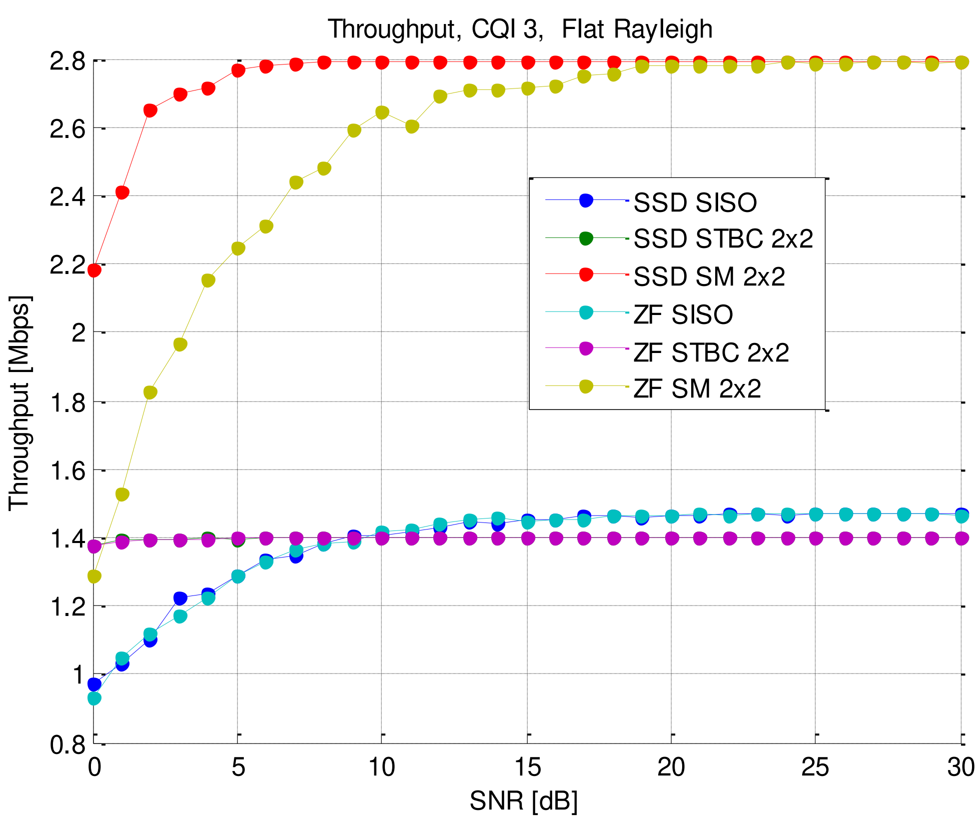


Fig.5 - 13. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (QPSK, ZF vs. SSD in Flat-fading channel)

Fig. 5-14, it is observed that with SSD detection the bit error rates are lower than with ZF detection, a vivid example that shows this is when we compare the SM curve with SSD (red curve) and with ZF (yellow), there clearly exist a very wide margin in between them. In contrast, the BER curves of SISO with ZF and SSD seems interwoven making it difficult to accurately and precisely determine the one with better BER performance.

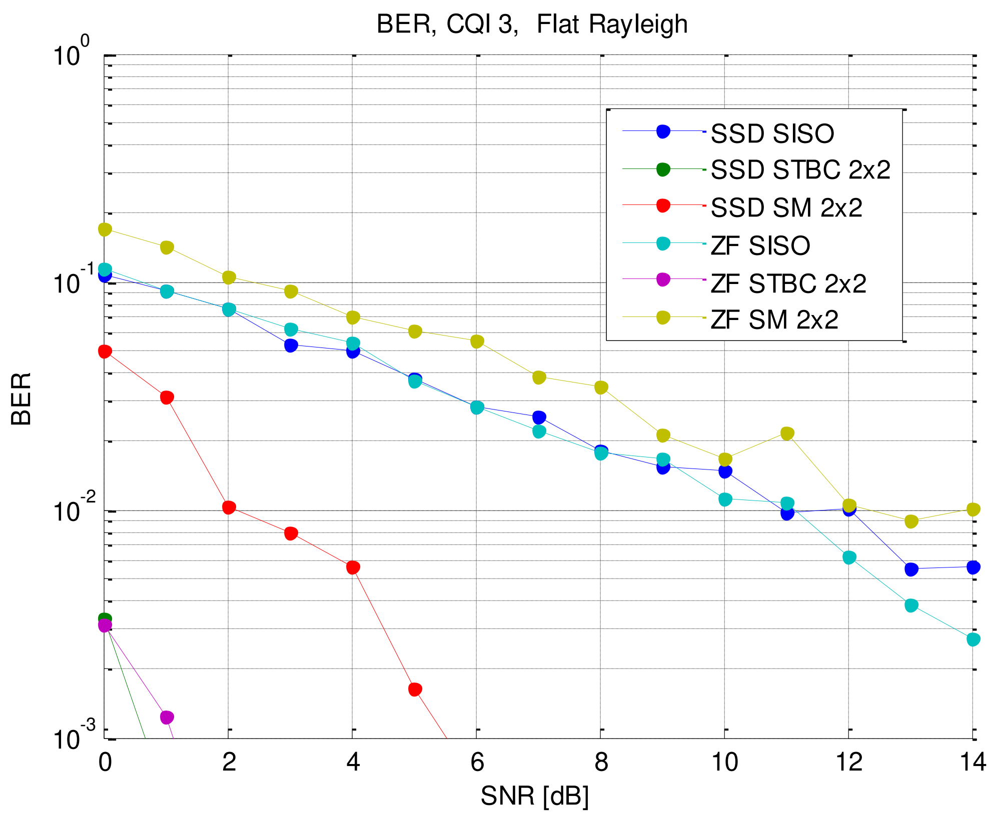


Fig.5 - 14. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (QPSK, ZF vs. SSD in Flat-fading channel)

B. 16 QAM

Throughput achieved with SSD is roughly the same as in ZF for SISO and transmit diversity but there is some increase in throughput with SSD than ZF when utilizing spatial multiplexing (SM).

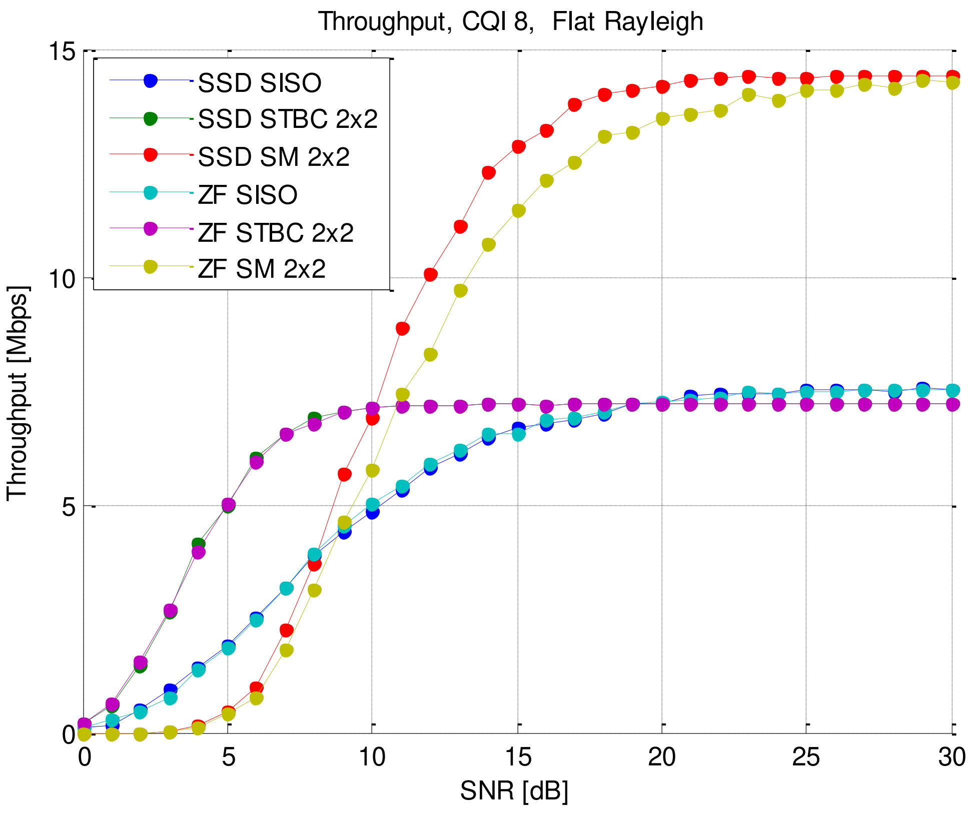


Fig.5 - 15. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16 QAM, ZF vs. SSD in Flat-fading channel

From Fig.5-16, transmit diversity has the best BER performance and there is roughly similar performance between SSD and ZF detection (purple and green curves), SISO performance with detection schemes (ZF and SSD) have similar BER with minimal differences. SM with ZF detection had the worst BER performance.

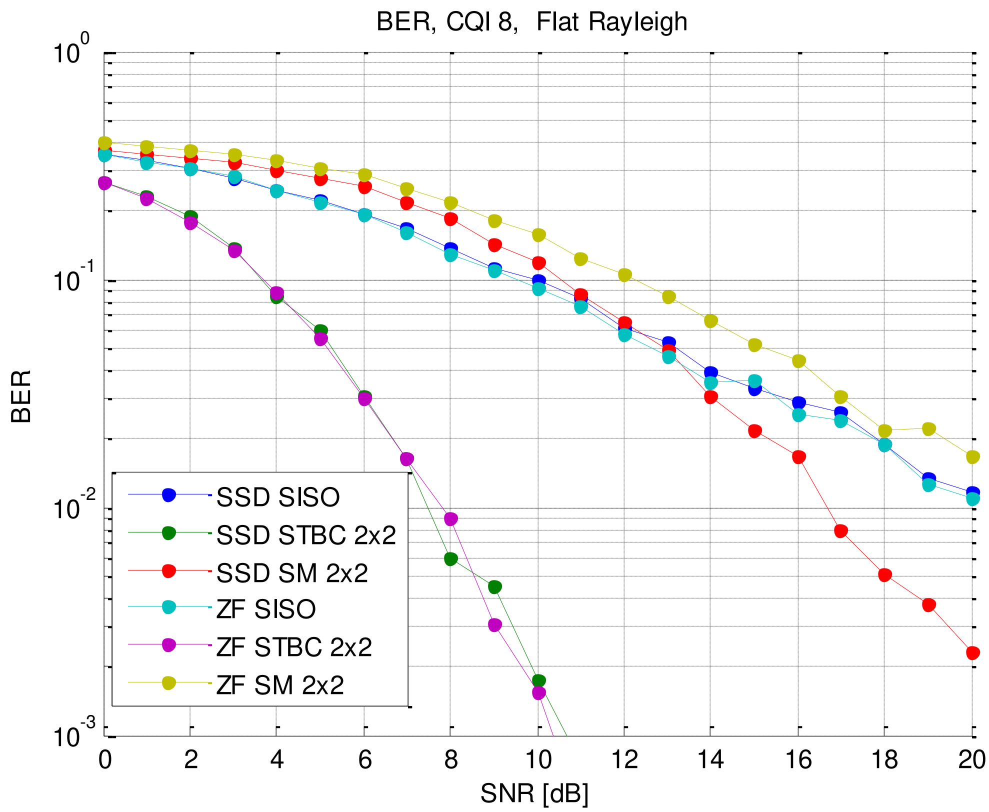


Fig.5 - 16. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16 QAM, ZF vs. SSD in Flat-fading channel)

C. 64 QAM

The performance displayed in fig.5-17 is displayed follows a similar trend like that obtained in 16 QAM except that it can be observed that throughput values have increased since the order of modulation has increased peaking at approximately at 34Mbps with SM employing SSD detection. Performance of SSD and ZF are very similar for SISO and transmit diversity.

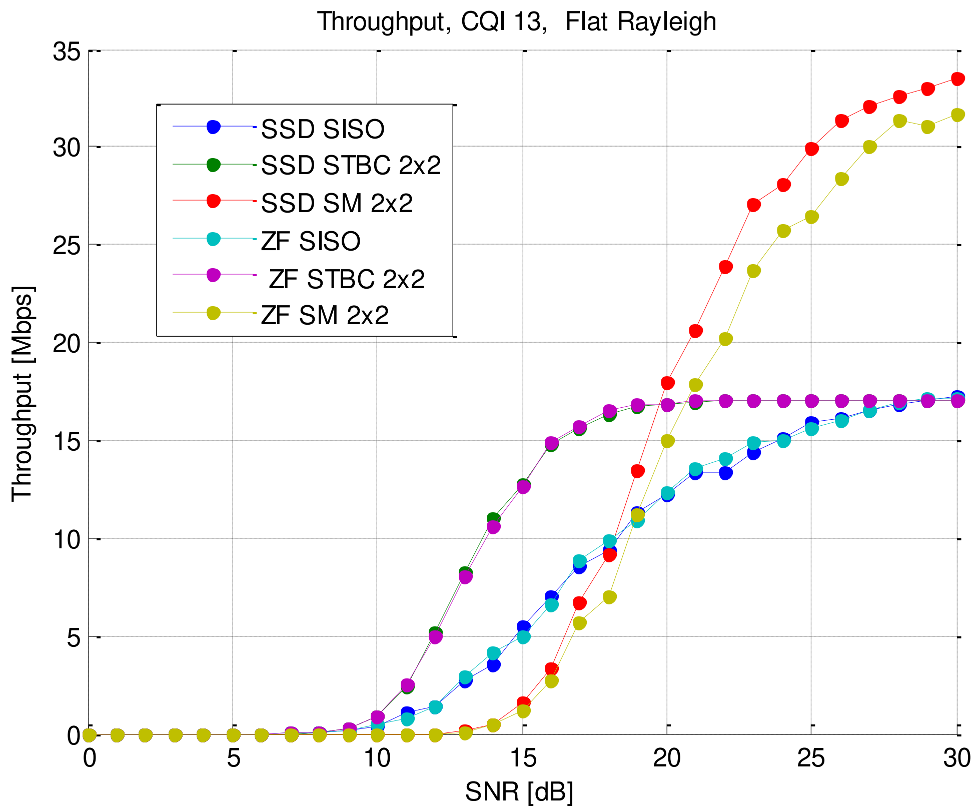


Fig.5 - 17. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (64 QAM, ZF vs. SSD in Flat-fading channel)

Here, the BER performance with 64 QAM are displayed, additional SNR is required for better performance. Transmit diversity with SSD and ZF detection exhibit similar performance, and a similar trend is noticed with SISO as well.

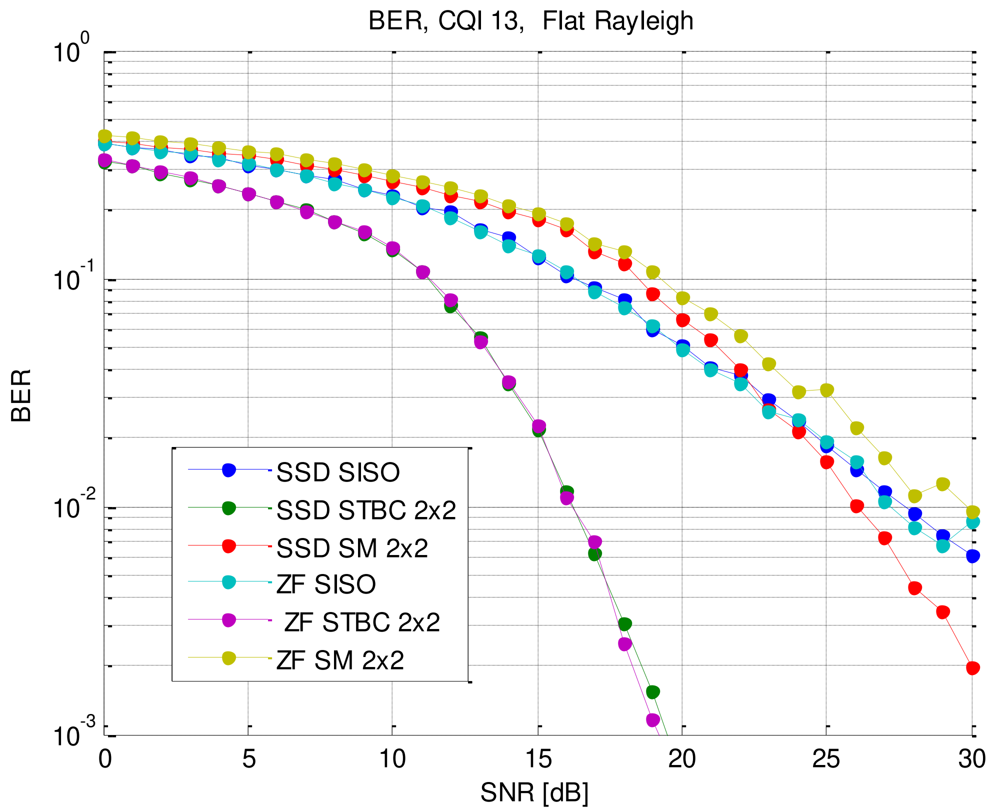


Fig.5 - 18. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (64 QAM, ZF vs. SSD in Flat-fading channel)

5.2.2.2 SSD vs. ZF Detection in ITU Pedestrian B Channel

A. QPSK

This section compares the throughput and BER performance of SISO; transmit diversity and SM MIMO schemes for SSD and ZF detection schemes in an ITU pedestrian B channel. In line with the theory of detection techniques in MIMO, generally, detection by SSD produces better results than ZF detection particularly in low SNR regions. Considering the figure below, the spatial multiplexing curves with SSD and ZF detection (red and yellow curves respectively), within the low SNR ranges between 0 – 5 dB, it is clearly observed that there is higher throughput attained with SSD. At 0dB, SM with ZF had a throughput value of 1Mbps while that with SSD attains about 2.6Mbps, this is a marked difference about 1.6Mbps. The transmit diversity scheme maintains a throughput value of 1.4Mbps, SISO performed lower than transmit diversity between 0 -2dB but surpasses transmit diversity and maintains throughput of approximately 1.45Mbps. It is reasonable to wonder why SISO can outperform a MIMO technique (transmit diversity in this case), the reason is that diversity techniques are designed mainly to enhance signal quality and not throughput, and this is validated by the BER curves in Fig.5-20.

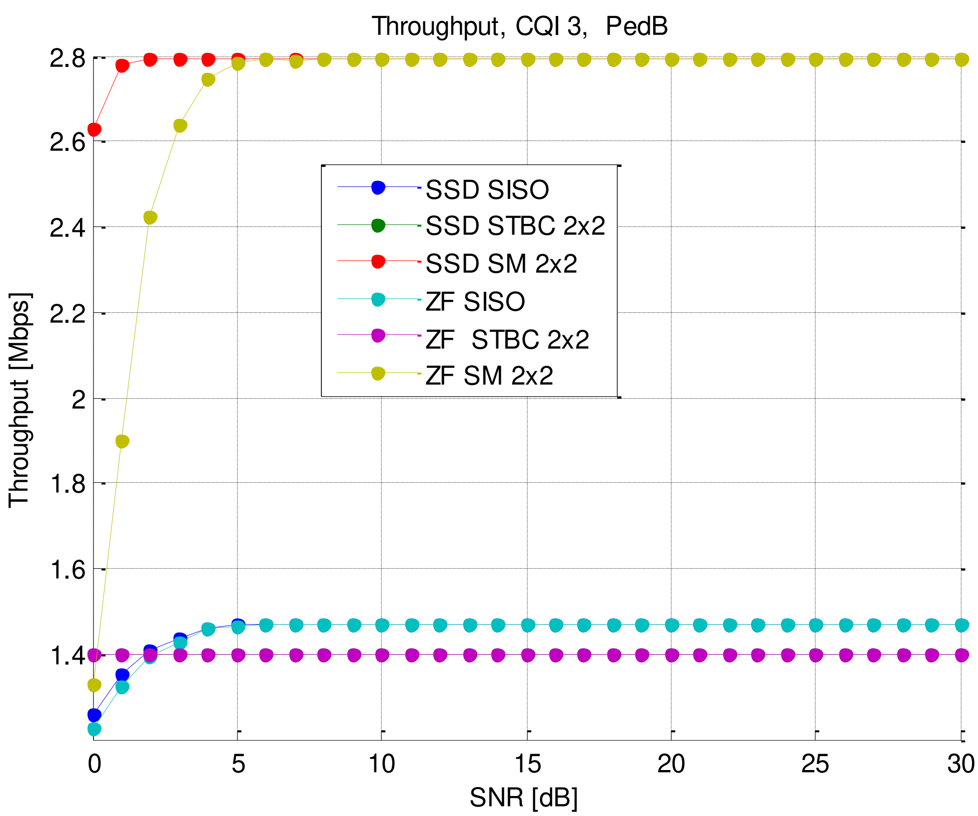


Fig.5 - 19. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (QPSK, ZF vs. SSD in ITU Pedestrian B channel)

Fig.5-20 shows the BER curves, transmit diversity scheme have very low error rates. Next to this is the SISO, SSD detection performs better than ZF, SM with ZF detection performed worst between 0 – 4dB.

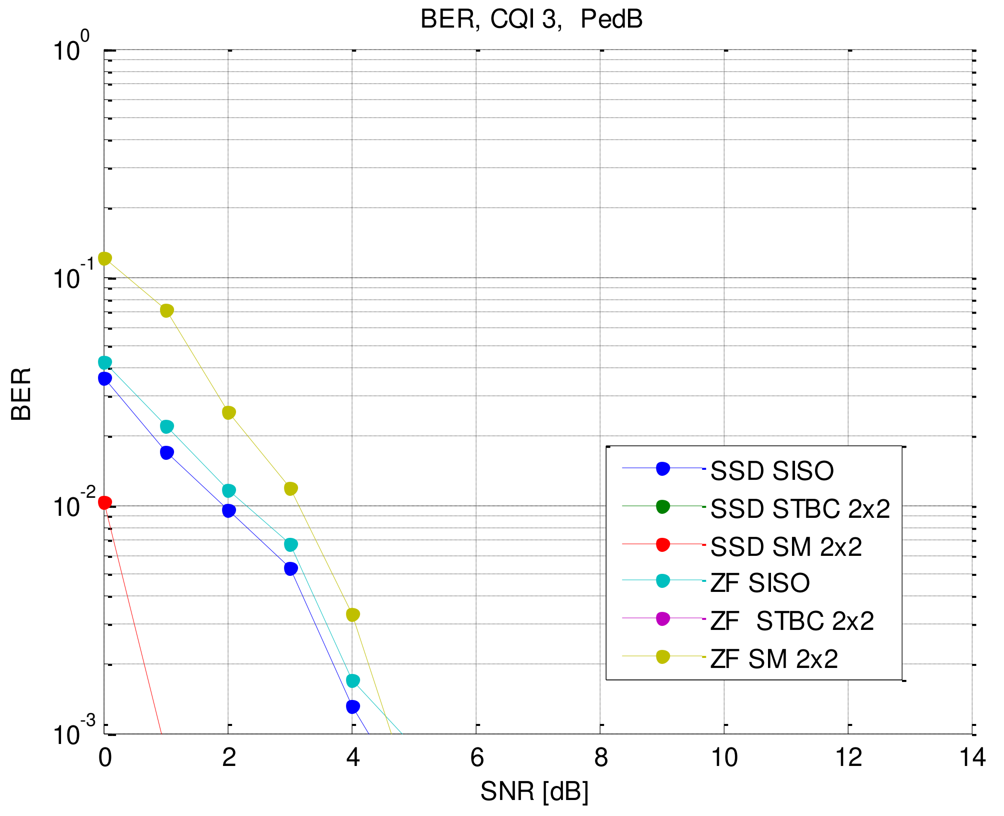


Fig.5 - 20. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (QPSK, ZF vs. SSD in ITU Pedestrian B channel)

B. 16 QAM

A similar trend as observed in QPSK is obtained in 16 QAM. Transmit diversity attains 6Mbps at 5dB SNR, while SISO attains approximately the same value of throughput at 10dB which is double of that required by transmit diversity. Transmit diversity therefore are very useful to attain reasonable peak rates at low SNR while assuring good signal quality. The detection schemes have minimal impact on the throughput for SISO and transmit diversity but there is an exception with SM, throughput performance is a little better in SM with SSD than with ZF between 5 – 15dB.

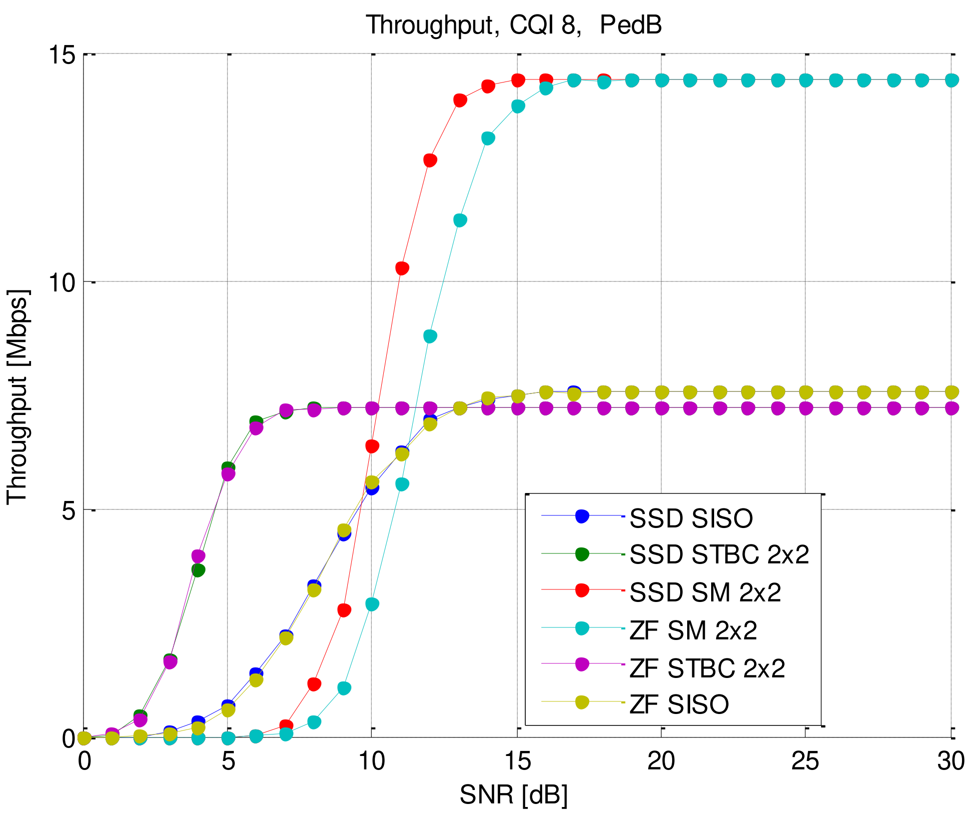


Fig.5 - 21. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, ZF vs. SSD in ITU Pedestrian B channel

Fig.5-22 displays the BER performance in the ITU Pedestrian B channel, which evidently has lower bit error rates as compared to that obtained in a flat-fading channel (fig.5-16). Without doubts, transmit diversity has the best performance in terms of bit error rates, SISO's performance was better than SM up till 12dB SNR thereabout. There is no marked impact of the detection schemes on transmit diversity and SISO, as both curves for each detection (ZF and SSD) for the two schemes are similar, but for SM, SSD is better and preferred.

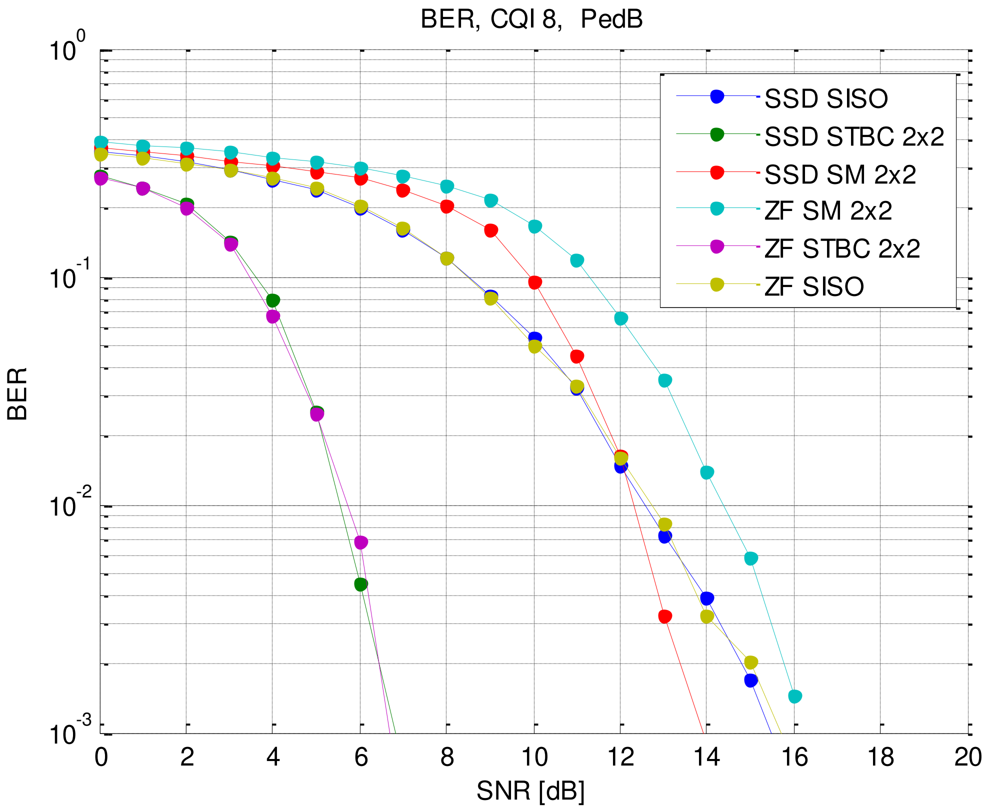


Fig.5 - 22. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, ZF vs. SSD in ITU Pedestrian B channel)

C. 64 QAM

This order of modulation is well suited for regions with high SNR values such as areas near the base station, the reason being that for low SNR value such as between 0 – 10dB, throughput is virtually zero but thereafter begins to increase. The performance in both detection schemes are virtually the same for transmit diversity and SISO. Performance of SM with SSD detection is better than with ZF detection, evidently indicating that increasing the order of modulation does not enhance the performance of one detection scheme over the other.

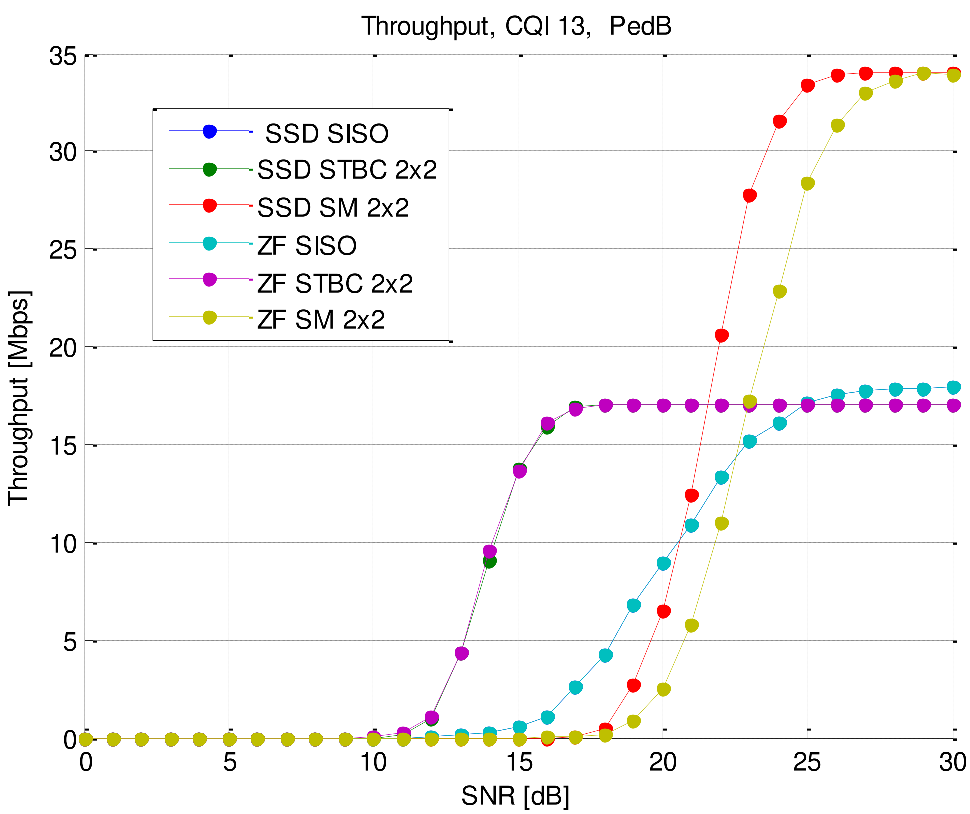


Fig.5 - 23. Throughput Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, Flat-fading vs. ITU pedestrian B with ZF detection)

Fig.5-24 presents the BER curves which shows close semblance to that obtained in 16 QAM but with increase in SNR required to attain low bit error rates. Once again, SSD and ZF detection in transmit diversity and SISO have just about the same performance. The worst performance occurs in SM with ZF detection. This makes SSD detection the preferred choice over ZF detection.

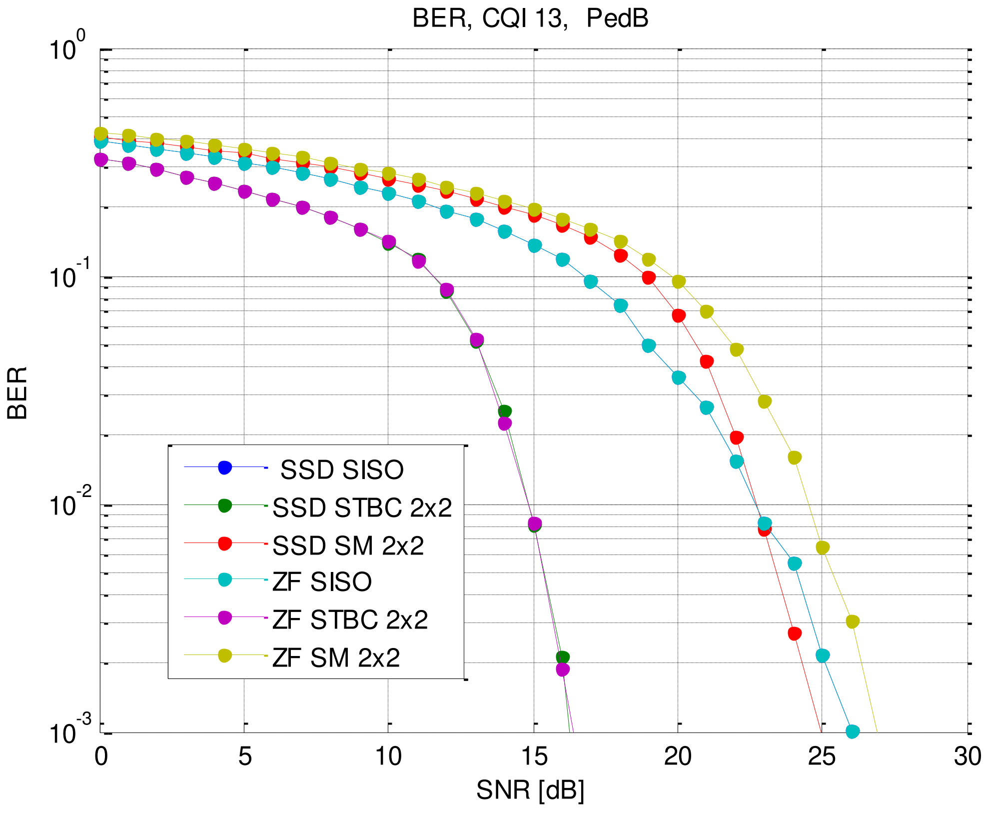


Fig.5 - 24. BER Performance of SISO vs. 2 x 2 SM, 2 x 2STBC (16QAM, Flat-fading vs. ITU pedestrian B with ZF detection)

5.3 Summary of Simulation Results

In summary, the analysis of the simulation graphs generally showed that Spatial multiplexing (SM) always had the highest throughput values, irrespective of the channel and modulation order. In terms of BER, transmit diversity consistently had the lowest BER values, this is completely in agreement with the theoretical explanations.

Flat-fading channel vs. ITU pedestrian B channel with soft sphere; and zero forcing detection scenarios:

- In this scenario, throughput and BER performance are generally better in the ITU pedestrian B channel than in the flat-fading channel but this performance is relative and subject to SNR values and order of modulation.
- For QPSK, performance in the ITU-B channel is better at low SNRs (typically between 0 – 5 dB) but at high SNR values (15dB and above) performance is equally the same.
- For 16 QAM, at low SNRs (0-10dB), performance in the flat-fading channel is better; at medium SNR values (10 – 20dB) performance in the ITU-B improves and exceeds that in the flat-fading. At high values (20dB and above) performance is just about the same.
- For 64 QAM, there is virtually no performance at low SNRs (0 – 10 dB), at medium SNR values (between 10 – 25dB) the flat-fading channel performs better at first but as the SNR increases, performance in ITU-B improves and exceeds it.

For Soft Sphere Detection vs. ZF detection in flat-fading channel; and ITU Pedestrian B Channel:

- In this scenario, Soft sphere detection generally proves to be better than zero forcing in both channel scenarios. A trend similar as obtained in the above scenario is observed here as well with respect to performance relative SNR value and order of modulation.
- For QPSK, performance of SSD is generally better than zero forcing at low SNRs for SM, but later becomes equivalent at higher values. For SISO and transmit diversity, the performances with SSD and ZF detection are similar. A similar observation applies to 16 QAM to 64 QAM but with an observed increase in required SNR.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In this thesis work, an effective study, analysis and evaluation of the LTE downlink performance with different MIMO techniques in comparison with the traditional SISO system has been carried out. The performance is evaluated with respect to two definitive metrics namely throughput and BER, considering the use of different decoders at the receiver (soft sphere and zero forcing decoders) in two different channel models, namely flat-fading and ITU pedestrian B channel. In both receivers, for higher order of modulation (16QAM and 64QAM), the flat-fading channel performs better for the low SNR regions (up to 4, 9, 12 dB) for transmit diversity, SISO and spatial multiplexing respectively. However, for low order of modulation, QPSK in this instance, performance in the ITU pedestrian B channel is better at the low SNR region. In rich multipath environments like ITU pedestrian B channel, performance for users far away from the base station is low due to losses caused by the presence of many scatterers, but for the flat-fading channel, performance is better in these low SNR areas particularly when SSD is used, however, additional SNR is required in the case of zero forcing decoder.

Analysis of the results obtained reveal that the performance of MIMO is better than SISO in both channel models particularly when SSD is employed. When high order modulation is utilized, performance in the flat-fading channel model is better than ITU pedestrian B channel at low SNR regions. Spatial multiplexing is ideal for achieving very high peak rates, while transmit diversity is a valuable scheme to minimize the rate of bit error occurrence thereby improving signal quality.

The vision of LTE is therefore nothing less than an actual possibility and a true reality as this evaluation has demonstrated that the design goals and targets of LTE can be met with a high degree of reliability and certainty. This performance evaluation also provides useful information on LTE downlink planning, design and optimization for deployment.

6.2 Future work

It would be worthwhile to evaluate the performance of the LTE downlink with the incorporation of adaptive MIMO switching capabilities. This study was performed for single user MIMO scenario. However, the real traffic is a mix of different users in a cell, therefore, it is essential to undertake studies with multi user MIMO as well.

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