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ASHOK KUMAR

LTE SYSTEM PERFORMANCE SIMULATIONS

Master of Science Thesis

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ABSTRACT

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Use of multimedia services, such as streaming of high quality videos on mobile devices is increasing drastically which requires high data rate and bandwidth on mobile devices. Therefore LTE system is introduced by 3GPP which promises higher throughput on mobile devices i.e. 326.4 Mbps in downlink and 86.4 Mbps in uplink.

Theoritically LTE system promises high throughput, high bandwidth utilization, low latency, high spectral efficiency, and high peak data rates than all other 3GPP technologies. The main motive behind this research is to analyze the LTE system performance in practical scenarios to estimate the practical system throughput and peak data rates in different situations.

LTE system level simulation are performed in this thesis to evaluate the performance in practical scenarios. The simulation are performed with LTE system level simulator to calculate the user and cell thoughput of the LTE network in different practical scenarios such as outdoor, indoor, deep indoor and in car with different network layouts, antenna downtilt angles and MIMO.

Simulation results show that the LTE system user and cell thoughputs are greatly affected by interference from the neighbouring cells and are different in practical situation than in theory. Results also show that the interference can be reduced by using different network layouts, antenna downtilting and MIMO. Hence high system throughput can be achieved by mitigating the effect of interference from the neighboring cells.

PREFACE

Research work carried out in this Master of Science Thesis "LTE System Performance Simulations" has been done for Radio Network Group at the Department of Communications Engineering, Tampere University of Technology.

I would like to thank my thesis supervisor Professor Jukka Lempiäinen and Dr. Jarno Niemelä for their guidance during this work. I would also like to thanks my colleagues and friends Usama Khan Sultan, Ali Bin Tariq, Mubashir Ali, Bashir Ahmed, Irfan Ullah, Muhammad Farhan, Faizan ul Haq and Nitesh Kaushik for their motivational and moral support. And I would also like to thank Department of Communication Engineering for providing me place in research environment.

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CONTENTS

List of Acronyms

2G	Second Generation
3G	Third Generations
3GPP	Third Generation Partnership Project
AC	Admission Control
ACK	Acknowledgment
ARQ	Automated Repeat Request
BCQI	Best CQI
BLER	Block Error Rate
BS	Base Station
C/I	Carrier to Interference Ratio
CN	Core Network
CP	Cyclic Prefix
CS	Circuit Switched
CQI	Channel Quality Information
DFT	Discrete Fourier Transform
EDCH	Enhanced Dedicated Channel
EDT	Electrical Downtilting
eNB	eNodeB
ePDG	Evolved Packet Data Gateway
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Network
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFR	Fractional Frequency Reuse
FFT	Fast Fourier Transform
FTP	File Transfer Protocol
GSM	Global System for Mobile communications
HARQ	Hybrid Automatic Repeat Request
HSPA	High Speed Packet Access

HSS	Home Subscriber Server
HTTP	Hypertext Transfer Protocol
HPBW	Half Power Beam Width
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
KPIs	Key Performance Indicators
LC	Load Control
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MDT	Mechanical Downtilting
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MRC	Maximal Ratio Combining
MS	Mobile Station
MU-MIMO	Multi User MIMO
NACK	Negative Acknowledgment
NLOS	Non Line Of Sight
OFDMA	Orthogonal FDMA
PAR	Peak to Average Ratio
PC	Power Control
PCEF	Policy Control Enforcement Function
PCRF	Policy Control and Charging Rules Function
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PDN	Packet Data Network
PF	Proportional Fair
P-GW	PDN Gateway
PS	Packet Switched
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation

QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RB	Resource Block
RLC	Radio Link Control
RNC	Radio Network Control
RR	Round Robin
RRC	Radio Resource Control
RRM	Radio Resource Management
SAW	Stop-and-wait
SC-FDMA	Single Carrier FDMA
SDMA	Spatial Division Multiple Access
S-GW	Serving Gateway
SM	Spatial Multiplexing
SU-MIMO	Single User MIMO
SINR	Signal to Interference Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TPC	Transmit Power Control
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
VoIP	Voice over Internet Protocol
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

List of Symbols

λ	Wavelength
d_{km}	Distance in Kilometers
f_{MHz}	Frequency in MHz
G_r	Receiver Antenna Gain
G_t	Transmitter Antenna Gain
h_{BS}	Height of Base Station
h_{MS}	Height of Mobile Station
L	Free Space Path Loss
P_t	Transmitted Signal Power
P_r	Received Signal Power
S_τ	Delay Spread
$S_\emptyset$	Angular Spread
Δf_c	Coherence Bandwidth

1. INTRODUCTION

Demand for multimedia services in mobile communication is dramatically increasing day by day. Previously available technologies such as GSM, UMTS, HSPA, and HSPA+ were enough capable of fulfilling the needs of voice and multimedia services for at least a decade. To fulfill the future needs of data communication on mobile devices, 3rd Generation Partnership Project (3GPP) has introduced a new technology which is known as Long Term Evolution of UMTS (LTE). LTE promises to provide higher data rates on mobile devices than all other mobile technologies i.e. 100 Mbps in downlink and 50 Mbps in uplink, the data rate can be further increased to 326.4 Mbps in downlink and 86.4 Mbps in uplink by using higher bandwidth, higher order modulation and MIMO.

LTE system has low latency and high bandwidth efficiency than all other technologies. The bandwidth of LTE is flexible such as 1.4, 3, 5, 10, 15, and 20MHz, which means service providers, have wide range of selectivity between the bandwidth according to area and the required capacity. From network planning point of view the selection of the bandwidth can be done in such a way that the areas with dense population such as urban areas are given higher bandwidth and the low dense areas such as rural areas are given the lower bandwidth to serve the same coverage area. The bandwidth is further divided into physical resource blocks (RBs) to be allocated to users according to scheduling algorithm used, depending upon the channel conditions.

In this thesis, performance of LTE system for different bandwidth, scheduling, network layouts and environments have been analyzed. The network layouts used for simulation in this thesis work are hexagonal and cloverleaf, the scheduling algorithms used are round robin, proportional fair and best CQI, and the environment used for simulations are urban, with different user situation such as outdoor, indoor, deep indoor and in car. The main idea behind the study of LTE system performance is to analyze the system practically as there are different parameters that affect system performance. Hence the

LTE system level simulations are carried out in different practical situation to analyze how the user and cell throughput of LTE system behaves in above mentioned scenarios.

The study of LTE system performance in this thesis report is divided into two parts, first part describes the theoretical concepts about LTE system and second part describes the LTE system level simulation results and analysis. In Chapter 2, basic introduction about cellular communication, basic propagation principles and environmental effect on radio waves in mobile communication are explained. In chapter 3, LTE system architecture both the Radio Access Network (RAN) and Core Network (CN) architecture along with signaling are explained. In Chapter 4, the air-interface technologies used in LTE system for both uplink and downlink along with other transmission related terminologies are explained. In Chapter 5, simulator, simulation parameters, simulation scenarios and network design, user distribution and resource allocation simulation results and error analysis are explained. Finally in Chapter 6, future work in the research area and the conclusion of the LTE system performance is explained.

2. WIRLESS COMMUNICATION

The exchange of information between two objects without any physical connection is defined as wireless communication. It is the convenient way of information exchange by avoiding hazards of handling cables all around. There are many kinds of wireless communication systems such Wireless Local Area Network (WLAN), Bluetooth, Infrared, Cordless, Mobile Communication Systems and so on. In this chapter basic wireless communication principle and radio propagation mechanisms, propagation environment and factors affecting radio propagation in mobile communication system are explained.

2.1. Cellular communication

The concept of cellular communication comes from the way the mobile networks are deployed. In cellular communication a large geographical area is subdivided into smaller areas, each area is called as cell. Each cell is served by a fixed Base Station (BS), and certain frequency allocation. The main reason behind the concept of cellular communication is frequency, it is the scarce resource and the main target of the operator and network planner is to utilize frequency as efficiently as possible. By dividing the large area into smaller cell we can utilize same frequency again and again.

There are many advantages of cellular concept for having small cells, such as low power consumption, more battery life and high capacity. The size of cell depends on the geographical area, such as in urban areas where we have highly dense population the smaller cells serve better and in rural areas where we have less dense population larger cells serve better from the capacity point of view. But by having smaller cell we need more cells to cover the certain area but comparatively we will also have higher capacity. Hence the size of cell is inversely proportional to the capacity and directly proportional to the coverage. The basic structure of the cellular communication system is show in Figure 2.1.

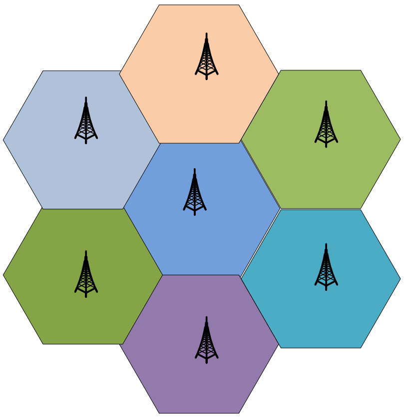

Figure 2.1: Cellular communication network structure

Every system has advantages and disadvantages, like every other system cellular communication system also has disadvantages. Apart from the fact that more BSs are needed in cellular communication to cover certain geographical area which in turns increase the capacity there is also interference in the network because of small distance between the BSs.

2.1.1. Interference in cellular communication

There are two kinds of interferences experienced in cellular communication, inter-cell interference and intra-cell interference. The inter-cell interference is caused by the neighboring cells and is high at cell edge specially in case of same frequency. The intra-cell interference is caused by the cell itself and is also called as own-cell interference. The intra-cell interference can be avoided by uplink power control. The inter-cell interference affects the performance of the network at cell edge. In order to avoid inter-cell interference different frequencies are used in the neighboring cells and the cell overlapping is minimized. In case of same frequency the inter-cell interference can be avoid by using BS antenna downtiling.

2.1.2. Antenna downtilting

Antenna downtilting is the mechanism of directing the antenna radiation pattern towards the ground. There are two types of antenna downtilting mechanisms, mechanical downtilting and electrical downtilting. In mechanical downtilting the complete antenna is tilted including all the antenna elements as shown in Figure 2.2 (a). In electrical downtilting the phase of the control signals is adjusted to different segment electrically and the distance between the back plate and each segment is varied. Hence the tilted front surface is formed as shown in Figure 2.2 (b). [1]

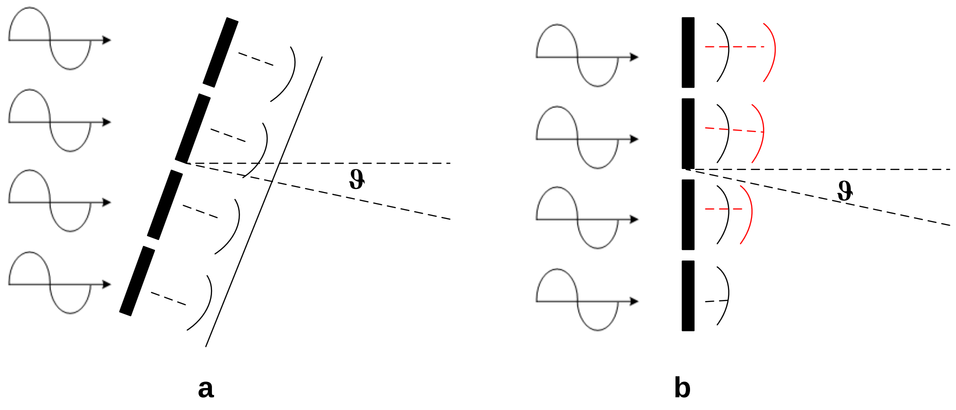

Figure 2.2: Mechanical and electrical antenna downtilting [1]

2.2. Radio propagation

In wireless communication the information is travelled from transmitter to the receiver in the form of electromagnetic waves. The electromagnetic waves are characterized by the frequency, amplitude, polarization and phase. The path between transmitter and receiver can be either simple line-of-sight (LOS) or non-line-of-sight (NLOS) which means there might be some obstacles in the way such as static or moving objects. During propagation the behavior of electromagnetic waves is affected by these obstacles and some variations might occur in the signal characteristics.

2.3. Free space loss

The attenuation in the transmitted signal strength that occur at the receiver due to the propagation of radio waves from transmitter to the receiver in the case of LOS transmission, where there is no any obstacle in the way is called free space loss. The free space loss is proportional to the distance between transmitter and receiver. The free space loss between transmitter and receiver can be calculated by using Friis free space formula as given in 2.1. [2]

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \qquad 2.1$$

where P_r is received power, P_t is the transmitted power, G_t is the transmit antenna gain, G_r receive antenna gain, λ is the wavelength of the transmitted signal and d is the distance between transmitter and receiver. Equation 2.1 can also be written in simplified form to calculate the free space path loss as shown in 2.2.

$$L = 32.4 + 20 log d_{km} + 20 log f_{MHz} \qquad 2.2$$

From the equation in 2.2, it is clear that free space loss is the function of frequency and distance between transmitter and receiver, which means as the frequency and/or distance increases free space path loss will increase.

2.4. Factors affecting radio wave propagation

In addition to the attenuation caused by free space, there are also some alterations in the received signal due to the obstacles in the path and it has broader effects on signal characteristics. Factors causing alteration in the signal characteristics are explained as follows.

2.4.1. Reflection and refraction of radio waves

Reflection and refraction of the radio waves occur when propagating waves collide with the objects of having large dimension greater than the wavelength of the propagating waves. The objects causing reflections and refractions are building, walls and surface of earth. [2] When radio waves collide with these objects part of the wave is propagated through the object and results in refraction and part of the wave is bounced back and results in reflection. The phenomenon of reflection and refraction affects the characteristics of radio waves. The proportion of reflection and refraction depends on the electrical properties of the incident medium. [3]

2.4.2. Scattering of radio waves

Radio waves are scattered when the collision of the propagating wave occurs with the objects of the smaller dimension than the wavelength of the propagating wave and the amount of obstacle per unit volume is greater. Scattering of the radio waves is caused by the roughness of the surface and small objects. Examples of scattering objects are street lamps, trees and other small and irregular objects. Due to scattering phenomenon the energy of the radio waves is spread all around and may results in higher energy at the receiver as compared to reflected model. [2]

2.4.3. Diffraction of radio waves

Diffraction of radio waves occurs when an obstacle of large size comes in the propagation path and there is no possible LOS path. The radio waves are then diffracted from the edges of the obstacle and we can still receive the transmitted signal in NLOS shadow region formed by the obstacle. The diffraction can be caused by building, mountains and any other large, curved and sharp objects. The phenomenon of diffraction can be explained by Huygen's principle. According to Huygen's principle all points on the wavefront are considered as secondary wavelets which unite to form a new wavefront which is in the direction of propagation. The propagation of these secondary wavelets into the shadow region causes diffraction. [2]

2.5. Multipath propagation

In mobile communication system, it is not always possible to get LOS path between transmitter and receiver due to reflection, scattering and diffraction of the radio waves through the obstacles available in the path. Hence, in this situation we get replicas of the transmitted signal at receiver at different time instants and from different directions. This is known as multipath propagation. In multipath propagation replicas of the transmitted waves are affected independently and differ in amplitude, phase and time at the receiver. The multipath propagation of radio waves can be characterized by delay spread, angular spread, and coherence bandwidth and is illustrated in Figure 2.2.

2.5.1. Delay spread

In multipath propagation replicas of transmitted signal are received by receiver at different time instants, these time variations of the multipath components is measured as delay spread. The delay spread of the multipath component depends on environment, that is higher in macrocellular rural and hilly environment and smaller in microcellular and indoor environment.

The delay spread S_τ of the multipath components is calculated from the power-delay profile $P_\tau(\tau)$ of the radio channel, which is defined as received power as function of delay.

$$S_\tau = \sqrt{\frac{\int_0^\infty (\tau-\bar{\tau})\, P_\tau(\tau) \mathrm{d}\tau}{P_{\tau\_tot}}} \qquad 2.3$$

where $\bar{\tau}$ is the average delay and P_{τ_tot} is the total received power. [4]

2.5.2. Angular spread

The angular spread of the multipath component is expressed as the deviation of the incident angle of the received signal in the vertical and horizontal planes. Angular spread can be calculated by the formula given in 2.4.

$$S_\emptyset = \sqrt{\int_{\bar{\emptyset}-180}^{\bar{\emptyset}+180} (\emptyset - \bar{\emptyset})^2 \frac{P(\emptyset)}{P_{\emptyset\_tot}} d\emptyset} \qquad 2.4$$

where $\bar{\emptyset}$ is the mean angle, $P(\emptyset)$ is the angular power distribution and $P_{\emptyset\_tot}$ is the total power. The angular spread is used to define the environment type, it has different values for different environment types such as 5-10 degrees in macro cells and 45 in micro cell environment, and it can be even higher, i.e. 360 degrees in indoor environment. It also has significant effect on antenna direction and space diversity reception. [4]

2.5.3. Coherence bandwidth

The coherence bandwidth is the function of delay spread and it represents the multipath propagation characteristic in frequency domain. It is the separation of frequency in multipath environment whose fading is correlated with each other. The coherence bandwidth can be calculated with the formula given in 2.5.

$$\Delta f_c = \frac{1}{2\pi S_\tau} \qquad 2.5$$

where Δf_c is the coherence bandwidth and S_τ is the delay spread. [4]

The coherence bandwidth is environment dependent and is also used to define the system type. If the coherence bandwidth of the system is smaller than the system bandwidth, it is called narrowband and it has frequency non-selective fading and is also called flat and if the coherence bandwidth is smaller than the system bandwidth it is called wideband system.

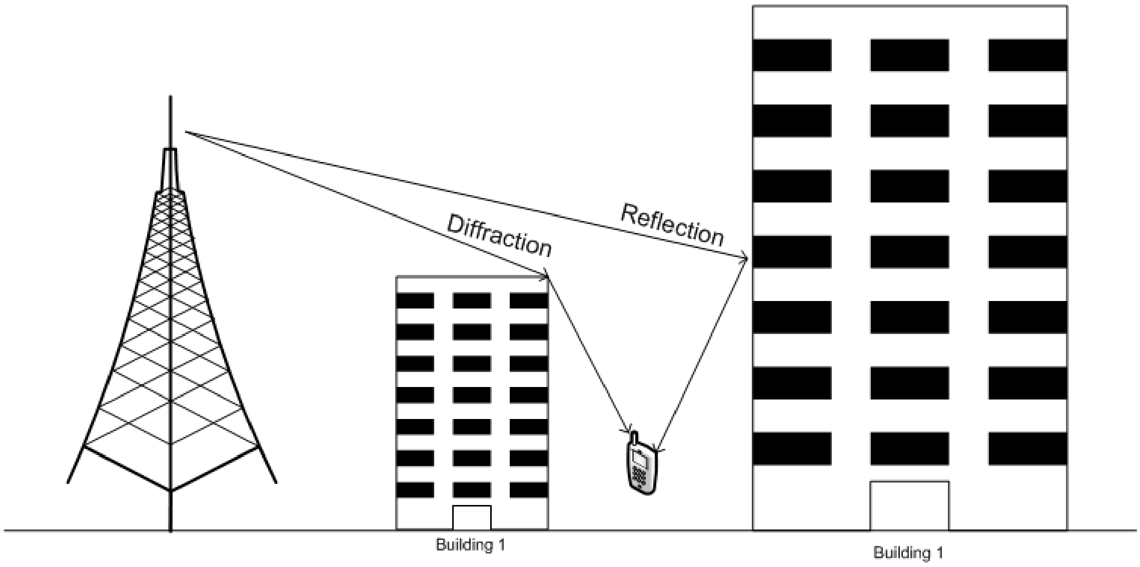

Figure 2.3: Multipath propagation

2.6. Fading of radio waves

The variation in the radio signal strength is known as fading. The fading in radio waves occur due to reflection, refraction, scattering and diffraction of radio waves with the obstacles in the path between transmitter and receiver. Different fading phenomenons in mobile communication are explained as follows.

2.6.1. Slow fading

The attenuation in radio signal strength caused by the large objects such as building, forest, hills and other long term fading obstacles in the propagation path is called as slow fading. It is also called as shadowing due to the receiver in the shadow region formed by these large obstacles in the path. In slow fading channel the transition in channel's impulse is slower than the transmitted signal. [6] Slow fading depends on the environment type and the radio frequency.

2.6.2. Fast fading

The attenuation caused in the radio signal strength due the small movement of the receiver or motion of the objects surrounding the receiver in multipath propagation environment is called the fast fading or short term fading. In fast fading channel the transition in channel's impulse response is rapid than the symbol duration. [6]

The phenomenon of slow and fast fading can simply be explained as the relationship between transition rate of channel and the transmitted signal.

2.6.3. Propagation slope

The term propagation slope defines the attenuation between transmitter and receiver. In free space path loss the radio waves are attenuated as the square of the distance between transmitter and receiver such as 20dB/dec in decibel scale. In mobile communication the signal level degradation is environment dependent, in macrocellular environment the degradation is around 25-50dB/dec depending on the terrain type. The propagation slope is lower near the transmitter and it increases with distance. The propagation slope depends on the base station antenna height and frequency. The distance at which the propagation slope changes is called the breakpoint distance and can be calculated by the formula given in 2.6.

$$B = 4\frac{h_{bs}h_{ms}}{\lambda} \qquad 2.6$$

where h_{bs} is the base station antenna height, h_{ms} is the mobile station antenna height and λ is the wave length. [4]

2.7. Propagation environments

The surrounding of the radio propagation is known as the propagation environment. The characteristics of radio waves are dependent on environment type. There are different environment types in mobile communication and they influence the radio wave propagation accordingly.

2.7.1. Characteristics of propagation environments

The radio propagation environments can be classified as outdoor and indoor environment. The indoor environment is defined as inside of the buildings, houses, railway station, and any other location which is under the roof and closed boundary. The outdoor environment is defined as the open air environment, which is further subdivided depending on the antenna height of the transmitter (base station). If the antenna height is above the average rooftop level it is called macro-cellular and if it is below the rooftop level is called micro-cellular environment. The macro-cellular environment is further subdivided depending on the terrain type and the number of natural and constructed obstacles. The subdivision of macrocellular environments is such that the areas with highly dense population and construction are called urban, areas with dense population but lower than urban is called suburban and the areas with less population and less or small construction such country side and mountains or hilly areas are called as rural environments. The outdoor environment of radio propagation with macro and micro cellular coverage is illustrated in Figure 2.3.

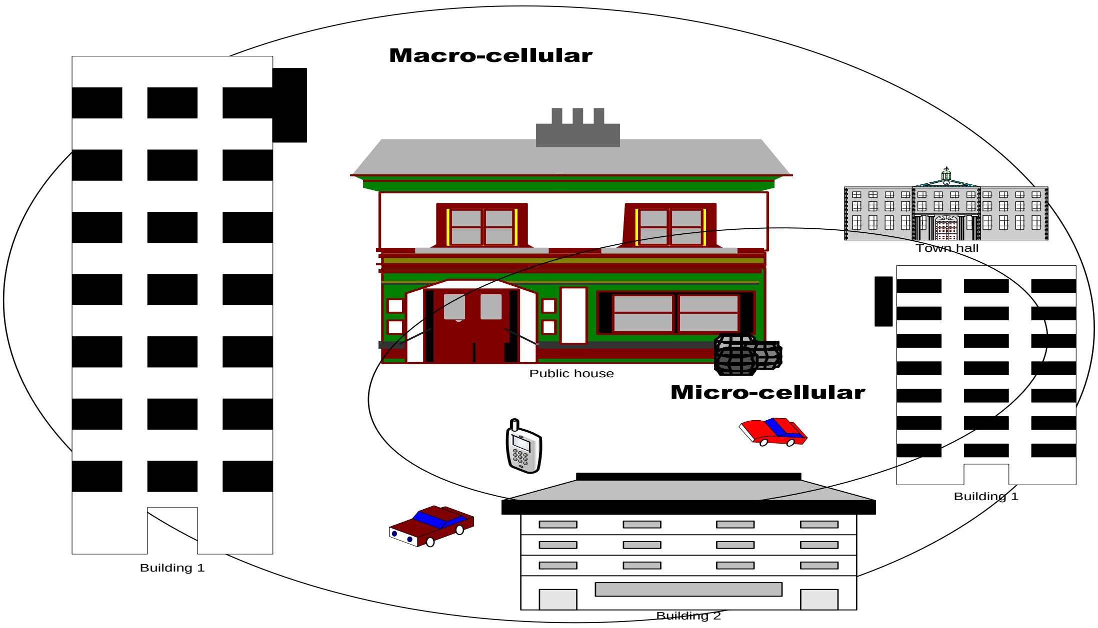

Figure 2.4: Radio propagation environments

As discussed earlier, the received radio signal characteristics and strength depends on the frequency and the environment of the propagation of radio waves. The influence of the propagation environments at a frequency of 900 MHz is demonstrated in the Table 2.1.

Table 2.1: Characteristics of radio propagation environments at 900 MHz [4]

Environment type	Angular Spread (^{0})	Delay Spread (μs)	Fast Fading	Slow Fading Standard deviation (dB)	Propagation slope (dB/dec)
Macro-Urban	5-10	0.5	NLOS	7-8	40
Macro-Suburban	5-10		NLOS	7-8	30
Macro- Rural	5	0.1	(N)LOS	7-8	25
Macro- Hilly Rural		3	(N)LOS	7-8	25
Microcellular	40-90	< 0.01	(N)LOS	6-10	20
Indoor	90-360	< 0.1	(N)LOS	3-6	20

Table 2.1 shows that the radio wave characteristics are different in different environment and it varies with environment types.

2.7.2. Propagation models

The characteristics of radio propagation are different in different environments. The morphology of the radio propagation environment has a significant effect on radio signal strength. In order to predict the alteration in radio signal in different environments propagation models are used. Propagation models are the mathematical formulation of the environment surrounding the radio propagation. The propagation models are environment dependent and are different in different environment type such as the propagation model for outdoor macro-cellular is different than the indoor environment. It also varies in urban, suburban and rural environments.

There are different types of propagation model defined for mobile communication, in this thesis simulation are performed with TS36942 urban propagation model and is explained in Chapter 5.

3. LTE NETWORK ARCHITECTURE

All mobile communications networks are based on two sub networks, radio access network (RAN) and core network (CN). These sub networks have different functionalities. The air interface between mobile user and the network is carried out by RAN and the network related functions, i.e. call routing, authentication, billing and other functionalities are carried out by CN. In this chapter overview of LTE system architecture, both the CN which is called Evolved Packet Core (EPC) and RAN which is called Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and their functionalities are explained.

3.1. LTE architecture

LTE system has flat architecture, which means there is no any Radio Network Controller (RNC) between base station and core network. All radio links related functions are integrated in base station which is called as eNodeB (eNB). LTE architecture is simplest architecture than all other 3GPP technologies and is shown in Figure 3.1.

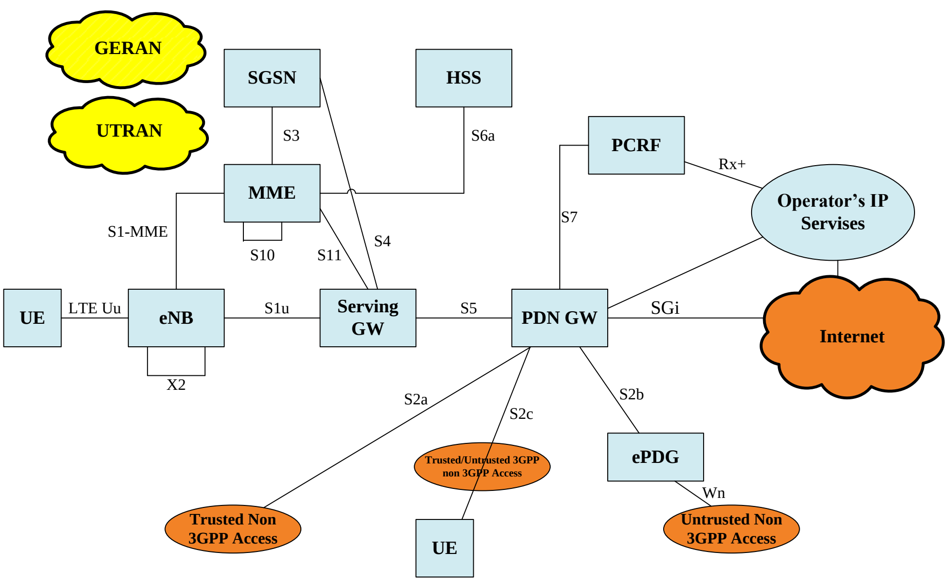

Figure 3.1: LTE architecture with interfaces [7]

Figure 3.1 shows the LTE system architecture and all interfaces with network elements and other 3GPP and non-3GPP technologies.

3.2. E-UTRAN architecture

The RAN of LTE (E-UTRAN) is the network of eNBs. The E-UTRAN is consists of user plane and control plane. The user plane consists of the functionalities such as Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), Medium Access Control (MAC) etc, and the control plane consists of Radio Resource Control (RRC) towards the UE. As explained earlier LTE has a flat architecture hence there is no any centralized controller in E-UTRAN. In E-UTRAN eNBs are inter-connected to each other by X2 interface and are connected to core network (EPC) by means of S1 interface. [8]

The S1 interface of eNBs with Mobility Management Entity (MME) and Serving Gateway (S-GW) are more specifically represented as S1-MME and S1-U respectively. The S1 interface supports many-many relation between MME/S-GW and eNBs, i.e. more than one eNBs can be connected to MME and eNB can be connected to more than one MME. [8]

The E-UTRAN architecture is shown in Figure 3.2, with X2 interfaces between eNBs and S1 interface of E-UTRA with EPC through MME and S-GW.

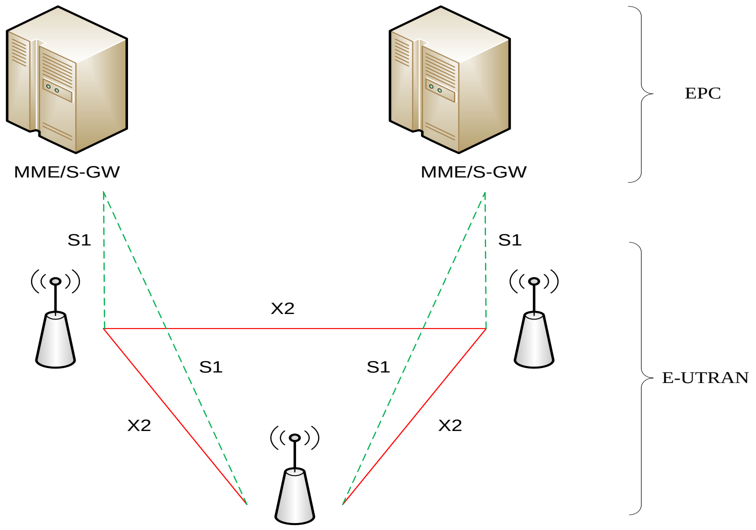

Figure.3.2: E-UTRAN architecture.

In LTE system all the radio-related functionalities are carried out by E-UTRAN and are summarized as follows. [9]

3.2.1. Radio resource management

Radio resource management (RRM) in mobile communication system can be defined as means of providing the mobile users with mobility experience seamlessly. In LTE, unlike other mobile communication system the RRM i.e. the radio bearers related functionalities such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic resource allocation of UEs in both uplink and downlink are carried out in E-UTRAN. [9]

3.2.2. Header compression

In mobile communication system, the efficient utilization of resources is most important. LTE is a Packet Switched (PS) network, hence the communication between users and the network takes place in chunks of data called packet. All packets consist of header containing information about sender and receiver. The header information is very important in PS network and it also creates overhead to the radio interface. Hence for the small packets it is important to have header compression to avoid unnecessary overhead and to ensure efficient utilization of radio interface. In LTE, header compression is done in the E-UTRAN. [9]

3.2.3. Security

In every communication system information security is the most important concern, especially in wireless or mobile communication where the information is exchanged through air-interface. To ensure privacy and unauthorized use of information, the user data is encrypted before transmitting into air and is called ciphering. In LTE, the information encryption is done in E-UTRAN. [9]

3.2.4. Connectivity

The connectivity of eNBs with EPC such as the signaling towards the MME and the bearer path towards the S-GW is also carried out by the E-UTRAN. [9]

The above mentioned functionalities reside in the eNBs. Unlike all other 3GPP technologies each of the eNBs in LTE is responsible for managing multiple cells. In eNBs many different layers are integrated and there is tight interaction between them, therefore it reduces the latency and increases efficiency of the network.

3.3. EPC architecture

The CN of LTE is known as the EPC, the EPC is the most simplified architecture than all other CN architecture available and it only supports PS domain. The EPC is responsible for all the connectivities of the LTE network with trusted or untrusted 3GPP or non 3GPP technologies. The EPC architecture is shown in Figure 3.3 with inter-connectivity of EPC core elements and connectivity of EPC with E-UTRAN and internet.

The main logical nodes of EPC are as follows.

- Mobility Management Entity
- Serving Gateway
- PDN Gateway

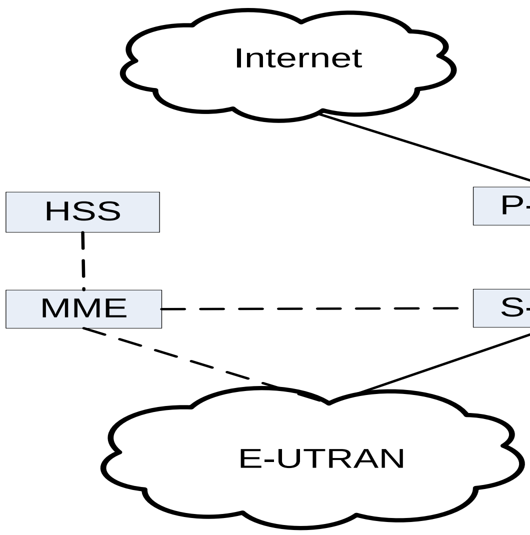

Figure: 3.3: EPC architecture. [10]

The simplified architecture of EPC is shown in the Figure 3.3, which contains the main EPC nodes. EPC is also consists of other logical nodes and functionalities such as Home

Subscriber Server (HSS) and Policy Control and Charging Rules Function (PCRF) [9]. All of the nodes in the EPC are logical nodes and they can be combined with each other such as MME, P-GW and S-GW can easily be combined into one node for physical implementation. The EPC logical nodes with their functionalities can be explained as follows.

3.3.1. Mobility management entity (MME)

It is the control plane node of EPC, and performs the signaling and control functionalities between user and the EPC such as network access to user, allocation of resources, and mobility management of the user i.e. tracking, roaming and handovers. MME functionalities also include the bearer management such as establishment, maintenance and release of bearers. [9][11]

3.3.2. Serving gateway (S-GW)

It is the user plane node of EPC, which connects the EPC to the E-UTRAN. It performs the transformation of the user IP packets to and from the P-GW and serves as mobility anchor for data bearer when user is moving between eNBs and also serves as mobility anchor between LTE and other 3GPP technologies. [9]

3.3.3. PDN gateway (P-GW)

P-GW is responsible for providing connectivity of the user with the PDNs. It is responsible for providing the IP address to the user. The main functionalities of P-GW involve policy enforcement, charging support and packet filtering in downlink for different QoS bearers. P-GW serves as the mobility anchor between LTE and other non-3GPP technologies such as CDMA2000 and WiMAX. [9]

3.3.4. Home subscriber server (HSS)

HSS is responsible for handling the information regarding the user, such as information about the allowed PDN connection and the roaming information of the user if it is allowed or not to the visited network. It handles all this information by creating a master copy of the user profile. It also records the user location in the control node such as MME of the visited network. [12]

3.3.5. Policy control and charging rule function (PCRF)

PCRF is responsible for policy control decision and flow based charging control functionalities. It is also responsible for providing QoS authorization and how the data flow is treated into the policy control enforcement function (PCEF) which resides into the PCRF and to ensure that the data flow is according to user's subscription profile. [13]

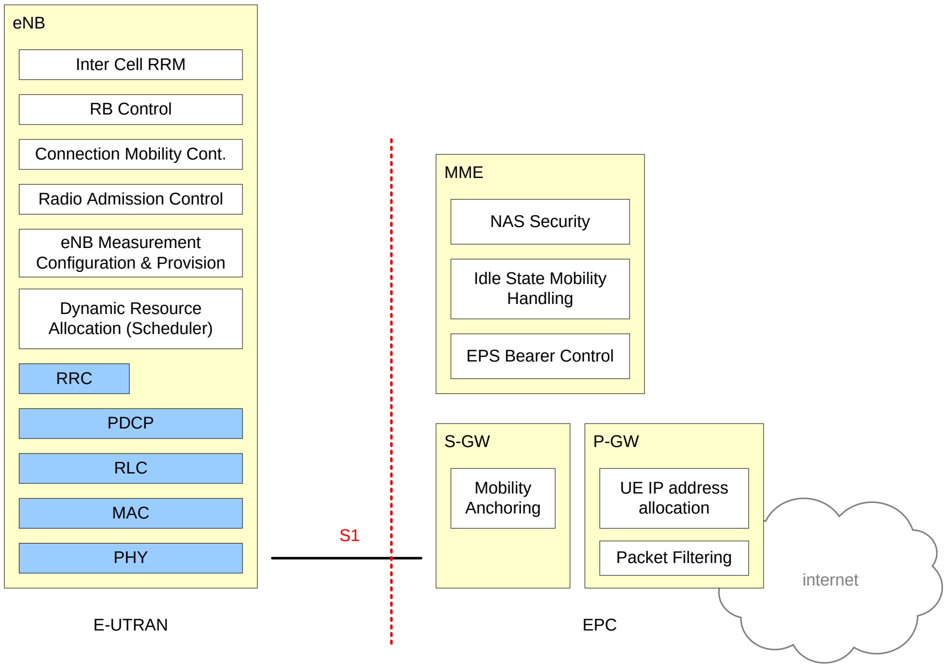

Figure 3.4: Functional split between E-UTRAN and EPC. [8]

The LTE overall architecture in terms of functionalities split between E-UTRAN and EPC is show in Figure 3.4.

3.4. Network interfaces

In mobile communication system, the network nodes are connected to other nodes with different functionalities to share the control and user information. In LTE system there are also different kinds of interfaces which inter-connect eNBs in E-UTRAN, nodes in EPC and interfaces which connect E-UTRAN with EPC. All possible interfaces in LTE network are shown in Figure 3.1 and are described as follows.

- LTE-Uu, it is the interface between user and the eNB. It uses radio Resource control (RRC) protocol to communication between user and eNB.

- X2, it is the interface between eNBs. It is responsible for inter-eNBs load management and user mobility between eNBs [14]. It is also used for inter-cell interference coordination by exchanging inference indicator and overload indicator between eNBs [15].

- S1-MME, it is the interface between MME and E-UTRAN.

- S1-U, it is the interface between eNBs and S-GW. It is the user plane transport tunnel based on IP and is used to send and retrieve IP packets between eNBs and S-GW. [15]

- S2a, it is the interface between the PDN-GW and trusted non-3GPP IP access and is used to provide the control and mobility support between these nodes.

- S2b, it is the interface between PDN-GW and untrusted non-3GPP access to communicate user packet between these nodes and it requires the security gateway such as evolved Packet Data Gateway (ePDG) in between.[16]
- S2c, it is the interface between PDN-GW and UE, it is used to provide control and mobility support and is the reference point implemented over trusted/untrusted 3GPP/non-3GPP access.
- S3, it is the interface between SGSN and MME and is used to communicate user and bearer information for mobility management in idle and active states.
- S4, it is the interface between SGSN and S-GW and is used to provide the user plane with control and mobility support and is based on Gn reference defined between GGSN and SGSN.
- S5, it is the interface between P-GW and S-GW and is used tunneling and tunnel management. In roaming scenario where P-GW is in other network then this is also called as S8.[16]
- S6a, it is the interface between MME and HSS and is used to communicate the authentication data between these nodes for authorizing the access to evolved system.

- S7, it is the interface between P-GW and PCRF and is used to communicate the QoS policy and charging rule between PCRF and PCEF which is located within the P-GW.
- S10, it is the interface between MMEs and is the reference point for MME relocation and inter-MME information exchange.
- S11, it is the interface between MME and S-GW and is the reference point.
- SGi, it is the interface between P-GW and operator’s IP network or external data network such as internet and other public or private data networks and it corresponds to Gi for 2G/3G accesses.
- Rx^{+}, it is the interface between PCRF and operator’s IP Services and is the Rx reference point between Application Function (AF) which requires flow based charging of IP bearer resources and PCRF.[17]
- Wn^{*}, it is the interface between ePDG and untrusted non-3GPP access and is used to force the traffic towards ePDG which is initiated by UE.

4. LTE AIR INTERFACE

In mobile communication systems exchange of information between mobile station and the base station takes place through air-interface. Air interface is technology dependent; every mobile communication system has different air-interface technologies for both uplink and downlink. It has broader effect on system performance, bandwidth utilization, and interference. In LTE system Orthogonal Frequency Division Multiple Access (OFDMA) is used in downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in uplink. In this chapter air-interface technologies used in LTE, both in uplink and downlink, and other transmission related terminologies are explained.

4.1. OFDMA

In LTE network OFDMA is used as the downlink multiple access scheme, it is the multicarrier technology in which transmitter consists of different subcarriers which are overlapping but orthogonal to each other. In OFDMA wide band frequency selective channel is subdivided into several narrow band non-selective channels. It is the special form of multi-carrier technique which can imply several hundreds of narrow band subcarriers to one transmitter in contrast to the conventional multicarrier technique in which there are few subcarriers of relatively wide bandwidth. [10] The main goal of the OFDMA is to enable the channel to be almost flat-fading and also to simplify the equalization process at the receiver. OFDMA has several properties that make it to be the best choice for LTE downlink multiple access technique such as high performance in frequency selective fading channel, low receiver complexity, high spectral efficiency, bandwidth flexibility, link adaptation, frequency domain scheduling and the compatibility with advanced receiver and antenna technologies like MIMO.[12][18]

Implementation of OFDMA system is based on digital technology. Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) are used to transform the signal from time domain to frequency domain and vice versa. The FFT length in LTE should be power of 2 such as 512, 1024 and so on. The block representation of OFDMA transmitter and receiver is shown in Figure 4.1.

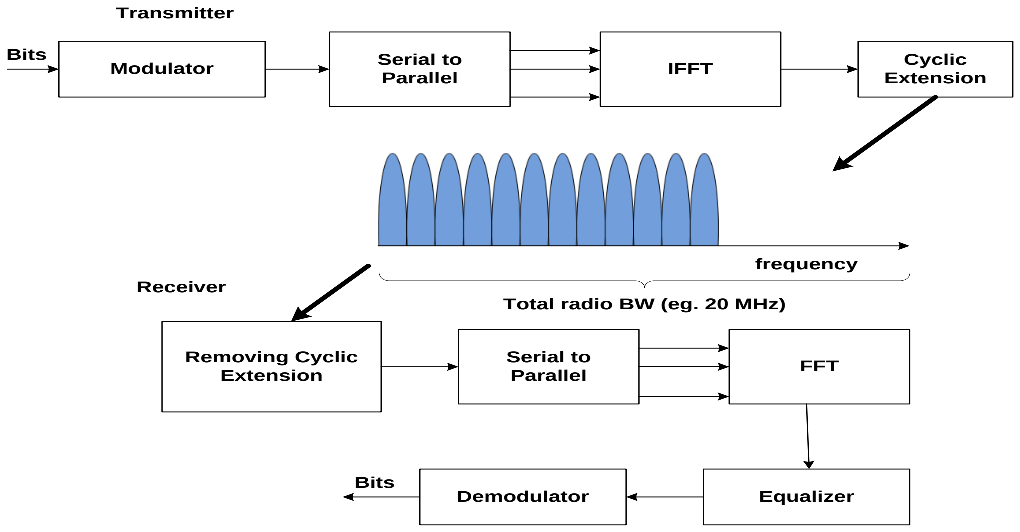

Figure 4.1: OFDMA transmitter and receiver block diagram. [12]

The transmitter and receiver principle of OFDMA as shown Figure 4.1 has different block with different functionalities. The modulator block is used to modulate the user data bits according to modulation scheme selected for transmission. After modulation of the data bit modulated symbols are then feed to the serial to parallel convertor where the modulated symbols are converted into parallel and are feed to the IFFT. At IFFT each parallel symbol corresponds to the input and represents a particular subcarrier. After converting the signal from frequency to time domain cyclic extension also called as Cyclic Prefix (CP) used as guard period to avoid the inter symbol interference is added and the signals are transmitted. At receiver, same process follows in reverse starting from removal of cyclic extension, serial to parallel conversion and FFT. At receiver there is block used for symbol detection after converting to frequency domain and is then feed to demodulator where data bits are demodulated.

In OFDMA the data transmission is in the form of Resource Block (RB), each resource block consists of 12 consecutive subcarriers with subcarrier spacing of 15 kHz forming a total of 180 kHz to be transmitted to the user. In time domain one RB is equal to 1 millisecond. The total number of RBs is different depending upon the transmission bandwidth starting from a minimum of 6 RBs to maximum of 110 RBs for 1.4 MHz to

20 MHz bandwidth respectively. The representation of RB in time and frequency domain with user data, number of subcarriers and total bandwidth of the RB is demonstrated in Figure 4.2.

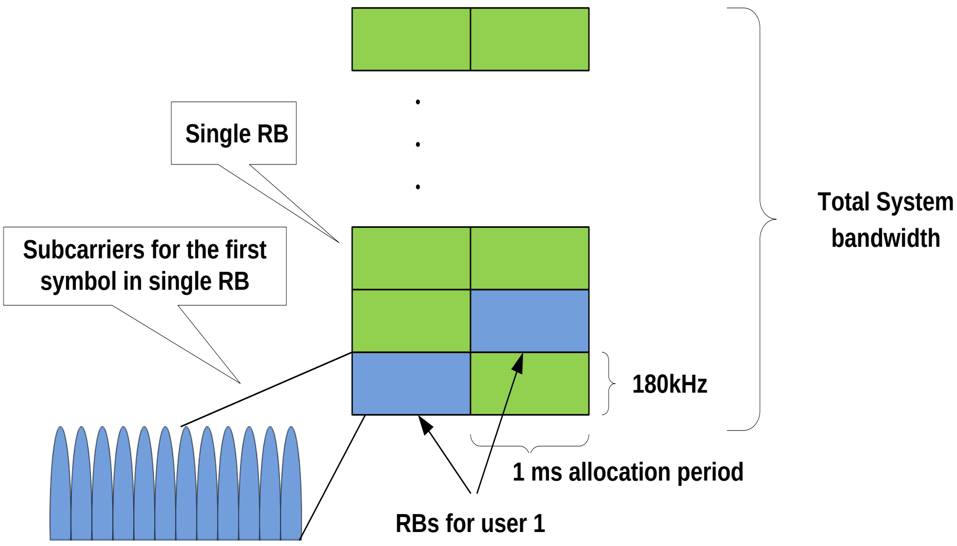

Figure 4.2: OFDMA resource allocation in LTE. [12]

In OFDMA the peak to average ratio (PAR) is very high, which means power at certain time instant is the sum of powers of all symbol transmitted in certain connection and is much higher than the average powers. The PAR is not the issue in the downlink due to high capabilities of power amplifier at eNB but it is not suitable from UE terminal point of view, therefore OFDMA is not recommended for uplink.

4.2. SC-FDMA

As OFDMA has very high PAR hence it is not suitable to be considered for uplink, therefore SC-FDMA is considered as the uplink multiple access scheme for LTE. SC-FDMA is the modified version of OFDMA, and it also called as the Discrete Fourier Transform (DFT) spread-OFDMA, it has similar transmitter and receiver architecture as in OFDMA with addition of DFT and Inverse DFT (IDFT) and is shown in Figure 4.3.

In SC-FDMA, frequency band is also divided into smaller sub-bands called subcarriers as in OFDMA. These subcarriers are transmitted sequentially rather than parallel as in OFDMA, hence the fluctuation in the transmitted signal waveform is reduce and low PAR is achieved. There are also 12 subcarriers in each RB in uplink, the subcarrier spacing in SC-FDMA is also 15 kHz and the RB is also of the bandwidth of 180 kHz as in OFDMA and it also has the same number of RBs in different bandwidth as in OFDMA which is from 6 to 110 RBs.

The sequential transmission of subcarriers leads to substantial inter-symbol interference and complexity in receiver design. Therefore, the adoptive frequency domain equalization is implemented in the eNB to cancel interference and the expensive linear amplification is avoided in UE by complex signal processing in eNB.

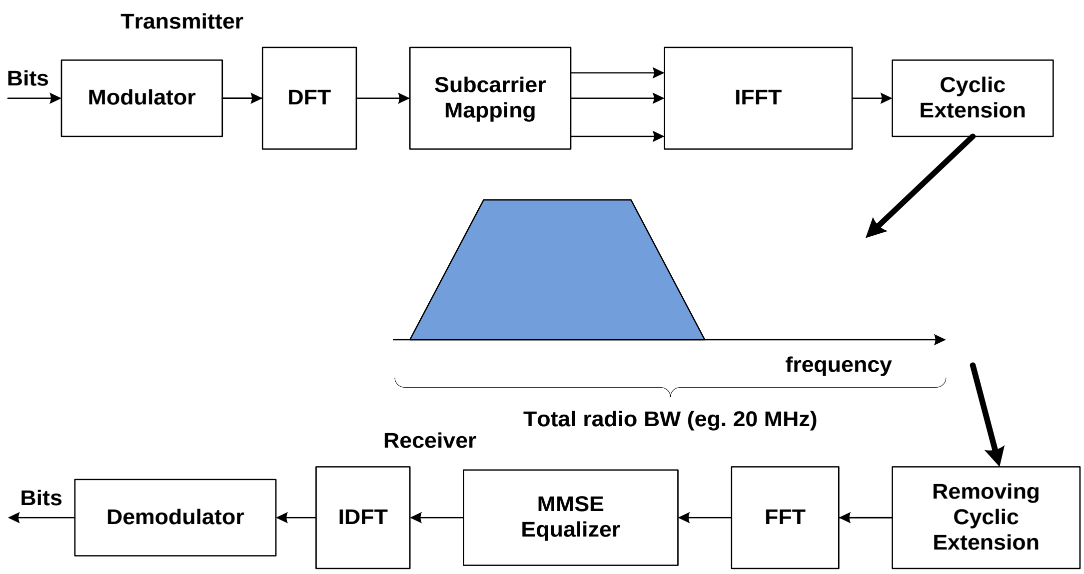

Figure 4.3: SC-FDMA transmitter and receiver block diagram. [12]

The transmitter and receiver principle in SC-FDMA as shown in Figure 4.3 has similar principle as in OFDMA. The additional block DFT used in SC-FDMA transmitter converts the complex time domain symbols into the frequency domain and are mapped to the subcarriers similarly at the receiver IDFT is used to convert frequency domain symbols back to time domain.

Subcarriers mapping in SC-FDMA RB is done in two different ways, distributed mode in which each user data is distributed over alternate subcarriers in the RB and the other localized mode in which each user is allocated with consecutive subcarriers in RB. [19] The representation of RB and subcarrier allocation to the users in SC-FDMA is shown in Figure 4.4.

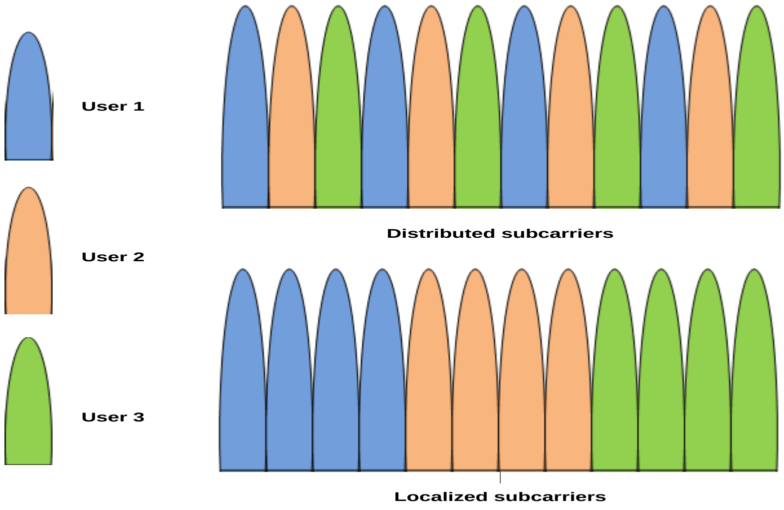

Figure 4.4: Subcarrier allocation for multiple users in SC-FDMA.

4.3. MIMO

Multi Input Multi Output (MIMO) system consists of more than one antenna for both transmission and reception of the signals in mobile communication system as shown in Figure 4.5.

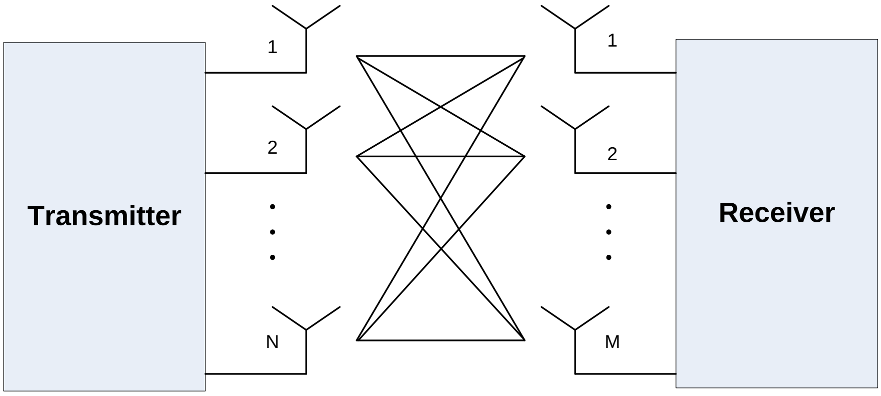

Figure 4.5: MIMO transmission between transmitter and receiver.

Figure 4.5 shows the NxM MIMO system where N is the number of transmit antennas and M is the number of receive antennas. In mobile communication system, radio waves are affected by the multipath fading and interference from the neighboring cells especially at the cell edge, hence multiple antennas are used at transmitter and receiver to mitigate these effects and to achieve high end-user throughput. It is the most efficient way of reducing the multipath effect in mobile communication systems with utilization of existing resources.

In MIMO system multiple antennas are placed in the transmitter with spacing between the antennas large enough such as multiples of the carrier wavelength depending upon the environment type and angular spread to achieve low correlation or independent fading channels. [20]

MIMO system is categories as spatial multiplexing (SM), pre-coding, and transmit diversity. In SM multiple parallel data streams over the single radio link are transmitted from two or more antenna with different data streams which are separated at receiver by means of signal processing and peak data rates are increased. In pre-coding the signal transmitted from multiple antennas are weighted at the receiver in order to maximize the SINR, hence the system performance is improved. In transmit diversity, the same data streams are transmitted from multiple antennas with some coding in order to exploit the gain which is achieved because of different fading between the antennas. [12]

In LTE network high data rate for end-users is the main target, the end-user data rate is greatly influenced by multipath propagation and inter-cell interference. Hence the MIMO system is the basic requirement defined for LTE in order to achieve high system throughput and peak data rates. There are different MIMO transmission schemes supported in LTE such as 2x2 and 4x4 MIMO and theoretically can increase the system throughput by 2 and 4 times respectively. In SM when a MIMO channel is completely assigned to single user for transmission of multiple modulation symbol streams using the same time-frequency resources is called as Single User-MIMO and when different users are scheduled on different spatial streams over the same time-frequency resources is called as MU-MIMO. The Multi User-MIMO gives more flexibility to the scheduler and also referred as Spatial Division Multiple Access (SDMA) and has higher overall system performance gain. [21]

4.4. LTE radio frame structure

The data transmission in downlink and uplink is carried out in radio frames. In LTE both downlink and uplink shares the same radio frame structure of length 10 ms. In LTE two different frame structures are defined, i.e. type-1 and type-2 which are applicable for Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) respectively.

4.4.1. Type-1 frame structure

In type-1 radio frame structure, the 10 ms frame is divided into 10 equally sized sub-frames of 1 ms each. The sub-frames are further subdivided into 2 slots of 0.5 ms. Type-1 radio frame structure in LTE is shown in Figure 4.4.

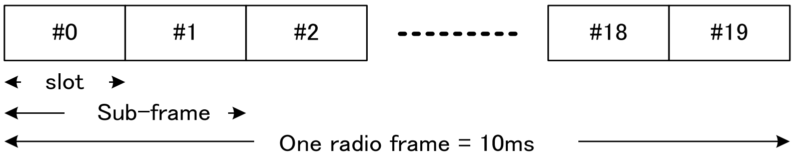

Figure 4.4: LTE type-1 radio frame structure [8]

There are 10 sub-frames for transmission in downlink and 10 sub-frames for transmission in uplink and the uplink and downlink transmission are separated in frequency domain. [6]

4.4.2. Type-2 frame structure

In type-2 radio frame structure, the 10 ms frame is divided into two half frames, which is further divided into 8 slots of 0.5 ms each and three special fields Downlink Pilot Time Slot (DwPTS), Guard Period (GP) and Uplink Pilot Time Slot (UpPTS). The length of DwPTS, GP and UpPTS is configurable which is in total 1 ms. Type-2 radio frame structure in LTE is shown in Figure 4.5.

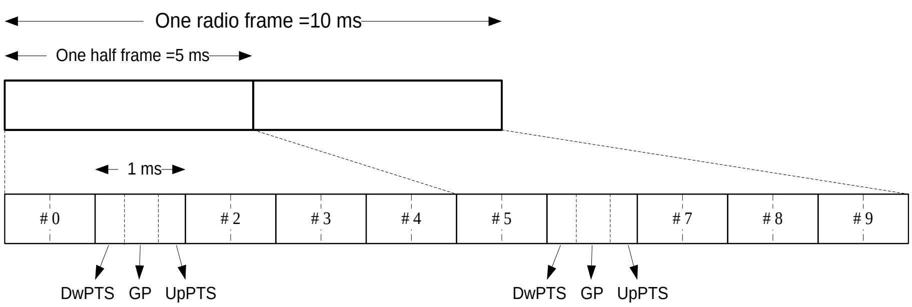

Figure 4.5: LTE type-2 radio frame structure. [8]

The GP is assigned for downlink and uplink transition and all other sub-frames or fields are assigned for either downlink or uplink transmission depending on the configuration. The uplink and downlink transmissions in type-2 radio frame structure are separated in time domain. [8]

4.5. Scheduling

In PS computer networks, the exchange of information is carried into small chunks of data called packets and users are served as first come first serve basis. Hence in order to utilize resources efficiently and fairly scheduling algorithm is used which is defined as the allocation of resources between users in a time instant. LTE is the PS network hence the information exchange is carried out in packets and each user is assigned with resources according to the scheduling algorithm used in the base station. In LTE there are two kinds of scheduling, channel aware scheduling and channel unaware scheduling, in channel aware scheduling the allocation of resources to the UEs differs, depending upon the channel characteristics and in channel unaware scheduling resource allocation is done without knowing the channel condition and characteristics. There are different kinds of scheduling algorithms used in LTE out of which three algorithms are analyzed in this thesis report and are explained as follows.

4.5.1. Maximum C/I scheduling

Maximum C/I is the channel aware scheduling algorithm, in this algorithm the allocation of resources between the users is done depending on the instantaneous channel conditions reported by the UE to the base station which is in the form of Channel Quality Indicator (CQI). According to the maximum C/I algorithm the users with the best instantaneous channel condition is scheduled. The maximum C/I algorithm can mathematically be explained as in 4.1.

$$k = arg \ \max_i R_i \qquad (4.1)$$

where k is the scheduling index, R_i is the instantaneous data rate of the user i. [22]

It is also called as best CQI (BCQI) which is used in this thesis report. From user perspective it is not a fair scheduling algorithm because users with very high channel conditions are served only and users with poor channel condition are lacking resources but it also improves the system throughput which can be seen in the result chapter.

4.5.2. Round robin scheduling

Round Robin (RR) is the channel unaware scheduling, in this algorithm the allocation of resources between users is done independent of the instantaneous channel conditions. According to the round robin scheduling algorithm the resource are equally allocated between the users irrespective of the channel conditions. Hence it is the most fair scheduling algorithm and provides every user with resource but it also reduces the overall performance as few resources might be wasted by users with poor channel conditions.

4.5.3. Proportional fair scheduling

Proportional Fair (PF) is the channel aware scheduling, in this algorithm the allocation of resource it done depending on the instantaneous channel conditions. According to the proportional fair scheduling resources are allocated to the users according to individual instantaneous channel condition. In proportional fair scheduling the short term channel conditions are exploited and long term average user data rate is maintained. Performance wise it falls between round robin and max C/I and it utilizes the fast variation in the channel condition as much as possible while maintaining the fairness between users to some extent. Resources are allocated to the users with relatively best channel conditions, hence for every time instant user which satisfies the condition in 4.2 is selected for transmission.

$$k = arg\max_{i} \frac{R_i}{\bar{R}_i} \tag{4.2}$$

where k is the scheduling index, R_i is the instantaneous data rate and $\bar{R}_i$ is the average data rate for user *i*. [22]

4.6. Link adaptation

In cellular networks received signal strength at the UE is dependent on the channel condition of the serving cell, the interference from the neighboring cells and noise power. The received signal power plays important role in network throughput, hence in order to optimize system performance the data rate information of the UE should be matched to the variations in the received signal quality due to interference and noise. The phenomenon used to overcome these variations is called Link Adaptation (LA) and is based on Adaptive Modulation and Coding (AMC).

In LA different modulation and coding schemes are used to overcome the signal quality variations, such as low order modulation which has very few data bits per modulated symbol such as Quadrature Phase Shift Keying (QPSK) which has higher tolerance to interference than higher order modulations such as 64 Quadrature Amplitude Modulation (QAM) which is highly sensitive to interference, noise and channel estimation. The coding rate is also changed according to the modulation scheme depending upon the channel conditions, such as lower coding rate is used for given modulation in case of lower signal-to-interference noise ratio (SINR) and high coding rate in case of higher SINR. In LTE network, modulation and coding rate are constant over the allocated frequency resources for a given user. [9]

4.7. HARQ

In wireless communication system, there are so many factors such as noise, interference and fading that affect the data transmission, and hence there could be possibility of error in the data packets at the receiver due to these factors. In order to provide error free transmission hybrid automatic repeat request (HARQ) is used, it is the combination of forward error correction (FEC) and automatic repeat request (ARQ). In LTE network HARQ is supported in physical downlink shared channel (PDSCH) and physical uplink shared channel (PUSCH) and the control channel for sending acknowledgment (ACK) and negative acknowledgement (NACK). [23][12]

In LTE network stop-and-wait (SAW) HARQ process is used, according to SAW process packet transmission is done in such a way that after every packet transmission it waits for the acknowledgement of error free reception and is sent by UE in the form of positive acknowledgment which is ACK and new packet is transmitted. If a packet arrives with error then UE sends a negative acknowledgment through NACK and new packet transmission is stopped and HARQ is processed until the ACK is received for previous packet or the maximum retries are reached. [24]

4.8. Frequency allocation

The performance of mobile communication networks is widely dependent on Signal to Interference Noise Ratio (SINR). In order to achieve high throughput, capacity and end user quality of service (QoS), SINR value must be high. Hence a careful frequency allocation is required while designing the network. In cellular communication SINR at the cell center is higher than at the cell edge which is very low because of the interference from the neighboring cells. The inter-cell interference at cell edge is high because of cell coverage overlapping, therefore an intelligent frequency planning scheme is essential to avoid inter-cell interference to maintain reasonable throughput and QoS at cell edge. In LTE different frequency allocation schemes are proposed and are explained as follows.

4.8.1. Classical frequency allocation

In classical frequency allocation scheme, there are two possibilities for radio network planner for allocation of frequency which are straight forward and are explained as follows.

- Reuse 1: In this scheme all the cells and sectors are allocated with full band of frequency as shown in Figure 4.6a. In this scheme peak data rates are higher and high throughput is seen at the center of the cell, but this scheme produce higher inter-cell interference at cell edge.
- Reuse 3: It is called as interference avoidance scheme. In this frequency allocation scheme total frequency band is divided into sub-bands and allocated to the alternative cells as shown in Figure 4.6b. This scheme leads to lower inter-cell interference but it also causes huge capacity loss.

4.8.2. Fraction frequency allocation

In fractional frequency allocation scheme, mix of both reuse 1 and reuse 3 is used as show in Figure 4.6. There are also two possibilities for fractional frequency allocation and is also called as Fraction Frequency Reuse (FFR) and are explained as follows.

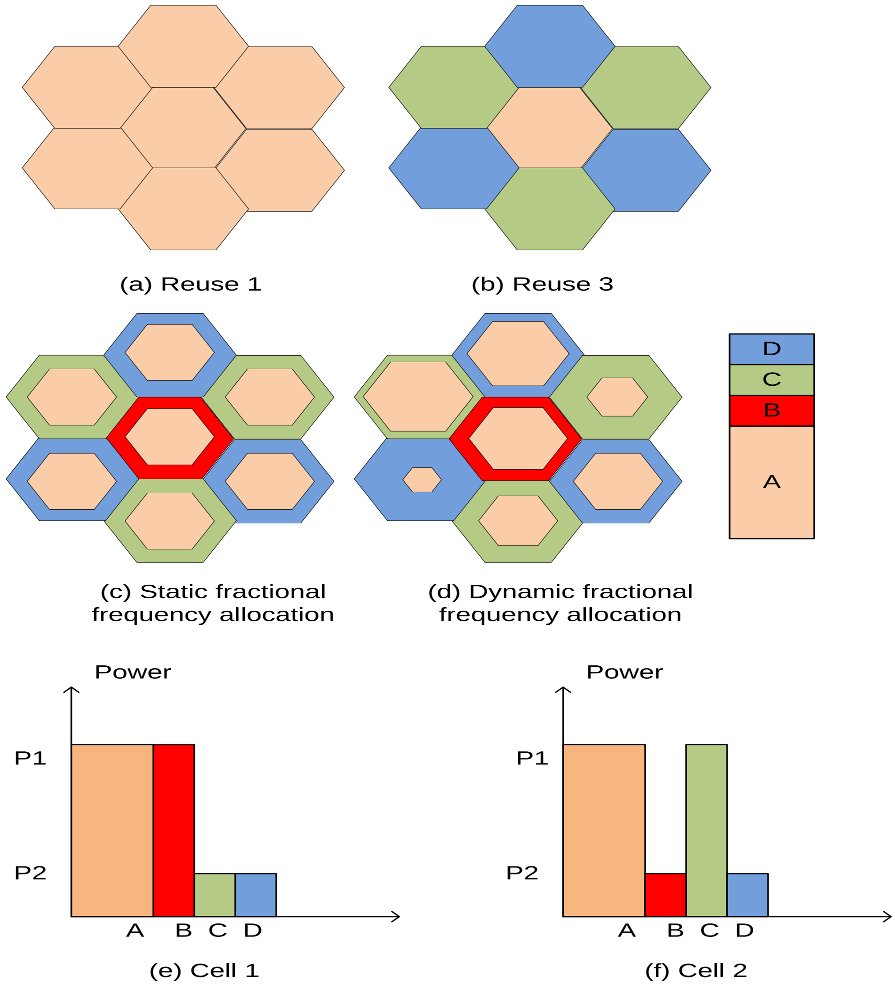

Figure 4.6: Frequency allocation schemes used in LTE. [25][26]

- Static fractional allocation: In this scheme bandwidth is allocated to the user depending upon their position which is determined by path loss. Such as user at cell-center is allocated according to the reuse 1 scheme and at cell-edge to the reuse 3 as shown in Figure 4.6c. In this scheme all cell are allocated with reuse 1 until a certain distance from cell-center which is defined by certain path loss threshold and rest of the area with reuse 3. In this way we can achieve high capacity and low inter-cell interference than straight forward reuse 3.

- Dynamic fractional allocation: In this fractional scheme, allocation of frequency depends on path loss and also on the load in both target cell and neighboring cells. Hence in the cell with high load reuse 1 is higher than the one with low load as shown in Figure 4.6d. In this way we can further increase the capacity of the network.

4.8.3. Partial isolation

In partial isolation scheme, frequency allocation is controlled by scheduler based on fractional allocation scheme which can be implemented as part of the scheduler decision. This scheme further utilizes the frequency that has not been used in fractional allocation and further increase the capacity and maintains the low inter-cell interference. This is done by dividing the frequency band into one central band and sub-bands and every cell can utilize full band of frequency by controlling the power level of the sub-bands as shown in Figure 4.6e and 4.6f.

4.9. Power control

In cellular communication system, power control is the key radio resource management function and refers to the adjusting of the output power level of transmitter for base station in downlink and for UE in uplink. Power control is used to improve network coverage, capacity, end-user QoS and power consumption. The cell coverage depends on the transmitted power level from BS and antenna height. When the maximum power is transmitted from BS the cell coverage is maximum, but the interference is also increased. Therefore the power control is used to increase the coverage and limiting the interference. By using efficient power control mechanism, the inter-cell interference is reduced and the system capacity and QoS is improved.

In LTE network, the power control is defined in uplink only and in downlink power allocation is defined, hence there is no power control defined in downlink except the power boosting of reference signal. In uplink, a slow power control is defined depending on the channel condition such as path loss, fading and interference. There are two different power controls defined in LTE uplink open loop and close loop power control. In open loop power control the user itself decides the power level depending upon the signal strength measurement while in close loop power control eNB generates the power control command for UE depending on the measurement of the signal strength. [27]

4.10. Link budget

In mobile communication, radio signals are attenuated in the path between BS and MS. Link budget calculations estimate the maximum allowed path loss between BS and MS. The maximum path loss is used to estimate the maximum cell range by using suitable propagation models depending on the environment type and the carrier frequency. The link budget calculation helps the network planner to estimate the number of required BSs to cover the target geographical area. The link budget is calculated for uplink and downlink. In this section the link budget calculations are shown for Global System for Mobile Communication (GSM), High Speed Packet Access and LTE. The relative link budget calculations show how well LTE system will perform when deployed with existing network. The link budgets are calculated in uplink with 2 antennas BS receive diversity for 64 kbps and in downlink at 1 mbps with 2 antennas mobile receive diversity. The link budget calculations for uplink and downlink are show in the Table 4.1 and 4.2 respectively. [12]

Table 4.1: Uplink link budgets [12]

Uplink	**GSM voice**	**HSPA**	**LTE**
Data rate (kbps)	12.2	64	64
Transmitter – UE			
Max Tx power (dBm)	33	23	23
Tx antenna gain (dBi)	0	0	0
Body loss (dB)	0	0	0
EIRP (dBm)	30	23	23
Receiver-NodeB			
NodeB noise figure (dB)	-	2	2
Thermal noise (dB)	-119	-108	-118.4
Receiver noise (dBm)	-	-106.2	-116.4

SINR (dB)	-	-17.3	-7
Receiver sensitivity (dBm)	-114	-123	-123
Interference margin (dB)	0	3	1
Cable loss (dB)	0	0	0
Rx antenna gain (dBi)	18	18	18
Fast fading margin (dB)	0	1.8	0
Soft handover gain (dB)	0	2	0
Maximum path loss	162	161.6	163.4

Table 4.2: Downlink link budgets [12]

Downlink	**GSM voice**	**HSPA**	**LTE**
Data rate (kbps)	12.2	1024	1024
Transmitter – NodeB			
Tx power (dBm)	44.5	46	46
Tx antenna gain (dBi)	18	18	18
Cable loss (dB)	2	2	2
EIRP (dBm)	60.5	62	62
Receiver-UE			
UE noise figure (dB)	-	7	7
Thermal noise (dB)	-119.7	-108.2	-104.5
Receiver noise (dBm)	-	-101.2	-97.5
SINR (dB)	-	-5.2	-9
Receiver sensitivity (dBm)	-104	-106.4	-106.5
Interference margin (dB)	0	4	4
Control channel overhead (%)	0	20	20
Rx antenna gain (dBi)	0	0	0
Body loss (dB)	3	0	0
Maximum path loss	161.5	163.4	163.5

5. LTE SYSTEM PERFORMANCE ANALYSIS

Performance of any system can be analyzed by two methods i.e. simulation of the system and the other method is by performing laboratory/field measurements with the help of equipment and measurement tools. From the mobile network's perspective the simulations are most important for analyzing the system behavior and its performance, for academic research as well as for practical implementation of the network. In this thesis report performance of LTE network is analyzed based on system level simulations performed on MATLAB based open source LTE System Level Simulator [28]. In this chapter brief explanation about the simulator, different parameters, scenarios used for simulations and simulation results are explained.

5.1. Simulator overview

LTE system level simulator is used to carry out this research work, it is MATLAB based open source simulator and can be used and modified for academic research purposes. The LTE simulator is modeled into two different ways, link level simulator and system level simulator. The link level simulator is suitable for developing the receiver structure, coding schemes or feedback strategies. In link level simulator it is not possible to reflect the effect of cell planning, scheduling of the users or interference. Hence the system level simulator is developed in order to solve these issues. In system level simulator, the physical layer is abstracted by a simplified model with high accuracy and low complexity. [29]

LTE system level simulator is consist of two core part, link measurement model and link performance model and is shown in Figure 5.1, apart from the core elements the system level simulator consists of different blocks for modeling LTE system. Hence the system level simulations are performed by implementing the LTE networks and utilization of the link level measurement and link performance models. The LTE network is implemented by considering the practical environment and modeling the network elements such as creation of BSs, user generation, user mobility management, traffic model, environment path loss calculation, fading phenomenon, resource allocation, interference management and etc.

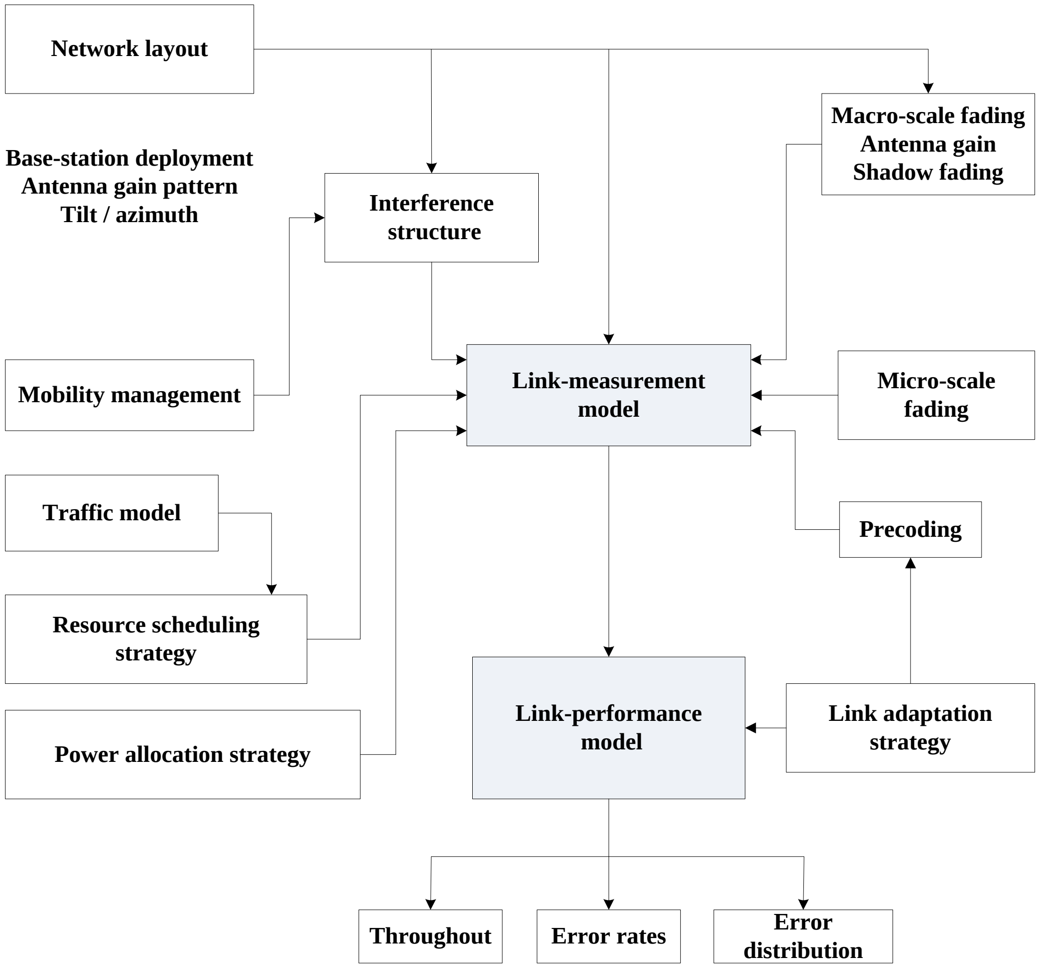

Figure 5.1: LTE system level simulator block diagram. [29]

The link measurement model is used to extract the measured link quality. It abstracts the measurement for link adaptation and resource allocation aiming to reduce the computational complexity during simulation by pre-generating the needed parameters as much as possible. The pre-generated traces are stored in the files and can be reused during simulations.

The link quality model is divided into three parts, macroscopic path loss, shadow fading and small scale fading. The macroscopic fading is modeled by using the propagation pathloss between eNB and UE and the antenna gain. The macroscopic fading is modeled as the pathloss maps and can be computed once and can be reused as long as the network layout is same. The shadow fading, caused by the large obstacle in the path between BS and MS is explained earlier in Chapter 2. It is approximated by lognormal distribution of mean 0 dB and the standard deviation of 10 dB. The macroscopic fading and shadow fading are position-dependent and time-invariant and are called as large scale fading. The small scale fading is time-dependent. It is different from shadow fading and macroscopic fading, therefore it needs to be modeled separately as the small amount of movements can change the waveform. The small scale fading is also called as micro scale fading and is implemented with different channel models for pedestrian and vehicular such as pedA, pedB and extended pedestrian model, and for vehicular channel VehA and VehB are modeled according to ITU recommendations in [30]. [29]

The link performance model estimates the throughout and error rate. The link performance is estimated by determination of the Block Error Rate (BLER) at the receiver for certain resource allocation and Modulation and Coding Scheme (MCS). There are 15 different type of MCSs defined in LTE and are driven by 15 CQIs and are implemented in the simulator. The CQI reporting from UE provides the eNB with figure of merit about the channel conditions of the particular users which help the eNB in resource allocations.

The link measurement and performance models can further be studied from [29], in the following subsections the simulator elements which are the main focus of the LTE system simulations are explained

5.1.1. Network layout

The concept of cellular communication is discussed earlier in Chapter 2, in which the large geographical area is divided into smaller areas called cells in order to avoid interference and to utilize the frequency resources efficiently. These cells are further studied in different network layouts such as hexagonal, triangular and rectangular. The LTE system level simulator has two different network layouts hexagonal and cloverleaf as shown in Figure 5.2. The network deployment is done in the form of ring; the cluster is formed by deploying different number of sites depending on the number of rings. If 0 number of ring is defined in system parameters then only one site is deployed with hexagonal or cloverleaf layout depending on the antenna angles defined, similarly with number of ring 1 it creates 6 more sites forming a ring around the center site making a total of 7 sites and number of rings 2 will create 2 rings with total of 19 sites each of 3 sectors. In this thesis report, 2 rings network is deployed with 19 sites with 3 sectors in each site and performance of the network is evaluated in both hexagonal and cloverleaf layouts and is explained in the results section.

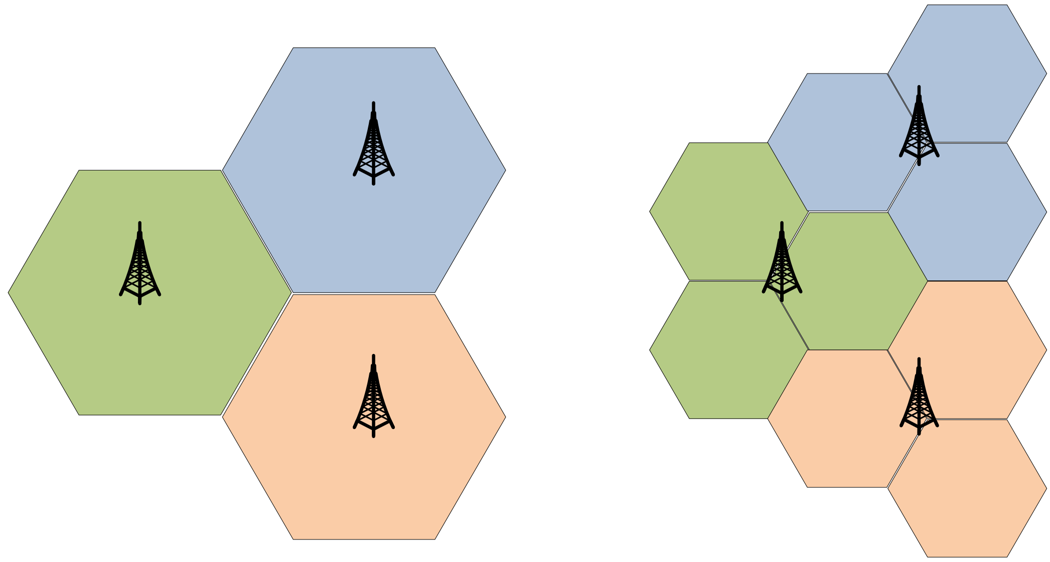

Figure: 5.2. Hexagonal and cloverleaf network layouts.

5.1.2. User distribution

Once the eNBs are deployed, the next step is the generation of UEs and spreading into the Region of Interest (ROI). User distribution in LTE system level simulator is done in two different ways one with users in the target sector only or into the entire network. In this thesis simulation of the LTE system are performed by distributing the users in such way that in every simulation users are randomly spread in the target sector only as shown in Figure 5.3, which means the users are served by the target sector predefined in system parameter file which is in the center-cell and all other cells are acting as interference. The simulations were repeated several times and each time the users were randomly spread so that in each round user has different initial position and are moving with a speed of 3 km/h in pedestrian case and with a speed of 50 km/h when in car.

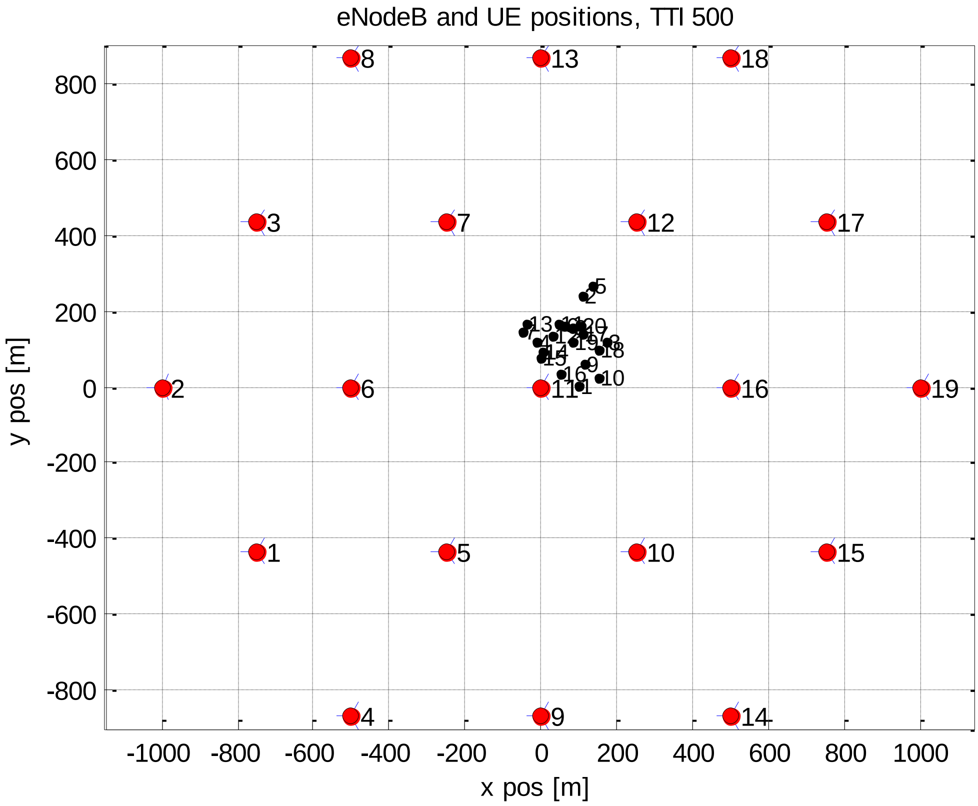

Figure 5.3: User distribution in the target sector.

5.1.3. Path loss model

As studied earlier in Chapter 2 the radio waves are affected during transmission and the signal level is attenuated, and the path loss between transmitter and receiver is dependent on the environment type in which the radio waves are propagated. There are different propagation models defined for calculating the path loss in different environments, in this thesis simulations are performed with TS36942 (Urban) path loss model defined by 3GPP and is mathematically expressed as in 5.1.

$$L_{dB} = 40(1 - 4 \times 10^{-3} \times h_{BS}) \times log_{10}R - 18\log_{10}(h_{BS}) + 21log_{10}f_c + 80 \quad (5.1)$$

where, f_c is the carrier frequency in MHz, h_{BS} is the transmitter antenna height in meters measured from average rooftop level, R is the distance between transmitter and receiver. [31]

5.1.4. Traffic modeling

As stated earlier in Chapter 3, LTE system is completely in PS domain it mean there is no circuit switched (CS) connection in LTE and data transmission is done into packets. In LTE system there are different types of traffic models such as Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP), Voice over Internet Protocol (VoIP), streaming, gaming etc. [31] In this thesis simulation are performed with the full buffer traffic model i.e. bursty or queuing traffic model is used, which means there is always unlimited data for every user. It is good to have full buffer traffic at the initial level to analyze system performance as every user will have data for entire simulation period and we can simulate the effect of environment as users move around the target sector.

5.1.5. Resource allocation

The resource allocation has a broader effect on system performance, as simulator applies frequency reuse 1. Therefore there is same frequency for every cell in the network, and hence the resource allocation is only in the form of RBs depending on the instantaneous channel condition, CQI reporting and the scheduling scheme used. The scheduling of the RBs is done according to CQI reported by UE based on the SINR values observed by the UE as shown in Figure 5.4.

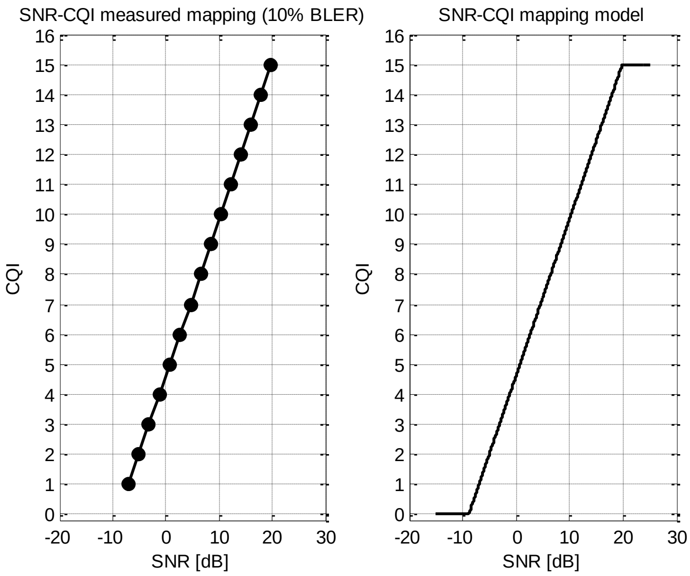

Figure 5.4: SINR-CQI mapping

The RBs allocations in every simulation scenario are shown in the Appendix A, from the simulation plots and mean RB allocation we can clearly see that the user and cell throughputs are completely dependent on the SINR distributions and CQI reporting which is used for assigning the RBs to the users. Figure 5.5 and 5.6 shows the SINR distribution in cloverleaf layout and Figure 5.7 and 5.8 shows the SINR in hexagonal layout.

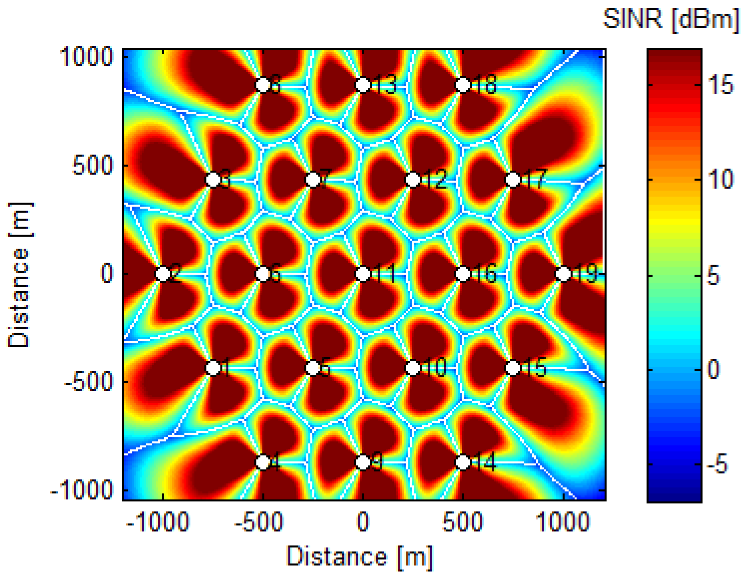

Figure 5.5: SINR distribution in cloverleaf layout.

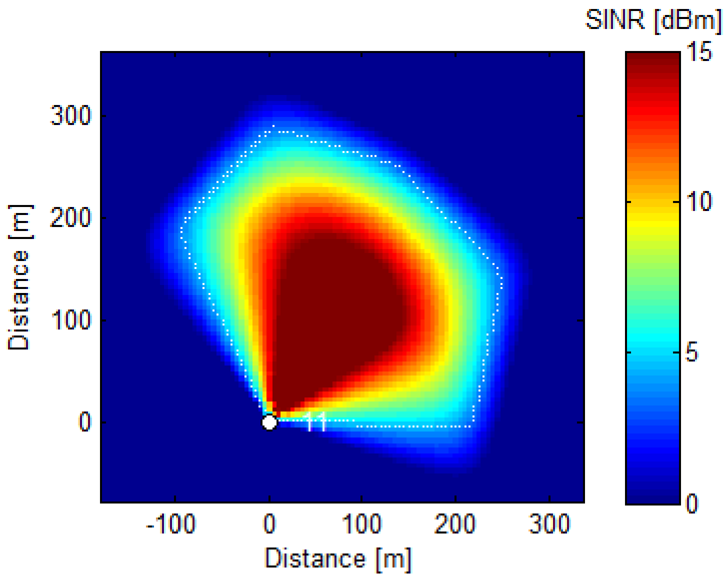

Figure 5.6: Target sector SINR distribution in clover leaf layout.

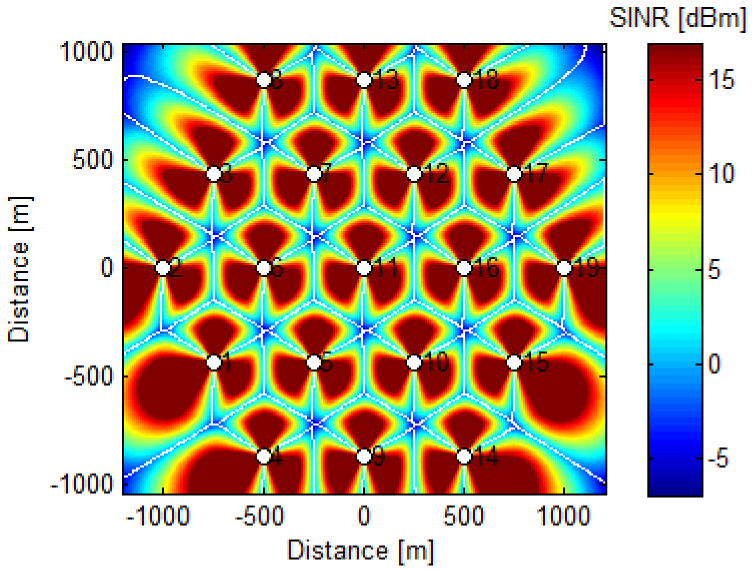

Figure 5.7: SINR distribution in hexagonal layout.

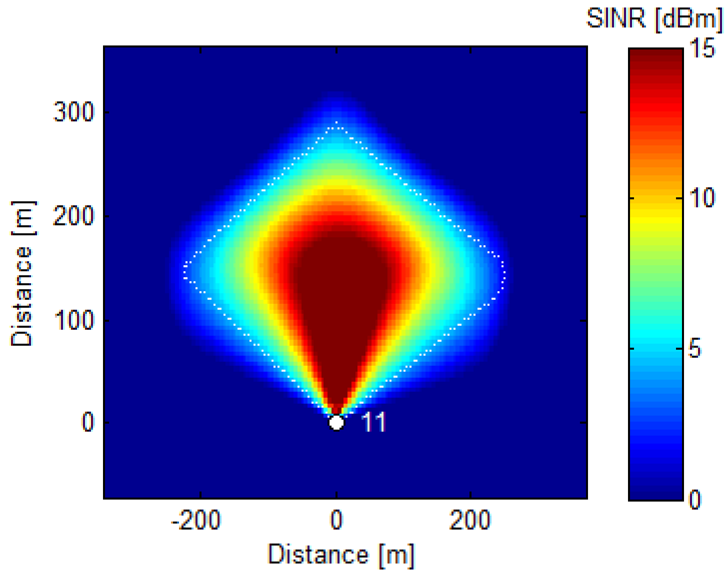

Figure 5.8: Target sector SINR distribution in hexagonal layout.

5.1.6. Antenna type and radiation pattern

The simulator implies different antenna models for simulations, the Kathrein 742215 antenna model with operating frequency of 2.14 GHz and different electrical downtilting angles from 0˚ to 10˚ is chosen for simulating the system performance. In this thesis report three different electrical downtilting angles are applied to the eNB and the results with effect of the antenna downtilting is analyzed. The antenna radiation pattern with 9° electrical downtilting is shown in Figure 5.9.

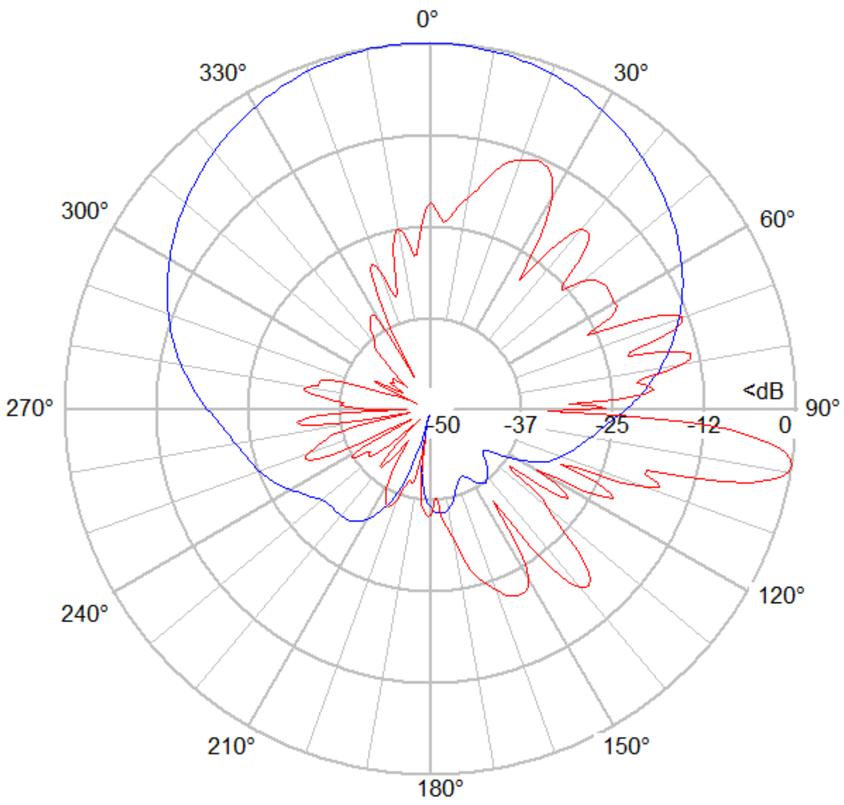

Figure 5.9: Kathrein 742215, 2.14GHz antenna radiation pattern with 9° downtilting. [32][33]

In Figure 5.9, the blue plot shows the horizontal radiation pattern and the red plot shows the vertical radiation pattern of 742215 at 9° downtilting.

5.2. Simulation parameters

The main simulation parameters which were considered during simulation are explained in the Table 5.1.

Table 5.1: LTE system performance simulation parameters

Parameter	Description
Frequency	2140 MHz

Bandwidth	20 MHz
No. of Sites	19 Sites, 3-Sector / Site
No. Of Users	20 UEs / Target sector
No. Of Simulations	20/ Scenario
Simulation Time	500 TTIs
Resolution	5m/Pixel
Path loss Model	TS36942
Path loss Environment	Urban
Inter-site Distance	*500m*
Micro-scale Fading	PedB , Veh-B
Tx Power	40 watts
Tx Mode	Single Antenna, 2x2 MIMO
Antenna Pattern	±45 degree HPBW, 30 dB front-to-back ratio
Antenna Gain (eNodeB)	15dBi
UE noise figure	9dB
Thermal Noise	-101dBm
UE Speed	3km/h , 50km/h
Scheduler	Proportional Fair/Round Robin/BCQI (Max C/I)

5.3. Simulation results

LTE system level simulations are performed in different scenarios in order to evaluate the performance of the network. Simulations performed in this report to evaluate the LTE system performance in practical scenarios are explained in this section starting from the comparison of PF, RR and BCQI scheduling algorithms, effect of MIMO on these scheduling algorithms, system performance in different network layouts, effect of electrical antenna downtilting, and performance in different environment type is analyzed.

5.3.1. Scheduling schemes

LTE system adopts different scheduling algorithms as discussed earlier. In order to evaluate LTE system performance in different scheduling algorithms system level simulations are performed and user and cell throughputs of PF, RR and BCQI are evaluated in this report and are shown in Figures 5.10 and 5.11.

From the plots we can see clearly that the user and cell throughput are higher in case of BCQI and peak data rate is also higher than PF and RR which is easily explained from the theory as discussed in Chapter 4 that in BCQI the resources are allocated to the users with high SINR values only, hence very few users with relatively high SINR values are served and all resources have been allocated to those users which results in high user and cell throughput in BCQI. In case of RR scheduling, both the user and cell throughout are lower than PF and BCQI as all the resources are distributed equally to all users irrespective of instantaneous channel conditions, therefore the resources allocated to the users with worst channel are lost hence it results in lower user and cell throughput and in case of PF scheduling the resource allocation is fair which means every user gets the resource depending upon the channel conditions which means that user with high SINR values will get more resource than users with low SINR value according to the CQI reported by the UE. Therefore from the operator service point of view the PF must be the most suitable in order to achieve reasonable system throughput by maintaining the QoS and fairness.

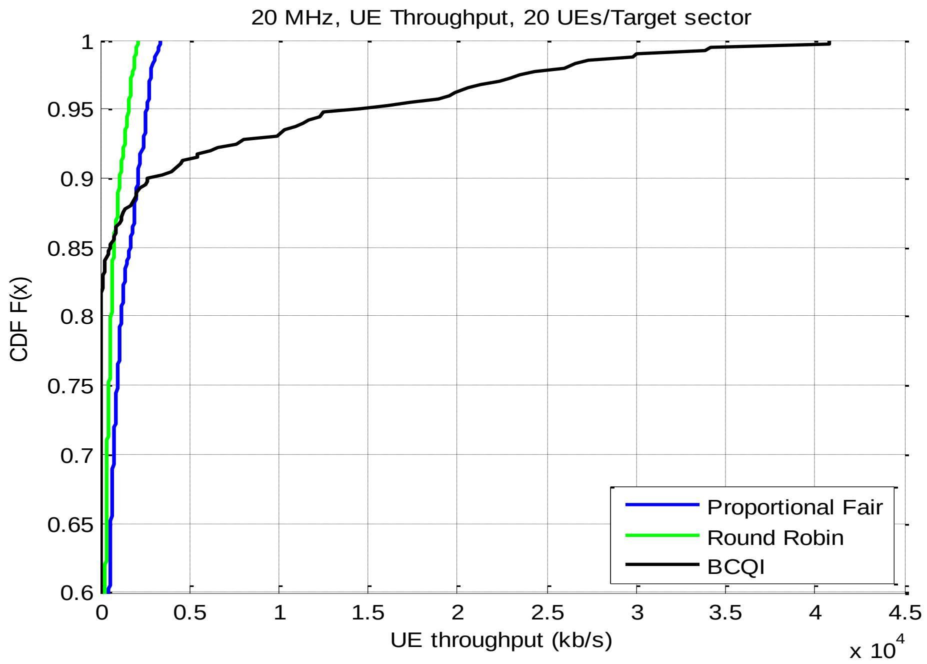

Figure 5.10: UE throughout plots for PF, RR and BCQI scheduling algorithms

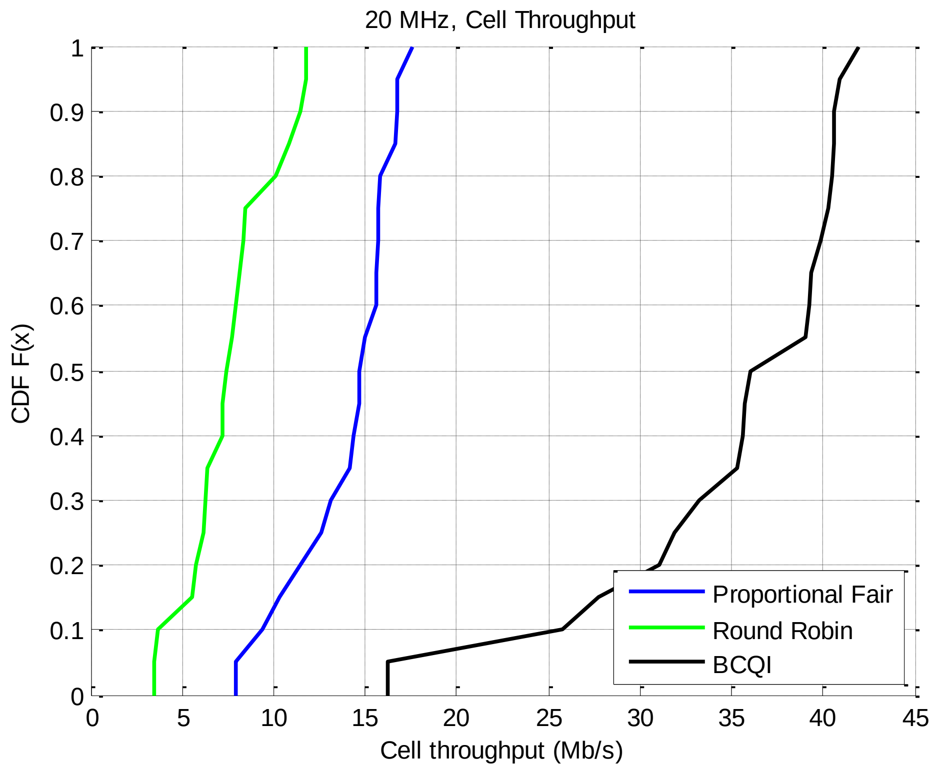

Figure 5.11: Cell throughout plots for PF, RR and BCQI scheduling algorithms

5.3.2. MIMO

The system performance is affected by multipath fading, shadowing, inter-cell interference and other environmental effects. The multipath fading effect is avoided by utilizing MIMO technique and the SINR value is improved hence the overall system performance is improved. Therefore 2x2 MIMO is applied and the LTE network is again simulated and the user and cell throughput are recalculated. From the plots in Figure 5.12 and 5.13 shows that that improvement in the user and cell throughput is observed. In theory MIMO improve the performance of the system depending on the number of antennas used simultaneously for transmission as explained in Chapter 4, by using 2x2 MIMO the performance is not doubled as in theory but it is improved than the single antenna case and it can be seen from the throughput plots. The improvement in case of RR and FP is 200 kbps and 500 kbps respectively at 100 percentile, but there is significant improvement from 0-90 percentile which is ~1 mbps. In case of BCQI, the improvement in user throughput is ~50 kbps and cell throughput is almost doubled. As the user throughput is already higher in BCQI hence there is not much improvement in case of MIMO but there is huge improvement in overall cell throughput.

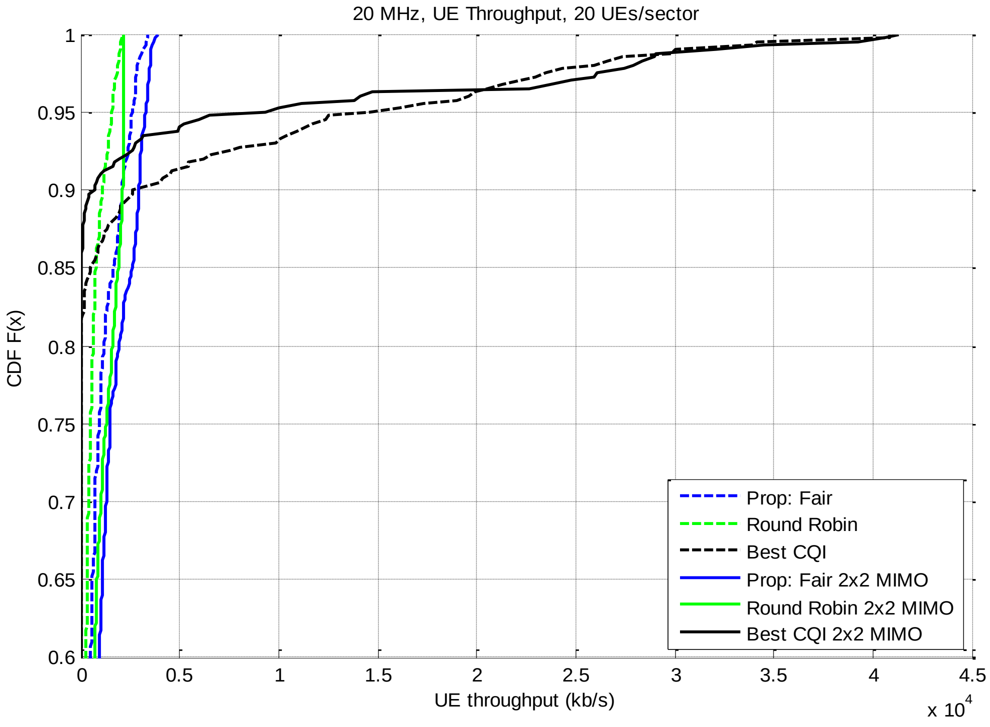

Figure 5.12: UE throughout plots for PF, RR and BCQI with 2X2 MIMO.

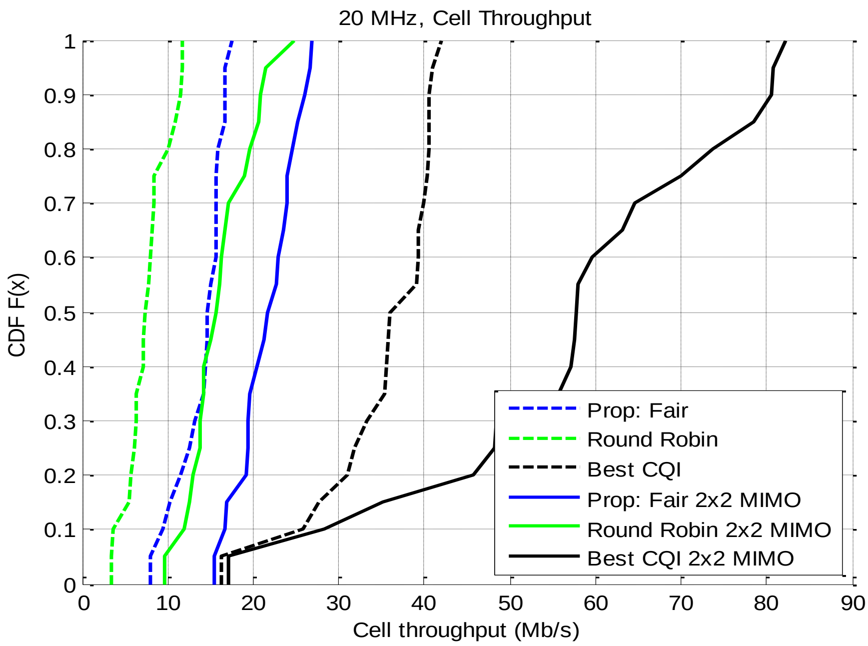

Figure 5.13: Cell throughout plots for PF, RR and BCQI with 2X2 MIMO.

5.3.3. Network layouts

The LTE system performance is evaluated in hexagonal and cloverleaf layout, the user and cell throughput plots are shown in the Figure 5.14 and 5.15, from the plots we can see that the user and cell throughputs are little better in cloverleaf layout than in hexagonal cell layout. It has been studied already in [34] for CDMA network that system performance is better in cloverleaf structure than in conventional hexagonal cell layout. It has also been seen in the system simulation that in LTE network also the cloverleaf network layout is performing better than hexagonal cell. The rest of the simulations performed are in cloverleaf layouts with different antenna tilting and environments.

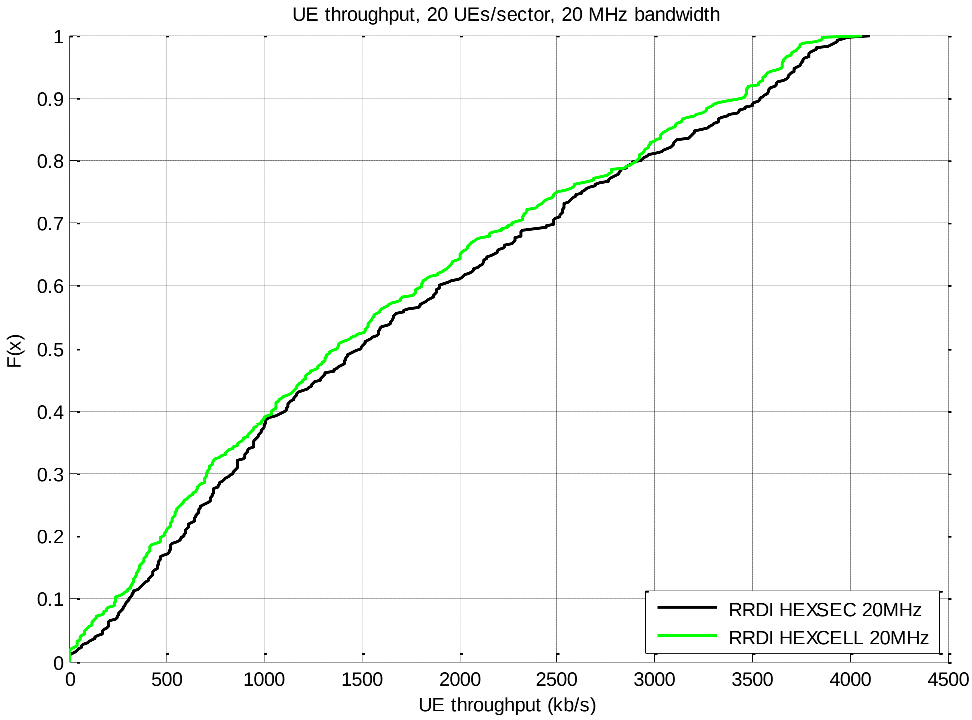

Figure 5.14: UE throughout plots for cloverleaf and hexagonal cell layouts

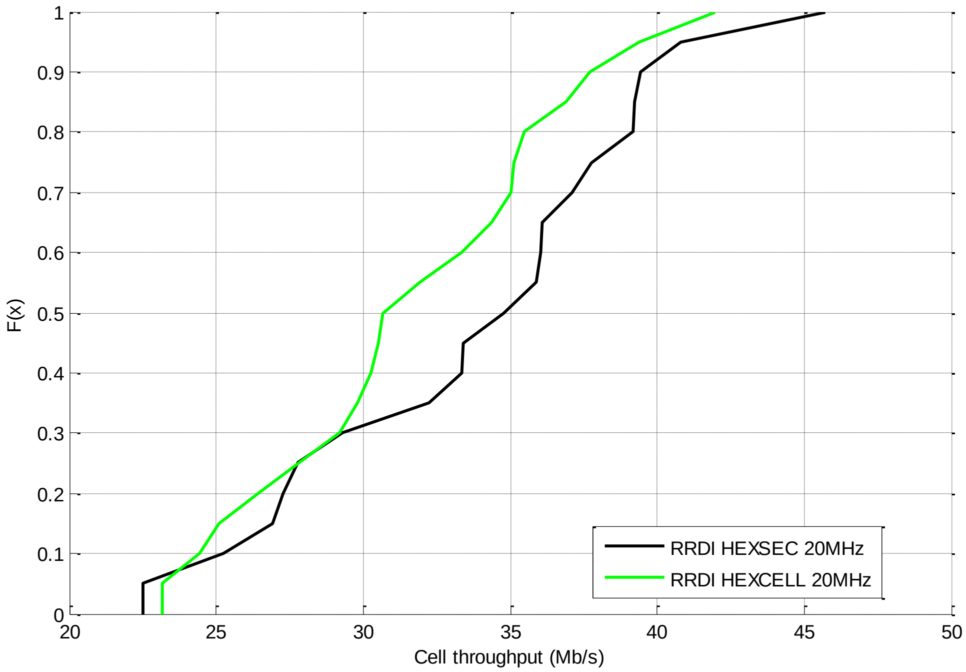

Figure 5.15: Cell throughout plots for cloverleaf and hexagonal cell layouts

5.3.4. Antenna downtilting

Antenna downtilting is a technique of directing the antenna beam towards the ground at the cell edge to reduce the inter-cell interference. In this thesis LTE simulations are performed with different antenna downtilting to reduce the inter-cell interference and the performance of the system is analyzed. Figure 5.16 and 5.17 show the user and cell throughput of LTE system with antenna downtilting of 3°, 6° and 9°. It can be seen from the plots that as antenna downtilting angle is increased the inter-cell interference is decreased due to direction of the antenna beams to the ground and SINR value is improved and the system performance is also increased due to low inter-cell interference and improved SINR and the CQI values reported by the UEs.

The system simulations were also performed to see the effect of antenna downtilting in indoor environment, here deep indoor environment is simulated with two antenna downtilting angles 6° and 9° and performance is analyzed. From the plots in Figure 5.18 and 5.19 we can see that there is not much difference in the user and cell throughput in case of deep indoor scenarios with 6° and 9° downtilting.

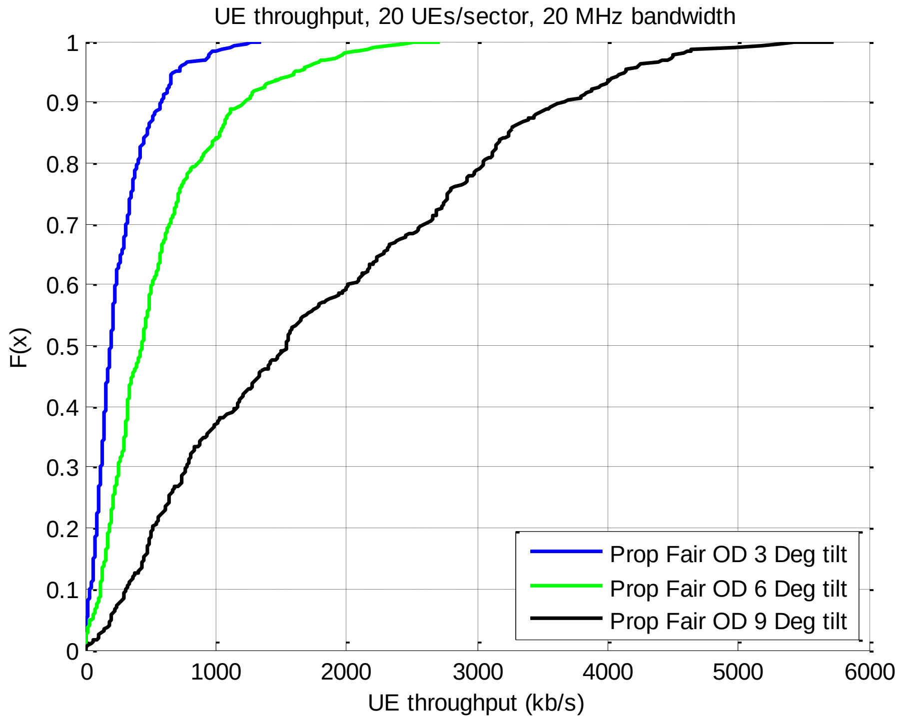

Figure 5.16: User throughout plots for urban environment with 3°, 6° and 9° electrical antenna downtilting.

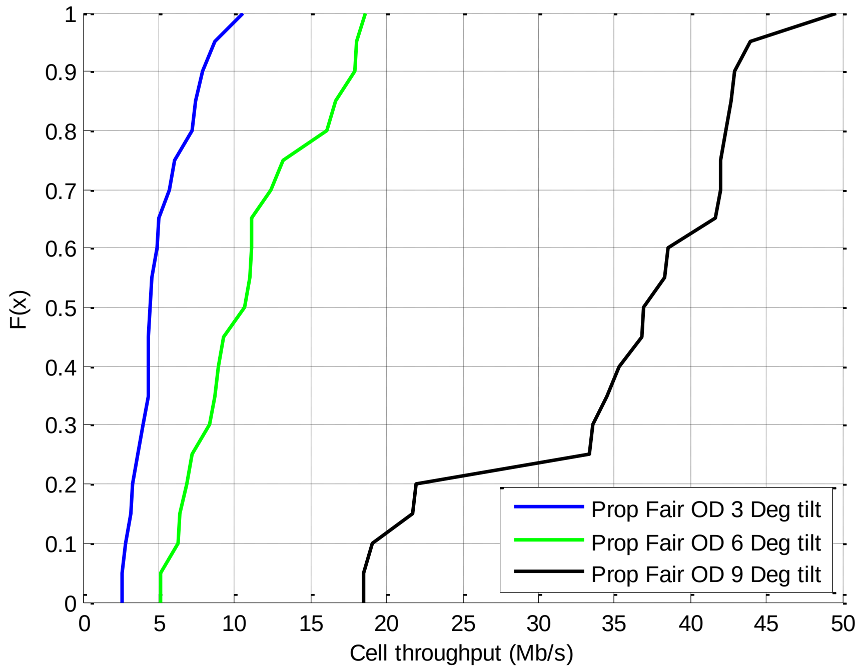

Figure 5.17: Cell throughout plots for urban environment with 3°, 6° and 9° electrical antenna downtilting.

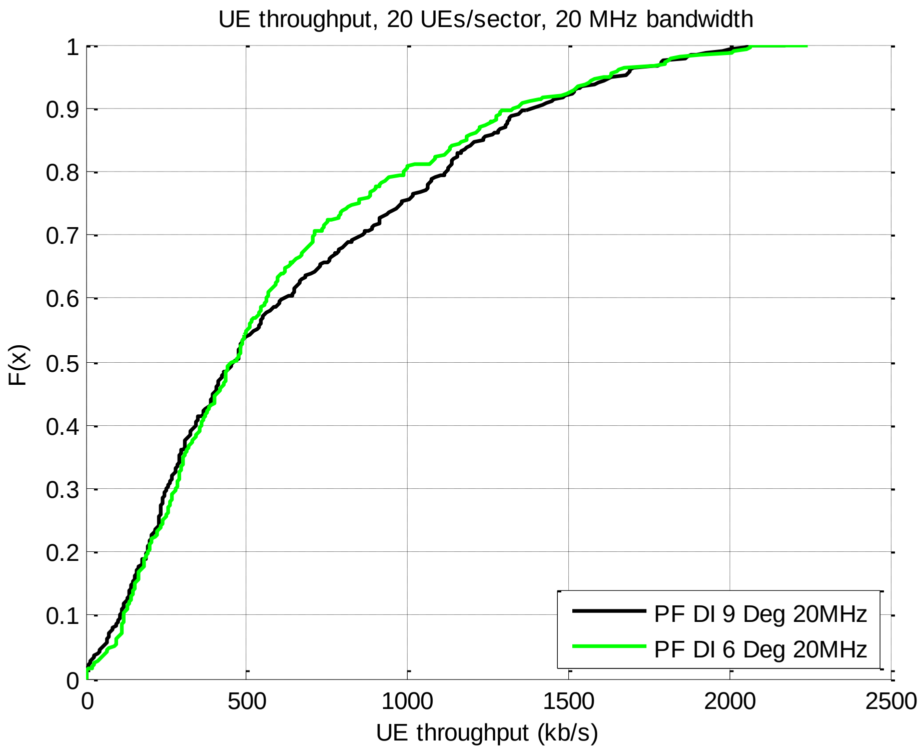

Figure 5.18: User throughput in deep indoor environment with 6° and 9° downtilting

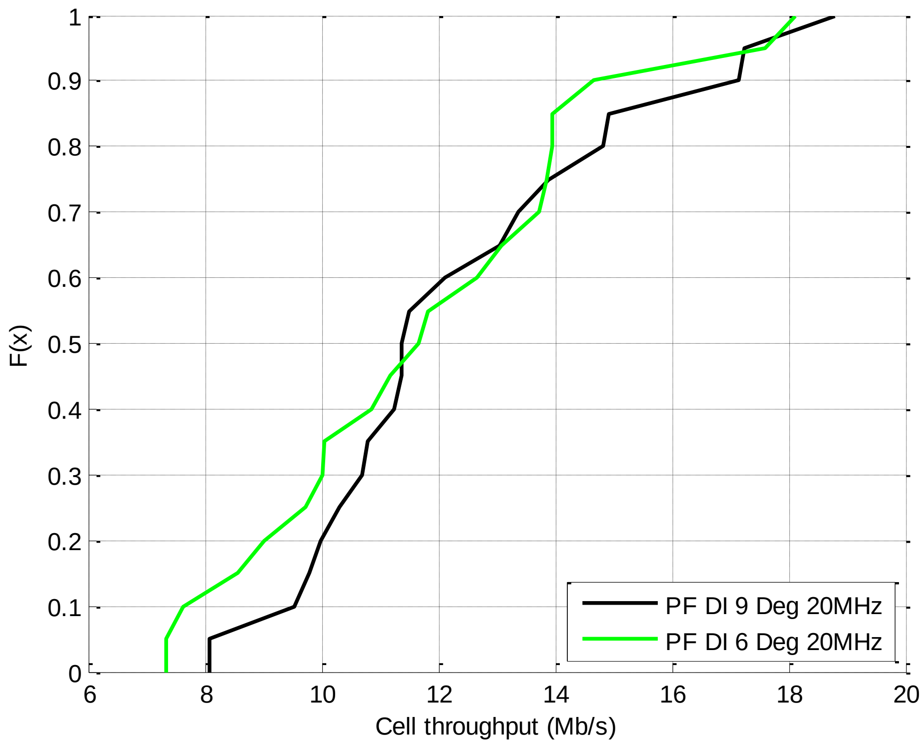

Figure 5.19: Cell throughput in deep indoor environment with 6° and 9° downtilting

5.3.5. Environments

The radio wave propagation environment has significant effect on system performance; hence the system performance is different in different environments due to environmental effects studied earlier in chapter 2. In this simulation scenario, LTE system was analyzed by performing simulation in macro-cellular urban environment with different user positions such as Outdoor (OD), Indoor (ID), Deep Indoor (DI) with speed of 3km/h and In Car (IC) with speed of 50 km/h. The simulations were carried out in cloverleaf layout with electrical antenna downtilting of 9°. The plots in the Figure 5.20 and 5.21 compare the user and cell throughputs of LTE network in outdoor, indoor, deep-indoor and in car. From the results the outdoor environment has better overall performance than others and in indoor scenario the peak data rate is near the outdoor but overall performance is lower than outdoor but higher than deep indoor and in car scenarios.

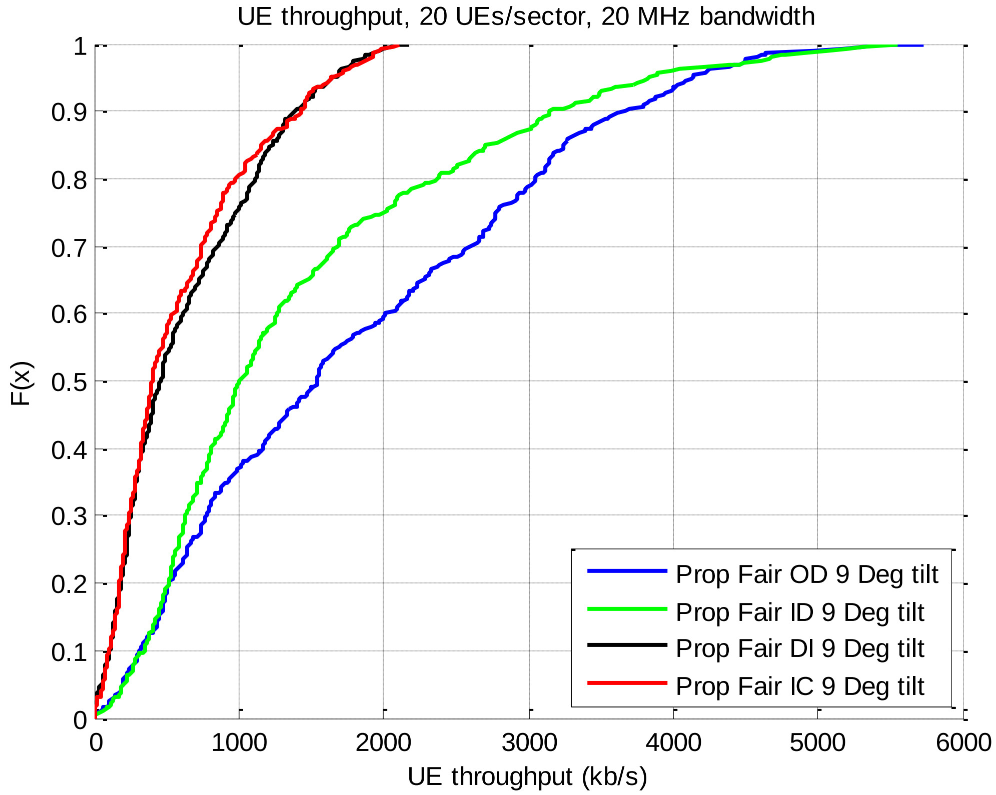

Figure 5.20: UE throughout plots for different environments with 9° downtilting

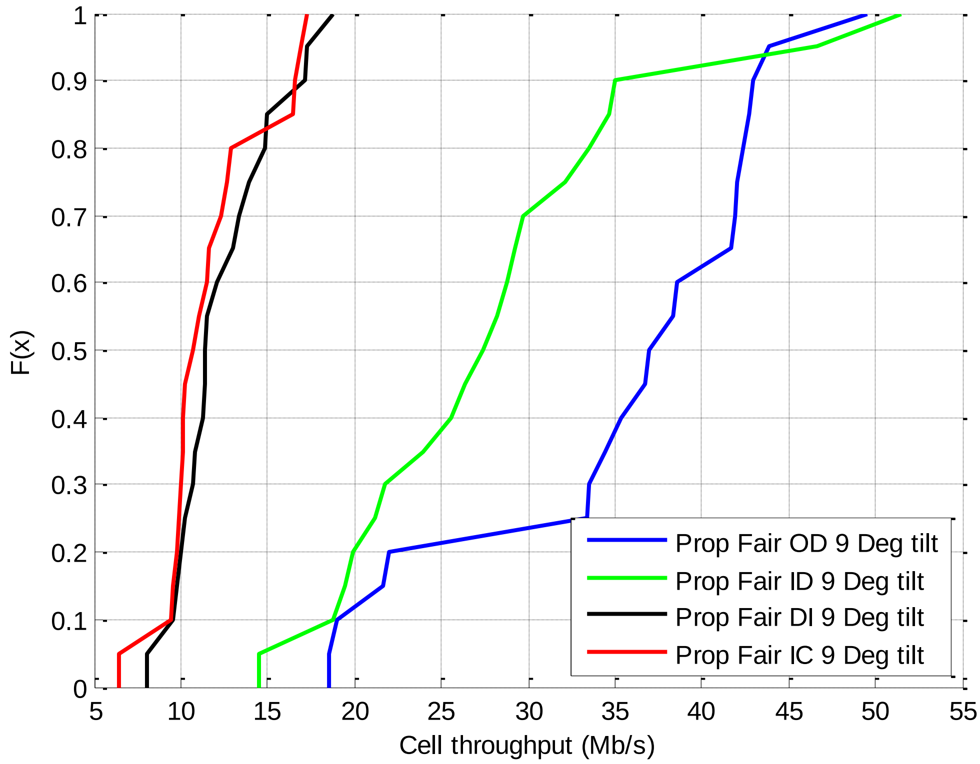

Figure 5.21: Cell throughout plots for different environments with 9° downtilting.

The environment types are categories by adding extra attenuation to the macroscopic path loss to simulate the effect of indoor, deep indoor and in car scenarios.

5.4. Summary

In this chapter different simulation were performed and user and cell throughputs were analyzed in every simulation scenario. The results obtained from the simulation were explained in every scenario and are summarized in Table 5.2:

Table 5.2: User and cell throughput values of all simulation cases

Simulation Type		**User throughput Mbps**	**Cell throughput Mbps**
SISO	Proportional Fair	3.4	17.56
	Round Robin	2.07	11.80
	Best CQI	40.8	41.94

MIMO	Proportional Fair	3.9	26.94
	Round Robin	2.2	24.77
	Best CQI	41.27	82.12
Antenna Tilting	Prop Fair 3° tilt	1.34	10.54
	Prop Fair 6° tilt	2.72	18.62
	Prop Fair 9° tilt	5.7	49.58
	DI with 6° tilt	2.24	18.1
	DI with 9° tilt	2.2	18.8
Network layouts	Hexagonal Sector	4.07	45.73
	Hexagonal Cells	3.85	41.97
Environments types	Prop: Fair OD 9°	5.7	49.58
	Prop: Fair ID 9°	5.5	51.49
	Prop: Fair DI 9°	2.1	18.8
	Prop: Fair IC 9°	2.1	17.32

5.5. Error Analysis

The simulation performed for LTE networks in this thesis report are the estimates of the network performance in order to get idea about the system performance and might be different than in real network. The simulator is solely based on the mathematical models of the system parameters and it might be different than in actual network environment, hence the results should be verified by performing field measurements in the same scenarios to get the actual system throughputs.

As in mobile communication, the radio channel is unpredicted and is highly dependent on environment and surrounding objects hence the realistic approximation of radio propagation environment is hard to achieve. The network environments are categories by introducing the additional attenuation and might be different than in case of real environment such as in case of indoor external attenuation is defined to represent user in indoor, deep indoor and in car scenarios. The path loss models defined in simulation might also be different than in real environment such as the slow fading values for different user position might be different in real network than in the simulation which is fixed in every scenario.

There might also be some bugs in the simulator and in the calculations, averaging and plotting of the results. Instead of having possibility of errors in the results due to differences in the realistic environment and simulator models it is good practice to perform simulation by estimating the system parameters as efficiently as possible for estimation of system performance and research purpose before actual implementation of the network. This way we can have some rough estimate of the network performance and it is also cost effective for operator's perspective.

6. CONCLUSION AND DISCUSSION

Theoretically LTE system promises higher bandwidth utilization, lower latency, high spectral efficiency and high peak data rate and system throughput. In practical situations there are different parameters that affect the system performance and we see the variations in the practical results. The main objective of this research is to analyze the LTE system performance in different practical situations. Therefore LTE system is simulated with different scheduling algorithms, different network layouts, antenna downtilting and different environments to analyze the effect of environment related parameters such as fast fading, slow fading, multipath propagation, and inter-cell interference.

From the results we can see that the PF scheduler performs better as it is fair with reasonable throughputs even though the throughput is high in case of BCQI but it is only for very few users as compared to PF and RR which is not fair from operator's perspective for providing its customer with high QoS. In the simulation results it is also noticed that 2x2 MIMO has significant effect on system throughput which is not seen as theoretical but due to practical environmental effects the results are not doubled but improvement is seen in the performance. In network layout simulations the cloverleaf layout gives little better results than in hexagonal cell layout due to lower inter-cell interference at cell edge in case of cloverleaf layout.

The downtilting of antennas also improves the system performance by avoiding the cell coverage overlapping which is called as cell isolation and reducing the inter-cell interference. The antenna downtilting is considered carefully, the excessive tilting might create a coverage gap and the user mobility will be affected. In case of deep indoor there is not much difference in the performance with 6° and 9° downtilting, it might be the case that 6° is the optimum downtilting angle in case of deep indoor which could also be explained as in deep indoor the signal level from the serving cell is lower hence the interference from the neighboring cell would also be lower hence there is not much improvement in case of 9° downtilting.

The system performance is also affected by different environments, due to the surrounding object and environment type. In the simulations it shows that the throughput is decreasing as user moves from outdoor to indoor because of the extra attenuation caused by the buildings and walls. In case of in car scenario the system performance is also affected and is poor which is possibly because of the speed, the users are observing the fast fading and the multipath propagation while in case of deep indoor the attenuation is due to penetration of signal into the buildings and slow fading which lowers the performance.

The research work carried out in this thesis can further be studied in rectangular and triangular layout, with user distribution in all cells to evaluate the full loaded network, and different traffic models could also be studied such as HTTP, FTP, streaming, gaming and VoIP. The interference coordination schemes could also be implemented to further reduce the inter-cell interference, different frequency allocation schemes could also be evaluated in system level simulations to see the effect of dividing the frequency band on overall system performance. The LTE system performance could also be evaluated for other low frequency band and also in rural and suburban areas with different inter-site distances and high order MIMO.

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Appendix A: Mean RB allocation during simulations

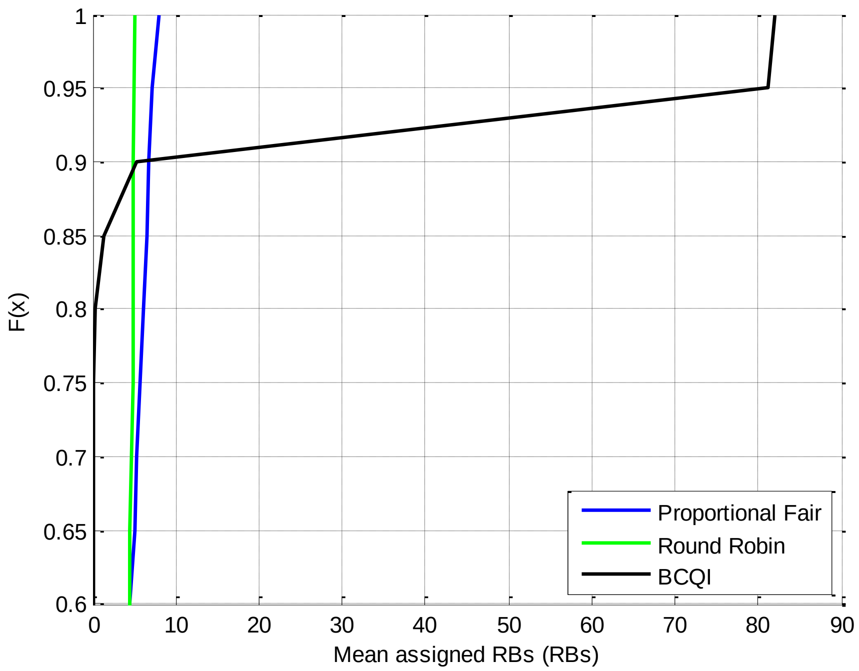

Figure A-1.1: Mean RB allocation in PF, RR and BCQI.

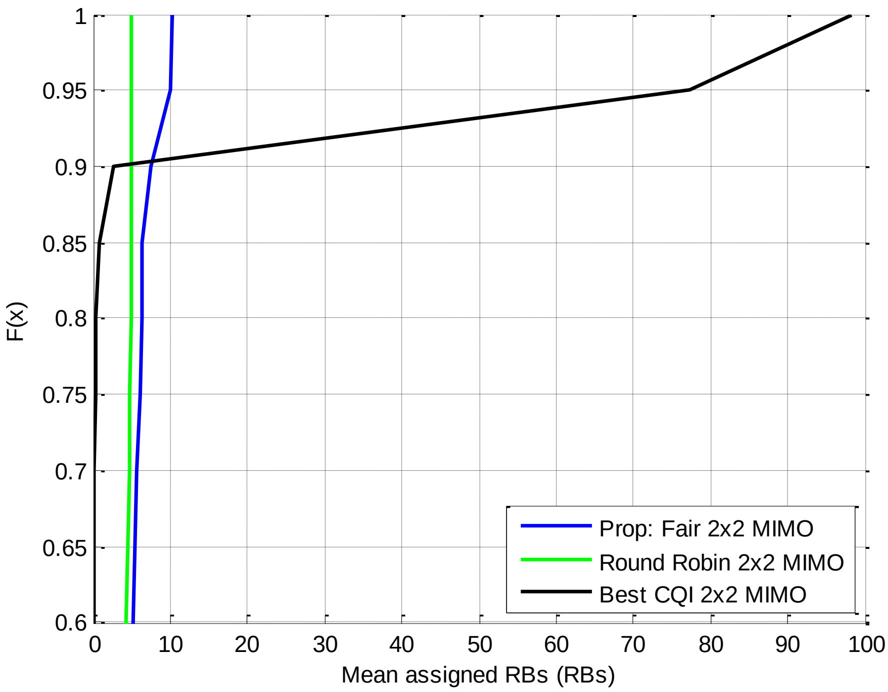

Figure A-1.2: Mean RB allocation in PF, RR and BCQI with 2X2 MIMO.

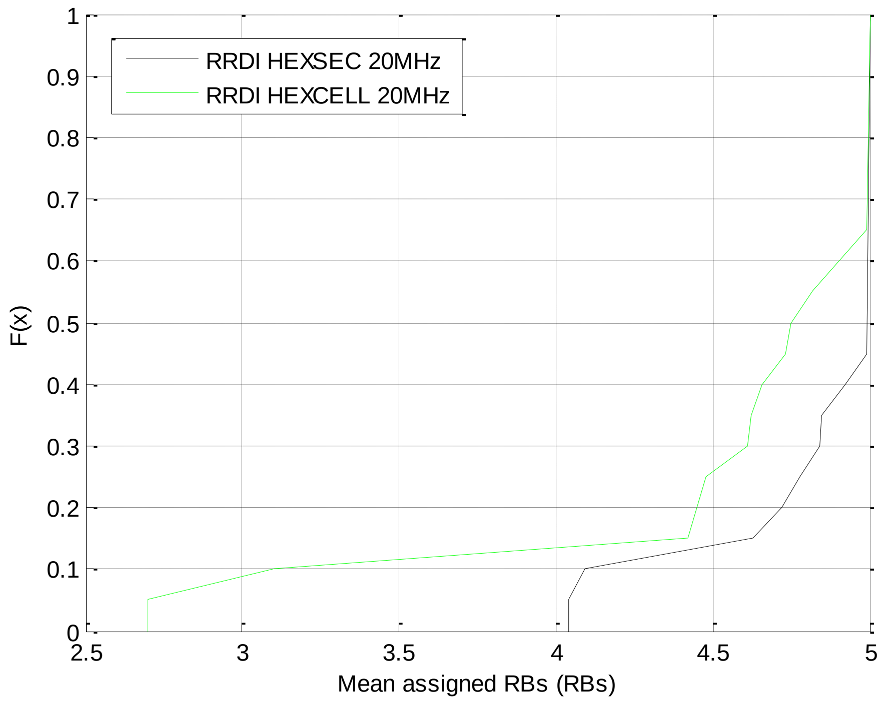

Figure A-1.3: Mean RB allocation in hexagonal and cloverleaf layouts.

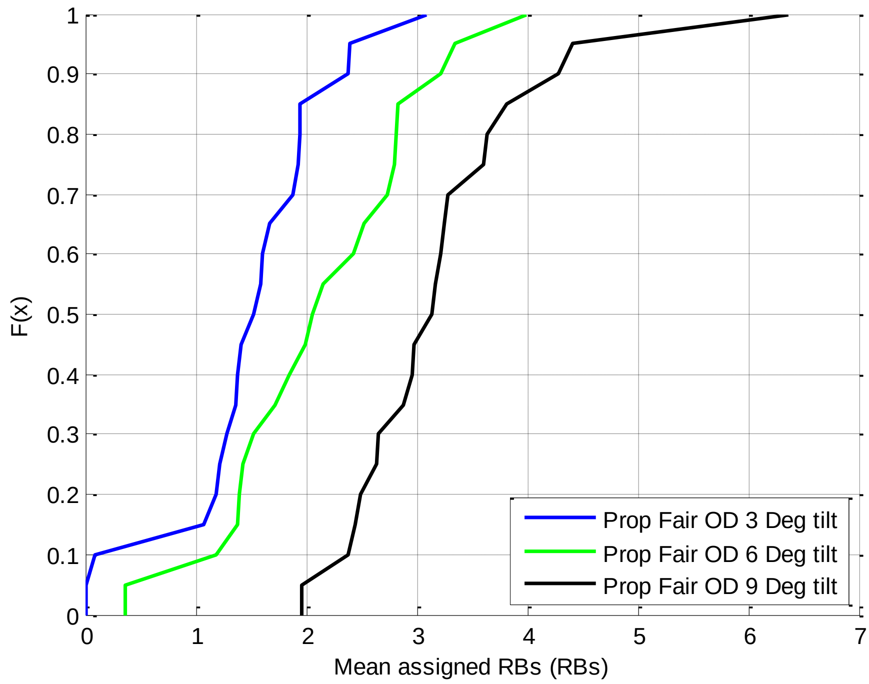

Figure A-1.4: Mean RB allocation in urban environment with 3°, 6° and 9° antenna downtilting.

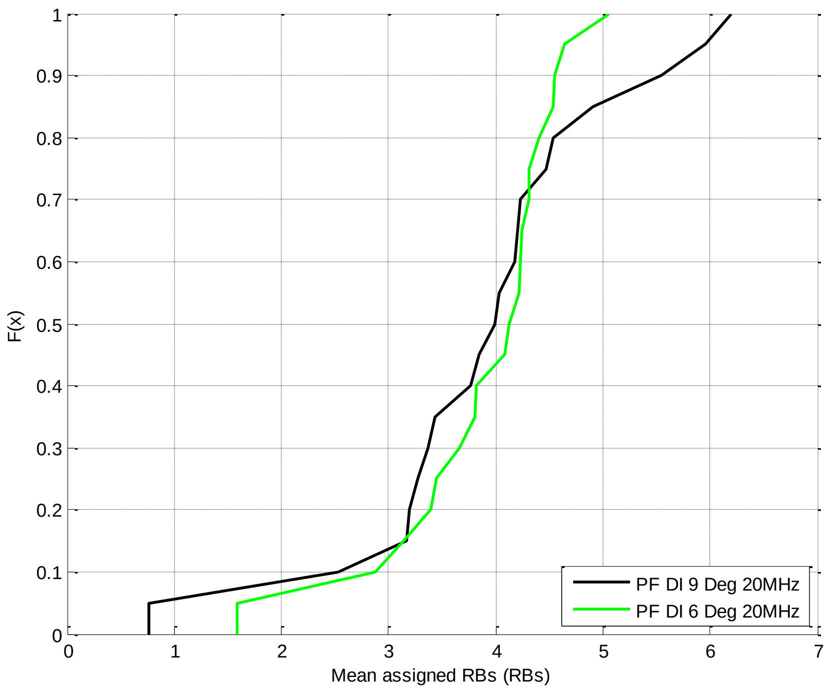

Figure A-1.4: Mean RB allocation in urban deep indoor environment with 6° and 9° antenna downtilting.

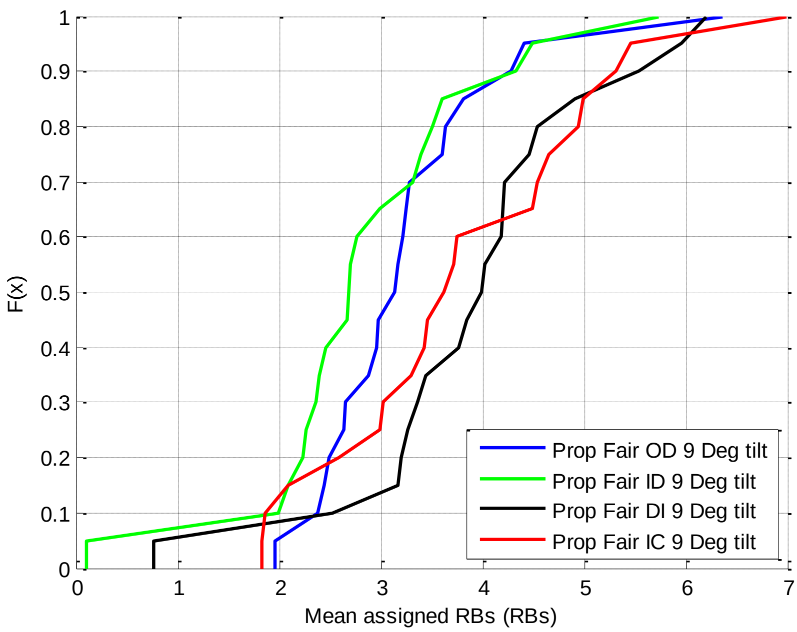

Figure A-1.4: Mean RB allocation in urban outdoor, indoor, deep indoor and in car environment with 9° antenna downtilting.