R.T.
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE

LONG TERM EVOLUTION (LTE) PERFORMANCE ANALYSIS

İLYAS SELLİ

MASTER THESIS

DEPARTMENT of ELECTRONICS and COMMUNICATIONS ENGINEERING

ADVISOR
ASSIST. PROF. DR. BÜLENT BOLAT

İSTANBUL, 2012

ACKNOWLEDGEMENTS

I am grateful to Assist. Prof. Dr. Bülent Bolat for his friendly support, encouragement and constructive criticism, for all his help in editing the final text and for valuable comments about my studies. Without his guidance as a great mentor, this work would not have been possible.

I want to thank to my dear friend Sabit Ekin for his technical assistance, help, support, interest and valuable hints.

Thanks also to my family who have been extremely understanding and supportive of my studies. I feel very lucky to have a family that shares my enthusiasm. Without the love and support of my family this would have been a very hard journey. I thank my father for teaching me good values such as honest hard work and my mother without whom I would not be the person that I am today.

Finally, I am dedicating this work to my beautiful love and soulmate, Neslihan, for giving me an unwavering love and support. I could not imagine how it would have been without you! Thank you for your encouragement

February, 2012

İlyas SELLİ

TABLE of CONTENTS

Page

NOTATION

Acronyms

3GPP	Third Generation Partnership Project
AMC	Adaptive Modulation and Coding
APN	Access Point Name
ARQ	Automatic Repeat Request/Query
AUC	Authentication Centre
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
BSC	Base Station Controller
BSS	Base Station System
BTS	Base Transceiver Stations
CP	Cyclic Prefix
CSI	Channel State Information
DFT	Discrete Fourier Transforms
DL	Downlink
EIR	Equipment Identification Register
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved UTRAN
FFT	Fast Fourier Transforms
FDD	Frequency-Division Duplex
FDM	Frequency Division Multiplexing
FDMA	Frequency-Division Multiple Access
GSA	Global mobile Suppliers Association
GSM	Global System for Mobile Communications
HARQ	Hybrid ARQ
HSDPA	High Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSS	Home Subscriber Server
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform

IMS	IP Multimedia Subsystem
ISI	Inter-Symbol Interference
LOS	Line-of-Sight
LTE	Long-Term Evolution
MIMO	Multiple Input Multiple Output
MCS	Modulation Coding Scheme
MME	Mobility Management Entity
NMS	Network Management System
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLSM	Open Loop Spatial Multiplexing
OSS-RC	Operations Support System – Radio and Core
PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PCRF	Policy Control and Charging Rules Function
PDCCH	Physical Downlink Control Channel
PDN-GW	Packet Data Network Gateway
PDSCH	Physical Downlink Shared Channel
PHICH	Physical Hybrid ARQ Indicator Channel
PMCH	Physical Multicast Channel
PRACH	Physical random access channel
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QOS	Quality of Service
RAT	Radio Access Technologies
RF	Radio Frequency
RNC	Radio Network Controller
SAE	System Architecture Evolution
SCTP	Stream Control Transmission Protocol
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFBC	Space-Frequency Block Coding
SGW	Serving Gateway
SGSN	Serving GPRS Service Node
SISO	Single Input Single Output
SM	Spatial Multiplexing
SNR	Signal to Noise Ratio
TCP	Transmission Control Protocol
TD	Transmit Diversity
TDD	Time-Division Duplex
TTI	Transmission Time Interval
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS Terrestrial Radio Access Network

LIST of FIGURES

Page

LIST of TABLES

Page

ABSTRACT

LONG TERM EVOLUTION (LTE) PERFORMANCE ANALYSIS

İlyas SELLİ

Department of Electronics and Communications Engineering
MSc. Thesis

Advisor: Assist. Prof. Dr. Bülent Bolat

Mobile networks have triggered advances and changes in telecommunications world over the last two decades. In addition to the voice communication, the data usage has grown day by day. The recent increase of the data usage in mobile networks and appearance of new applications such as online gaming, mobile TV, streaming contents have greatly motivated the 3rd Generation Partnership Project (3GPP) to work on the Long Term Evolution (LTE). 3GPP LTE is the evolution of the Universal Mobile Telecommunications System (UMTS) which will make possible to deliver high quality multimedia services according to the users' expectations. LTE offers many significant improvements over previous technologies such as UMTS and High-speed packet access (HSPA). Higher downlink and uplink speeds, lower latency and simpler network architecture are among the new and important features that are provided in LTE. In this thesis, the simulations for the performance analysis of LTE are presented. The effects of different parameters and other factors are investigated. The performance analysis results are shown in terms of Block Error Ratio (BLER) and Throughput versus Signal-to-Noise Ratio (SNR).

Key words: Long term evolution, 3rd generation partnership project, universal mobile telecommunications system, high-speed packet access

ÖZET

UZUN VADELİ EVRİMDE PERFORMANS ANALİZİ

İlyas SELLİ

Elektronik ve Haberleşme Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

Tez Danışmanı: Yrd. Doç. Dr. Bülent Bolat

Son 20 yıla bakıldığında mobil ağlar, telekomünikasyon dünyasındaki değişim ve gelişimleri tetiklemektedir. Ses haberleşmesine ek olarak data kullanımı günden güne artmaktadır. Son zamanlarda mobil ağlardaki data kullanımının artışı ve çevrimiçi oyun, mobil TV, kesintisiz içerik gibi uygulamaların ortaya çıkması, üçüncü nesil mobil iletişim ortaklık projesini (3GPP), Uzun Vadeli Evrim (LTE) teknolojisi konusunda çalışmaya yönlendirmiştir. LTE, Evrensel Mobil İletişim Sistemi (UMTS)`nin gelişmiş hali ve kullanıcı beklentilerine göre yüksek kalitede çoklu ortam servisleri sağlamayı mümkün kılan bir teknolojidir. LTE, UMTS ve Yüksek Hızlı Paket Erişimi (HSPA) gibi sistemlere göre önemli gelişimler vaadetmektedir. Yüksek veri indirme ve yükleme hızları, daha düşük gecikme ve daha basit ağ mimarisi LTE`nin getirdiği yeni ve önemli özelliklerdir. Bu tezde LTE performans analizi simülasyonları sunulacaktır. Farklı paramatrelerin ve diğer faktörlerin etkisi araştırılacaktır. Performans analizi sonuçları, Blok Hata Oranı (BER) ve veri ye karşı Sinyal-Gürültü (SNR) oranına göre gösterilecektir.

Anahtar Kelimeler: Uzun vadeli evrim, üçüncü nesil mobil iletişim ortaklık projesi, evrensel mobil iletişim sistemi, yüksek hızlı paket erişim

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Mobile networks have triggered advances and changes in telecommunications world over the last two decades, and mobile operators have grown to dominate the industry, offering their subscribers a service set as rich as their wire-line competitors, plus mobility. The number of subscribers who use mobile technologies has increased in the last years. In addition to the voice communication, the data usage has grown day by day. It is expected that the data traffic volume will exceed the voice traffic volume very soon. While end users expects faster upload and download speeds, operators look for high data capacity with low costs. 3rd Generation (3GPP) Long Term Evolution (LTE) is designed to meet those targets and it is the latest standard in the mobile network technology tree. It is a project of the 3rd Generation Partnership Project, operating under a name trademarked by one of the associations within the partnership, the European Telecommunications Standards Institute (ETSI).

The current telecommunications networks are known as 3G (third generation). LTE is introduced as 4G (fourth generation). But first release of LTE does not fully comply with the 4G requirements. 4G requirements have been included in LTE Advanced. LTE Advanced is backwards compatible with LTE and uses the same frequency bands, while LTE is not backwards compatible with 3G systems.

There are 3 main reasons to develop the LTE. One of them is increasing data rates and the other ones are improving the spectrum efficiency and allowing spectrum flexibility

(1.25, 2.5, 5, 10, 15 and 20 MHz) for flexible radio planning. The other advantages of the LTE are reducing packet latency, reducing radio access network cost and simplifying the network to flat all-IP packet-based network architecture.

LTE should at least support an instantaneous downlink peak data rate of 100Mbps within a 20 MHz downlink spectrum allocation (5bps/Hz) and instantaneous uplink peak data rate of 50Mbps within a 20 MHz uplink spectrum allocation (2.5bps/Hz) considering 2 receive antennas and 1 transmit antenna at User Equipment (UE) [1].

According to Global mobile Suppliers Association (GSA), 22 LTE networks have entered commercial service in 2010 and 37 LTE networks will be commercially launched by the end of 2012.

1.2 Aim of Thesis

This thesis studies consists of LTE performance analysis. It is aimed to analyze the impacts of different parameters (such as number of UEs, Bandwidth (BW) Retransmission (HARQ), Channel types, Transmit modes) and other factors which affect the LTE performance. Performance analysis results are shown in terms of Block Error Ratio (BLER) and Throughput versus Signal-to-Noise Ratio (SNR).

1.3 Hypothesis

In this thesis, the effects of different parameters and other factors will be investigated. These parameters and factors can be listed as Hybrid Automatic Repeat Request (HARQ), transmit mode, number of user equipment, channel bandwidth, channel type (AWGN, Flat Rayleigh, PedA, PedB, VehA, and VehB), CQI value and simulation length. When HARQ is used, it is expected to have better performance from LTE system regarding to throughput and Block Error Rate(BLER). Single Input Single Output (SISO),Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO) transmit modes will be tested and it is expected to observe the best performance on MIMO. In other words, it is assumed to have better throughput and BLER result when the number of anttennas are increased. Also it is expected to have better results when channel bandwidth, CQI values and simulation lenghts are increased. However, it is expected to see that when the number of UEs are increased, throughput will decrease. When the simulations are performed, expectations and results will be compared.

CHAPTER 2

TECHNICAL OVERVIEW OF LONG TERM EVOLUTION OF 3GPP (LTE)

2.1 Orthogonal Frequency-Division Multiplexing (OFDM)

The basic of the mobile radio channel can be described by multi-path reception. The signal sent to the receiver does not contain only a direct line-of-sight (LOS) radio wave. It also contains a large number of reflected radio waves that arrive at the receiver at different times. Delayed signals are the result of reflections from terrain features such as trees, hills, mountains, vehicles, or buildings (see figure 2.1). These reflected, delayed waves interfere with the direct wave and cause inter-symbol interference (ISI), which in turn causes significant degradation of network performance and because of this a wireless network should be designed to minimize adverse effects [1].

To have broadband mobile communication systems, it is necessary to use high-bit-rate transmission of at least several megabits per second. However, transmitting the data with high bit rates causes the delayed waves. One of the methods to solve this problem is equalizing these signals at the receiver. But it is really difficult to equalize the signals with efficient and low-cost hardware while data is transmitted with high bit rates.

Orthogonal frequency division multiplexing (OFDM) helps to overcome such a multi-path-fading environment. OFDM is one of the applications of a parallel-data-transmission scheme, which reduces the influence of multi-path fading and makes complex equalizers unnecessary.

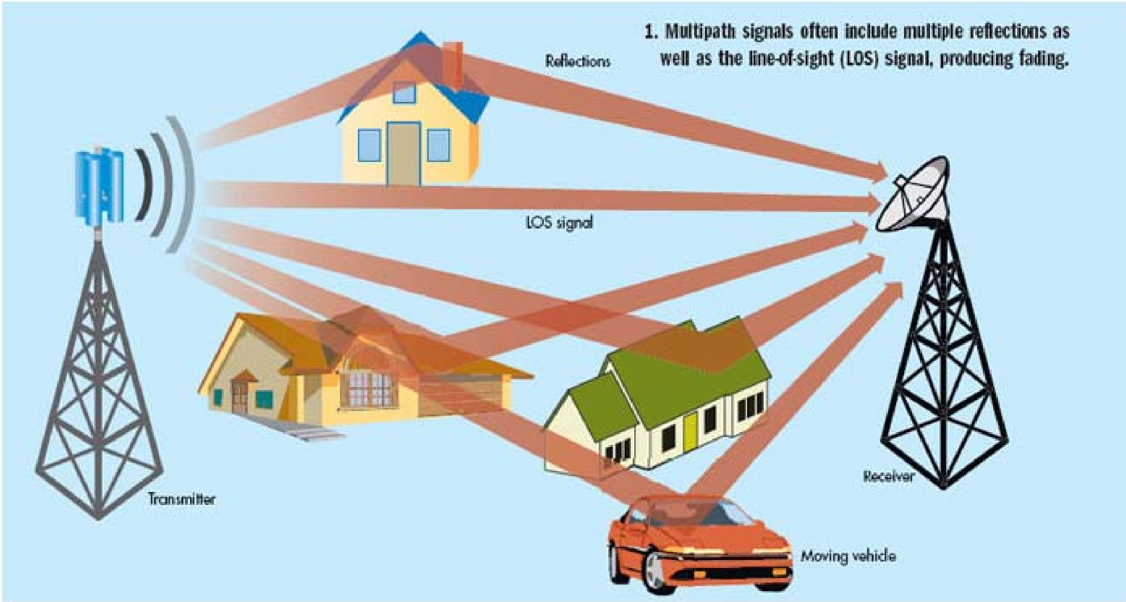

Figure 2.1 Reflected signals [1]

There are a couple of ways for multi-carrier transmission. OFDM is one of them and differs from others with the method that a single data stream is transmitted over a number of lower-rate sub-carriers (SCs). OFDM can be considered as either a modulation or multiplexing technique. One of the main reasons to use OFDM is to increase robustness against frequency-selective fading or narrowband interference. In a single-carrier system, a single fade or interferer can cause the entire link to fail, but in a multicarrier system, only a small percentage of the SCs will be affected [1].

Normally, we should avoid spectral overlap of channels to eliminate the interference. But this causes to inefficient use of the available spectrum. OFDM uses overlapping multicarrier technique and it overcomes the inefficient use of the available spectrum.

Figure 2.2 illustrates the difference between the conventional non-overlapping multicarrier technique and the overlapping multicarrier modulation technique.

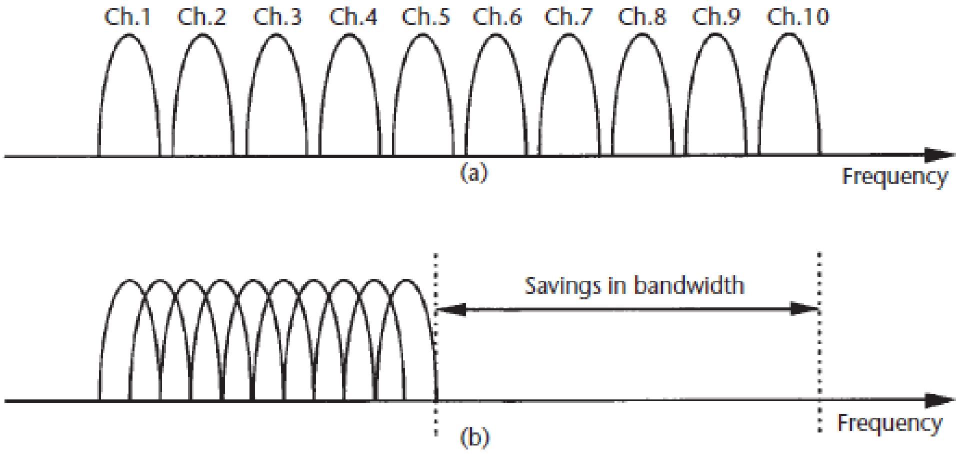

Figure 2.2 Concept of the OFDM signal: (a) Conventional multicarrier technique [1]
(b) Orthogonal multicarrier modulation technique [1]

It is expected to see orthogonality between different modulated carriers since it causes to reduce cross talk between single carriers. Under the illustration of these explanations, half of bandwidth is saved by using overlapping multi-carrier modulation technique.

The OFDM transmission has a lot of key advantages. As described above, it is a useful method to deal with multi-path. OFDM is the most suitable method for broadcast applications since creating single-frequency network is possible with it. Also OFDM can deal with narrowband interference. Because narrowband interference affects only limited percentage of SCs. Capacity can be increased by modifying the data rate per SC according to the SNR of the related SC, in slow time varying channels.

However, OFDM also has some disadvantages according to the single carrier modulation. One of these disadvantages is OFDM has large peak-to-average-power ratio and this causes to reduce the power efficiency of the radio frequency (RF) amplifier. Also OFDM is more sensitive to frequency offset and phase noise [1].

2.2 Orthogonal Frequency-Division Multiple Access (OFDMA)

The A stands for access. It means that OFDM is not only a great modulation method, it also can provide multiple access to a common bandwidth or channel to multiple users. OFDMA is a multi-user OFDM that allows multiple access on the same channel. LTE uses OFDMA to locate many users in the same channel at the same time. OFDMA distributes sub-carriers among users, so all users can transmit and receive at the same time within a single channel. In addition to that, subcarrier-group subchannels can be matched to each user to provide the best performance.

In OFDM systems, subgroup of SCs is assigned to each user. With the help of this property, percentage of the carriers on each user would be low. Each user could be assigned from one to many SCs in an 4G LTE system. In LTE, SC spacing is 15 kHz. So in a 10-MHz band, the total number of SCs would be 666. In practice, 512 would be used instead of 666. If 6 SCs are assigned to each subscriber, there would be 85 users in the band. In other words, the number of SCs which are assigned to each subscriber will depend on the user's bandwidth and speed needs.

LTE uses OFDMA technology in the downlink and Single-Carrier Frequency-Division Multiple Access (SC-FDMA) in the uplink. The reason of OFDMA selection for the LTE downlink is achieving high spectral efficiency. In the OFDMA, multiple accesses illustrated in Figure 2.3, are achieved by allocating different sub-channels to different users logically on demand basis.

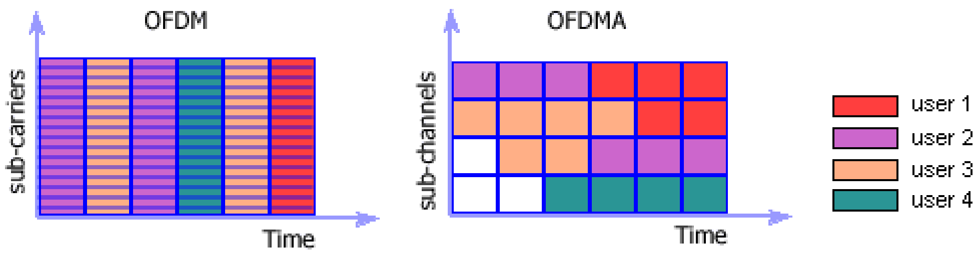

Figure 2.3 Difference between channel allocation using OFDM and OFDMA scheme [2]

OFDMA meets the LTE requirement for spectrum flexibility and enables cost-efficient solutions for very wide carriers with high peak rates. While OFDMA is thought as the best technique for the downlink, it is not the best solution for uplink due to the weaker Peak-To-Average Power Ratio (PAPR) properties of an OFDMA signal. Because it cause worse uplink coverage.

2.3 Single Carrier Frequency Division Multiple Access (SC-FDMA)

Single Carrier Frequency Division Multiple Access (SC-FDMA) is preferred for LTE uplink while OFDMA technique is used for LTE downlink. SC-FDMA is a new multiple access technique that utilizes single carrier modulation, Discrete Fourier transforms (DFT) spread orthogonal frequency multiplexing, and frequency domain equalization [4]. There are no many differences between SC-FDMA and OFDMA but it is called SC-FDMA in literature. If SC-FDMA and OFDMA is compared according to their structures, the main difference is DFT mapper. Transmitter and receiver structure for SC-FDMA and OFDMA are given in Figures 2.4 and Figure 2.5.

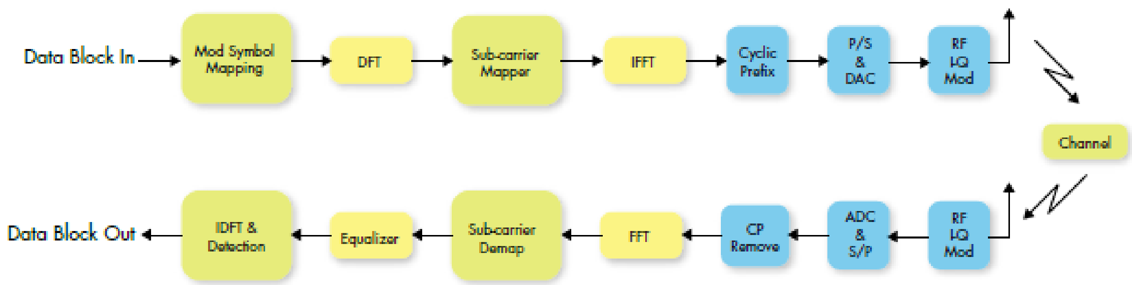

Figure 2.4 SC-FDMA transmitter and receiver [7]

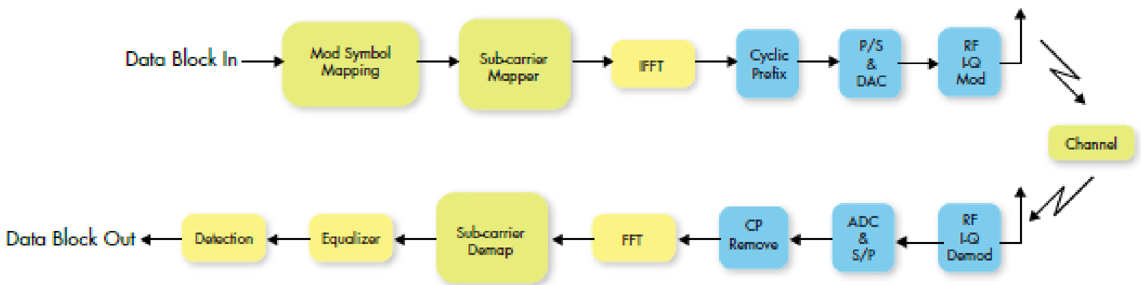

Figure 2.5 OFDMA transmitter and receiver [7]

In the comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols; it is seen that OFDMA transmits four QPSK data symbols in parallel, one per SC. But SC-FDMA transmits the four QPSK data symbols in series at for times the rate and each data symbol would have N x 15 kHz bandwidth. In other words, the difference is that in a SC-FDMA signal, the data symbols spread over all the SCs carrying information and produces a virtual single-carrier structure [6]. The difference between OFDMA and SC-FDMA can be seen in Figure 2. 6. As it can be seen, while OFDMA signal is a multi-carrier, the SC-FDMA signal is like a single-carrier, which explains the “SC” in its name. One SC-FDMA symbol in the time domain is calculated by computing the trajectory traced by moving from one QPSK data symbol to the next and this is done at N times the rate of the SC-FDMA symbol such that one SC-FDMA symbol contains N consecutive QPSK data symbols [8].

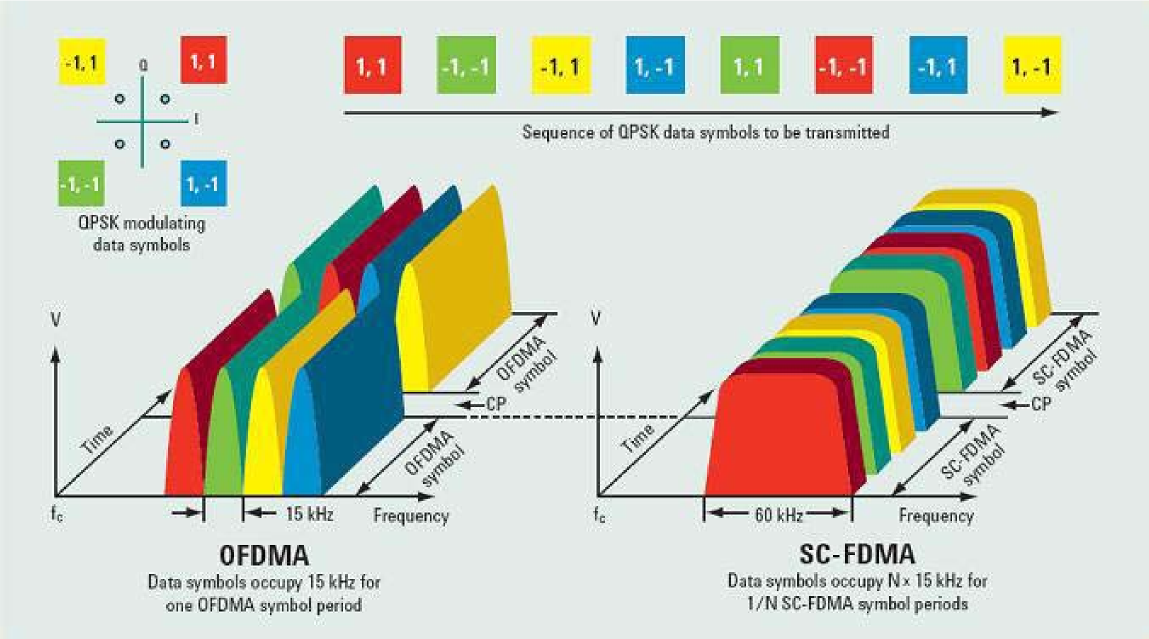

Figure 2.6 Comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols [8]

SC-FDMA offers similar performance and complexity as OFDM. However, the main advantage of SC-FDMA is the low PAPR (peak-average-power ratio) of the transmit signal [7]. Battery life is one of the important parameters which affect all mobile devices. Although battery performances have been improved a lot in the recent years, it is still one of the key factors for a mobile device to use minimum battery power. Within a mobile network, the most power is consumed while the radio frequency signal is transmitted to the base station via the antenna. So it is needed to ensure that it works in as efficient mode as possible. As a result it is necessary to employ a mode of transmission that has as near a constant power level when operating. Unfortunately

OFDM has a high peak to average ratio. Power is not a problem for the base station but it is really important for the mobile. As a result, LTE uses SC-FDMA as a modulation scheme. This combines the low peak to average ratio offered by single-carrier systems with the multipath interference resilience and flexible SC frequency allocation that OFDM provides.

CHAPTER 3

LTE AND LTE ADVANCED BACKGROUND

3.1 Introduction to LTE

3G technologies provide higher bit rates than 2G technologies and increase the average revenue per user for wireless data services. Although 3G brings advanced technologies, there is still more opportunities for wireless operators to take advantage of the increasing demand for wireless technology by providing lower latency and higher throughput. Therefore, there is still revenue opportunity in the wireless technologies with the next generation networks. Long term evolution is the next generation network solution beyond 3G. In the new telecommunication world, Internet applications such as Voice over IP (VoIP), video streaming, mobile TV, etc. evolve from fixed to mobile and LTE networks have the capability to respond these new trends.

Although LTE is the next generation network solution, there are some challenges for LTE. The most important challenge is to provide better cost and performance than DSL technologies, while maintaining mobility, service control and maximizing network capacity with limited spectrum resources.

Specific technical requirements include: Low latency and high throughput, efficient always-on operation, support for real-time and non-real-time applications, flexible spectrum allocations, re-use of existing cell site infrastructure, high spectrum efficiency for unicast, multicast and broadcast data.

In addition to the requirements above, there is a set of minimum performance requirements defined by the 3GPP Long-Term Evolution (LTE). These objectives include: Increased spectral efficiency and capacity, lower cost per bit, improved quality of experience (QoE).

Two key enabling technologies will help the industry meet and exceed the LTE performance objectives [9]. These technologies are Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input/Multiple Output (MIMO).

3.2 LTE Physical Layer

The LTE physical layer is responsible for coding, physical-layer hybrid-ARQ processing, modulation, multi-antenna processing, and mapping of the signal to the appropriate physical time–frequency resources. In a LTE network, LTE base station (eNodeB) and UE have different capabilities. Also LTE physical downlink and uplink are quite different. LTE specifications define both FDD and TDD modes of operation. But generic frame structure is used with FDD. Alternative frame structures are defined for use with TDD.

As it is discussed previously, OFDMA is the basic of the LTE downlink. In order to understand the OFDMA from the LTE perspective, we should have a look to the Physical layer generic frame structure. In OFDMA, a specific number of sub-carriers for predetermined amount of time are assigned to the users and these are called as physical resource blocks (PRB). PRBs are managed by a scheduled function at the eNodeB.

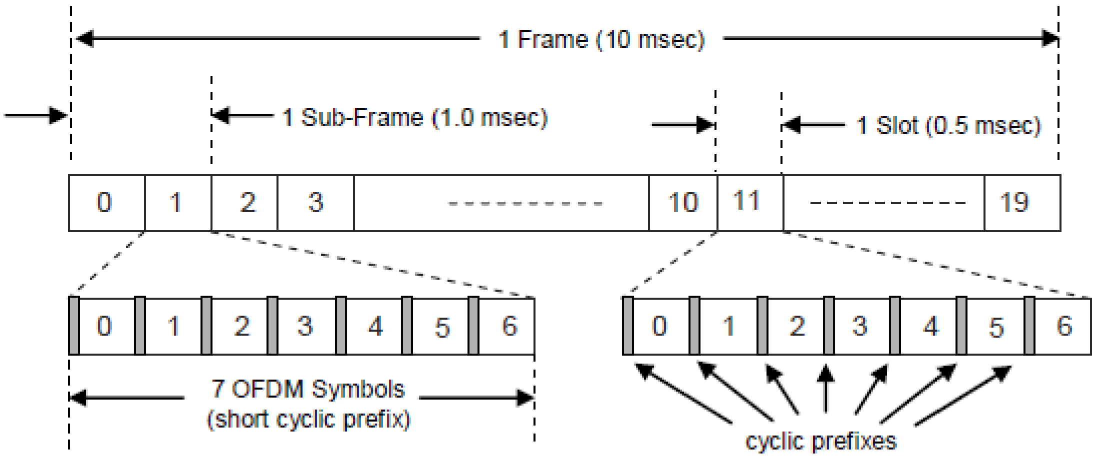

Figure 3.1 LTE generic frame structure [10]

As it is seen in Figure 3.1, LTE frames are 10 ms long. These frames are divided in to 10 subframes and each subframe is 1 ms. Each sub-frame is further divided into two slots, each of 0.5 ms duration. Slots consist of either 6 or 7 ODFM symbols, depending on whether the normal or extended cyclic prefix is employed [7].

Table 3.1 LTE downlink physical layer parameters [10]

Channel Bandwidth (MHz)	1,25	2,5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Sub-carrier Spacing (kHz)	15					
Sampling Frequency (MHz)	1,92	3,84	7,68	15,36	23,04	30,72
FFT Size	128	256	512	1024	1536	2048
Occupied Sub-carriers (Inc. DC sub-carrier)	76	151	301	601	901	1201
Guard Sub-carriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
Occupied Channel Bandwidth (MHz)	1,14	2,265	4,515	9,015	13,515	18,015
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	90%
OFDM Symbols/Subframe	7/6 (short/long CP)					
CP Length (Short CP) (µs)	5,2 (first symbol) / 4.69 (six following sybol)					
CP Length (Long CP) (µs)	16,67					

In LTE, possible bandwidth values of the system changes between 1.25 MHz and 20 MHz and the other parameters are defined according to this bandwidth range as shown in table 3.1. Number of available SCs is determined according to the overall transmission bandwidth of the system. A PRB is defined as consisting of 12 consecutive SCs for one slot (0.5 msec) in duration and also a PRB is the smallest element of resource allocation assigned by the base station scheduler [7].

The LTE supports physical channels and physical signals which are defined LTE physical layer. Physical channels carry information blocks received from the MAC and higher layers and physical signals are used for system synchronization, cell identification and radio channel estimation.

The types of downlink physical channels are Physical Downlink Shared Channel (PDSCH), Physical Broadcast Channel (PBCH), Physical Multicast Channel (PMCH), Physical Control Format Indicator Channel (PCFICH), Physical Downlink Control Channel (PDCCH) and Physical Hybrid ARQ Indicator Channel (PHICH). The types of uplink physical channels are Physical random access channel (PRACH) , Physical uplink control channel (PUCCH) and Physical uplink shared channel (PUSCH).

Let's look at the physical channels that are mentioned above briefly:

- PDSCH is the main physical channel used for unicast transmission, but also for transmission of paging information.
- PBCH caries part of the system information, required by the terminal in order to access the network.
- PMCH is used for MBSFN operation.
- PDCCH is used for downlink control information, mainly scheduling decisions, required for reception of PDSCH and for scheduling grants enabling transmission on the PUSCH.
- PHICH carries the hybrid-ARQ acknowledgement to indicate to the terminal whether a transport block should be retransmitted or not.
- PCFICH is a channel providing the terminals with information necessary to decode the set of PDCCHs. There is only one PCFICH in each cell.
- PUSCH is the uplink counterpart to the PDSCH. There is at most one PUSCH per terminal.

- PUCCH is used by the terminal to send hybrid-ARQ acknowledgements, indicating to the eNodeB whether the downlink transport block(s) was successfully received or not, to send channel-status reports aiding downlink channel-dependent scheduling, and for requesting resources to transmit uplink data upon. There is at most one PUCCH per terminal.
- PRACH is used for random access.

3.2.1 Physical Signals

There are two types of signals, Reference signal and Synchronization signal. Reference signals used to determine the channel impulse response (CIR). Synchronization signals which carry network timing information.

3.2.1.1 Reference Signal

Channel estimation is needed to be performed by a mobile terminal to carry out coherent demodulation of different physical channels. Channel estimation can be enabled by adding known reference symbols into the OFDM/SC-FDM time frequency grid. There are three kinds of reference signals for the LTE downlink: cell-specific downlink reference signals, UE-specific reference signals and MBSFN reference signals [12]. Also there are two types of reference signals for the LTE uplink: demodulation reference signal (DRS) and sounding reference signal

Figure 3.2 shows an example of reference symbols for 1 antenna transmission. The reference signals structure changes according to the antenna configuration.

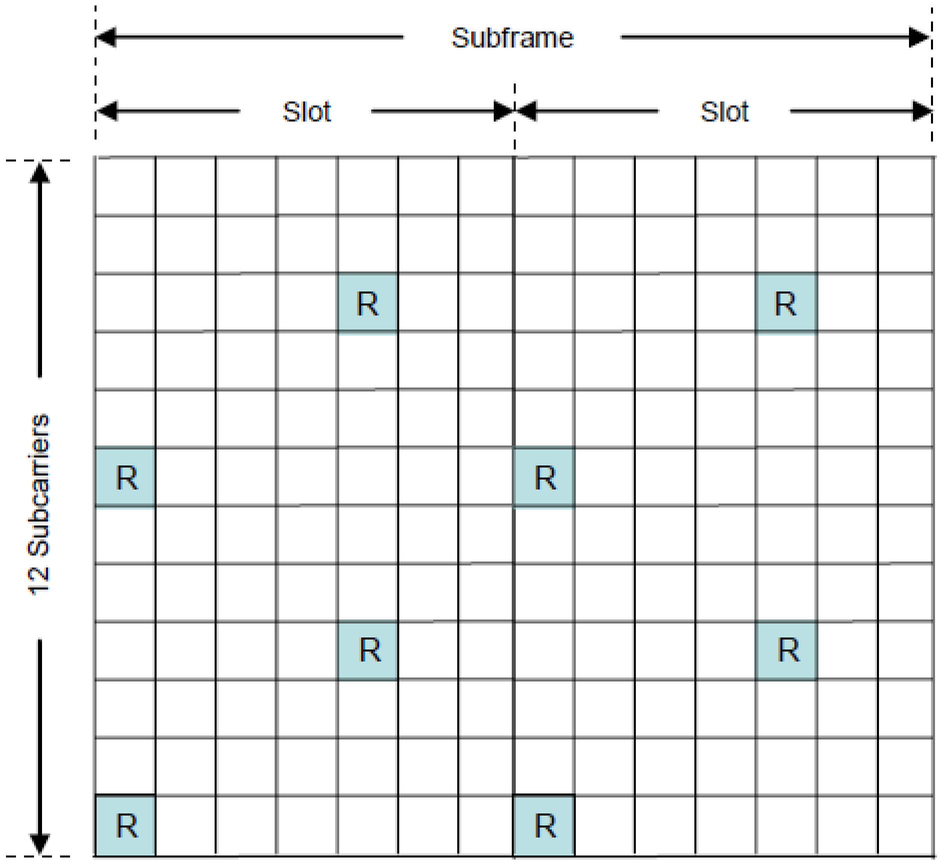

Figure 3.2 LTE reference signals are interspersed among resource elements [12]

3.2.1.2 Synchronization Signals

Synchronization signals use the same type of pseudo-random orthogonal sequences as reference signals. These are classified as primary and secondary synchronization signals, depending how they are used by UE during the cell search procedure. Both primary and secondary synchronization signals are transmitted on the 72 SCs centered around the DC SC during the 0th and 10th slots of a frame (recall there are 20 slots within each frame) [10].

3.3 Adaptive Modulation and Coding (AMC)

Adaptive Modulation and Coding is a link adaptation method in cellular communications system. AMC aims to match dynamically the transmission parameters to the channel conditions to improve the overall spectral efficiency. The quality of a signal received by a UE depends on a couple of parameters. These are can be summarized as the channel quality from the serving cell, the distance between the desired and interfering base stations, the level of interference from other cells and the noise level. There are 2 parts in AMC and they are modulation scheme and code rate.

There are a couple of modulation techniques which can be used for AMC. If QPSK method is used for modulation, it will be more robust and can tolerate higher levels of interference but provides a lower transmission bit rate since QPSK can encode two bits per symbol. On the other hand, if 64QAM is used for modulation, it will provide higher bit rate but is more prone to errors due to its higher sensitivity to interference, noise and channel estimation errors. Therefore it is worth to use when the Signal to Interference and Noise Ratio (SINR) is sufficiently high. For a given modulation, the code rate can be chosen depending on the radio link conditions: A lower code rate can be used in poor channel conditions and a higher code rate in the case of high SINR [12]. Typically higher order modulation with higher code rates are assigned to the users which are close to the base station, but the modulation-order and/or code rate will decrease as the distance from base station increases, in a system with AMC.

Modulation and Coding Scheme (MCS) is selected by eNodeB for the downlink data transmissions in LTE. While eNodeB is doing this selection, it uses Channel Quality Indicator (CQI) feedback criteria which transmitted by the UE in the uplink. CQI feedback is an indication of the data rate which can be supported by the channel. Also SINR and the characteristics of the UE's receiver should be considered for the CQI feedback. In general, in response to the CQI feedback the eNodeB can select between QPSK, 16-QAM and 64-QAM schemes with a wide range of code rates. A simple method by which a UE can choose an appropriate CQI value could be based on a set of Block Error Rate (BLER) thresholds. The UE would report the CQI value corresponding to the MCS that ensures BLER ≤ 10% based on the measured received signal quality [12].

ENodeb is responsible to schedule the uplink resources. Also it is responsible to assign certain time/frequency resources to the UEs and inform UEs about transmission format to use. The scheduling decisions may be based on QoS parameters, UE buffer status, uplink channel quality measurements, UE capabilities, UE measurement gaps, etc [13]. An identical channel coding structure is used for the uplink, while the modulation scheme may be selected between QPSK and 16QAM. The 64QAM is optional for the LTE uplink.

3.4 Hybrid Automatic Repeat Request (HARQ) and Channel Quality Indicator (CQI)

In LTE, HARQ and CQI are two important features that provide transmission robustness.

3.4.1 HARQ

H-ARQ combines detection and Forward Error Correction (FEC) plus a retransmission of the erroneous packet [14]. H-ARQ uses a FEC code that can correct some frame errors. The H-ARQ operation described above discards erroneously received packets and requests retransmission. Even if the some packets are erroneous, the received signal still contains information and this information is lost by discarding the erroneous packets. This problem is solved by hybrid ARQ with soft combining. There are 2 methods for H-ARQ with soft combining. These are: Chase combining and Incremental Redundancy (IR). The difference between these 2 methods is whether the retransmitted bits are required to be identical to the original transmission or not.

In the Chase combining method, the retransmitted bits are identical to the original transmission. After each retransmission, the receiver uses maximum-ratio combining to combine each received channel bit with any previous transmissions of the same bit and the combined signal is sent to the decoder [15]. Chase combining does not provide any advantages to have additional coding gain. But it increases the accumulated received Eb / N0 for each retransmission (Figure 3.3).

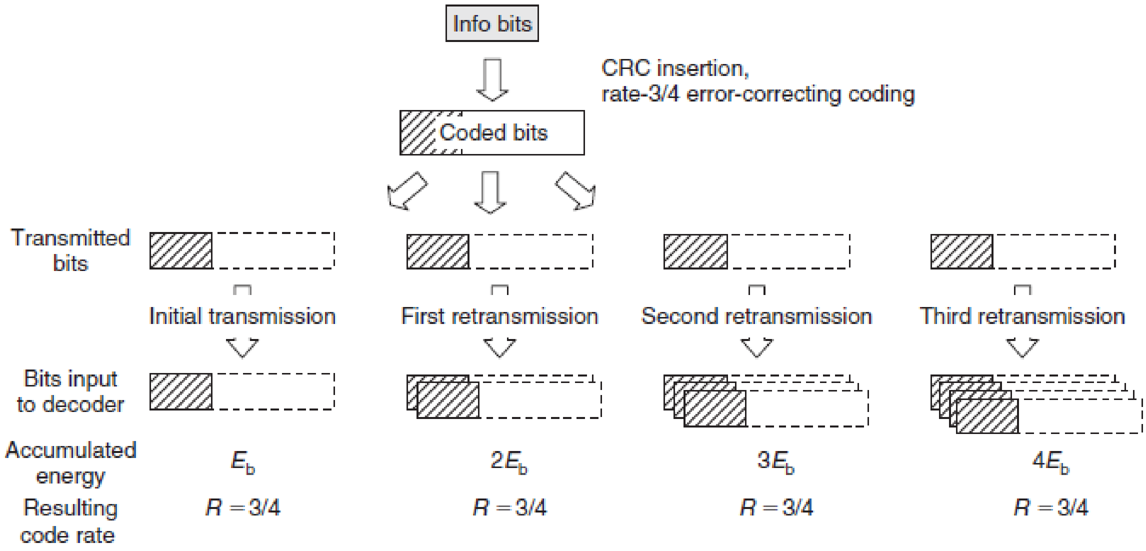

Figure 3.3 Example of chase combining [15]

In Incremental Redundancy method, the retransmitted bits are not needed to be identical to the original transmission. In this method, multiple sets of coded bits are generated. But they are representing the same set of information bits. Whenever a retransmission is required, the retransmission typically uses a different set of coded bits than the previous transmission. The receiver combines the retransmission with previous transmission attempts of the same packet. Incremental redundancy can be seen as a generalization of Chase combining or, stated differently, Chase combining is a special case of incremental redundancy [15].

In Incremental Redundancy, in the first transmission only a limited number of the coded bits are transmitted. In the retransmissions, additional coded bits are transmitted. As an example, assume a basic rate-1/4 code. In the first transmission, only every third coded bit is transmitted, effectively giving a rate-3/4 code as illustrated in Figure 3. 4. In case of a decoding error and a subsequent request for a retransmission, additional bits are transmitted, effectively leading to a rate-3/8 code. After a second retransmission the code rate is 1/4. In case of more than two retransmissions, already transmitted coded bits would be repeated. In addition to a gain in accumulated received Eb / N0, incremental redundancy also results in a coding gain for each retransmission. The gain with IR compared to Chase is larger for high initial code rates while at lower initial coding rates, Chase combining is almost as good as IR.

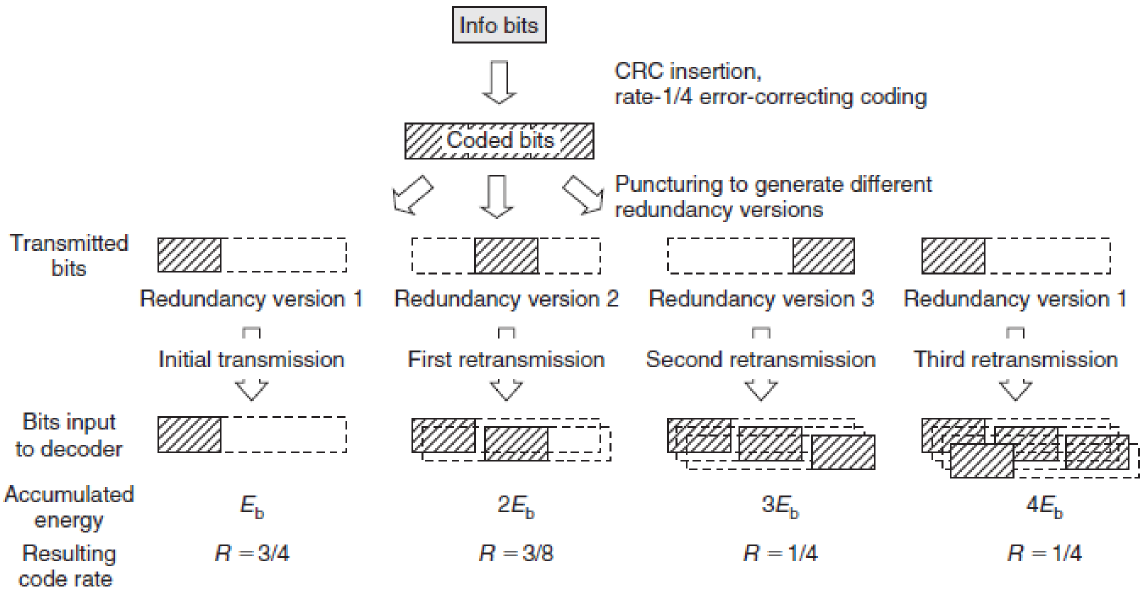

Figure 3.4 Example of incremental redundancy [15]

In the discussion so far, it has been assumed that the receiver has received all the previously transmitted redundancy versions. If all redundancy versions provide the same amount of information about the data packet, the order of the redundancy versions are not critical. As a result, transmission integrity is guaranteed by the application of a Hybrid Automatic Repeat Request retransmission scheme. The performance of the retransmission handling strongly influences the performance of LTE both on the physical layer as well as from a network perspective. Therefore, one of the central features that provide transmission robustness is hybrid- ARQ, which in LTE provides physical layer retransmission using incremental redundancy and chase combining.

3.4.2 CQI

CQI can be thought as an indicator which represents the channel quality. However, CQI actually represent the data rate on the current channel conditions which can be supported by UE. In other words, CQI is a recommended data rate which is equivalent to transport block size.

The CQI does not clearly represent the channel quality measures because different data rates might be supported by different UE in the identical environments. In addition to that, quality of service depends on the quality of receiver. If a UE has a better receiver, it can be utilized to provide better service (higher data rates) to such a UE and this provides a benefit with advanced receiver structures for the end user. For a power-controlled channel, the gain from an advanced receiver is seen as a lower transmit power at the NodeB, thus providing a benefit for the network but not the end user.

The way to calculate the CQI is using performance metrics. Some of these performance metrics are signal-to-noise ratio (SNR), signal-to-interference plus noise ratio (SINR), signal-to-noise plus distortion ratio (SNDR), etc. After these performance metrics are measured, they can be used to calculate the CQI for the channel. In a communication system, different transmission scheme uses different CQI for a given channel. For example, time-division multiple access (TDMA) can use different CQI than OFDMA. The other factors that can considered for CQI are receiver type (for multiple-input multiple output), interference, channel estimation error and so forth.

Block Error Rate (BLER) is an important factor for a UE for the selection of appropriate CQI value. The UE would report the CQI value corresponding to the MCS that ensures BLER ≤ 10% based on the measured received signal quality [16]. The list of modulation schemes and code rates with CQI values supported by 3GPP LTE standards is shown in Table 3.2.

Table 3.2 CQI table for modulation schemes [17]

CQI index	Modulation	Approximate code rate	Efficiency (information bits per symbol)
0	No Transmission	--	--
1	QPSK	0.076	0,1523
2	QPSK	0.12	0,2344
3	QPSK	0.19	0,3770
4	QPSK	0.3	0,6016
5	QPSK	0.44	0,8770
6	QPSK	0.59	1,1758
7	16QAM	0.37	1,4766
8	16QAM	0.48	1,9141
9	16QAM	0.6	2,4063
10	64QAM	0.45	2,7305
11	64QAM	0.55	3,3223
12	64QAM	0.65	3,9023
13	64QAM	0.75	4,5234
14	64QAM	0.85	5,1152
15	64QAM	0.93	5,5547

3.5 Multiple Input Multiple Output (MIMO)

MIMO, Multiple Input Multiple Output, is one of the major features of the LTE, introduced to increase the peak data rates through multi-stream transmission. MIMO is the use of multiple antennas at both transmitter and receiver. This can be used to obtain a diversity gain and thereby increase the carrier-to-interference ratio at the receiver [15]. MIMO is important for LTE to achieve the requirements for throughput and spectral efficiency.

MIMO transmits two or more data streams in the same channel at the same time, using multi-antennas at transmitter and receiver. There are 2 main features of the MIMO. One of them is achieving high throughput without consuming extra radio frequency. Achieving higher spectral efficiency is very important because of the scarcity of available radio frequencies. The other main feature is achieving high link reliability of wireless communication.

A MIMO system consists of N transmit and M receive antennas (Figure 3.5). In a MIMO system, each antenna does not receive only the direct components intended for it, but also receives the indirect components intended for the other antennas, in the same channel. A time independent, narrowband channel is assumed. The direct connection from antenna 1 to 1 is specified with h11, etc., while the indirect connection from antenna 1 to 2 is identified as cross component h21, etc. From this is obtained transmission matrix **H** with the dimensions **n x m** [18].

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{..} & h_{1m} \\ h_{21} & h_{22} & h_{..} & h_{2m} \\ h_{..} & h_{..} & h_{..} & h_{.m} \\ h_{n1} & h_{n2} & h_{n.} & h_{nm} \end{bmatrix}$$

Formula 1: Matrix H

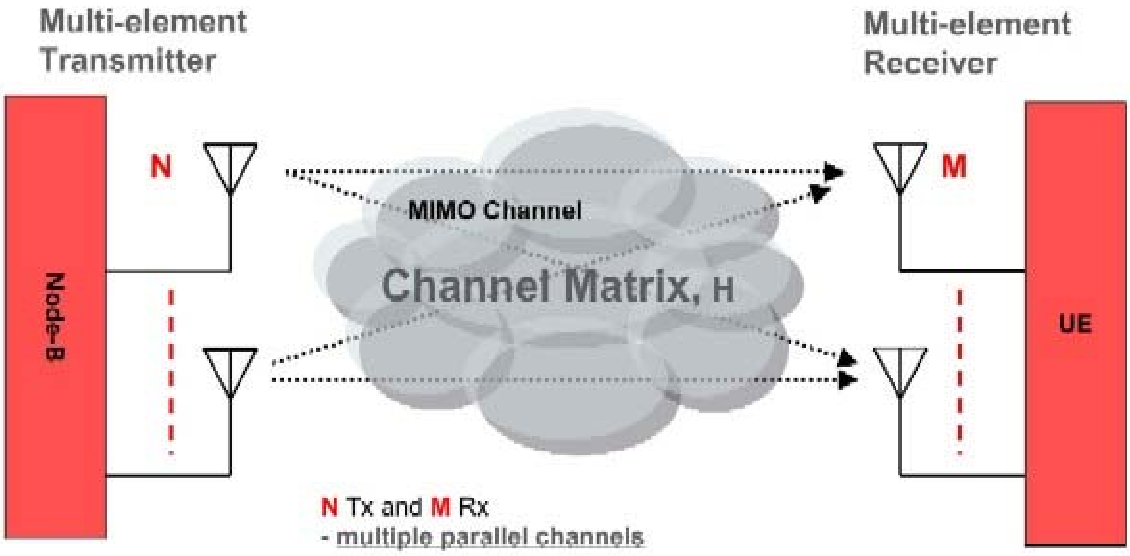

Figure 3.5 General MIMO [19]

There are 2 functionality modes of MIMO. They are Spatial Multiplexing mode and Transmit Diversity mode.

3.5.1. Spatial Multiplexing

In the spatial multiplexing mode, the data streams transmitted can belong to one single user (single user MIMO/SU-MIMO) (see Figure 3.6) or to different users (multi user MIMO/MU-MIMO) (see Figure 3.7).

3.5.1.1 Single User MIMO

When the data rate is to be increased for a single UE, this is called Single User MIMO (SU-MIMO)

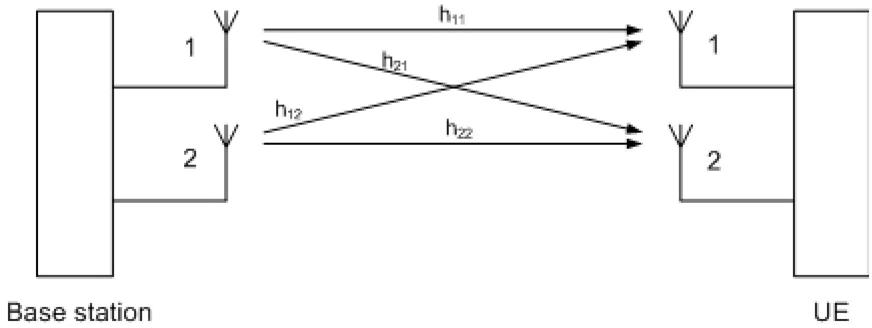

Figure 3.6 SU-MIMO

3.5.1.2 Multi User-MIMO

When the individual streams are assigned to various users, this is called Multi User MIMO (MU-MIMO). This mode is particularly useful in the uplink because the complexity on the UE side can be kept at a minimum by using only one transmit antenna. This is also called 'collaborative MIMO'.

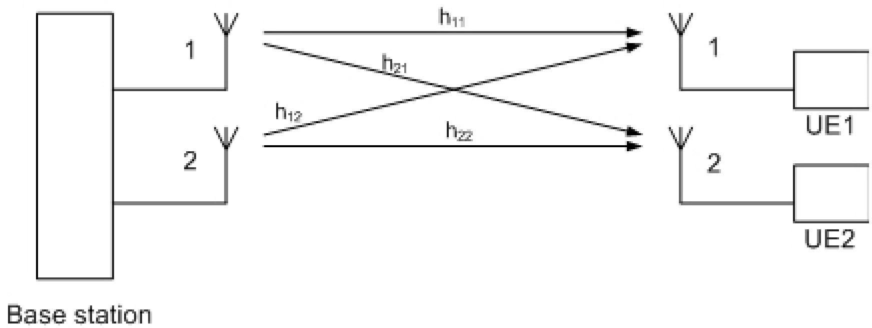

Figure 3.7 MU-MIMO

3.5.2 Spatial Diversity

The purpose of spatial diversity is to make the transmission more robust. There is no increase in the data rate. This mode uses redundant data on different paths.

3.5.2.1 Transmit Diversity

When there are more Transmit than Receive antennas, this is called Transmit diversity. The simplest scenario uses two Transmit antennas and one Receive antenna (Multiple Input Single Output (MISO, 2x1)).

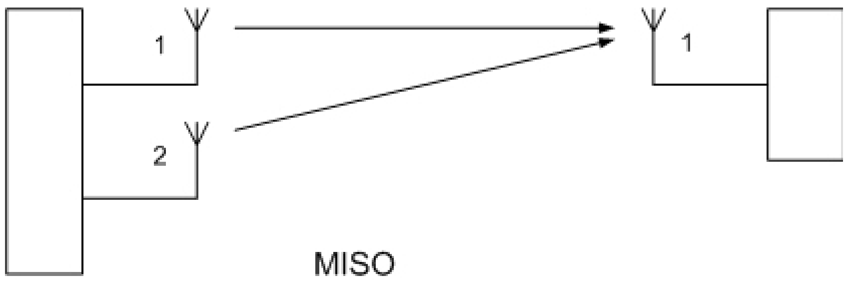

Figure 3.8 MISO

3.6 LTE Frequency Bands & Spectrum Allocations

There are a lot of LTE frequency bands which are designated for the use with LTE. While some of the LTE frequency bands are already used by other wireless systems, some of the frequency bands are new.

3.6.1 FDD and TDD LTE frequency bands

While FDD spectrum requires 2 frequency bands, one for uplink and one for downlink, TDD uses same frequency band for uplink and downlink. Briefly, there are different LTE band allocations for TDD and FDD. In some cases frequency bands can overlap, so there is possibility for TDD and FDD transmission for being on a particular LTE frequency band.

In LTE communication system, UE will need to detect whether FDD or TDD transmission can be made on a given frequency band. UE can detect FDD and TDD on the same band and it needs to choose the correct transmission type.

3.6.1.1 FDD LTE frequency band allocations

The FDD frequency bands are paired to allow simultaneous transmission on two frequencies. There is enough separation between bands to enable the transmitted signals not to affect the receiver performance.

Table 3.3 FDD LTE frequency bands [4]

LTE Band Number	Uplink (MHz)	Downlink(MHz)
1	1920 - 1980	2110 - 2170
2	1850 - 1910	1930 - 1990
3	1710 - 1785	1805 -1880
4	1710 - 1755	2110 - 2155
5	824 - 849	869 - 894
6	830 - 840	875 - 885
7	2500 - 2570	2620 - 2690
8	880 - 915	925 - 960
9	1749.9 - 1784.9	1844.9 - 1879.9
10	1710 - 1770	2110 - 2170
11	1427.9 - 1452.9	1475.9 - 1500.9
12	698 - 716	728 - 746
13	777 - 787	746 - 756
14	788 - 798	758 - 768
17	704 - 716	734 - 746
18	815 - 830	860 - 875
19	830 - 845	875 - 890
20	832 - 862	791 - 821
21	1447.9 - 1462.9	1495.5 - 1510.9
22	3410 - 3500	3510 - 3600

Note: LTE bands 15 & 16 are reserved, but not yet defined.

3.6.1.2 TDD LTE frequency band allocations

In LTE TDD, frequency band are not paired since same band is used for both uplink downlink.

Table 3.4 TDD LTE frequency band [4]

LTE Band Number	Allocation(MHz)
33	1900 - 1920
34	2010 - 2025
34	2010 - 2025
35	1850 - 1910
36	1930 - 1990
37	1910 - 1930
38	2570 - 2620
39	1880 - 1920
40	2300 - 2400
41	3400 - 3600

All of these bands are available in each of the world's regions. Table 3.5 for instance illustrates the typical deployment areas for the different FDD variants.

There are regular additions to the LTE frequency bands / LTE spectrum allocations as a result of negotiations at the ITU regulatory meetings. These LTE allocations are resulting in part from the digital dividend, and also from the pressure caused by the ever growing need for mobile communications. Many of the new LTE spectrum allocations are relatively small, often 10 - 20MHz in bandwidth, and this is a cause for concern. With LTE-Advanced needing bandwidths of 100 MHz, channel aggregation over a wide set of frequencies many be needed, and this has been recognized as a significant technological problem.

Table 3.5 Usage of the frequency variants within the world's regions [20]

Band	Europa	Asia	Japan	Americas
1	X	X	X	
2				X
3	X	X		
4				X
5		X		X
6			X	
7	X	X		
8	X	X		
9			X	
10				X
11			X	
12				X
13			X	
14				X
15				X
16				X
17				X
18			X	

CHAPTER 4

LTE ARCHITECTURE

In contrast to the circuit-switched model of previous cellular systems, Long Term Evolution has been designed to support only packet-switched services. It aims to provide seamless IP connectivity between user UE and the packet data network (PDN), without any disruption to the end users' applications during mobility.

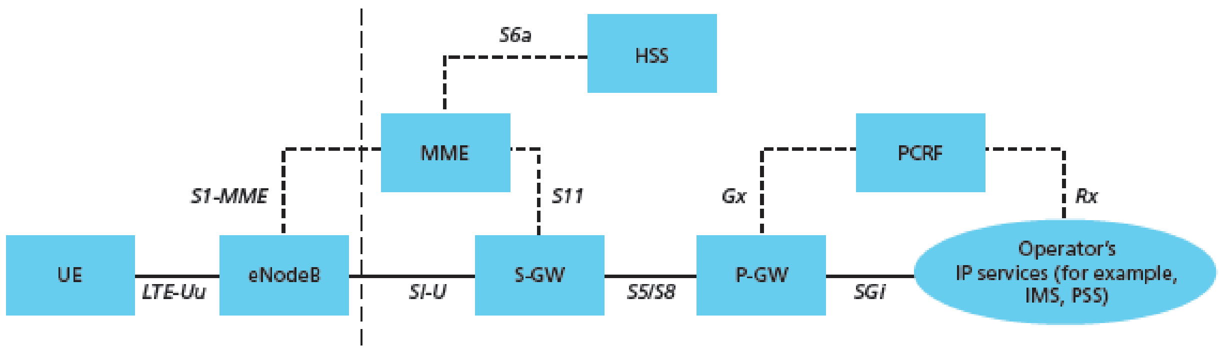

Figure 4.1 The EPS network elements [24]

The evolved packet system (EPS) includes EPC, LTE, and the UE. EPS provides the user with IP connectivity to a PDN for accessing the Internet, as well as for running services such as Voice over IP (VoIP). An EPS bearer is typically associated with a QoS. Multiple bearers can be established for a user in order to provide different QoS streams or connectivity to different PDNs. For example, a user might be engaged in a voice (VoIP) call while at the same time performing web browsing or FTP download. A VoIP bearer would provide the necessary QoS for the voice call, while a best-effort bearer would be suitable for the web browsing or FTP session.

The network must also provide sufficient security and privacy for the user and protection for the network against fraudulent use.

This is achieved by means of several EPS network elements that have different roles. Figure 4.1 shows the overall network architecture, including the network elements and the standardized interfaces. At a high level, the network is comprised of the CN (EPC) and the access network E-UTRAN. While the CN consists of many logical nodes, the access network is made up of essentially just one node, the evolved NodeB (eNodeB), which connects to the UEs. Each of these network elements is interconnected by means of interfaces that are standardized in order to allow multi-vendor interoperability. This gives network operators the possibility to source different network elements from different vendors. In fact, network operators may choose in their physical implementations to split or merge these logical network elements depending on commercial considerations. The functional split between the EPC and E-UTRAN is shown in Figure 4.2. The EPC and E-UTRAN network elements are described in more detail below [24].

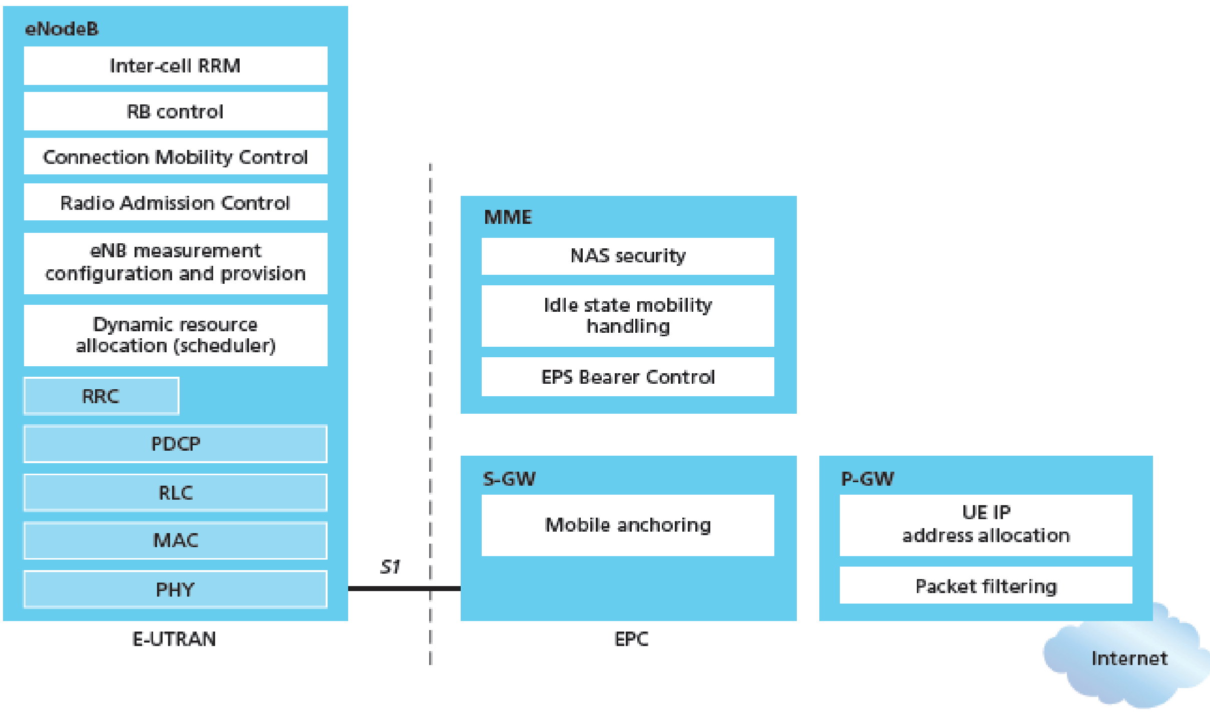

Figure 4.2 Functional split between E-UTRAN and EPC [24]

4.1 The Core Network

The core network (called EPC in SAE) is responsible for the overall control of the UE and establishment of the bearers. Evolved Packet Core (EPC) is the IP-based core network between LTE and other networks. On the user plane, EPC connects LTE with the SGW, and on the control plane, with the MME.

The PDN-GW provides the user plane interface to other packet data networks.

EPC defines a series of new network functions that flattens the architecture by reducing the number of nodes in the network, which promises to reduce capital and operational expenditures; thereby reducing the overall cost per megabyte of traffic running over the EPC, while improving network performance

The main logical nodes of the EPC are:

• PDN Gateway (P-GW)

• Serving Gateway (S-GW)

• Mobility Management Entity (MME)

In addition to these nodes, EPC also includes other logical nodes and functions such as the Home Subscriber Server (HSS) and the Policy Control and Charging Rules Function (PCRF). Since the EPS only provides a bearer path of a certain QoS, control of multimedia applications such as VoIP is provided by the IP Multimedia Subsystem (IMS), which is considered to be outside the EPS itself.

PCRF – The Policy Control and Charging Rules Function is responsible for policy control decision-making, as well as for controlling the flow-based charging functionalities in the Policy Control Enforcement Function (PCEF), which resides in the P-GW. The PCRF provides the QoS authorization (QoS class identifier [QCI] and bit rates) that decides how a certain data flow will be treated in the PCEF and ensures that this is in accordance with the user's subscription profile.

HSS – The Home Subscriber Server contains users' SAE subscription data such as the EPS-subscribed QoS profile and any access restrictions for roaming. It also holds information about the PDNs to which the user can connect. This could be in the form of an access point name (APN) (which is a label according to DNS naming conventions describing the access point to the PDN) or a PDN address (indicating subscribed IP address(es)). In addition the HSS holds dynamic information such as the identity of the MME to which the user is currently attached or registered. The HSS may also integrate the authentication center (AUC), which generates the vectors for authentication and security keys. HSS can be thought as HLR in the GSM network.

PDN-GW – The PDN Gateway acts as the interface between the LTE network and Packet Data Networks (PDNs), such as the Internet or SIP-based IMS networks (fixed and mobile). The PDN-GW is the mobility anchor point for intra-3GPP access system mobility and for mobility between 3GPP access systems and non-3GPP access systems. The function is responsible for IP address allocation, charging, deep packet inspection, lawful intercept, policy enforcement, and other services.

MME – The Mobility Management Entity (MME) resides in the control plane and manages states (attach, detach, idle, RAN mobility), authentication, paging, mobility with 3GPP 2G/3G nodes (SGSN), roaming, and other bearer management functions.

SGW – The Serving Gateway (SGW) sits in the user plane where it forwards and routes packets to and from the eNodeB and Packet Data Network Gateway (PGW). The SGW also serves as the local mobility anchor for inter-eNodeB handover and roaming between two 3GPP systems. SGW and MME work as SGSN in GSM network.

4.2 The Access Network

The access network of LTE, E-UTRAN, simply consists of a network of eNodeBs, as illustrated in Figure 4.3. For normal user traffic (as opposed to broadcast), there is no centralized controller in E-UTRAN; hence the E-UTRAN architecture is said to be flat.

The eNodeBs are normally interconnected with each other by means of an interface known as “X2” and to the EPC by means of the S1 interface — more specifically, to the MME by means of the S1-MME interface and to the S-GW by means of the S1-U interface.

The protocols that run between the eNodeBs and the UE are known as the “AS protocols.”

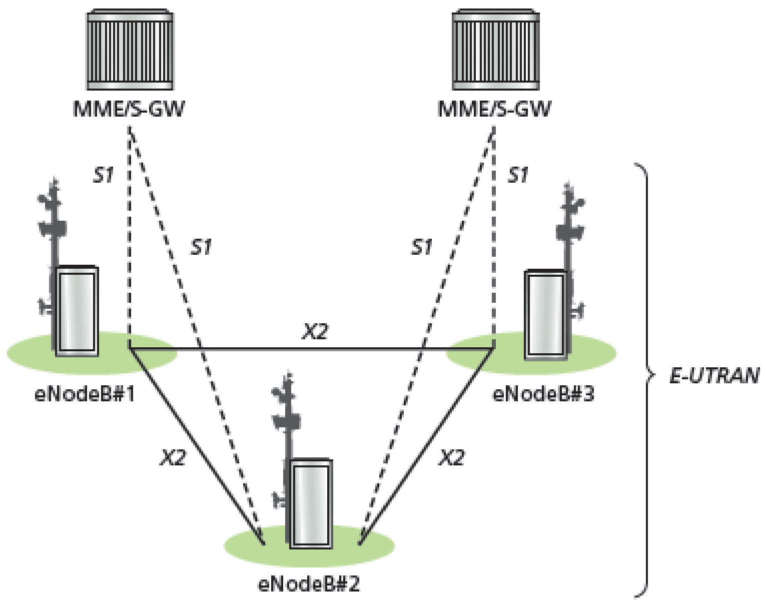

Figure 4.3 LTE Access Network [25]

The E-UTRAN is responsible for all radio-related functions, which can be summarized briefly as:

• Radio resource management (RRM) – This covers all functions related to the radio bearers, such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources to UEs in both uplink and downlink.

• Header Compression – This helps to ensure efficient use of the radio interface by compressing the IP packet headers that could otherwise represent a significant overhead, especially for small packets such as VoIP.

• Security – All data sent over the radio interface is encrypted.

• Connectivity to the EPC – This consists of the signaling toward MME and the bearer path toward the S-GW.

On the network side, all of these functions reside in the eNodeBs, each of which can be responsible for managing multiple cells. Unlike some of the previous second- and third-generation technologies, LTE integrates the radio controller function into the eNodeB. This allows tight interaction between the different protocol layers of the radio access network (RAN), thus reducing latency and improving efficiency. Such distributed control eliminates the need for a high-availability, processing-intensive controller, which in turn has the potential to reduce costs and avoid “single points of failure.”

CHAPTER 5

SIMULATIONS AND ANALYSIS

5.1 Simulator

LTE simulator has been developed by Institute of Communications and Radio-Frequency Engineering Vienna University of Technology. There 2 types of simulators for the LTE. They are;

- LTE Link Level Simulator
- LTE System Level Simulator

The LTE simulators are published under a non-commercial academic use license.

In this thesis, LTE Link Level Simulator is used. The LTE simulators are implemented in Matlab and require the following packages:

- Matlab 7.8.0 (R2009a)
- Communications Toolbox 4.1
- Signal Processing Toolbox 6.

The main file of the LTE Link Level Simulator is LTE_sim_main.m. And also there is another file to run the simulations. It is the LTE_sim_batch.m, which performs the following tasks:

1. Setting the SNR range for the simulation.
2. Loading a configuration file.
3. Executing the LTE_sim_main.m main simulation file.
4. Saving the results to a file.

The simulator allows for the following settings to be adjusted (please check reference [20] for a complete list):

- Number of User Equipments (UEs) attached to the eNodeB.
- Uplink delay
- Number of frames to simulate
- SNR
- transmit and receive antenna numbers
- channel model
- transmit mode (as defined by the standard)
- scheduling algorithm

By adjusting the above parameters, the Block Error Ratio (BLER) and throughput results are simulated.

Below you can find a list of exemplary parameters that you may want to configure in the batch file:

Cqi i: set of MCSs that are used for the simulation. If you want to simulate for all possible CQIs, just set cqi_i t be [1:15].

N subframes: the length of the simulation, or how many subframes (TTIs) are simulated.

SNR vec: a vector containing the SNRs that will be used for each simulation run. Use an SNR range adequate to the CQI that you are simulating.

LTE load parameters: load the parameter file that configures the simulator. Four preconfigured options are given.

LTE load parameters SUSISO: Single-user SISO simulation

LTE load parameters MUSISO: Multı-user (preconfigured to two users) SISO simulation

LTE load parameters SUMIMO: Single-user Multiple-Input-Multiple-Output (MIMO) simulation

LTE load parameters MUMIMO: Multi-user (two users) MIMO simulation

5.2 Analysis of Parameters

The 3rd Generation Partnership Project (3GPP)'s Release 8 LTE has defined the next (future) step of 3G cellular technology. LTE offers many significant improvements over previous technologies such as UMTS/HSPA. Higher downlink and uplink speeds, lower latency and simpler network architecture are among the new and important features that are provided in LTE.

In this work, the simulations for the performance analysis of LTE are presented. The effects of different parameters and other factors are investigated. The important parameters and settings in each simulation are shown as in the Table 4.1. In figures below the performance analysis results are shown in terms of Block Error Ratio (BLER) and Throughput versus Signal-to-Noise Ratio (SNR). Notice that the title of each figure shows the (important) settings and parameters used in the corresponding simulation.

Table 5.1 Simulation Parameters

Parameter	***Value***
Number of User Equipments (UEs)	1, 5, 10, and 20
Bandwidth (BW)	1.4, 5, and 10 MHz
Retransmission (HARQ*)	0 and 3
Channel types**	AWGN, Flat Rayleigh, PedA, PedB, VehA, and VehB
Filtering	Block Fading
Simulation length	500 Subframes
Transmit modes	SISO, TxD(2x1 and 4x2) and OLSM(4x2)***
Receiver type	Soft Sphere Decoder

*Hybrid Automatic Repeat request, possible values are 0, 1, 2 and 3
**ITU channel models: PedA 3km/h, PedB 10km/h , VehA 30km/ h, VehB 120km/h
***OLSM: Open Loop Spatial Multiplexing.

Channel Quality Indicators (CQI) is related to the Modulation and Coding Schemes (MCSs), this relation is determined by 3rd Generation Partnership Project as in Technical Specification Group Radio Access Network, "Evolved universal terrestrial radio access (E-UTRA); physical layer procedures," 3GPP, Tech. Rep. TS 36.213, Mar. 2009. 04.2. shows the specific values of CQI and corresponding modulation schemes.

Table 5.2 4-bit CQI Table

CQI index	modulation	code rate x 1024
0	out of range	
1	QPSK	78
2	QPSK	120
3	QPSK	193
4	QPSK	308
5	QPSK	449
6	QPSK	602
7	16QAM	378
8	16QAM	490
9	16QAM	616
10	64QAM	466
11	64QAM	567
12	64QAM	666
13	64QAM	772
14	64QAM	873
15	64QAM	948

5.3 Simulation Results

In LTE, one of the main features that provide transmission robustness is hybrid-ARQ (HARQ), which in LTE provides physical layer retransmission using incremental redundancy and soft combining. A transmission scheme based on H-ARQ combines detection and Forward Error Correction (FEC) plus a retransmission of the erroneous packet. LTE additionally uses soft combining, in which a given received packet is combined with the previously received packets and the resulting more powerful FEC code is then decoded. Hence, for each H-ARQ retransmission that the LTE system can employ, an improvement of the Block Error Rate (BLER) or throughput is expected.

From Figure 4.1 and Figure 4.2, the LTE simulations for the HARQ evaluation process were performed for a single-user scenario corresponding to the simulation parameters shown on figures' titles in 5MHz BW and when there is no HARQ, while Figure 4.3 and Figure 4.4 with the same parameters when there are 3 retransmissions. Even there is no much difference on high SNR values, the difference on the throughput and BLER can easily be observed that in lower SNR values such as -5 to 5 dB, there is significant improvement thanks to HARQ.

In addition to HARQ, the effects of MIMO are also investigated in figures from 4.1 to 4.4. In these four figures the throughput of SISO, 2x1 (MISO) transmit diversity (TxD), 4x2 transmit diversity (MIMO), and 4x2 Open Loop Spatial Multiplexing (OLSM) is compared when transmitting over Pedestrian B (PedB) channel type over 5MHz channel BW. Again in these simulations the CQI value is set to 7.

The maximum throughput values achieved by the different MIMO schemes in Figures depends on the number of transmit antennas and on the number of data streams. If more transmit antennas are utilized for the transmission, more pilot symbols are inserted in the OFDM frame and thus lower maximum throughput can be achieved.

In the case of Open-Loop Spatial Multiplexing (OLSM), spatial multiplexing forms multiple independent links (on same channel) between transmitter and receiver to communicate at higher total data rates (Increases data rates by transmitting parallel data streams). Two spatially separated data streams are transmitted, thus leading to twice the maximum throughput of the 4x2 TxD systems. Because of the relationship between the diversity gain and spatial multiplexing gain, when diversity gain is accepted as Baseline, the spatial multiplexing gain will be (min{4,2},0)=(2,0)= 2 times in our figures. This affect can be seen from the figures below (approximately 5.25x2=10.5Mbps).

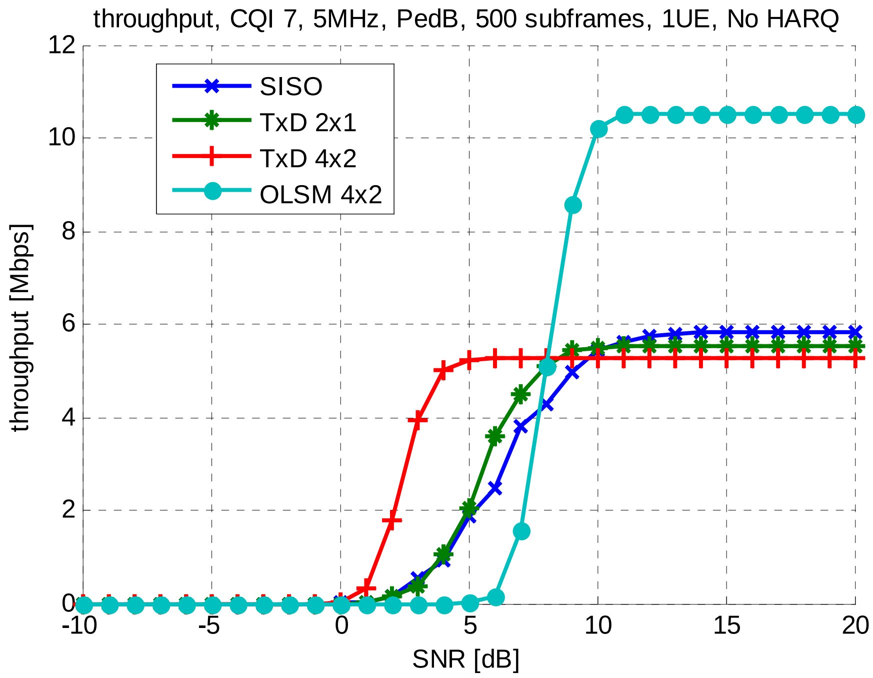

Figure 5.1 Throughput performances of the SISO, MIMO and OLSM in 5MHz with No HARQ.

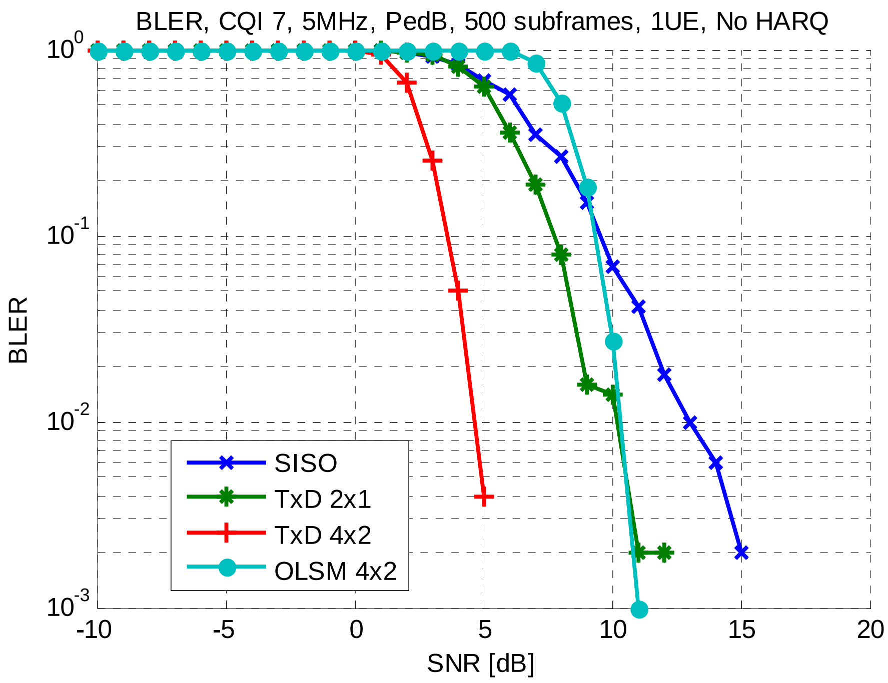

Figure 5.2 BLER performances of the SISO, MIMO and OLSM in 5MHz with No HARQ.

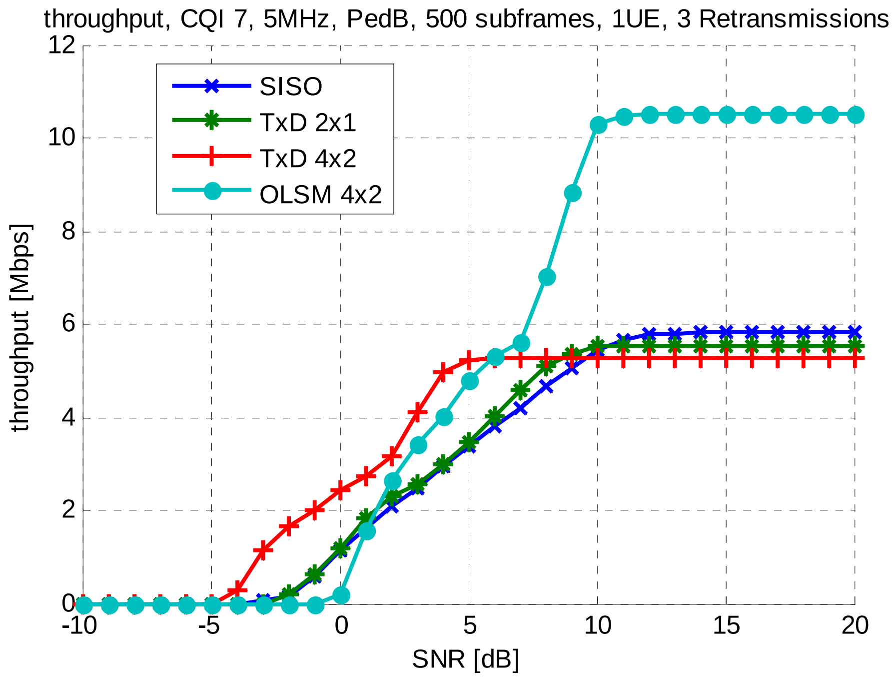

Figure 5.3 Throughput performances of the SISO, MIMO and OLSM in 5MHz with 3 Retransmissions.

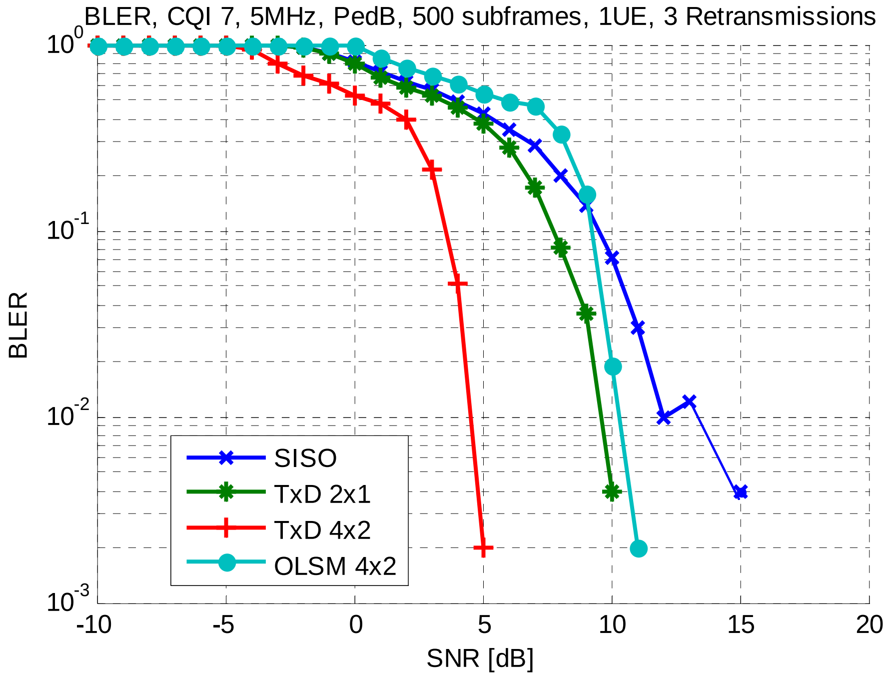

Figure 5.4 BLER performances of the SISO, MIMO and OLSM in 5MHz with 3 Retransmissions.

In Figure 4.5 and Figure 4.6, under the same simulation settings and parameters of Figure 4.1 and Figure 4.2 (No-HARQ), the performance of LTE is investigated for 10MHz

BW. As expected, both BLER and throughput results are improved with respect to (w.r.t.) 1.4MHz and 5MHz. Throughput value is about 22 Mbps for 10 MHz while the throughput results are about 2.5 Mbps and 11 Mbps for 1.4 MHz and 5MHz respectively. It shows that there is a linear improvement in the throughput results with respect to BW. But there is no big improvement with respect to the BLER results.

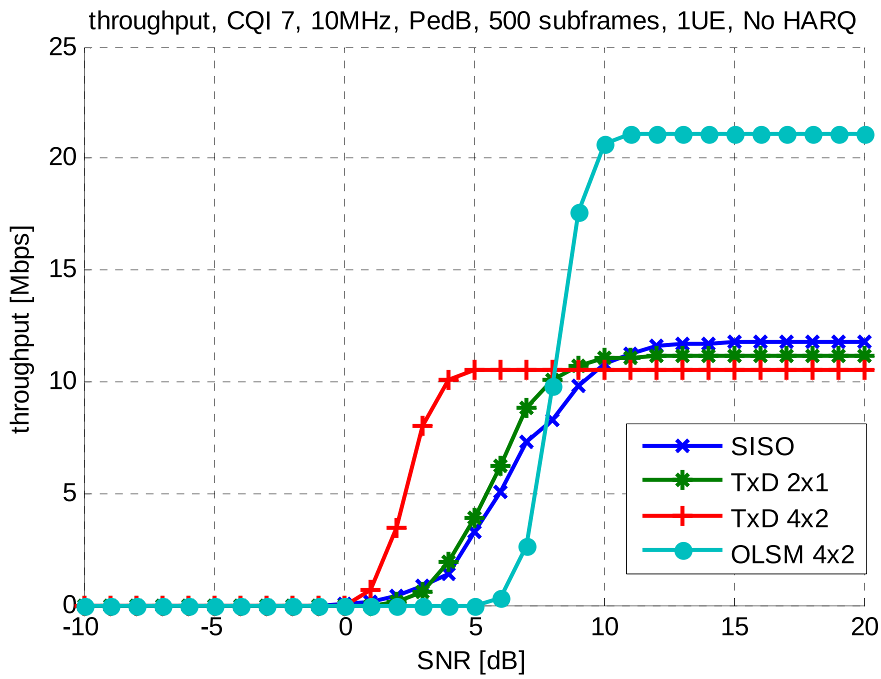

Figure 5.5 Throughput performances of the SISO, MIMO and OLSM in 10MHz with No HARQ

Maximum throughput is achieved with OLSM since spatial multiplexing works by creating separate data streams on multiple antennas. In spatial multiplexing, the eNodeB divides the data to be sent to a given UE on a given sub-channel into data streams, called layers. The number of layers is the same as the rank of the transmission. Transmission rank is determined according to channel conditions at the UE, as well as other considerations such as available resources at the eNodeB. Each layer reaches each Rx along a different path. The UE then reconstructs the layers using information from all antennas.

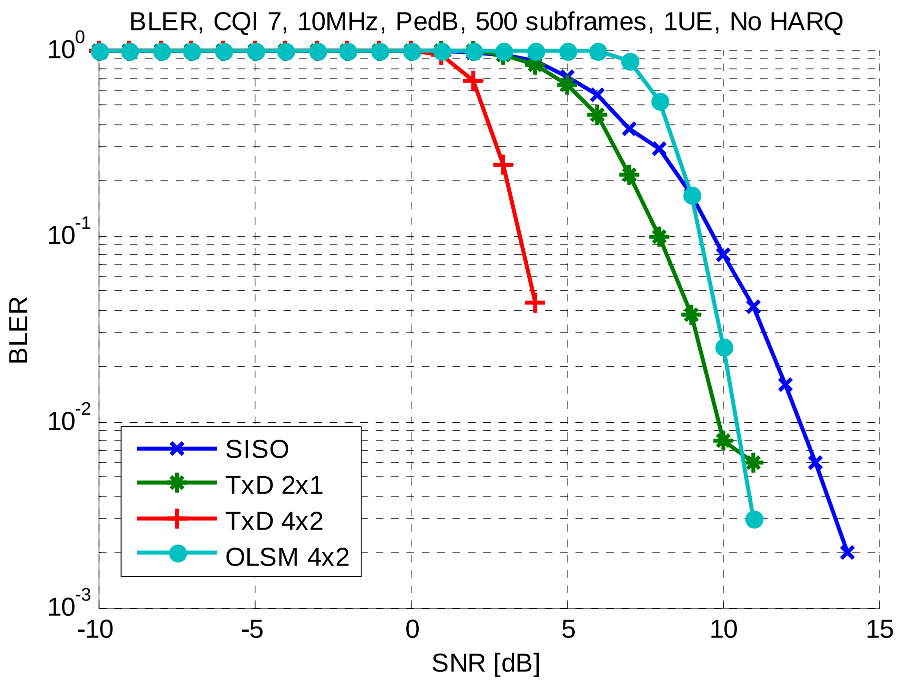

Figure 5.6 BLER performances of the SISO, MIMO and OLSM in 10MHz with No HARQ

Figure 4.7 and Figure 4.8 show the throughput and BLER results for different number of user equipments (UEs) over 5MHz channel BW and PedB channel type for SISO system implementation. It can be observed that as the number of UEs increases the throughput decreases, while BLER increases for high SNR values, which is expected. However, for lower SNR values there is no significant difference in the performance of the system.

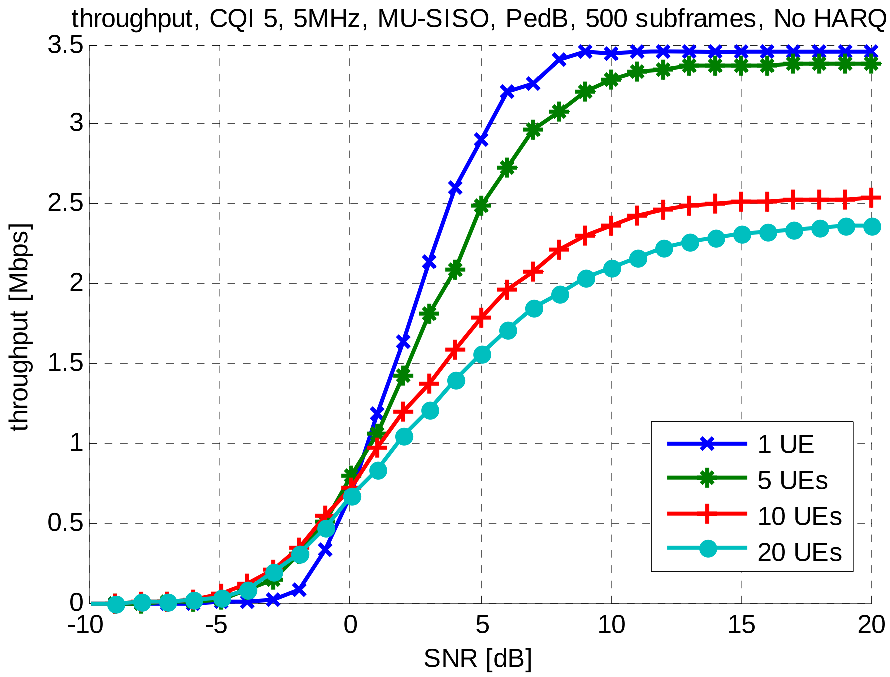

Figure 5.7 Throughput results for different number of UEs.

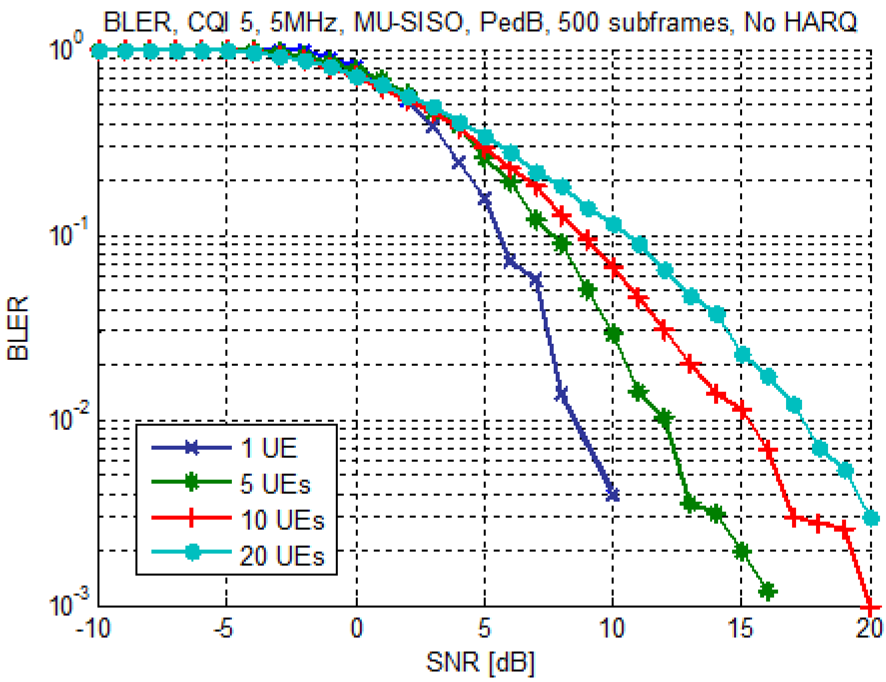

Figure 5.8 BLER results for different number of UEs.

In Figure 4.9 and Figure 4.10 the throughput and BLER results for different channel BWs are shown such as 1.4, 5 and 10MHz, again for PedB channel type and SISO system implementation. In 1.4MHz the saturated throughput is about 0.8Mbps, and

3.5Mbps and 7Mbps for 5MHz and 10MHz, respectively. Figure 4.9 shows that there is about 2x improvements in 10MHz w.r.t. 5MHz and more than 7x gain w.r.t. 1.4MHz channel BWs. These improvements show that there is a linear improvement in the throughput as the channel BW increases.

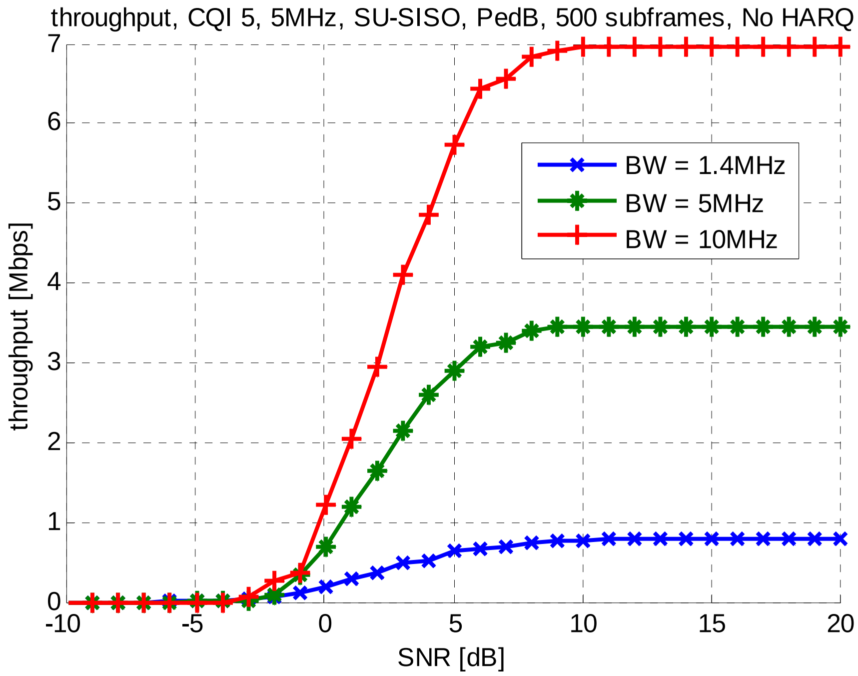

Figure 5.9 Throughput results for different channel bandwidths.

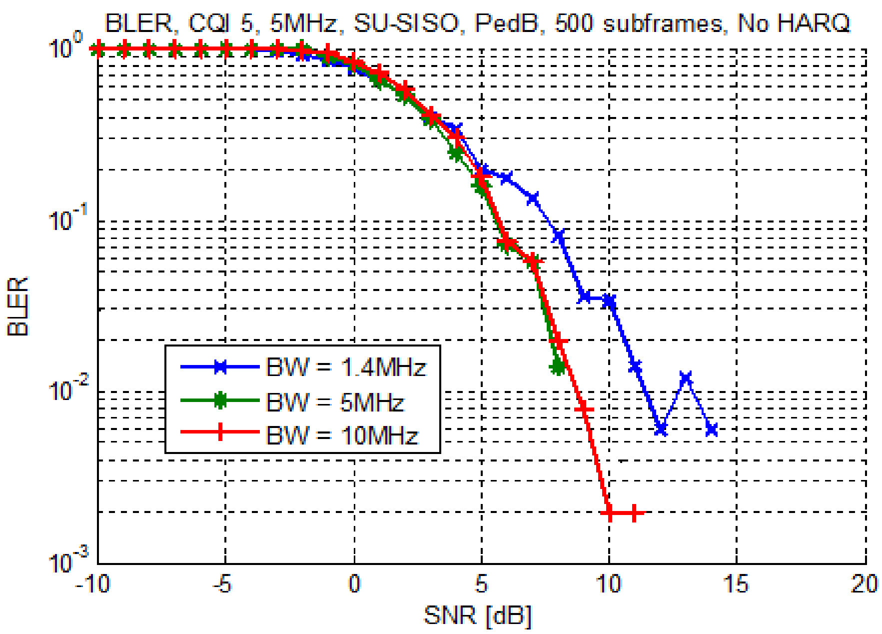

Figure 5.10 BLER results for different channel bandwidths.

The effect of different channel types is shown in Figure 4.11 and Figure 4.12 including non-fading environment (AWGN). One can see that for the high and low SNR values all the channel types are reaches the same value (3.5Mbps at high SNR). However, for the medium SNR values there are some throughput differences for different channel models as shown. Moreover, as per average gain of the different channels, we can say that all channel types give approximately the same channel gain performance.

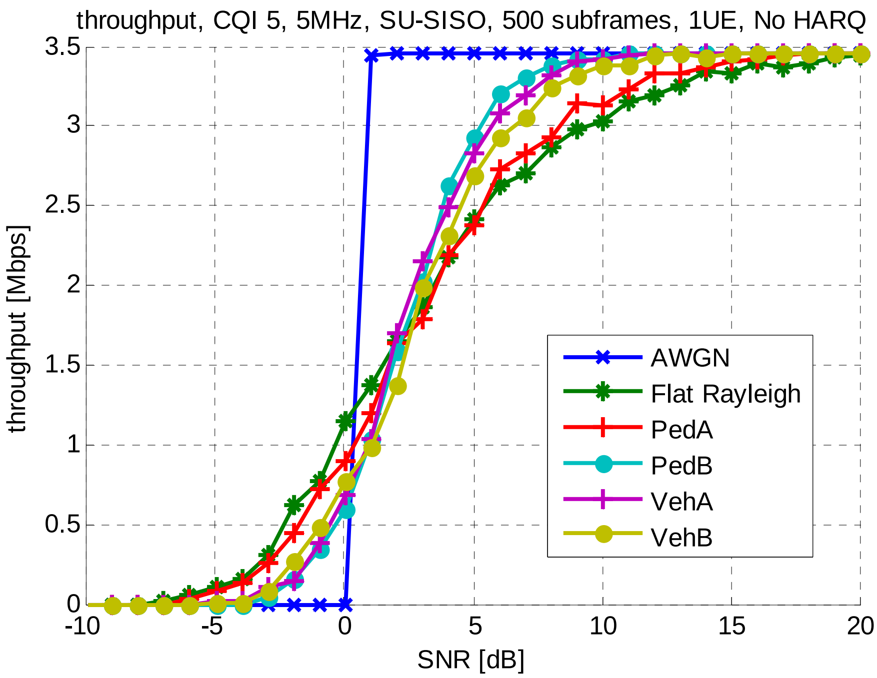

Figure 5.11 Throughput results for different channel types.

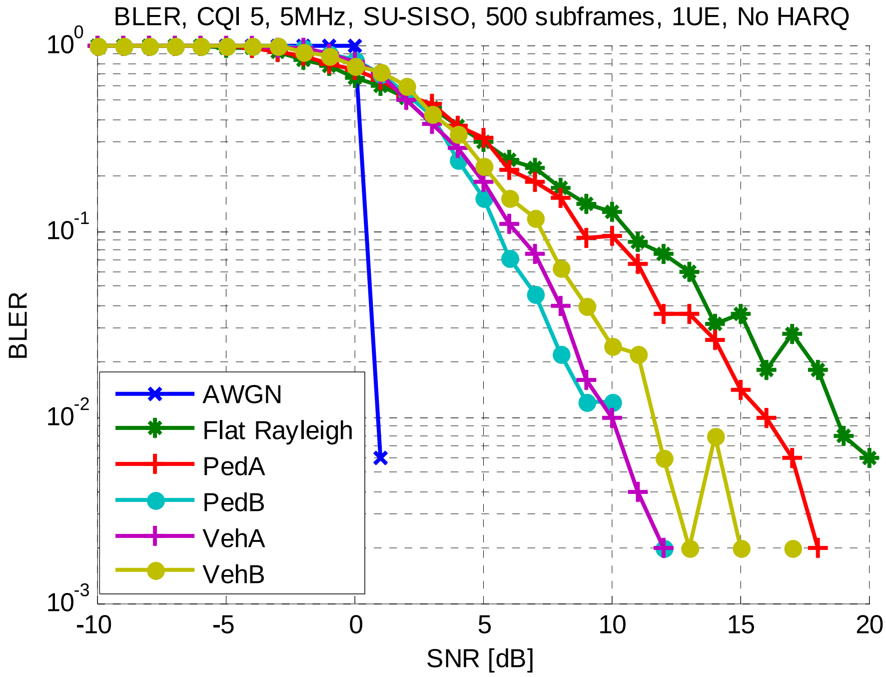

Figure 5.12 BLER results for different channel types.

To investigate the effects of the Modulation and Coding Scheme (MCS) corresponding to each CQI value, AWGN channel the simulations are performed. The MCS determines both the modulation alphabet and the Effective Code Rate (ECR) of the channel encoder. Figure 4.13 and Figure 4.14 show the throughput and BLER results of CQIs from 1 to 15 without using HARQ in 5MHz with SISO system. We can see that each curve is approximately spaced 2dB from each other, and as expected for higher order of modulation, the system performance is improved. In LTE, adaptive modulation and coding has to ensure a BLER value smaller than 10 %. The SINR-to-CQI mapping required to achieve this goal can thus be obtained by plotting the 10% BLER values of the curves with respect to the number of transmission. In Figure 5.13, the throughput curves are plotted for every CQI value. Here, HARQ is switched off and no retransmissions are performed. It is expected that the distance from the capacity curve is increasing with increasing CQI value. The performance is very similar with or without using the number of retransmissions. The reason for the similar performance is that in an AWGN channel the switching between the modulation and coding schemes can be done perfectly and hardly any retransmissions are required.

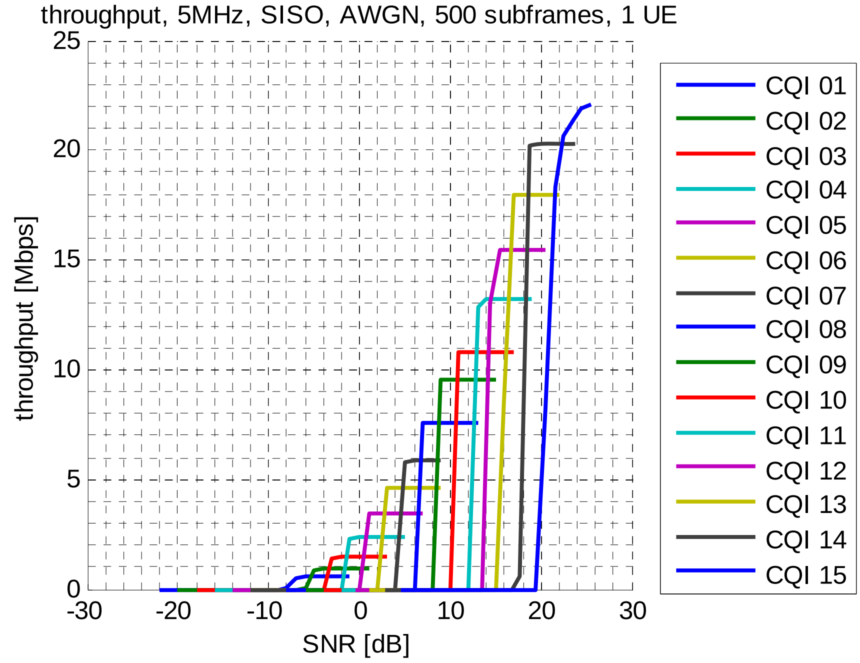

Figure 5.13 Throughput performances over an AWGN channel for individual CQIs with no HARQ and in 5MHz.

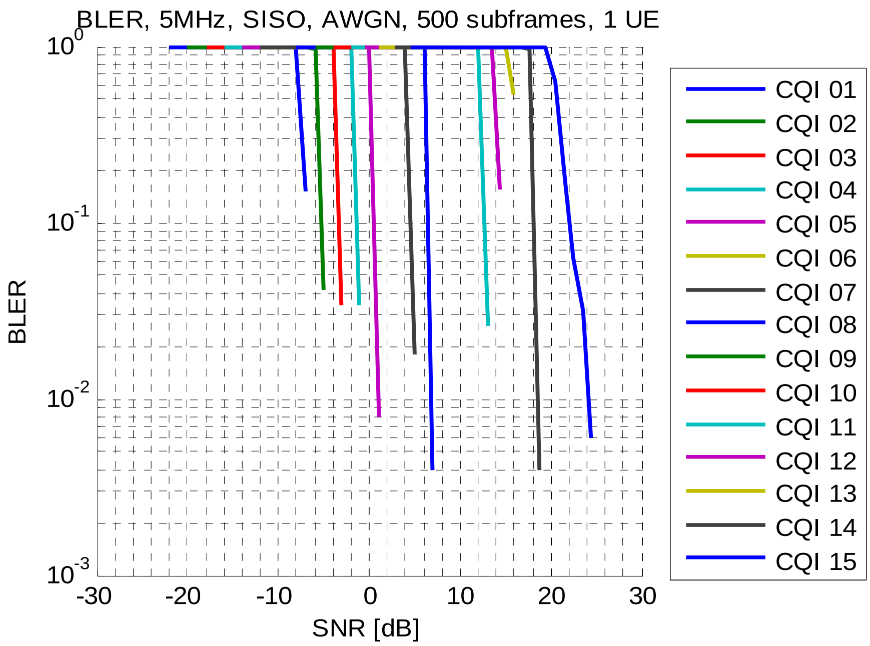

Figure 5.14 BLER performances over an AWGN channel for individual CQIs with no HARQ and in 5MHz.

CHAPTER 6

RESULTS and SUGGESTIONS

6.1 Results

Result part is added to thesis to check whether the expectations which are indicated in the hypothesis are met with the simulation results.

In the light of the simulation results, it is observed that when the HARQ is used, even there is no much difference on high SNR values, the difference on the throughput and BLER can easily be observed that in lower SNR values such as -5 to 5 dB, there is significant improvement thanks to HARQ.

The maximum throughput values achieved by the different MIMO schemes depends on the number of transmit antennas and on the number of data streams. If more transmit antennas are utilized for the transmission, more pilot symbols are inserted in the OFDM frame and thus lower maximum throughput can be achieved.

It has been observed that as the number of UEs increases the throughput decreases, while BLER increases for high SNR values. Nonetheless, for lower SNR values there is no significant difference in the performance of the system. Also it has been observed that when the channel bandwidth is increased, there is a linear improvement in the throughput.

The effect of different channel types has been investigated including non-fading environment (AWGN). One can see that for the high and low SNR values all the channel types are reaches the same value. However, for the medium SNR values there are some throughput differences for different channel models. Moreover, as per average gain of the different channels, we can say that all channel types give approximately the same channel gain performance.

To see the effects of the MCS corresponding to each CQI value, AWGN channel the simulations have been performed. The MCS determines both the modulation alphabet and the Effective Code Rate (ECR) of the channel encoder. The throughput and BLER results have been compared for CQIs from 1 to 15 and as expected for higher order of modulation, the system performance has improved.

It has been expected that LTE should at least support an instantaneous downlink peak rate of 100 Mbps. However, when the overall results are considered, it is seen that maximum throughput that has been achieved is about 22 Mbps. The reason of the lower throughput values can be explained with the used BW, modulation scheme and code rate. Since the simulator does not support the 20 MHz BW in the used version of it, results could not be observed for 20 MHz BW. If the results are compared for 5 MHz and 10 MHz, the throughput result which is observed for 10 MHz is twice of the result which is observed for 5 MHz BW. In the illustration of these results, it can be expected to have improved results with 20 MHz BW. On the other hand, the other important parameter which has important effects on the results is CQI value. In the simulation results, CQI 7 is used. According to Table 5.2, CQI 7 corresponds to 16 QAM and 0.37 code rate. In Figure 5.13, effects of the Modulation and Coding Scheme (MCS) corresponding to each CQI value have been investigated. According to results, CQI 15 (64QAM) has better result from CQI 7 (at least 3 times). Thus, it can be said that in 20 MHz bandwidth with 64QAM modulation, more than 100 Mbps throughput can be achieved.

6.2 Suggestions

With the multiple new technologies, LTE is well positioned to meet the requirements of next generation mobile network from both the users and the operators. LTE is destined to provide greatly improved user experience, delivery of new revenue generating mobile services and will remain a strong advantage to other wireless technologies in the next decade. It will also enable the operators to offer higher performance, mass-market mobile broadcast services, through a combination of high bit-rates and system throughput with low latency in both uplink and downlink directions.

In this thesis, the performance of the LTE network is depicted with the indicators of HARQ, transmit mode, number of user equipments, channel type and CQI values and the subscriber's numbers supported by the system. Also the maximum throughput value of LTE system is calculated with according to the different channel bandwidths.

As the thesis is based on 3GPP LTE standards Release 8, the MIMO technology for the uplink is not applied during the system performance analysis calculations. Release 9 of the 3GPP LTE standards has been developed, and new features and requirements will be added for the later version and LTE advanced phase which provides room for improvements. Models proposed in this thesis can be further developed and enhanced by considering these updates and give a more comprehensive and accurate estimation for the LTE network.

REFERENCES

[1] Prasad, R., (2004). "OFDM for Wireless Communications Systems", Universal Personal Communications, Boston & London, ISBN: 1580537960

[2] Mobile Dev & Design (MD&D), OFDM or OFDMA, http://mobiledevdesign.com /tutorials/ofdm-or-ofmda/, 25 March 2011

[3] Gilberto, B., Luis, A., Simone, F., etc., (2008). "OFDMA vs. SC-FDMA: Performance comparison in local area IMT-A Scenarios". IEEE Wireless Communications, October 2008

[4] Radio-Electronics, LTE OFDM, OFDMA and SC-FDMA, http://www.radio-electronics.com/info/cellulartelecomms/lte-long-term-evolution/lte-ofdm-ofdma-scfdma.php, March 2011

[5] Harri, H. and Antti, T., (2009) "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access", John Wiley and Sons, Ltd., ISBN: 978-0-470-99401-6

[6] Moray R., (2010) "3GPP LTE: Introducing Single-Carrier FDMA", Agilent Measurement Journal

[7] “Single Carrier FDMA in LTE”, Ixia Worldwide Headquarters, November 2009

[8] University of Colorado at Boulder, 3GGP LTE-Evolved UTRA – Radio Interface Concepts, http://ecee.colorado.edu/~ecen4242/LTE/radio.htm, April 2011

[9] “Nortel Long-Term Evolution (LTE): The vision beyond 3G”, 2008

[10] Zyren J., (2007). **“**Overview of the 3GPP Long Term Evolution Physical Layer”, Freescale Semiconductor, 3GPPEVOLUTIONWP (rev 0)

[11] 3GPP TS 36.213, (2009). "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures", version 8.8.0 Release 8

[12] Zhang, L., (2010). ” Network Capacity, Coverage Estimation and Frequency Planning of 3GPP Long Term Evolution”, Master thesis, Linköpings Institute of Technology - Department of Electrical Engineering, Linköping

[13] “UMTS Long Term Evolution (LTE) Technology Introduction”, Rohde & Schwarz, September 2008

[14] Ikuno, J.C, Wrulich M. and Rupp, M., (2009), “PERFORMANCE AND MODELING OF LTE H-ARQ “, in International ITG Workshop on Smart Antennas (WSA), Berlin, Germany

[15] Dahlman E., Parkval S., Skold J. and Beming P., (2008). “3G Evolution HSPA and LTE for Mobile Broadband”, Second Edition, Academic Press, Burlington

[16] Javvin Network Management & Security, Channel Quality Indicator (CQI), http://www.javvin.com/wireless/CQI.html, April 2011

[17] 3GPP TS 36.213, (2009). "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures", version 8.8.0 Release 8

[18] “Introduction to MIMO”, Schindler, Schulz, Rohde & Schwarz, July 2009

[19] Radio-Electronics, 3G LTE Tutorial - 3GPP Long Term Evolution, http://www.radion.co.in/mimo_basics , June 2011

[20] Holma, H., Toskala, A., (2009) "LTE for UMTS - OFDMA and SC-FDMA Based Radio Access", John Wiley and Sons

[21] Schulz B., (2009), “LTE Downlink MIMO Verification”, Rohde & Schwarz Application Note

[22] Mehlfhrer, C., Wrulich, M., Ikuno, J. C., Bosanska, D. and Rupp, M., (2009), "Simulating the Long Term Evolution Physical Layer," in Proc. of the 17th European Signal Processing Conference (EUSIPCO 2009), Aug. 2009, Glasgow, Scotland.

[23] Vienna University of Technology, LTE Simulators, http://www.nt.tuwien.ac.at/ltesimulator, March 2011

[24] Alcatel-Lucent, The LTE Network Architecture, www.alcatel-lucent.com, May 2011

[25] A White Paper from the UMTS Forum: “Standardising the future of mobile communications with LTE”, February 2008

[26] CISCO, Network Solutions White Paper, http://www.cisco.com/en/US/prod/collateral/wireless/ps11035/ps11047/ps11072/white_paper_c11602886_ns1076_NetworkingSolutionsWhitePaper.html, December 2011

APPENDIX -A

LTE PERFORMANCE ANALYSIS RESULTS FOR 1.4 MHZ

In this work, the performance analysis of LTE is presented for bandwidth 1.4 Mhz. The effects of different parameters and other factors are investigated. The parameters and settings are shown as below.

Table A.1 Simulation Parameters

Parameter	***Value***
Number of User Equipments (UEs)	1
Bandwidth	**1.4MHz**
Retransmission	0 and 3
Channel type	Flat Rayleigh and PedB* Uncorrelated
Filtering	Block Fading
Simulation length	5000 Subframes
Transmit modes	SISO, TxD(2x1 and 4x2) and OLSM**

*ITU channel models: PedA 3km/h, PedB 10km/h , VehA 30km/ h, VedA 120km/h
**OLSM: Open Loop Spatial Multiplexing.

In figures below the Block Error Ratio (BLER) and Throughput versus Signal-to-Noise Ratio are shown. The title of each figure shows the (important) settings and parameters used in the corresponding simulation.

From Figure A.1 and Figure A.3, the LTE simulations for the HARQ evaluation process were performed for a single-user scenario corresponding to the simulation parameters shown on figures' titles in 1.4 MHz BW, channel type is flat Rayleigh and when there is no HARQ while Figure A.2 and Figure A.4 with the channel type PedB when there is 3 retransmissions. Even there is no much difference on high SNR values, the difference on the throughput and BLER can easily be observed that in lower SNR values such as -5 to 5 dB, there is significant improvement thanks to HARQ.

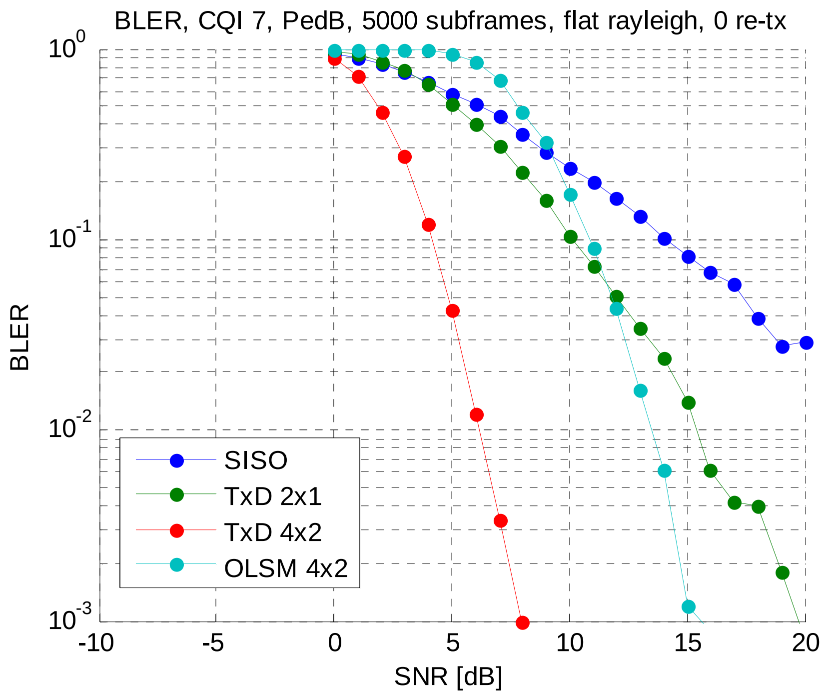

Figure App. A. 1 BLER performance of the SISO, MIMO and OLSM in 1.4MHz with No HARQ on flat rayleigh channel

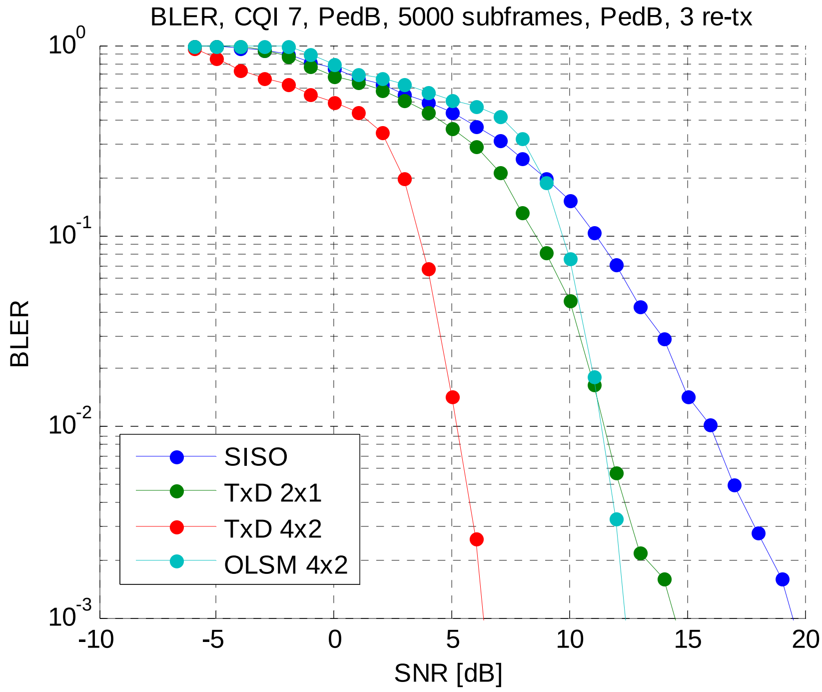

Figure App. A. 2 BLER performance of the SISO, MIMO and OLSM in 1.4MHz with 3 Retransmissions on PedB channel

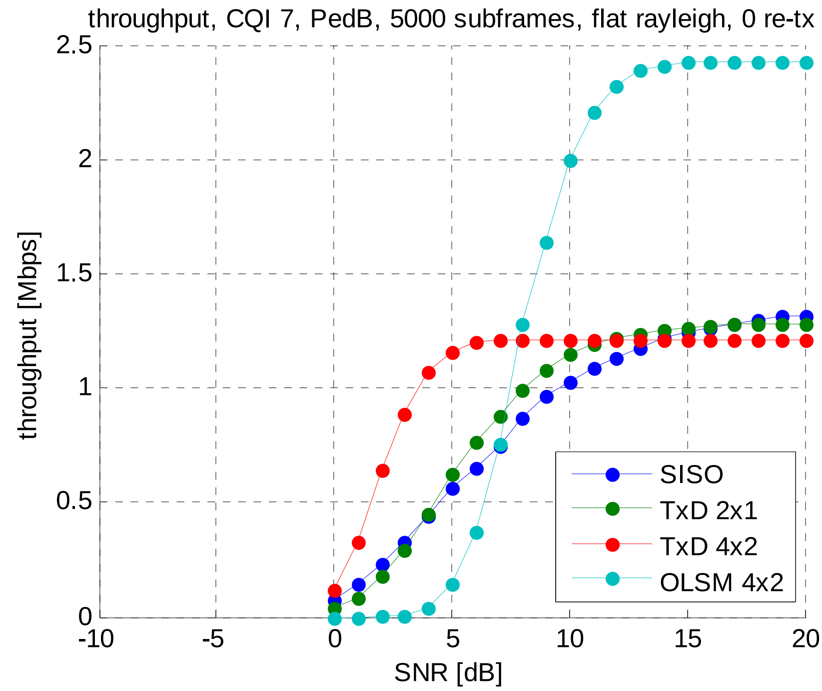

Figure App. A. 3 Throughput performance of the SISO, MIMO and OLSM in 1.4 MHz with No HARQ on flat rayleigh channel

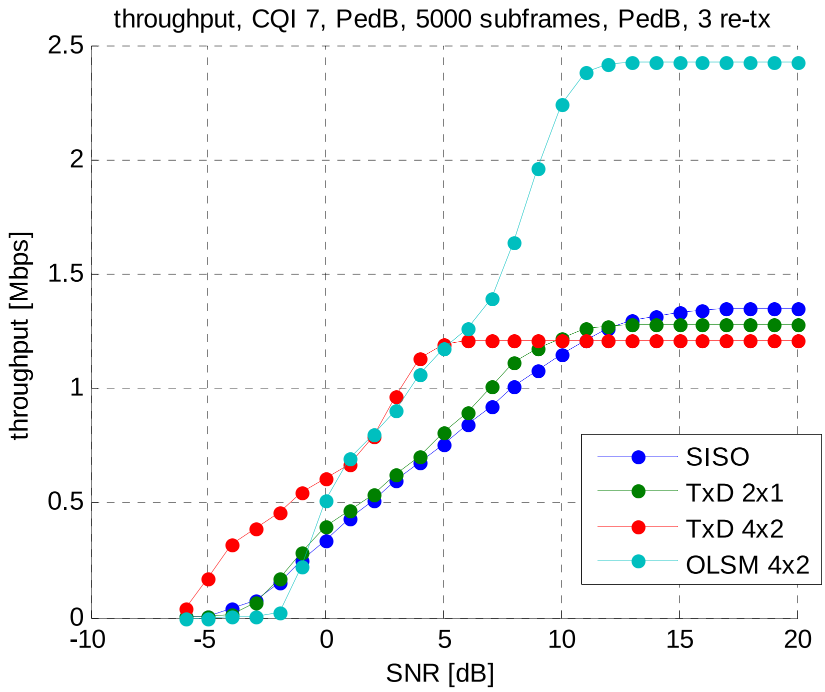

Figure App. A. 4 Throughput performance of the SISO, MIMO and OLSM in 1.4MHz with 3 Retransmissions on PedB channel

Figure A.5 and Figure A.6 represent the results for the channel type flat rayleigh and when there is 3 retransmissions. The difference on the throughput and BLER can easily be observed that in lower SNR values such as -5 to 5 dB, there is significant improvement thanks to HARQ. Same results are observed for Figure A.7 and Figure A.8 when HARQ is not used for PedB channel. Also when the results are compared according to the channel types PedB and flat rayleigh for the same HARQ values, there are no big differences for the throughput and BLER. There is very small improvement between 5-15 SNR values when PedB channel is used.

Figure A.9 and Figure A.10 show BLER and throughput for an AWGN simulation using the each CQI value. We can see that each curve is approximately spaced 2dB from each other, and as expected for higher order of modulation, the system performance is improved.

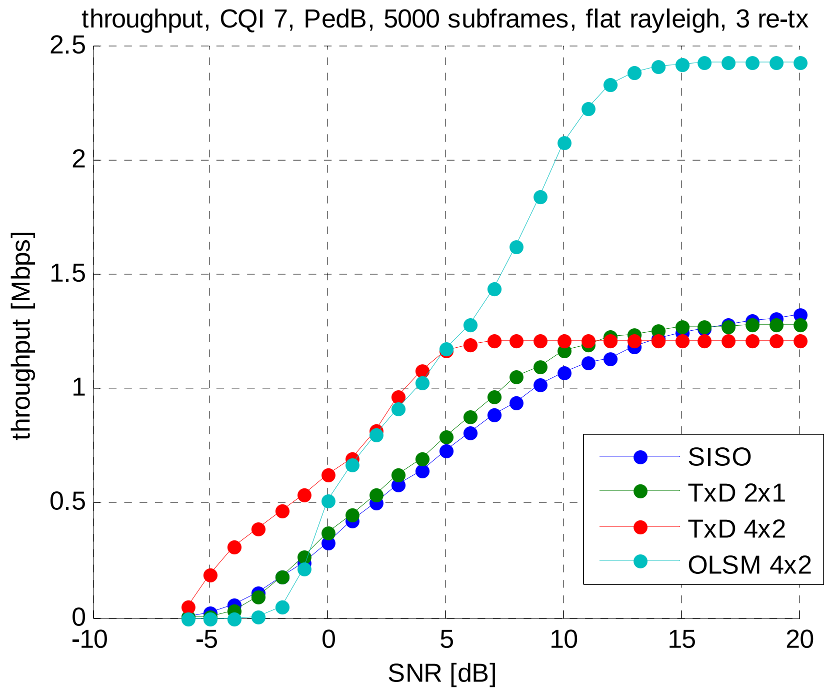

Figure App. A. 5 Throughput performance of the SISO, MIMO and OLSM in 1.4 MHz with 3 retransmission on flat rayleigh channel

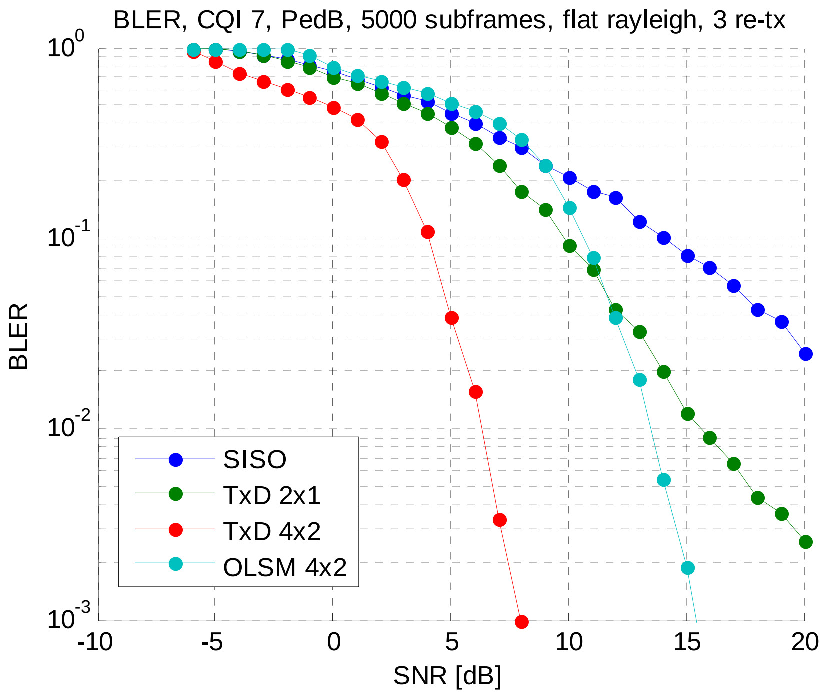

Figure App. A. 6 BLER performance of the SISO, MIMO and OLSM in 1.4 MHz with 3 retransmission on flat rayleigh channel

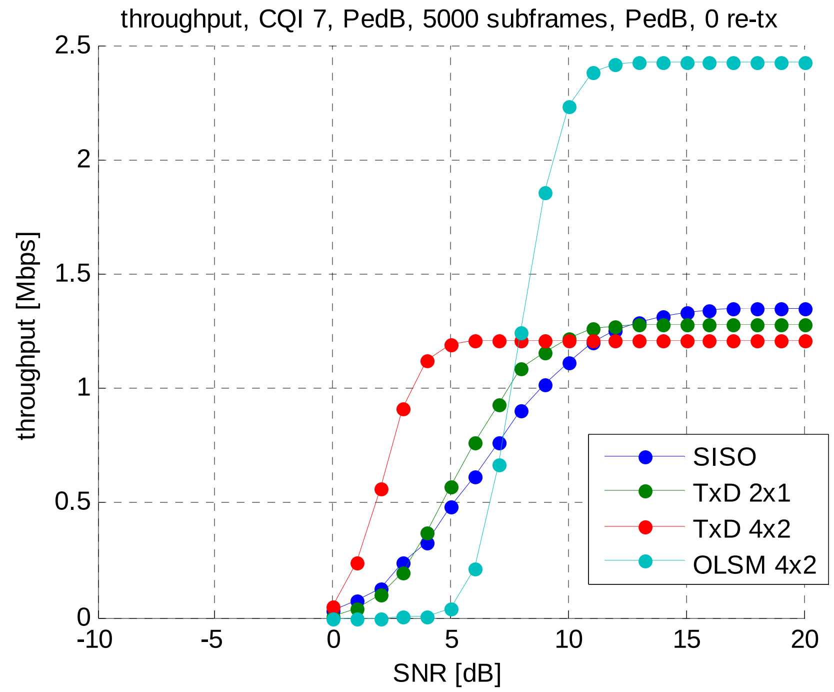

Figure App. A. 7 Throughput performance of the SISO, MIMO and OLSM in 1.4 MHz with no HARQ on PedB channel

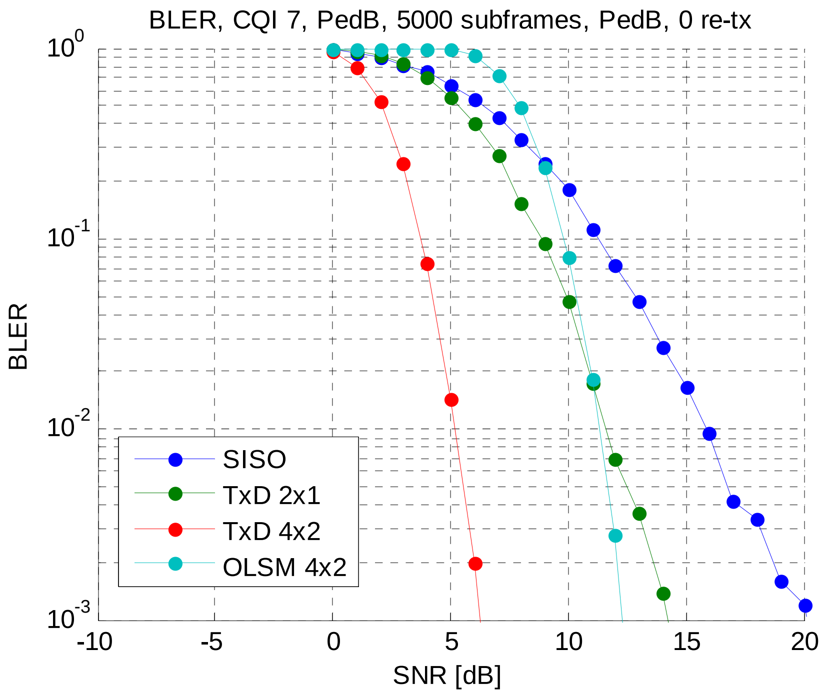

Figure App. A. 8 BLER performance of the SISO, MIMO and OLSM in 1.4 MHz with no HARQ on PedB channel

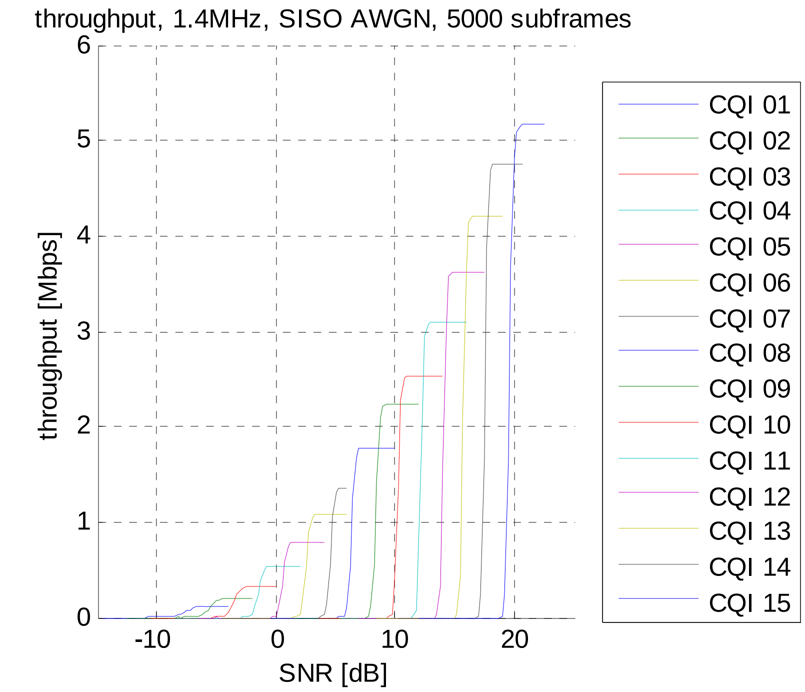

Figure App. A. 9 Throughput performance over an AWGN channel for individual CQIs with no HARQ and in 1.4 MHz

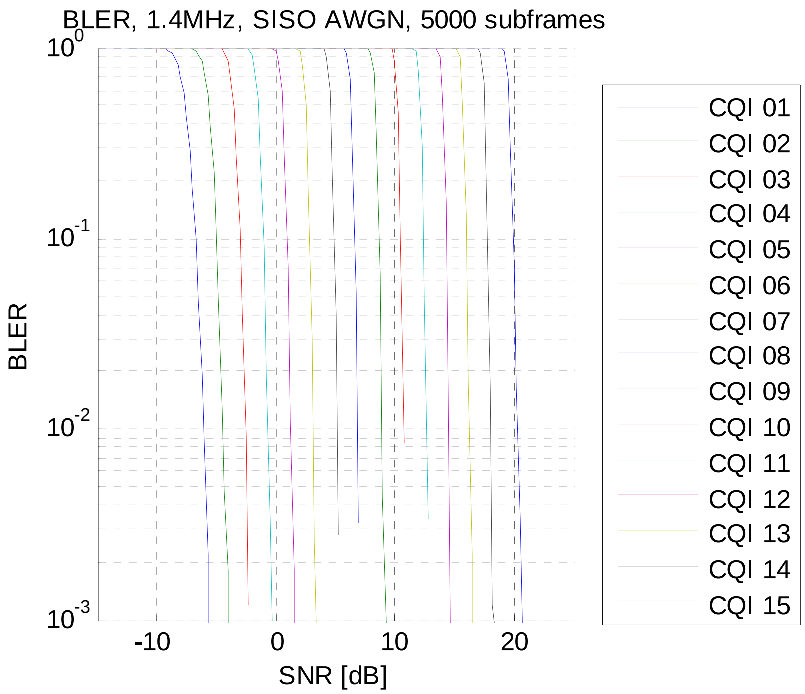

Figure App. A. 10 BLER performance over an AWGN channel for individual CQIs with no HARQ and in 1.4 MH

CURRICULUM VITEA

PERSONAL INFORMATIONS

Name Surname	ILYAS SELLI
Date/Place of Birth	20.01.1983 Goksun / Kahramanmaras
Foreign Languages	English
e-mail	ilyas.selli@gmail.com

EDUCATION

Degree	**Department**	**School/University**	**Graduate date**
Master Degree	Telecommunication Engineering	Yıldız Technical University	2012
Bachelor Degree	Electrical-Electronics Engineering	Eskisehir Osmangazi University	2006
High School		Cizre High School	2001

WORK EXPERIENCE

Date	**Company**	**Position**
April 2011 -	Ericsson Telecommunication Turkey	Services Engineer
2006 - 2011	Nortel Netas	Global Product Support Engineer

PROJECTS

1. Rotation number and speed control of DC motor (PIC) Project
2. Linear Control project (Three wheel mobile robot was tried to design. Matlab was used in this project.)
3. Speaker recognition by using common vector approach method.