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LTE-ADVANCED: TECHNOLOGY AND PERFORMANCE ANALYSIS

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LIST OF ABBREVATIONS

1G	First generation
2G	Second generation
3GPP	Third Generation Partnership Project
4G	4th generation
AN	Access Network
ACCS	Autonomous component carrier selection
ANR	Automatic Neighbor Relation
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code division multiple access
CC	Component Carrier
CoMP	Coordinated Multi-point
CP	Cyclic Prefix
CN	Core Network
DNS	Domain Name Service
DL	Downlink
DF	Decode and Forward
DFDMA	Distributed FDMA
DFT	Discrete Fourier Transform
EPS	Evolved Packet System
EPC	Evolved Packet Core
Eb	Bit energy
eNB	eNodeB
FD	Frequency-Domain
FDD	Frequency Division Duplexing
FFT	Fast Fourier Transform
FFS	Fee-For-Service
GSM	Global System for Mobile Communications
GUTI	Globally Unique Temporary ID
GP	Guard Period
GTP	GPRS Tunneling Protocol
GPRS	General Packet Radio Service
GERAN	GSM/Edge Radio Access Network
HSPA	High Speed Packet Access
HSS	Home Subscription Server
HeNB GW	Home eNodeB Gateway

HeMS	Home eNodeB Management System
HRPD	High Rate Packet Data
HPLMN	Home Public Land Mobile Network
IP	Internet Protocol
ISD	International Subscriber Dialing
ITU	International Telecommunication Union
IFFT	inverse Fast Fourier Transform
ICIC	inter-cell interference coordination
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
LFDMA	Localized FDMA
LAN	Local Area Network
LTE	Long-Term Evolution
L1	Layer 1
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi-User MIMO
MANET	Mobile Ad Hoc Network
MATLAB	Matrix Laboratory
MAN	Metropolitan Area Network
MME	Mobility Management Entity
MP	Media players
MAC	Medium-Access Control
NGMN	Next Generation Mobile Networks
NAS	Non-Access Stratum
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDN	Packet Data Network
P-GW	Packet Data Network Gateway
PCRF	Policy and Charging Resource Function
PCC	Policy and Charging Control
PCEF	Policy and Charging Enforcement Function
RRM	Radio Resource Management
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PTS	Pilot Timeslots
PAPR	Peak-to-Average Power Ratio
PCI	Physical Cell ID
POE	Probability of Error

Pe	Error Probability
PSD	Power Spectral Density
PCRF	Policy and Charging Rules Function
PMIP	Proxy Mobile IP
PLMN	Private Land Mobile Network
QoS	Quality of Service
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QWERTY	Standard Computer or Typewriter Keyboard
RF	Radio Frequency
RRC	Radio Resource Control
RLC	radio link control
ROHC	Robust Header Compression
RAN	Radio Access Network
RAT	Remote Administration Tool
RNC	Radio Network Controller
SNR	Signal-to-Noise Ratio
SC-FDMA	Single Carrier Frequency Domain Multiple Access
SINR	Signal to Interference-and-Noise Ratio
SIMO	Single Input, Multiple Output
SGSN	Serving GPRS Support Node
SDO	Serial Data Out
SAE	System Architecture Evolution
S-GW	Serving Gateway
SIP	Session Initiation Protocol
SON	Self organizing networks
SISO	Single input single output
SU-MIMO	Single-User MIMO
TDD	Time Division Duplexing
TTI	Transmission time interval
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
UE	User Equipment
UL	Uplink
VPLMN	Visited Public Land Mobile Network
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WP5D	Working Party 5D

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Abstract

Wireless data usage is increasing at a phenomenal rate and driving the need for continued innovations in wireless data technologies to provide more capacity and higher quality of service. In October 2009, 3rd Generation Partnership Project (3GPP) submitted LTE-Advanced to the ITU as a proposed candidate IMT-Advanced technology for which specifications could become available in 2011 through Release-10 . The aim of "LTE-Advanced" is to further enhance LTE radio access in terms of system performance and capabilities compared to current cellular systems, including the first release of LTE, with a specific goal to ensure that LTE fulfills and even surpass the requirements of "IMT-Advanced" as defined by the International Telecommunication Union (ITU-R) .
This thesis offers an introduction to the mobile communication standard known as LTE Advanced, depicting the evolution of the standard from its roots and discussing several important technologies that help it evolve to accomplishing the IMT-Advanced requirements. A short history of the LTE standard is offered, along with a discussion of its standards and performance. LTE-Advanced details include analysis on the physical layer by investigating the performance of SC-FDMA and OFDMA of LTE physical layer. The investigation is done by considering different modulation schemes (QPSK, 16QAM and 64QAM) on the basis of PAPR, BER, power spectral density (PSD) and error probability by simulating the model of SC-FDMA & OFDMA. To evaluate the performance in presence of noise, an Additive White Gaussian Noise (AWGN) channel was introduced.
A set of conclusions is derived from our results describing the effect of higher order modulation schemes on BER and error probability for both OFDMA and SC-FDMA. The power spectral densities of both the multiple access techniques (OFDMA and SC-FDMA) are calculated and result shows that the OFDMA has higher power spectral density.

KEYWORDS: LTE, IMT-Advanced, LTE-Advanced, 4G

1. INTRODUCTION

During the past decade the wireless communications industry has increased drastically with over four billion subscribers (**Figure 1.1**). While the first generation (1G) analog cellular systems had only voice communication with limited roaming, the second generation (2G) digital systems offer better voice quality and higher capacity. Besides, roaming has become more widespread especially in European countries because of limited standards and common spectrum allocations (Beming&Frid 2007).

The two most used second-generation (2G) cellular systems are GSM (global system for mobile communications) and CDMA (code division multiple access). The 2G systems like the 1G analog systems, were first designed to support voice communication and later, released of these standards also supported data transmission, despite the fact that the data rates were lower than those supported by dial-up connections.

Although, in the last decades only a few selected people could use the service, because it was very expensive. Today, the mobile communications are used by a large part of the world population and it has become a part of everyone's life. The amount of the subscribers is rising. That's why the tasks of evolving mobile technologies are changed from being national or regional concern to wide complex task undertaken by global standards-developing organizations such as the Third Generation Partnership Project (3GPP).

Mobile communication technologies are divided into the following generations:

- 1G being the analog mobile radio systems of the 1980s
- 2G the first digital mobile systems
- 3G the first mobile systems handling broadband data.

Often the Long-Term Evolution (LTE) which is the first release of the LTE (release 8) is called "4G", but it is in fact the "3.9G" and most specialists also assert that the real developed level of the 4G is LTE release 10, also known as LTE-Advanced. This is because the large amount of labels and the constant competition between them is forcing to increase the new level of the mobile system generations. What is important is the actual system capabilities and how they have evolved.

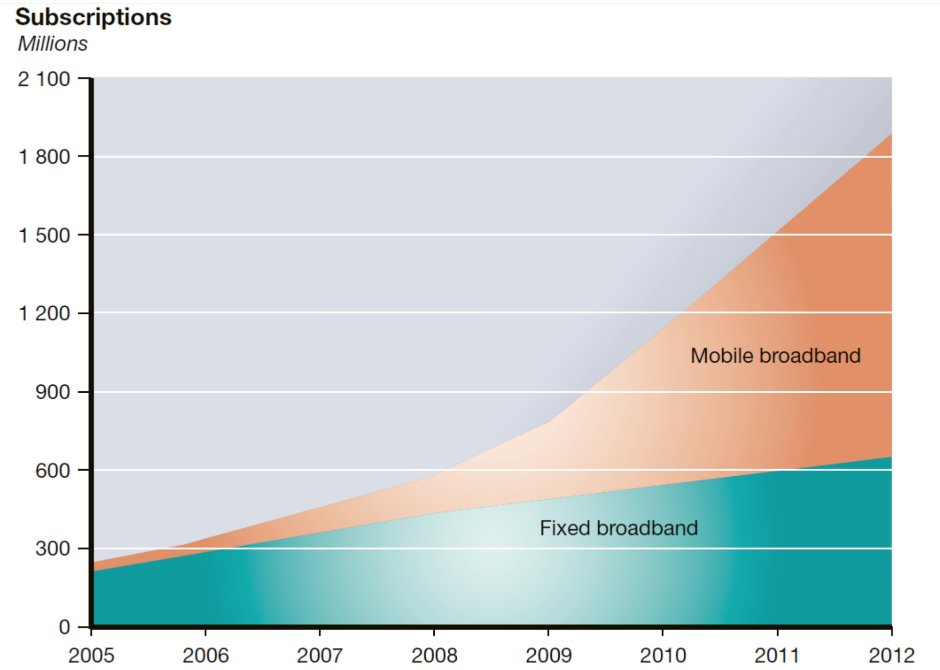


Figure 1.1: Mobile users subscriptions(Beming&Frid 2007)

LTE and LTE-Advanced are the same technology, with the "Advanced" label primarily being added to show the relation between the LTE release 10 (LTE-Advanced) and ITU/IMT-Advanced. This does not make the LTE-Advanced a different system from the LTE and it is not the final evolution step to be taken for the LTE, in any way.

The 3GPP project developed the first 3G system (WCDMA/HSPA) and now continues to develop the LTE and LTE-Advanced. The first release of the 3G standards couldn't reach the promised high-speed data transmissions because in practice the data rates were much lower than it was required by the standards. To make the 3G systems efficient for data transmission, a serious commitment was done by the 3GPP. While HSPA systems were being developed and deployed, the IEEE 802 LMSC (LAN/MAN Standard Committee) introduced the IEEE 802.16e standard for the mobile broadband wireless access. This standard was introduced as an enhancement to the earlier IEEE 802.16

standard for the fixed broadband wireless access. OFDMA (orthogonal frequency division multiple access) has been created and introduced as a different access technology which has better data rates and spectral efficiency than provided by the HSPA. Although the IEEE 802.16 family of standards is officially called WirelessMAN in the IEEE, it has been dubbed WiMAX (worldwide interoperability for microwave access) by an industry group named the WiMAX Forum. The mission of the WiMAX Forum is to promote and certify the compatibility and interoperability of broadband wireless access products. The Mobile WiMAX introduced their developed version of the 3G systems which is based on OFDMA technology. The beyond 3G system in the 3GPP is called evolved universal terrestrial radio access (evolved UTRA) and is also widely referred to as a LTE (Long-Term Evolution) (Dahlman&Parkval2011).

The background of the LTE and beyond systems are described in chapter 2. Chapter 3 represents the LTE based systems' network architecture including its 4 subsystems, interfaces and protocols. Chapter 4 explains the details of the LTE radio-interface physical layer. Chapter 5 contains the Technology components of LTE-Advanced, such as MIMO, CoMP, relay nodes, femtocell and Self organizing networks (SON). The Simulation model and the Simulation results are provided in chapter 6. Finally this thesis is summarized and future work ideas are given in chapter 7.

2. BACKGROUND

LTE-Advanced is a 3GPP standard which describes technological advancements to the Long Term Evolution (LTE). As described in the IMT-Advanced (International Mobile Telecommunications) it should have highly flexible radio interface that aims bridging the gap between the 3rd generation and the 4th generation (4G) standards.

2.1 Long Term Evolution (LTE) Goals

The objective of the LTE is to give a high-data-rate, low-latency and packet-optimized radio access technology supporting flexible bandwidth deployments. At the same time, a new network architecture was made with the goal of supporting packet-switched traffic with seamless mobility, quality of service and little latency. The followings are some of the architectural requirements designed by 3GPP Standards Body for the LTE according to "Traian 2010"

1. An All-IP based system

2. Flat Architecture for Optimized Payload Path

3. Excellent scalability

4. High level of security in Access Network (AN) as well as Core Network (CN)

5. Simple QoS model

6. Low delay times between nodes

7. Efficient radio usage

8. Flexible spectrum utilization

9. Cost efficient deployment

Some of the above mentioned targets were achieved by implementing a Flat Architecture with a less number of nodes. The fewer number of nodes helped in reducing latency times and improved overall performance.

2.2 3GPP Release 8 9 10

Although the work on the LTE standard was almost over, the works on the LTE Advanced were kicked off, which is also known as 3GPP Release 10. To make it backward compatible, the LTE-Advanced must share bandwidth with the first release of LTE as well as should be compatible with the equipment of the first release. The 4G should offer a data rate of 1 Gbps with a 100 MHz bandwidth. While OFDM gives an easy way to increase capacity by adding additional subcarriers, the scheduler must include a mix of terminal. While looking at the proposal for the standard, the 3GPP working groups have focused mainly on the physical level. These includes analysis on relay nodes, scalable system bandwidth over 20 MHz, the local optimization of air interface, diversity MIMO, flexible use of spectrum, etc. In the end, the standardization is expected to be included in 3GPP Release 10 timeframe. The importance and timeframe of the LTE Advanced mostly depends on the success of the LTE as the LTE Advanced is built entirely on existing specifications of LTE. After the correction and improvement phase of Release 9, major developments have been introduced to the LTE Release 10. As the LTE- Advanced meets the most standards for ITU 4G, 3GPP work plan is similar to the schedule of ITU. (B. Furht & Ahson / 2009 pp1-2).

2.3 LTE-Advanced Requirements

With the work starting on LTE Advanced, a number of key requirements and key features are coming to light. There are many high level aims for the new LTE Advanced specification. According to (Seidel 2008) the requirement specifications are as follows.

- Peak data rate DL: 1 Gbps, UL: 500 Mbps
- Transmission bandwidth: Wider than approximately 70 MHz in DL and 40 MHz in UL
- Latency: C-plane from Idle (with IP address allocated) to Connected in <50 ms and U-plane latency shorter than 5 ms one way in RAN taking into account 30% retransmissions (FFS)
- Cell edge user throughput 2 times higher than that in LTE
- Average user throughput 3 times higher than that in LTE
- Capacity (spectrum efficiency) 3 times higher than that in LTE
- Peak spectrum efficiency DL: 30 bps/Hz, UL: 15 bps/Hz
- Spectrum flexibility: Support of scalable bandwidth and spectrum aggregation
- Mobility: Same as that in LTE
- Coverage should be optimized or deployment in local areas/micro cell environments with ISD up to 1 km
- Backward compatibility and interworking with LTE with the 3GPP legacy systems

3. LTE-ADVANCED NETWORK ARCHITECTURE

The LTE network architecture was designed to support the packet-switched traffic with seamless mobility, minimal latency and quality of service (QoS). These means that all services including voice will be provided with packet switched connection. The evolution of the core network is known as SAE - System Architecture Evolution. This new architecture has been designed to provide a remarkably higher level of performance, in accordance with the requirements of the LTE.

3.1. Introduction to SAE and Evolved Packet System

The System Architecture Evolution (SAE), normally referred to as EPC, is the name of the Third Generation Partnership Project (3GPP) standardization work item, which is responsible for the evolution of the packet core network. (Jian Chen, Ling-di Ping 2009). This work item is closely related to the LTE work item, which contains the evolution of the radio network. Evolved Packet System (EPS) covers the core network, the radio access and the terminals that make up the whole mobile system. It also gives support for other non-3GPP high-speed RANs, for example, WLAN, WiMAX etc.

3.2 LTE-Advanced Network Architecture

The **Figure 3.2.2** describes the LTE Network Architecture with its basic system configuration and logical nodes. These elements are required when E-UTRAN is involved in the Access Network.

The architecture is sub-divided in four main sub-systems: **Figure 3.2.1**

1. Evolved Packet Core (EPC)

2. Evolved Universal Terrestrial Radio Access Network (E-UTRAN)

3. User Equipment (UE)

4. Services Domain

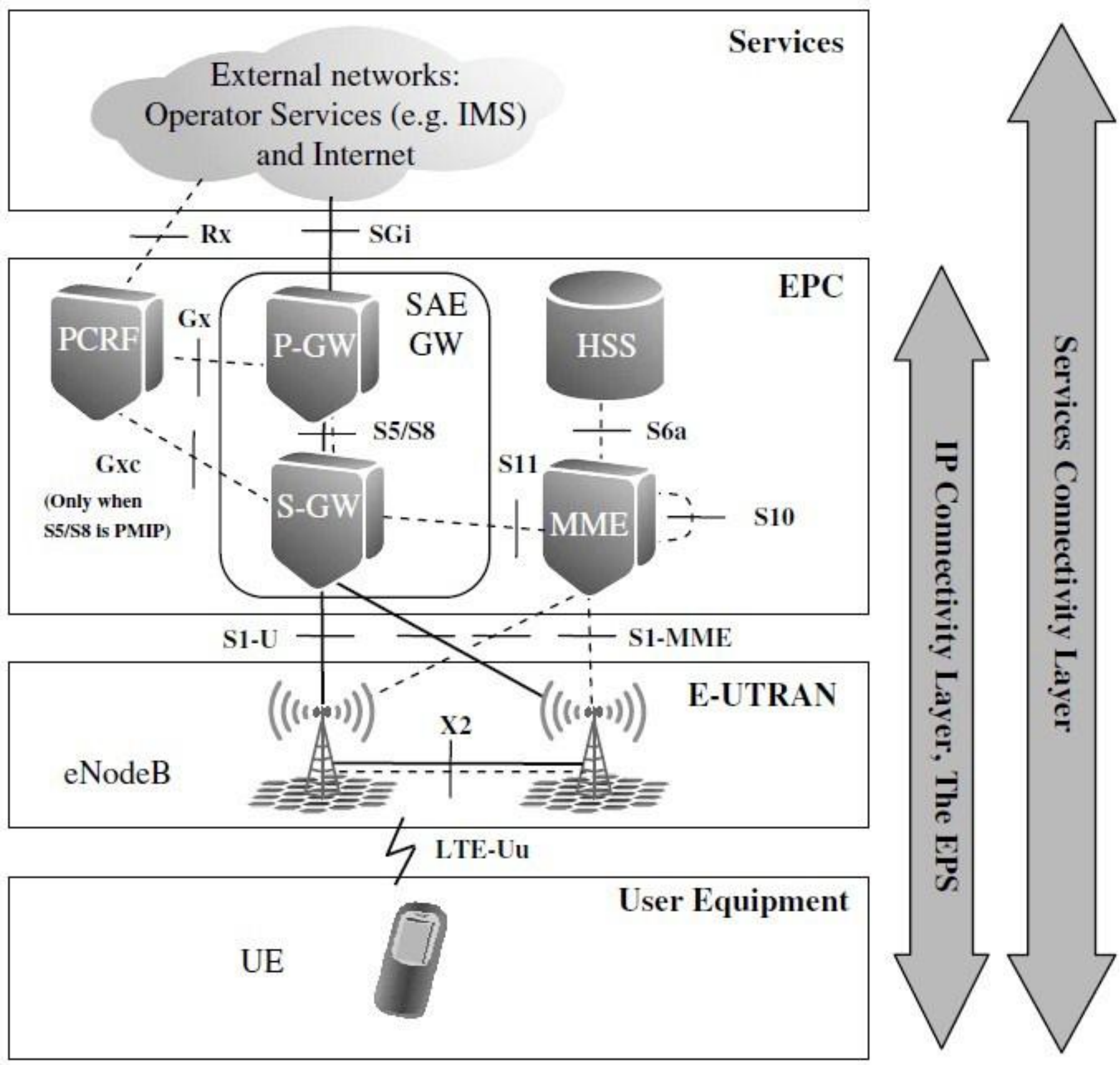


Figure 3.2.1: LTE Network Architecture(Holma & etc 209)

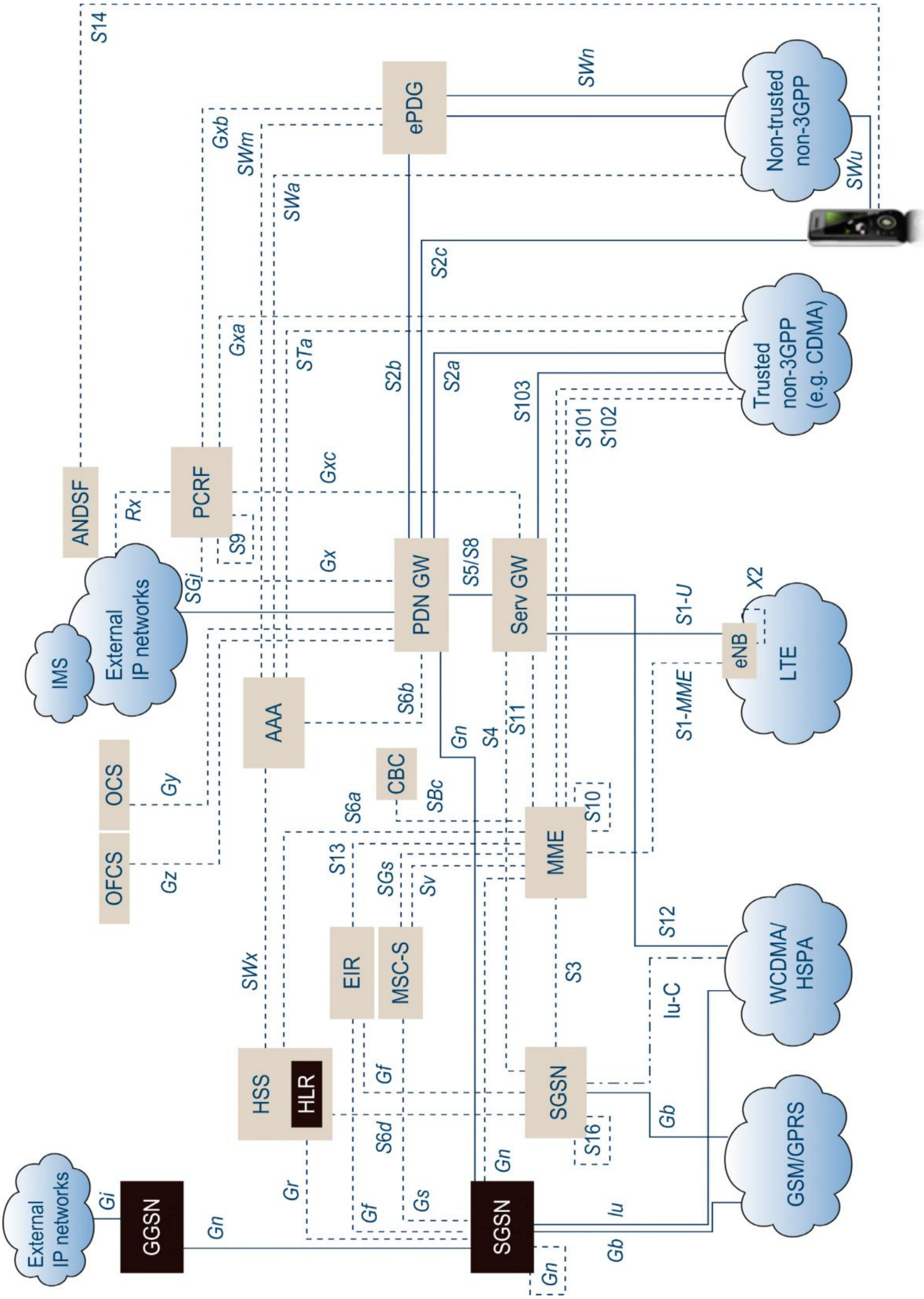


Figure 3.2.2: Architecture overview(Khan 2009)

3.2.1 Evolved Packet Core

The LTE Core network architecture was designed with the objective to simplify the overall architecture. The EPC is an essential evolution from GSM / GPRS core network used for the GSM and WCDMA / HSPA. The EPC supports access to the packet-switched domain only, with no access to the circuit switched domain. It consists of several different types of nodes, some of which are the Mobility Management Entity (MME) , Serving Gateway (S-GW) and Packet Data Network Gateway (PDN Gateway, P-GW) (Preben Mogensen, Byung K. Yi /2009).

3.2.1.1 Mobility management entity

The Mobility Management Entity (MME) is the central management entity for the LTE accesses. It is responsible for the connection of the UE by selecting the gateway through which messages are to be exchanged and a level of resources for the UE in cases of attachment and handover. From the perspective of the Core Network, the MME is a main node for controlling the access network of the LTE. During the first attach as well as during handover between the LTE networks, if necessary, it selects the Serving GW for a UE. It is responsible for the activation and de-activation of the bearers on behalf of a UE and also tracking and paging procedures for UEs in idle mode. The MME is responsible for authenticating the end-user, through interaction with the HSS. For UEs, which are in roaming, the MME stops the S6a interface to the UEs home HSS. The MME also ensures that the UE has permission to use an Operator’s PLMN and also forces any roaming restrictions that the UE may have. In addition, the MME provides control plane functionality for mobility between the LTE and 2G/3G access networks. The S3 interface terminates at the MME from the SGSN (Corici, Vingarzan 2010).

The selection of the MME is done by the MME selection function. Based on the network topology, the Selection process depends on the MME which serves the particular location that a UE is in. If there are several MMEs to serve a particular area, the choice is based on a few different criteria, e.g selecting an MME that reduces the need to change it later or perhaps based on the load balancing needs. MME selection function is located only in the eNB. The architecture supports multiple eNBs connected to multiple Serving GWs as well as MMEs. When an UE tries to connect to E-UTRAN, it provides the eNB with GUTI(Globally Unique Temporary ID) parameters which makes the selection of the suitable MME based on how the GUTI is constructed easier. The GUTI is a worldwide unique identity that shows a specific subscriber context in a specific MME (Harri Holama and Antti Toskala 2009). The information about the load status of the MME's is also provided to the eNB within a pool via S1-AP signaling and thus can provide extra information to the eNBs connected to the MME pool. This gives an efficient selection of MME within a pool and also allows triggers towards the UE (using Tracking Area Update or S1 Release procedures) to reconnect to a different MME within a pool when required. From the UE movement point of view, the process of MME selection is also efficient and has been developed to minimize the MME change when serving within certain operating boundaries. When no routing to an MME can be determined from the information provided by the UE, the eNB is responsible for the selection of a desired MME at the UE attachment.

Another responsibility of the MME is Non-Access Stratum (NAS) signaling, which terminates at the MME; the MME also acts as the termination point in the network for the security of NAS signaling, and management of security keys, handling the ciphering protection. Lawful Intercept related to signaling was also handled by the MME (H. Holama & A. Toskala 2009 pp28-29, Agilent bonus material).

3.2.1.2 Serving Gateway (S-GW)

For both the GTP-based and PMIP based network architectures, the Serving GW performs several functions. First, the Serving GW stops the interface towards E-UTRAN; every UE which gets connected to an EPS is aligned with a single Serving GW.

The Domain Name Service (DNS) may be used to resolve a DNS string of possible Serving GW addresses which serve the UE's location. The Serving GW selection function selects an appropriate Serving GW to serve an UE. The selection of Serving GW is done on the same way as for the MEE. It is affected by a few criteria; on the first place is the fact that its service area may reduce the necessity to change the Serving GW at a later time. Secondly, Serving GW selection may be based on the load balancing needs between different Serving GWs (R. Kreher & K. Gaenger 2011 p12).

Because of the possibility to use either GTP or PMIPv6 over the S5 and S8 interfaces as well as during roaming, there might be multiple PDN connections involving HPLMN and VPLMN, Serving GWs may need to support both protocols for a single UE connected to different PDNs. This may be needed in case a UE has two PDN connections, one with PDN GW in Visited PLMN and one with PDN GW allocated in the Home PLMN. If the PMIPv6 is used on S5 between the Serving GW and the PDN GW in the Visited PLMN, GTP can be used for the other PDN connection with PDN GW in the Home PLMN (M. Olsson & S. Sultana 2009 pp114-116).

As soon as the UE is connected with a Serving GW, it handles the forwarding of end-user data packets as well as performs as a local anchor point when required for inter-eNodeB handover. During handover from LTE to other 3GPP access technologies, for example inter-RAT handover for other 3GPP access technologies, the Serving GW terminates the S4 interface and provides a connection for transferring user traffic from 2G/3G network systems and the PDN GW. The Serving GW sends one or more 'endmarkers' to the source eNodeB, RNC or SGSN, in order to assist the re-ordering function in the eNodeB, during both the inter-NodeB and inter-RAT handovers,. (H. Holma & etc 2009 p30-31)

The Serving GW will terminate the downlink (DL) path for data, whenever a UE is in idle state. The Serving GW triggers paging towards the UE, in case if new packets arrive. The Serving GW stores and manages information relevant to the UE; for example an internal network routing information or parameters of the IP bearer service.

Finally, the Serving GW is responsible for the reproduction of user traffic in case of lawful intercept.

3.2.1.3 Packet Data Network Gateway (P-GW)

The PDN GW, acting as the entry and exit point for the UE data traffic, provides connectivity to external PDNs for the UE. If an UE needs to access more than one PDN, it may be connected to more than one PDN GW. For the UE, the PDN GW allocates an IP address. In both the GTP-based and the PMIP-based versions of the SAE architecture, these PDN GW functions may be applied (R. Kreher & etc.2011 p13).
As a gateway, a part of the PDN GW role may be performing packet filtering or deep packet inspection, on a per-user basis. The PDN GW also performs service level gating control and rate enforcement through rate policing and shaping. The PDN GW also marks the uplink and downlink packets with the DiffServ Code Point, as a part of QoS perspective. Finally, a key role of the PDN GW is to act as an anchor for mobility between 3GPP and non-3GPP technologies such as 3GPP2 (CDMA/HRPD) and WiMAX (H. Holma & etc 2009 p55).

3.2.1.4 Policy and Charging Resource Function (PCRF)

The PCRF (Policy and Charging Rules Function) is one of the most important part of the EPC architecture or in the 3GPP packet core architecture in general, named PCC (Policy and Charging Control) which is responsible for quality-of-service (QoS) handling and charging **Figure 3.2.1.4**.

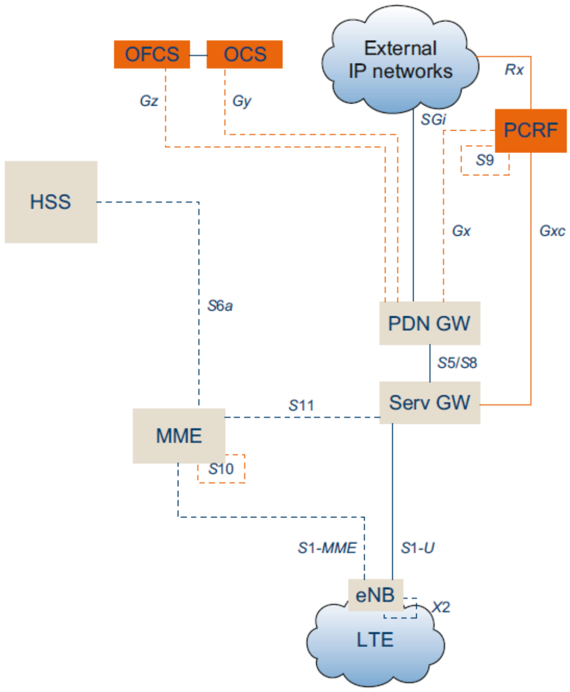


Figure 3.2.1.4: Adding policy control and charging support to the basic EPC architecture(Khan 2009)

As a policy and charging control element of the SAE architecture, the Policy and Charging Rules Function (PCRF) involves a flow-based charging control as well as policy control decision functionalities. This means that it provides a network-based control related to the flow-based charging, service data flow detection, QoS and gating towards the Policy and Charging Enforcement Function (PCEF) (Holma & etc.2009 pp27-28, R. Nossenson).

For service-aware QoS and charging control, PCC provides operators with latest tools. In wireless networks, where the bandwidth is usually limited by the radio network, it is important to make sure that a utilization of the radio and transport network resources is efficient. Moreover, different services have very different requirements on the QoS, which are required for the packet transport. Since a network generally carries many different services for different users at the same time, it is important to ensure that each service is provided with an appropriate transport path and that the services can co-exist (K.Bogineni, R. Ludwig 2009).

When it comes to bandwidth and QoS treatment, PCC makes it possible for a centralized control to ensure that the service sessions are provided with a proper transport. For both the IP Multimedia Subsystem (IMS) as well as non-IMS services, the PCC architecture provides control of the media plane. The PCC also enables the means to control charging on a per-service basis.

The aim of 3GPP was to define an access-agnostic policy control framework, and with this, make it applicable to a number of accesses such as E-UTRAN, GERAN, UTRAN, HRPD and WiMAX.

When a complete roaming model for PCC was introduced, this allows operators to have the same dynamic PCC, also enables the same access to services, independently of the location, whether a user is making this access through a gateway in a visited or their home network (M. Olsson& etc. 2009 pp174-175).

3.2.1.5 Home Subscription Server (HSS)

The HSS, acting as a database, stores the master copy of the subscriber profile, which may contain information about the services that are applicable to the user. This may include information about the allowed PDN connections, and whether it is allowed or not to roaming to the particular visited network. The HSS also stores the Identities of those P-GWs that are in use, for supporting mobility between non-3GPP RANs. The Authentication Center (AuC) is a storage of the permanent key. The key is used to calculate the authentication vectors. The vectors are sent to a visited network for deriving subsequent keys for integrity protection and encryption and user authentication. The AuC is also a part of the HSS (Lescuyer & Lucidarme 2008 pp47-49).

3.2.2 Evolved Universal Terrestrial Radio Access Network (E-UTRAN)

The most important function of the EPC is to give IP connectivity to the terminal for both data and voice services. The IP-based packet-switched domain is innately supported by E-UTRAN. The E-UTRAN or Evolved UTRAN is a 3GPP term denoting the RAN that implements the LTE radio interface technology.

The development in E-UTRAN is mostly centered on one point, the evolved Node B (eNodeB). All radio functionalities are situated there, i.e. the eNodeB is the termination point for all radio related protocols. The EUTRAN, as a network, is nothing but a mesh of eNodeBs connected to neighboring eNodeBs with the X2 interface. (Furht & etc. 2009 pp6-8)

3.2.3.1 eNodeB

There is at least one eNodeB in the LTE radio network which is the LTE base station. The functionality of the eNodeB has all the features that are needed for realizing the actual wireless connections between the network and user devices.
The eNodeB performs radio resource management and provides the radio interface for Long-Term Evolution (LTE) including radio admission control, radio bearer control, and scheduling of downlink and uplink radio resources for individual UEs. The eNodeB also supports the user plane data’s IP header compression and encryption. The interconnected between eNodeBs are executed via an interface named X2 (logical); this interface has many uses, e.g. handover. The S1 interface is used of eNodeBs and the EPC connection, which is divided into the control plane and the user plane. The control plane interface called S1- MME, terminates in the MME. Meanwhile, the S1-U interface terminates at the Serving GW and handles user plane traffic. The S1 interface supports pooling, which is a many-to-many relation between the eNodeBs and the MMEs as well as between the eNodeBs and the Serving GW. Another use of the S1 interface is support network sharing. With this, operators may share the radio network,

that is the eNodeBs, while maintaining their own EPC networks (H. Holama & etc. 2009 p6, Lescuyer & etc. 2008 pp173-177).

3.2.3.2 X2 Interface

The LTE was created to operate with a one-cell frequency reuse, which means that the same time–frequency resources can be used in surrounding cells. Mainly, the basic control channels are designed to operate properly under relatively low signal-to-interference ratio that may be experienced while using reuse-one frequency deployment.

From a point of view of general system-efficiency, to operate with one-cell reuse and have access to the entire available spectrum in each cell is always beneficial. Though, this may result to relatively large changes in the signal-to-interference ratio, which affects also on the achievable data rates, over the cell area with potentially only relatively low data rates being available at the cell border. Hence, the cell-edge user quality and the system performance, especially, can be further enhanced by allowing for some coordination in the scheduling between cells (Alcatel Lucent white paper 2009).

The main objective of such inter-cell interference coordination (ICIC) is, in case of possibility, avoid simultaneously scheduling transmissions to/from terminals at the cell border in neighboring cells, and in term, avoiding the worst-case interference situations. In order to support such interference coordination, the LTE specification involves several messages that may be used for communicating between eNodeBs using X2 interface (Furht & etc. 2009 p120).

The X2 interface, connecting eNodeBs to each other, is mostly used to support active-mode mobility. It may also be used for multi-cell Radio Resource Management (RRM) functions. The X2 interface is used to support lossless mobility between encircling cells by using packet forwarding. The signaling on X2 interface between eNBs is used for handover preparation. Coordination of scheduling decisions across many cells that exist in different eNodeBs is also supported using signaling over the X2 interface. In LTE scheduling is carried out locally at the eNodeB as there is no higher-level node. This is done by originating messages that carries information about the scheduling strategy between neighboring eNodeBs using the X2 interface. An eNodeB can then use the information provided by a neighboring eNodeB as input to its own scheduling process (Alcatel Lucent white paper 2009).

3.2.4.User Equipment (UE)

'Terminal', 'End-User Terminal', and 'User Equipment (UE)' terms stand for the demonstration of actual device communicating with the network. Data modems devices of the first generation of LTE, which sometimes are used with the name USB dongles, can be attached to standard laptop computers. Very often people mix up 'mobile device' with a mobile phone. Today, this is the most requested target-user device and they are in use as portable form factors since the 1980s. Mobile phones have been made for voice services. Later service capabilities have been added, primarily SMS support, e-mail and web surfing, which are very popular for Smartphones that are advanced mobile phones. In some cases they include more advanced means for text entry or through pressure sensitive screens in combination with hand-writing recognition techniques.

Portable computers equipped with wireless communication support are another type of device that are increasing fast in numbers, for example, standard portable computers added with external modem that is connected over USB, or portable computers which are produced with built-in support for mobile broadband services.
The widely accepted tendency is that more and more 'add-on' functionality is built into mobile phones (including Smartphones) making them a devices for general purposes. And now it is more than the actual communication services, for instance:

• MP3 and MP4 players
• Photo and video shooting Camera
• FM radio receiver
• GPS receiver for positioning using satellite systems
• Games

All these features help us to escape carrying various devises for different needs and also generate and use large amount of data. The amount of data managed in the device rapidly increases, as the resolution and quality of integrated cameras and screens are persistently increasing. Some of this data may be downloaded to or uploaded from the device. Mobile broadband solutions based on HSPA or LTE are optimized to support efficient data transfer to devices regardless of physical location. There are many intricate missions that designers of mobile devices have to deal with.

There are many challenges that designers of mobile devices have to address.
Some of them are as follows.

- The need of powerful processors to execute more advanced services, support higher data speeds and to feed screens of higher resolution.
- Requirements on decreasing the weight and thickness of the devices as the users tend to prefer light-weight and decent size phones.
- Support for multiple radio technologies like GSM/GPRS, WCDMA/HSPA, LTE, Bluetooth and WLAN in the same device.

Due to that the power levels and frequency bands are very different, some of the radio technologies used in one single device can be used simultaneously (for instance WLAN and HSPA or LTE). In this case no unacceptable interference is generated between the radios. But for the devices that may support for instance GSM and LTE at the same time, is however considered more complicated and more expensive to design, as they require more advanced filters to cancel out interference between radio technologies. Instead, some solutions have been designed to support efficient handovers between radio technologies (Olsson & etc. 2009 pp53-57).

There are eight different UE categories, often called UE Classes, which are defined for the LTE-Advanced, among which the first five classes are defined in the first generation of LTE. But the most important thing to notice is that the LTE uses far less UE Classes than HSPA. As shown in the **Table 3.2.4.1** below, the UE Class 1 device does not support MIMO functionality but the UE's from Class 2 - 4 will support 2x2 MIMO, whereas UE Class 5 can support 4x4 MIMO.

Table 3.2.4.1: LTE-Advanced UE Categories

UE category	Max. data rate (DL/UL) (Mbps)	Downlink				Uplink		
		Max. # DL-SCH TB bits/ TTI	Max. # DL-SCH bits/TB/ TTI	Total soft channel bits	Max. #. spatial layers	Max.# UL-SCH TB bits/TTI	Max. # UL-SCH bits/TB/ TTI	Support for 64 QAM
Category 1	10/5	10296	10296	250368	1	5160	5160	No
Category 2	50/25	51024	51024	1237248	2	25456	25456	No
Category 3	100/50	102048	75376	1237248	2	51024	51024	No
Category 4	150/50	150752	75376	1827072	2	51024	51024	No
Category 5	300/75	299552	149776	3667200	4	75376	75376	Yes
Category 6	300/50	[299552]	[TBD]	[3667200]	*	[51024]	[TBD]	No
Category 7	300/150	[299552]	[TBD]	[TBD]	*	[150752/102048 (Up to RAN4)]	[TBD]	Yes/No (Up to RAN4)
Category 8	1200/600	[1200000]	[TBD]	[TBD]	*	[600000]	[TBD]	Yes

It is important to note that regardless of whatever category a UE belongs to, it has to be capable of receiving transmissions from up to four antenna ports, as the base stations (eNBs) in LTE will have smart antennas (MIMO capabilities). Also, regardless of the UE class, all UE's should have a frontend of 20 MHz in order to receive their allocation anywhere the eNB would like to schedule it. (DHRUV SHAH 2010)

3.2.5. Services Domain

The Services domain is not a fixed entity in the EPC. It may include various service machinery sub-systems like IP Multimedia Sub-system (IMS) based services that the operator may use to allow services using the Session Initiation Protocol (SIP). In this case, the operator may easily place a server into their network, and the UEs connect to that via some agreed protocol which is supported by an application in the UE (H.Holma & etc.2009 p34).

3.3 EPS Interfaces

3.3.1 EPS Overview

EPS consists of several domains and each of them is a group of logical nodes that interwork to provide a specific set of functions in the network. **Figure 3.3.1** illustrates 3GPP specifications which should be implemented by a network.

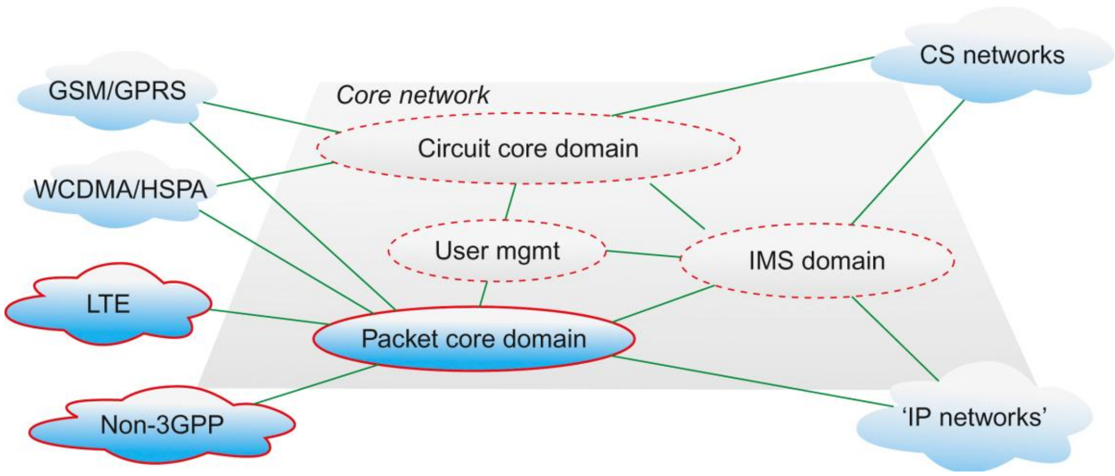


Figure 3.3.1: 3GPP architecture domains.(Khan 2009)

The four clouds on the left of diagram indicate different RAN domains that can connect to the EPC. These includs the second and third generations of mobile access networks specified by the 3GPP, mostly known as GSM and WCDMA respectively. Of course LTE is the latest mobile broadband radio access as specified by 3GPP. Finally, there is a domain called 'non-3GPP access networks'. This indicates any packet data access network that is not defined by the 3GPP standardization body. The examples are WLAN, fixed network accesses or some combination of these.

The Core Network is parted into many domains (Circuit Core, Packet Core and IMS), which interoperate with each other over several specific interfaces. The Circuit Core domain is composed of units and functions that allow the support for circuit-switched services over GSM and WCDMA.

The user management domain provides coordinated subscriber information and supports roaming and mobility between and within the different domains.

The Packet Core domain is composed of units and functions that let support for packet-switched services (mostly IP connectivity) over GSM, WCDMA and HSPA. Therewith, the Packet Core domain also provides support for packet-switched services over LTE and non-3GPP access networks which in whole have nothing to do with the Circuit Core. The packet core domain also supports functions for management and forcing of service and bearer level policies such as QoS.

The IMS domain is composed of units and functions that ensure support for multimedia sessions based on SIP (Session Initiation Protocol), and applies the IP connectivity provided by the functions in the Packet Core domain.

The user management domain is defined for handling of the data related to the subscribers that uses the services of the other domains. Usuallly, in the 3GPP specifications, its not a separate domain . Rather, there are user management functions in the Circuit Core, Packet Core and IMS domains interacting with subscriber data bases defined by 3GPP (Olsson & etc. 2009 pp33-37).

3.3.2 Uu and S1-MME

The S1-MME interface is specified between the eNodeB and the MME and the E-UTRAN-Uu interface is specified between the UE and the eNodeB. The S1-MME interface provides support for functionality such as handover, paging, transparent transport of messages between UE and MME as well as the UE context management.
The protocol stack for E-UTRAN-Uu and S1-MME is shown in **Figure 3.3.2.1**

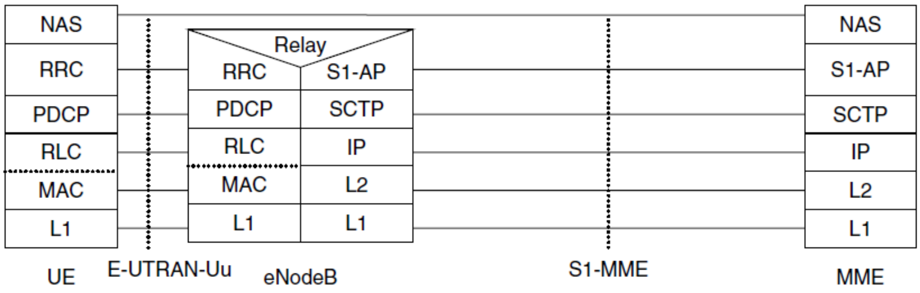


Figure 3.3.2.1 Protocol stack for E-UTRAN-Uu and S1-MME

As it is presented in the **Figure 3.3.2.1** the NAS protocols run straight between the UE and the MME while the eNodeB simply acts as a transparent relay. Access stratum (AS) are protocol layers below NAS on E-UTRAN-Uu and S1-MME. The AS protocols on the E-UTRAN-Uu (RRC, RLC, PDCP, MAC and the physical LTE layer) support the NAS protocols by transporting the NAS messages across the E-UTRAN-Uu interface and utilize the Radio Resource Management. Furthermore, the AS protocols on S1-MME (S1-AP, SCTP, IP, etc.) utilize functionality such as handover, paging, UE context management and transparent transport of messages between MME and eNodeB. The NAS layer includes an EPS session management (ESM) protocol and an EPS mobility management (EMM) protocol. The ESM protocol provides procedures for the handling of EPS bearer contexts. The EMM protocol allows procedures for the security for the NAS protocols and control of mobility. This protocol is used for the control of user plane bearers together with the bearer control provided by the access stratum (3GPP TS 24.301 & 3GPP TS 36.410).

3.3.3 eNodeB ↔ Serving GW (S1-U)

The S1-U is the user plane interface carrying user data traffic, received from the terminal, between the eNodeB and Serving GW. For the per bearer user plane tunneling and inter-eNB path switching during handover, S1-U acts as a reference point between the E-UTRAN and S-GW. The GPRS Tunneling Protocol for the User Plane (GTP-U) is used at this reference point (Akyildiz & D. Gutierrez-Estevez 2010).

3.3.4 MME ↔ MME (S10)

S10 - This is a control interface between the MMEs which is exclusively based on GTPv2-C. This interface is used for LTE access only. The main function, which is to transfer the contexts for individual terminals attached to the EPC network and thus sent on a per UE basis, runs over this protocol. This is the reference point between the MME-to-MME information transfer and the MMEs for MME relocation. This reference point provides mobility functions for the intra-E-UTRAN handover/ relocation. In other words, signaling procedures on this interface are triggered by UE mobility. This type of MME relocation in the 3GPP 23.401 is called S1 handover. Hence, S10 is seen as special type of S1 interface and the S1AP is used at this reference point (M. Olsson & etc 2009 p234, 3GPP 23.401).

3.3.5 MME ↔ Serving GW (S11)

The S11 interface is defined between the MME and the Serving GW. Because of the separation of the user and control plane functions the between Serving GW and MME, the S11 interface is used to create a new session, like establishing the necessary resources for the session and then manage these sessions by modifying, deleting and changing any sessions for each PDN connection and for a terminal that has established connection within EPS.

The S11 interface is always activated by some events either directly from the NAS level signaling from the terminal when

1. a device is getting attached with the EPS network or
2. adding new bearers to an existing session, handover cases, or
3. activated during network initiated procedures such as PDN GW-initiated bearer modification procedures.

S11 interface keeps the user and control plane procedures in synchronization for a terminal during the period when the terminal is seen active/attached in the EPS. The S11 interface is used to relocate the Serving GW, in case of handover, when it establishes direct or indirect forwarding tunnel for user plane traffic as well as manages the user data traffic flow (3GPP TS 29.274).

3.3.6 Serving GW ↔ PDN GW (S5/S8)

The S5/S8 interface is specified between the Serving GW and the PDN GW. The S5 interface is used in roaming scenarios when both Serving GW and PDN GW are located in the visited network, or in non-roaming scenarios when the Serving GW is located in the home network. The roaming scenario is also referred to as Local Breakout. The S5 reference point provides user plane tunneling and tunnel management between the S-GW and PDN-GW. It is used in case of S-GW relocation due to UE mobility and if the S-GW needs to be connected to a non-collocated PDN-GW for the required PDN connectivity. The GTP is the protocol used at this reference point for both the user plane and control plane.

The S8 interface is just a roaming variant of the S5 which is used in roaming scenarios with the PDN GW in the home network and the Serving GW in the visited network. The S8 reference point is used by roaming subscribers only. It is the inter-PLMN reference point providing the user plane and control plane between the S-GW in the Visited PLMN (VPLMN) and the PDN-GW in the Home PLMN (HPLMN). The S8 is the inter-PLMN variant of the S5, based on the GTP as well, and can be compared to the Gp interface defined for the GERAN GPRS. It also utilizes transfer of (QoS) policy and charging control information between the home PCRF and the visited PCRF in order to support the local breakout function (3GPP TS 23.402).

3.3.7 SGSN ↔ MME (S3)

The S3 interface is defined between the S4-based SGSN and the MME for supporting handover to/from 2G/3G radio access network for 3GPP accesses. The functions provided by S3 include transfer of the information related to the terminal that is being handed over, handover/relocation messages and thus the messages are for individual terminal basis. As it is the central point between the MME and SGSN, the SGSN may serve for UTRAN, GERAN, or both of them. On the S3 we can see control-plane-information for user and bearer information exchange for inter-3GPP access network mobility (inter-RAT handover) in the idle and/or active state. If the connection was set up originally in the E-UTRAN and is handed over to UTRAN/GERAN the appropriate user plane streams are routed across the S4 reference point. What happens in case the UTRAN/GERAN to E-UTRAN handover depends on the fact whether S-GW acts as an anchor for UTRAN/GERAN traffic or not? If this is true the user plane tunnel can be switched smoothly between S4 and S1-U during the handover. The protocol used at the S3 reference point is the GTP-C (3GPP TS 23.401).

3.3.8 SGSN ↔ Serving GW (S4)

The S4 interface is defined between the SGSN supporting Serving GW and the 2G/3G radio access. It also has equivalent functions as the S11 interface does, but it acts only for the 2G/3G radio access networks. This interface supports only GTPv2-C and in case the 3G network has not enabled direct tunnel for user plane traffic from RNC to/ from Serving GW, it utilizes procedures to enable user plane tunnel between the SGSN and Serving GW (3GPP TS 23.401).

3.3.9 SGSN ↔ SGSN (S16)

The S16 interface is defined between two SGSNs. As in the case of S4, this interface exclusively uses GTPv2-C and is for 2G/3G accesses only when it is on an EPS network. The main functions of this protocol is transferring the contexts of individual terminals, attached to the EPC network and are thus sent on a per UE basis as it was for the S10 interface (3GPP TS 29.303).

3.4 Protocol Architecture

The architecture of the radio interface protocol is based on the same architecture defined for the HSPA. The names of the protocols are the same, as well as the functions are similar. Some dissimilarities come from the differences in the multiple access techniques of the LTE and HSPA. Others are related to the fact that the LTE is a packet-only system, meaning that there are no requirements to support the legacy circuit-switched domain.

The user plane protocol stack is given in **Figure 3.4.1**. One can note that the packet data convergence protocol (PDCP) and the radio link control (RLC) layers, which were used to be terminated in RNC on the network side are now terminated in eNB.

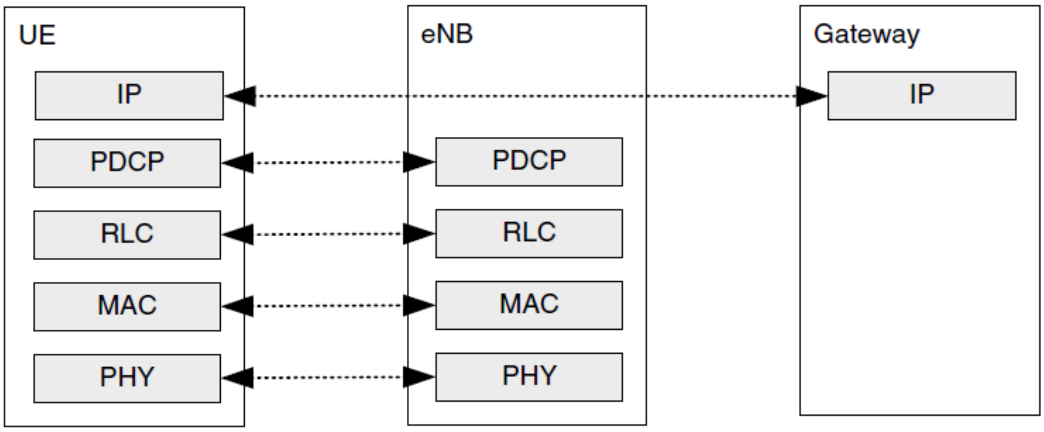


Figure 3.4.1. User plane protocol.

Figure 3.4.2 shows the control plane protocol stack. Here also the RRC functionality originaly implemented in the RNC is now incorporated into eNB. The control plane functions of the RLC and MAC layers are the same as for the user plane. The RRC functions include system information broadcast, radio bearer control, paging, RRC connection management, mobility functions and UE measurement reporting and control. Independently from the non-access stratum (NAS) protocols, all radio interface protocols terminate in the eNodeB on the network side. The NAS protocol terminates in the MME on the network side and at the UE on the terminal side and performs functions such as EPS (evolved packet system) bearer management, authentication and security control, etc. (Rohde & Schwartz).

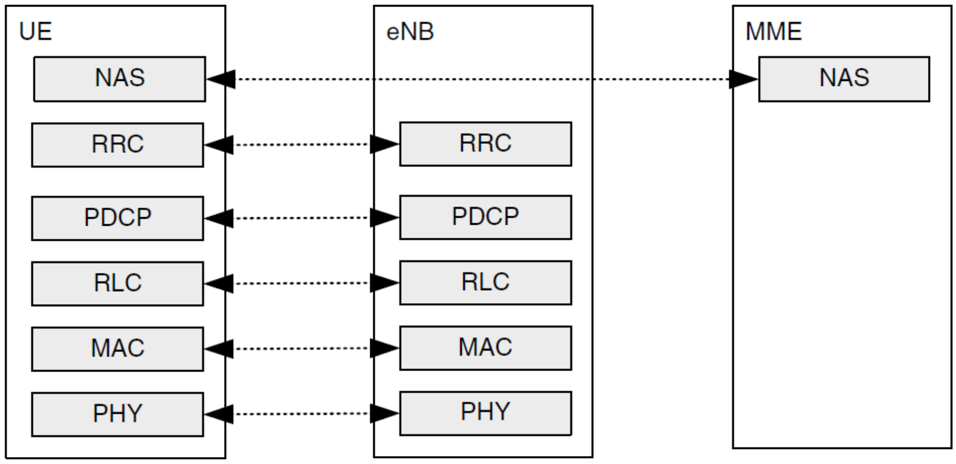


Figure 3.4.2.Control plane protocol stack.

Packet Data Convergence Protocol (PDCP) performs IP header compression for reducing the number of bits to be transmitted over the radio interface. The header-compression mechanism is based on Robust Header Compression (ROHC). This standardized header-compression algorithm is also used for several other mobile-communication technologies. It is also responsible for ciphering. The PDCP protocol performs the corresponding deciphering and decompression operations at the receiver side. There is only one PDCP entity per radio bearer configured for a terminal. From the control plane, the PDCP is responsible for the integrity protection of the transmitted data, as well as in-sequence delivery and duplicate removal for handover (2009 EventHelix.com).

Radio-Link Control (RLC) is responsible for duplicate detection, segmentation/concatenation, in-sequence delivery to higher layers and retransmission handling. The RLC utilizes services to the PDCP in the form of radio bearers. There is only one configured RLC entity per radio bearer for a terminal (3GPP TS 36.322).

Medium-Access Control (MAC) utilizes hybrid-ARQ retransmissions, uplink and downlink scheduling and multiplexing of logical channels. For both uplink and downlink, the scheduling functionality is located in the eNodeB. The hybrid-ARQ protocol is also present in the MAC protocol for both the transmitting and receiving ends. The MAC provides, in the form of logical channels, services to the RLC (3GPP TS 36.321).

Physical Layer (PHY) utilizes coding/decoding, multi-antenna mapping, modulation/demodulation, and other typical physical-layer functions. The physical layer provides services to the MAC layer in the form of transport channels (3GPP TS 36.201).

Radio Resource Control (RRC) is responsible for managing the RAN-related procedures. This may include broadcast of system information necessary for the terminal to be able to communicate with a cell. It also handles transmission of paging messages originated from the MME for notifying the terminal about incoming connection requests. Paging is used in the RRC_IDLE state when the terminal is not connected to a particular cell. RRC also handles Connection management, including setting up bearers and mobility within LTE. This includes Mobility functions such as cell (re)selection measurement configuration and reporting(UTRAN Radio Interface protocols).

Non-Access Stratum (NAS) control-plane functionality which is handled by the MME, is responsible for the EPS bearer authentication, security, management and other idle-mode procedures such as paging. NAS is also responsible for assigning to a terminal an IP address (3GPP TS 24.301).

4.LTE RADIO-INTERFACE PHYSICAL LAYER

The long term evolution (LTE) of the Universal Mobile Telecommunications System's (UMTS) Terrestrial Radio Access (UTRA) has been termed E-UTRA. A continuous work activity started in April 2008 in 3GPP focuses on the enhanced version of LTE, the LTE-Advanced. E-UTRA of LTE system provides spectrum flexibility with bandwidths between 1.25 MHz and 20 MHz. Peak data rates range up to 100 Mbit/s in the downlink and 50 Mbit/s in the uplink at a maximum bandwidth of 20 MHz. LTE-Advanced aims to further enhance the LTE system to fulfill and even surpass the IMT-Advanced (International Mobile Telecommunications) requirements given by ITU for the 4G mobile communication system. With spectrum aggregation, transmission relay, cooperative communication, cognitive radio technologies and scalable system bandwidth up to 100 MHz, LTE-Advanced is designed to meet the peak data rate of 1 Gbit/s. The key technologies in E-UTRA systems are OFDMA (Orthogonal Frequency Division Multiple Access) in the downlink and SC-FDMA (Single Carrier Frequency Division Multiple Access) for uplink transmission.

4.1 LTE-Advanced Requirements

The most important requirements requirements for LTE-Advanced are the following

Data Rate:

Peak data rate of 1 Gbps for downlink (DL) and 500 Mbps for uplink (UL).

Latency:

In LTE-Advanced in the C-plane the transition time from Idle to Connected should be lower than 50ms. In the active state, a dormant user should take less than 10ms to get synchronized and the scheduler should reduce the U-plane latency at maximum.

Peak Spectral Efficiency:

The system should support downlink peak spectral efficiency up to 30 bps/Hz and uplink peak spectral efficiency of 15 bps/Hz with an antenna configuration of 8 × 8 or less in DL and 4 × 4 or less in UL.

Average Cell Spectral Efficiency:

The 3GPP defined a base coverage urban scenario with inter-site distance of 500m and pedestrian users. Assuming this scenario, average user spectral efficiency in DL must be 2.4 bps/Hz/cell with MIMO 2 × 2, 2.6 bps/Hz/cell with MIMO 4 × 2 and 3.7 bps/Hz/cell with MIMO 4 × 4, whereas in UL the target average spectral efficiency is 1.2 bps/Hz/cell and 2.0 bps/Hz/cell with SIMO 1×2 and MIMO2×4, respectively.

Spectral Efficiency of Cell Edge:

In the same scenario with 10 users, cell edge user spectral efficiency will be 0.07 bps/Hz/cell/user in DL 2 × 2, 0.09 in DL 4 × 2 and 0.12 in DL 4 × 4. In the UL, this cell edge user spectral efficiency must be 0.04 bps/Hz/cell/user with SIMO 1 × 2 and 0.07 with MIMO 2 × 4.

Bandwidth:

In terms of spectrum flexibility, the LTE-Advanced system will support scalable bandwidth and spectrum aggregation with transmission bandwidths up to 100MHz in DL and UL.

Mobility:

The mobility and coverage requirements are identical to LTE Release 8. There are only differences with indoor deployments that need additional care in LTE-Advanced (Femtocells deployment). LTE-Advanced must guarantee backward compatibility and interworking with LTE and other networks.

4.2 LTE-Advanced Frame Structure

The duplexing of uplink and downlink transmissions is normally carried out in frequency or time domain and is known as Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD), respectively. Two frame structure types are defined for E-UTRA: frame structure type 1 for FDD mode, and frame structure type 2 for TDD mode. The frame structure defines the frame, slot, and symbol in the time domain. In FDD mode each radio frame is 10 ms long and consists of 10 subframes as shown in **Figure 4.2.1**. Each subframe contains two slots. The Slots consist of 6 or 7 ODFM symbols, which depends on the employed cyclic prefix. There are two types of CP, the normal and the extended. The total number of available subcarriers depends on the overall transmission bandwidth of the system(Rohde&Schwartz).

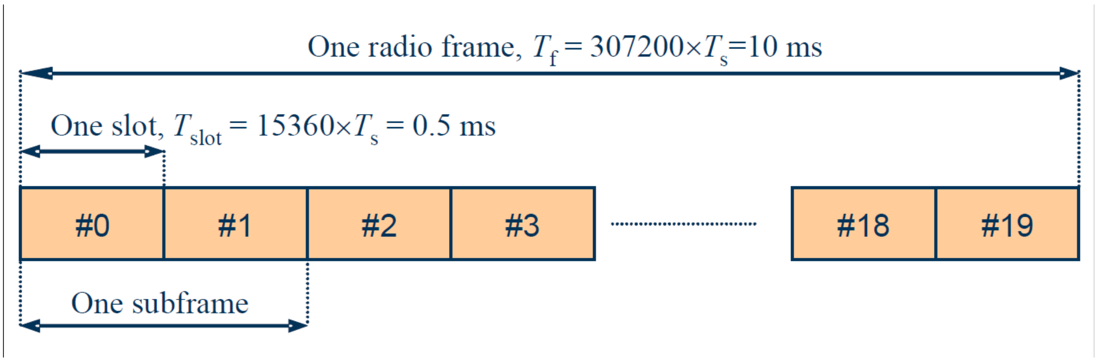


Figure 4.2.1: Frame structure FDD(Rohde&Schwartz)

A resource block which is the smallest unit in time and frequency is defined to consist of 12 sub-carriers in frequency and 14 continuous symbols in time domain. This makes one resource block to span 180 kHz in frequency and 1ms time respectively **Table 4.2.1**.

Table 4.2.1 Available Bandwidth is divided into Physical Resource Blocks

Bandwidth (MHz)	1.25	2.5	5.0	10.0	15.0	20.0
Subcarrier bandwidth (kHz)	15					
Physical resource block (PRB) bandwidth (kHz)	180					
Number of available PRBs	6	12	25	50	75	100

The sub-frame is also the minimum transmission time interval (TTI). The choice of short TTI helps to achieve the requirements of low latency. In FDD Both the uplink and the downlink have the same frame structure but they use different spectra (Zyren2007).

For voice transmission, where the uplink/downlink traffic is symmetric, the choice of FDD is suitable due to the symmetry in the two channels. Therefore, it is entirely used in the 2G and 3G networks.

TDD Frame structure consists of two 5 ms half-frames for a total duration of 10 ms and is for 5 ms switch-point periodicity. Subframes consist of either an uplink or downlink transmission. For separating uplink and downlink, a special subframe which contain the downlink and uplink pilot timeslots (DwPTS and UpPTS) separated by a transmission gap guard period (GP) exists. (Sánchez, D. Morales-Jiménez).

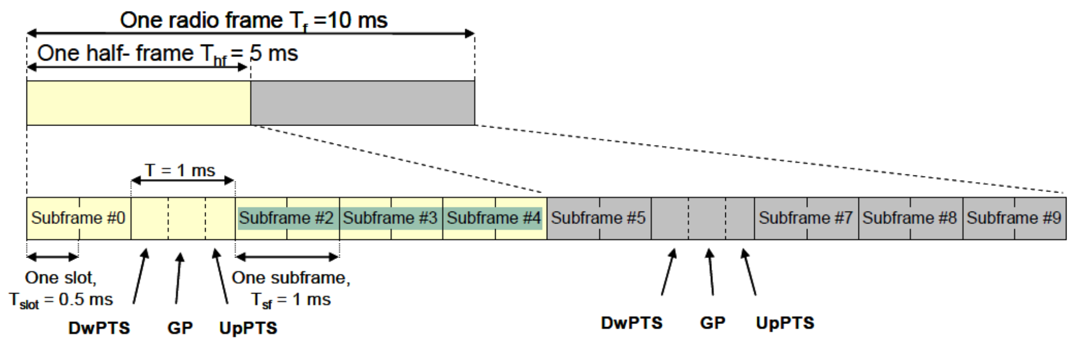


Figure 4.2.2 Frame structure TDD(Rohde&Schwartz)

There are seven uplink/downlink configurations used for either 5ms or 10ms switch-point periodicities. A special sub-frame exists in both half frames in case of 5ms switch-point periodicity whereas, for 10ms switch-point periodicity the special frame exists only in the first half-frame. In case of 10 ms switch-point periodicity the special subframe exists in the first half frame only. Subframes 0 and 5 and DwPTS are always reserved for downlink transmission. UpPTS and the subframe immediately following the special subframe are always reserved for uplink transmission. **Table 4.2.2** shows the supported uplink-downlink configurations, where "D" denotes a subframe reserved for downlink transmission, "U" denotes a subframe reserved for uplink transmission, and "S" denotes the special subframe (Rohde&Schwartz).

Table 4.2.2 Uplink-Downlink configurations for LTE TDD

Uplink / Downlink Configuration	Downlink to Uplink Switch Periodicity	Sub-Frame Number									
		0	1	2	3	4	5	6	7	8	9
0	5ms	D	S	U	U	U	D	S	U	U	U
1	5ms	D	S	U	U	D	D	S	U	U	D
2	5ms	D	S	U	D	D	D	S	U	D	D
3	10ms	D	S	U	U	U	D	D	D	D	D
4	10ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5ms	D	S	U	U	U	D	S	U	U	D

TDD has attracted much interest from a research point of view because it allows uplink and downlink transmission to share the same channel at different times, and thus can be adapted according to the traffic condition. TDD requires a guard period to separate the two transmissions. If the transmissions from neighboring cells are not fully aligned, a base station may receive interference from the downlink transmission of its neighboring base stations, and vice versa. In many situations, this mutual interference significantly penalizes the uplink performance due to the relatively low uplink transmit power. (Wang 2010)

4.3 DownLink

The LTE PHY specification is designed to support bandwidths from 1.25 MHz to 20 MHz and up to 100Mhz with Carrier Aggregation. OFDM was selected as the basic modulation scheme because of its robustness in the presence of multipath fading. Downlink multiplexing is accomplished via OFDMA

The overall motivation for OFDMA in LTE and in other systems has been due to the following properties: (Holma& etc 2009 pp 67-70)

- good performance in frequency selective fading channels;
- low complexity of base-band receiver;
- good spectral properties and handling of multiple bandwidths;
- link adaptation and frequency domain scheduling;
- compatibility with advanced receiver and antenna technologies.

4.4 OFDMA (Orthogonal Frequency Division Multiple Access)

The downlink transmission scheme for both E-UTRA FDD and TDD modes is based on conventional OFDM. In past years Orthogonal Frequency-Division Multiplexing (OFDM) has become known as a successful air-interface technique. In Orthogonal Frequency Division Multiplexing the Frequency-Domain (FD), the bandwidth is divided into a number of non-overlapping subchannels, each of which carries a specific carrier known as a subcarrier (Sánchez&Jiménez). While each subcarrier is separately modulated by a data symbol, the overall modulation operation across all the subchannels is a result of a frequency-multiplexed signal. Each of the center frequencies for the sub-carriers is selected from the set that has such a difference in the frequency domain that the neighboring sub-carriers have zero value at the sampling instant of the desired sub-carrier. As a consequence of their orthogonality, when communicating over perfectly distortion less channels, this process ensures that the subcarrier signals do not interfere with each other (Hanzo, Akhtman 2011). The practical implementation of an OFDMA system is based on Fast Fourier Transform (FFT) and the inverse operation (IFFT) to move between time and frequency domain representation. In OFDMA transmitter, the available spectrum is divided into number of orthogonal subcarriers **Figure 4.4.1**. Because of the simplicity of the receiver, In downlink, the chosen transmission scheme is OFDM with Cyclic Prefix (CP). OFDM gives a frequency structure that divides the data over a number of sub-carriers. The spacing between two sub-carriers is fixed at 15 kHz with 66.67µs OFDMA symbol duration. The high bit-rate data stream passes through modulator, where adaptive modulation schemes such as (QPSK, 16-QAM, 64-QAM) is applied. This sequence of modulated symbols is converted into parallel frequency subcarriers by serial to parallel converter (Holma&etc 2009 pp70-75).

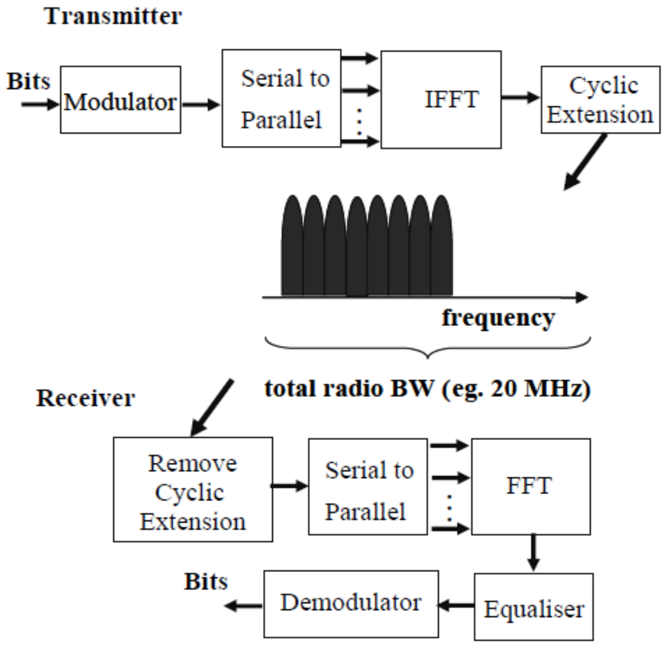


Figure 4.4.1 OFDMA transmitter and receiver(Holma& etc 2009)

The IFFT stage converts these complex data symbols into time domain and generates OFDM symbols. To avoid ISI, a Guard Interval is inserted between two consecutive symbols. The Guard Interval is then filled with the CP. This means that a copy of fixed number of last samples is appended to the start of the slot. The duration of the CP should be greater than the channel impulse response or delay spread. The receiver does not deal with the ISI but still have to consider the channel impact for every single subcarrier that have experienced amplitude changes and frequency dependent phase. In LTE systems, the OFDMA uses two types of CP that are normal CP and extended CP. The normal CP is used for high frequencies (urban areas) and extended CP for lower frequencies (rural areas).

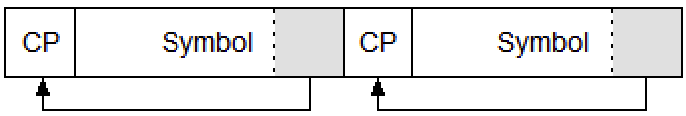


Figure: 4.4.2 Cyclic Prefix (Holma& etc 2009)

At the receiver, the CP is first removed and then subcarriers are converted from parallel to serial sequence. Further the FFT converts the OFDM symbols into frequency domain followed by equalizer and demodulation as shown in **Figure: 4.4.2.**

As the OFDMA transmission in the frequency domain consists of several parallel subcarriers, which in the time domain correspond to multiple sinusoidal waves with different frequencies filling the system bandwidth with steps of 15 kHz, the signal envelope starts to vary strongly. The momentary sum of sinusoids leads to the Gaussian distribution of different peak amplitude values. This causes some challenges to the amplifier design as, in a cellular system, one should aim for maximum power amplifier efficiency to achieve minimum power consumption. This requires the amplifier to use additional back-off. The use of additional back-off leads to higher amplifier power consumption. As a result, the battery energy is consumed faster. This is not considered to be a major problem on the network side but for small mobile devices running on their own batteries it creates more challenges (Holma&Toskala2009).

4.5 UpLink

The uplink access is based on single carrier frequency division multiple access (SC-FDMA) that ensures increased uplink coverage due to low peak-to-average power ratio (PAPR) compared to OFDMA. SC-FDMA signals have better PAPR properties relative to an OFDMA signal. This is one of the main reasons why SCFDMA was selected as LTE and beyond systems uplink access scheme. The PAPR characteristics are important for cost-effective design of UE power amplifiers.

There are different possibilities of generating an SC-FDMA signal. DFT-spread- OFDM (DFT-s-OFDM) has been selected for E-UTRA. For DFT-s-OFDM, a size-M DFT is first applied to a block of M modulation symbols. The same QPSK, 16QAM and 64 QAM are used as uplink E-UTRA modulation schemes as in the case of downlink, some modulation schemes are optional for the UE. In SC-FMA Transmitter symbols pass through a serial to parallel converter, as in Downlink, followed by a DFT block as shown in **Figure 4.5.1**.

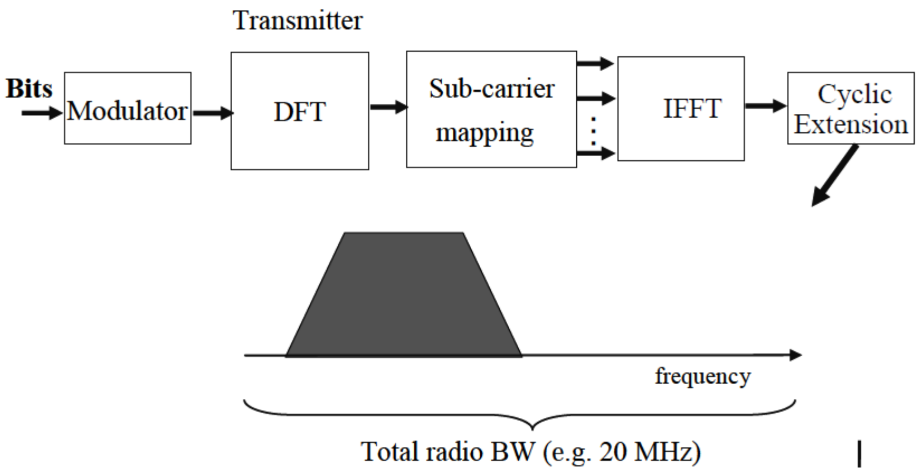
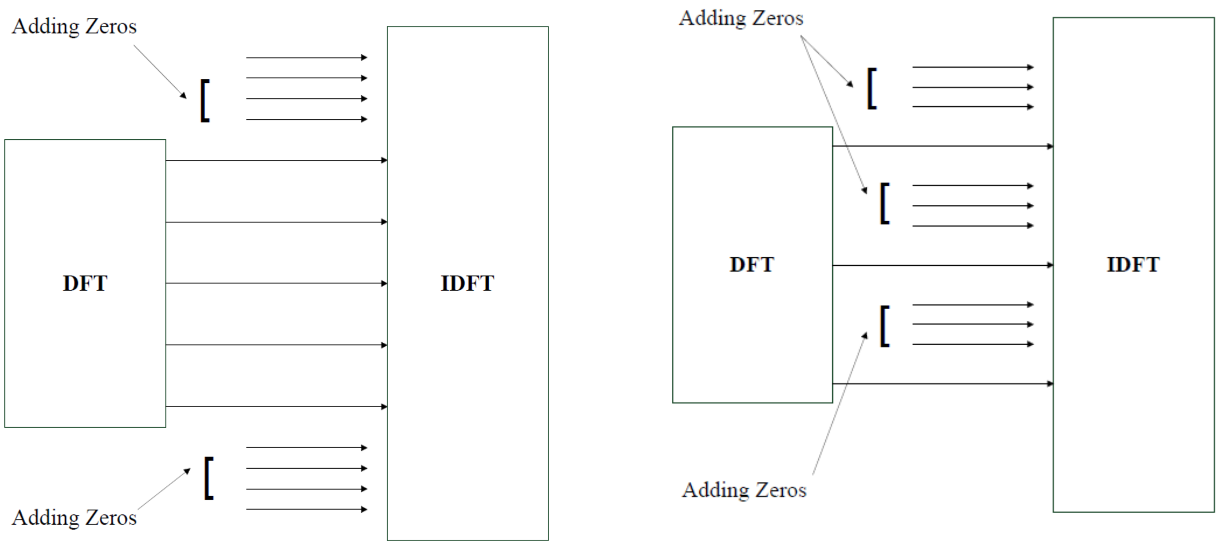


Figure 4.5.1: SC-FDMA Transmitter(Holma& etc 2009)

The DFT transforms the modulation symbols into the frequency domain. The discrete Fourier symbols from the output of DFT block are then mapped with the subcarriers in subcarrier mapping block. After mapping this frequency domain modulated subcarriers pass through IDFT for time domain conversion. The rest of transmitter operation is similar as OFDMA.

The sub-carrier mapping plays an important role in the transmitter of SC-FDMA. It maps each of the N DFT output on a single subcarrier out of M subcarriers, where M is the total number of subcarriers for available bandwidth. The subcarrier mapping is achieved by two methods; localized subcarrier mapping and distributed subcarrier mapping. The modulation symbols in localized subcarrier mapping are assigned to M adjacent subcarriers, whereas in distributed mode, the symbols are uniformly spaced across the whole channel bandwidth. Localized subcarrier mapping also referred as localized SCFDMA (LFDMA) whereas distributed subcarrier mapping referred as distributed SCFDMA (DFDMA). In transmitter, the IDFT assigns zero amplitude to the unoccupied subcarriers in both modes of subcarrier mapping. The IFDMA is more efficient in SC-FDMA, in that the transmitter can modulate the signal in time domain without using DFT and IDFT. If Q = MxN for the distributed mode with equidistance between subcarriers then it is called Interleaved FDMA (IFDMA) (Sorger1998). Where M is number of subcarriers, Q is number of users and N is number of subcarriers allocated per users. In distributed mapping, N-discrete frequency signals are mapped uniformly spaced sub-carriers, where as in localized mapping, N-discrete frequency signals are mapped on N consecutive subcarriers, as shown in **Figure: 4.5.2** (a) and **Figure: 4.5.2** (b) respectively.



a) Localized FDMA

b) Distributed FDMA

Figure: 4.5.2: FDMA(Holma& etc 2009)

eNodeB is responsible for scheduling of uplink resources. The eNodeB assigns certain time/frequency resources to the UEs and informs UEs about transmission formats to use. The QoS parameters, UE buffer status, uplink channel quality measurements, UE capabilities, UE measurement gaps play an important role for scheduling decisions. In uplink, data allocates certain amount of one resource block (Rumney2009). Uplink resource block size in the frequency domain consists of 12 subcarriers, i.e. the same as in downlink. But, not all integer multiples are allowed. In order to simplify the DFT design in uplink, only factors 2,3, and 5 are allowed. Unlike the downlink, UEs are always assigned contiguous resources in the LTE uplink.

SC-FDMA receiver shown in **Figure 4.5.3.** is almost the same as conventional OFDMA with additional blocks of subcarrier demapping, IDFT and optional shaping filter. This filter corresponds to the spectral shaping used in the transmitter. The subcarrier demapping of M-mapped subcarrier results N-discrete signals. In the end, IDFT converts the SC-FDMA signal to the signal constellation (Holma&etc 2009 pp76-80).

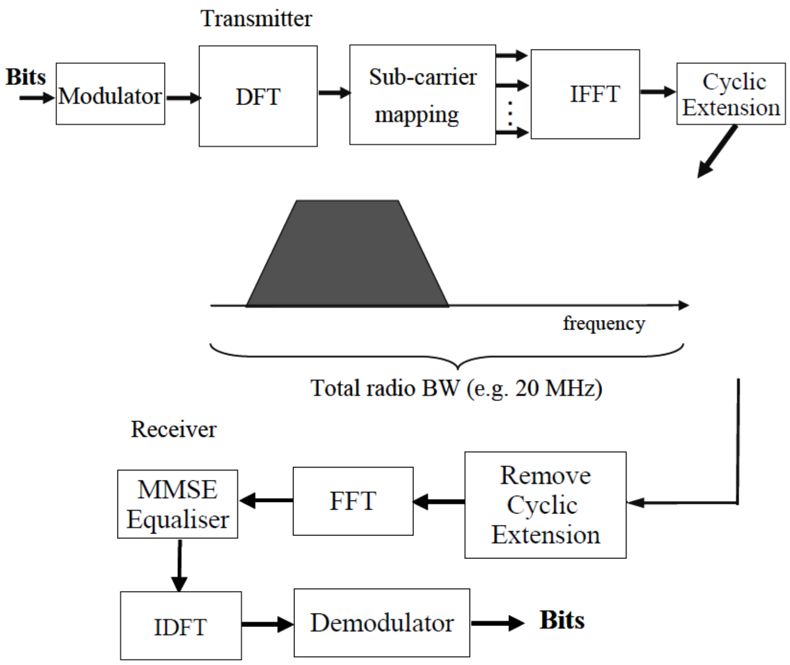


Figure 4.5.3. SC-FDMA Receiver (Holma& etc 2009)

In uplink transmission of LTE, there are some additional data carrying signals such as; reference signal, random access preamble and control signal etc. These signals are characterized as sequence signaling and have constant amplitude with zero autocorrelation. In contrast with data carrying signals, these signals are not part of SC-FDMA modulation scheme.

5.TECHNOLOGY COMPONENTS OF LTE-ADVANCED

As the LTE-Advanced is the next major step in the evolution of UTRAN Long Term Evolution (LTE) release 8, high level targets of LTE-Advanced are to meet or exceed the IMT-Advanced requirements set by ITU-R . The technology components being identified as a part of the LTE-Advanced include component carrier aggregation to enable up to 100MHz bandwidth, advanced MIMO options up to 8x8 in DL and 4x4 in UL, coordinated multiple point transmission and reception (CoMP), relay nodes (RN) and autonomous component carrier selection (ACCS) for uncoordinated femto cell deployment, Self organizing networks(SON) etc..

5.1 Carrier Aggregation

To achieve higher peak data rate, the bandwidth of the LTE-Advanced systems should be much wider than current 3G systems. It is expected to be as high as 100 MHz. Several carriers can be aggregated to form a wide bandwidth. Each component carrier may appear as LTE carrier to legacy users while LTE-A users are able to transmit and receive on several component carriers simultaneously. This is known as carrier aggregation and the aggregated carriers are named as Component Carrier (CC)s in Third Generation Partnership Project (3GPP) (Yuan Zhang Wang 2010). Two possible aggregation scenarios are possible– contiguous and noncontiguous aggregation of component carriers in a single band **Figure 5.1.1**, and non-contiguous aggregation of component carriers over multiple bands.

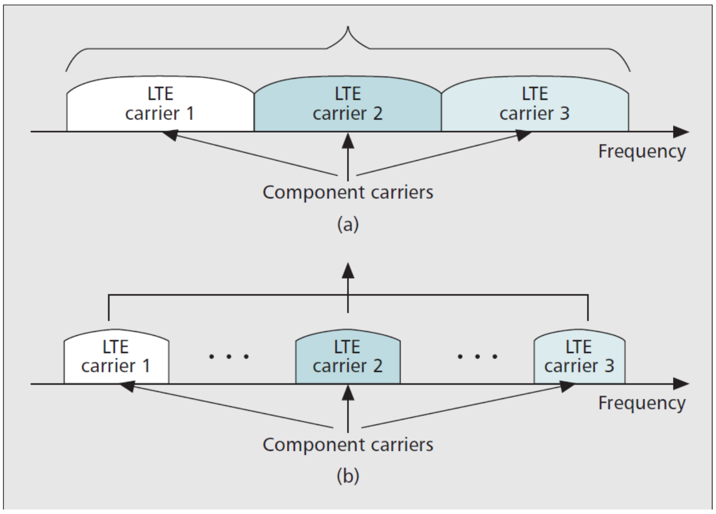


Figure 5.1.1. Carrier aggregation types:a) continuous;b) non-continuous.(Ratasuk2010)

Each component carrier will handle separate data stream that is aggregated or segmented at the MAC layer. Under LTE physical layer specifications, the peak data rate for 20 MHz system bandwidth is 299.552 Mbps in the downlink with two-layer spatial multiplexing and 75.376 Mbps in the uplink. With carrier aggregation, these peak rates will scale linearly with the number of carriers. For instance, with carrier aggregation of 5×20MHz carriers in the downlink, peak theoretical downlink data rate 1.4978 Gbps can be achieved without any additional features. In the uplink, peak data rate in excess of 500 Mbps can be achieved through carrier aggregation together with spatial multiplexing(Ratasuk, Tolli and Ghosh 2010).

In both types of CA techniques multiple LTE carriers are aggregated to serve a single UE. Because of UE complexity, capability, power consumption, and cost, it is easier to implement continuous CA without making many changes to the physical layer structure of LTE systems. To achieve continuous CA for an LTE-Advanced UE unit, it is possible to use a fast Fourier transform (FFT) module and a radio frequency (RF) component while providing backward compatibility to the LTE systems. Moreover, it is easier to implement resource allocation and management algorithms for continuous CA, compared to non-continuous CA. It is difficult to allocate continuous 100 MHz bandwidth for a mobile network, according to the existing spectrum allocation policies. Therefore, the non-continuous CA technique gives a useful approach to mobile network operators to enable full utilization of current spectrum resources. These include the unused scattered frequency bands and those already allocated for some legacy systems, such as GSM and 3G systems (Yuan Zhang Wang 2010)

5.2Relay Nodes

The next-generation wireless network is envisaged to incorporate multi-hop ad hoc characteristics into cellular network infrastructure. Multi-hop communication is a Mobile Ad hoc NETworks (MANETs) which considers generic and pure ad hoc networks without infrastructure. Multi-hop communication is seen as an annex to the next-generation cellular networks to increase coverage and capacity at cell borders. Multi-hop communication is being considered as one technology component for LTE-Advanced. Relay is a new element introduced in the LTE-Advanced. Relaying architecture for LTE-Advanced networks is composed of one or more relays between an evolved NodeB and a User Equipment (Lo&Niemegeers2009).

A number of different relaying mechanisms have been developed in the past few years, namely amplify-and-forward and decode-and-forward strategies.

Amplify-and-Forward Relaying Strategy

Amplify-and-forward relay is also known as wireless repeater or Layer 1 (L1) relay. In LTE, L1 comprises the PHY layer. The repeater receives a signal, amplifies and reshapes it, then retransmits the signal to the destination. The transceiver at both sides of L1 relay can operate either on the same (inband) or on an orthogonal carrier frequency (outband). In the latter case, the repeated signal would not interfere with any direct signal received at the destination, but a frequency reuse factor of one is not possible. Additional radio resource management functionality is needed at eNodeB to allocate frequency bands for eNodeB-to-relay and relay-to-UE transmissions. For the inband case, directional antennas can be employed to mitigate the interference caused by simultaneous eNodeB-to-relay and relay-to-UE transmissions. Similarly, at the relay simultaneous reception from UEs and transmission by the relay also causes interference. L1 relay is suitable for mitigating coverage holes(Ivamura&Takahashi).The main advantages of repeaters are simplicity, low cost and low delay. The disadvantage is that repeaters provide no means for isolating received noise and interference from the desired signals. In other words, noise and interference are also amplified and retransmitted together with the desired signals. As a result, the SINR of the signal is not improved at the output of the L1 relay(Huang Ulupinar& Agashe2010).

Decode-and-Forward Relaying Strategy

The decode-and-forward relaying strategy involves decoding of source signal at the relay node. The re-encoded signal is then forwarded to the destination. The major advantage of decode-and-forward relaying is that noise and interference are not propagated to the destination. The drawback is that the decoding and re-encoding process incurs a significant delay as compared with the Amplify-and- Forward relays. Depending on which functions are included in the relay, the relay structures can be classified into a Layer 2 (L2) relay and a Layer 3 (L3) relay. For L2 or L3 relays, the eNodeB-to-relay and relay-to-UE transmissions can be inband or outband as in the case of L1 relays. **Figure 5.2.1:** (Dahlman, Parkvall 2011)

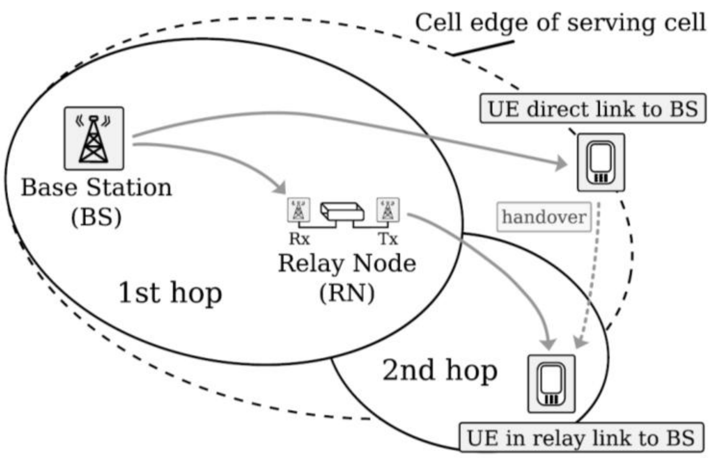


Figure 5.2.1: Relaying scenario: (Huang 2010)

Layer 2 (L2) Relay

The layer 2 relay is a Decode and Forward (DF) type of relay technology by which RF signals received on the downlink from the base station are demodulated and decoded and then encoded and modulated again before being sent on to the mobile station. This demodulation and decoding processing performed at the radio relay station overcomes the drawback in layer 1 relays of deteriorated received SINR caused by amplification of intercell interference and noise. A better throughput-enhancement effect can therefore be expected compared with the layer 1 relay. At the same time, the layer 2 relay causes a delay associated with modulation/demodulation and encoding/decoding processing. In this type of relay, moreover, radio functions other than modulation/demodulation and encoding/decoding are performed between the base station and mobile station transparently with respect to the radio relay, which means that new radio-control technology are needed(Dahlman, Parkvall 2011).

Layer 3 (L3) Relay

The layer 3 relay also performs demodulation and decoding of RF signals received on the downlink from the base station, but then goes on to perform processing(chiphering, segmentation) for retransmitting user data on a radio interface and finally performs encoding/modulation and transmission to the mobile station. Similar to the layer 2 relay, the layer 3 relay can improve throughput by eliminating inter-cell interference and noise, and additionally, by incorporating the same functions as a base station, it can have small impact on the standard specifications for radio relay technology and on implementation. Its drawback, however, is the delay caused by user-data processing in addition to the delay caused by modulation/demodulation and encoding/decoding processing. In addition to performing user-data regeneration processing and other described above, the layer 3 relay station also features a unique Physical Cell ID (PCI) on the physical layer different than that of the base station. In this way, a mobile station can recognize that a cell provided by a relay station differs from a cell provided by a base station: (Huang& etc 2010).

5.3 Multiple Input Multiple Output (MIMO)

Multiple Input Multiple Output (MIMO) refers to the use of multi-antenna technique at both transmitter and receiver side. In order to achieve the ambitious requirements for throughput and spectral efficiency in LTE and beyond systems, (MIMO) systems form an essential part. High-order SU-MIMO with more antennas is necessary to achieve the target peak spectral efficiency in LTE-Advanced which is 30bit/s/Hz. this. With the implementation of MIMO, the system can support downlink peak data rates of up to 1200 Mb/s with 8 × 8 within 20MHz bandwidth.

Two types of multiple antenna operations are defined **Figure 5.3.1**:

• Single-User MIMO (SU-MIMO) for single UE

• Multi-User MIMO (MU-MIMO) for multiple UE

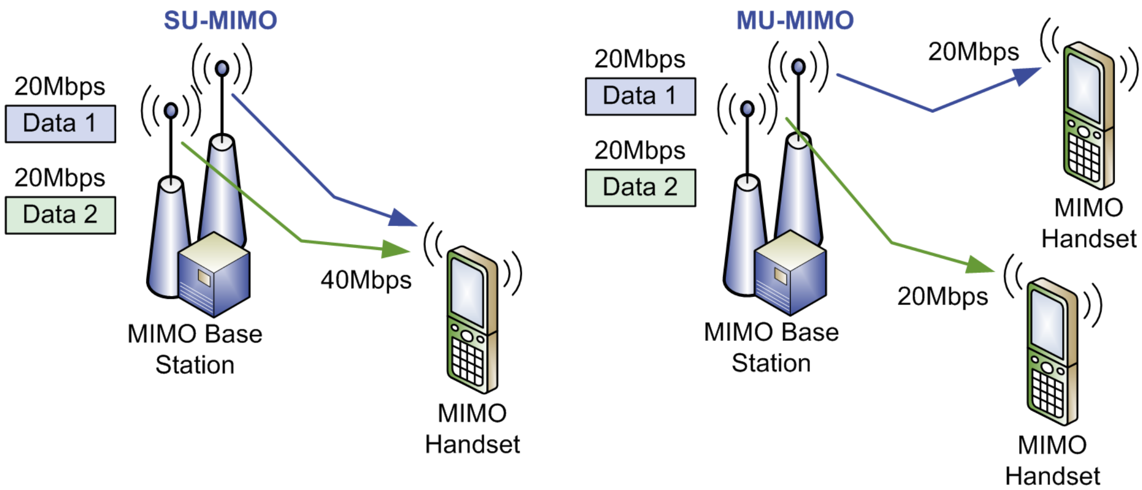


Figure 5.3.1: SU-MIMO and MU-MIMO (mpirical.com)

In downlink, improved multi-user (MU-) MIMO schemes are studied in order to provide a higher degree of frequency domain scheduling flexibility and enhanced multi-user interference suppression. The studied methods for interference suppression include for example making the terminal aware of the interference caused by the other user(s) sharing the same set of transmission resources as well as improved precoding at the transmitter side(Khan 2009 ch7).

UE requires two transmitters for implementing SU-MIMO in uplink . This is a serious challenge in terms of battery consumption, cost and size. Furthermore, the increased uplink data rates which is possible to get from SU-MIMO are not as important as in the case of downlink due to asymmetrical traffic distribution. Although a UE typically has a single transmitter in its baseline configuration, it is still possible to support MIMO. For transmit function, unlike the receive function, It does not require the transmitters to be in the same physical device or location. Thus uplink MIMO can be implemented using two transmitters belonging to two different UEs. This creates the potential for an increase in uplink capacity, although an individual user will see no increase in data rates. When the eNB has to select two UEs for pairing with MU-MIMO, it will choose two de-correlated channels. The eNB will also instruct the UE to adjust its timing and power so that all signals arrive at the eNB receiver at approximately the same level and time. With the antennas located in different devices, the transmit paths are assumed to be uncorrelated. These conditions give the eNB scheduler the opportunity to control two UEs to transmit data simultaneously using the same subcarriers. Therefore MU-MIMO could be a valuable technique for improving uplink capacity (Rumney2009 ch1, Khan 2009 ch7).

5.3 Coordinated Multi-point (CoMP) Technology

COMP allows the cell - edge users to coordinate and simultaneously receive and send signals from/to the users of multiple cells. The performance of downlink can be significantly improved if the signals from multiple cells coordinate in order to avoid mutual interference. On the uplink side, the signals of multiple cells are received and combined. If multiple cells are coordinated and scheduled at the same time, interference among cells can be suppressed and the signal to noise ratio of the received signals can be increased.

CoMP is mainly divided into two modes: intrasite CoMP and inter-site CoMP. This division is based on the relationships between the nodes to be coordinated

Intrasite CoMP covers association within a single site. Large volumes of information can be exchanged between multiple cells within a site, as there is no restriction on backhaul capacity.

Inter - site CoMP covers association with multiple site, which has higher requirements on backhaul capacity and delay. The performance of inter-site CoMP is limited by delays and backhaul capacity.

CoMP includes uplink CoMP reception and downlink CoMP transmission(NTT Docomo 2011).

Uplink CoMP reception increases a celledge user's throughput by coordinating multiple cells to receive the user's data.

Downlink CoMP transmission adopts two forms of collaboration , Co-scheduling / beamforming which depends on whether service data is obtained on multiple coordinated points and joint processing **Figure 5.3.1**.

Joint processing happens when multiple cells coordinate and act as a single virtual cell to serve terminals together. Usually this offers better transmission gains but has higher requirements on delay and backhaul capacity.

Collaborative dispatch/beam forming coordinates the transmission weights and corresponding scheduling to minimize interference among multiple cells and dynamically exchanges information among multiple cells. The terminals must measure the channels of multiple cells and provide feedback, including the interference precoding vector from the neighboring cells that produce strong interference and the expected precoding vector from the serving cell. When transmitting beams, coordinating the schedulers of multiple cells assists each cell to reduce interference on its neighboring cells. This ensures the signal strength expected by the users of a cell (NTT Docomo 2011)

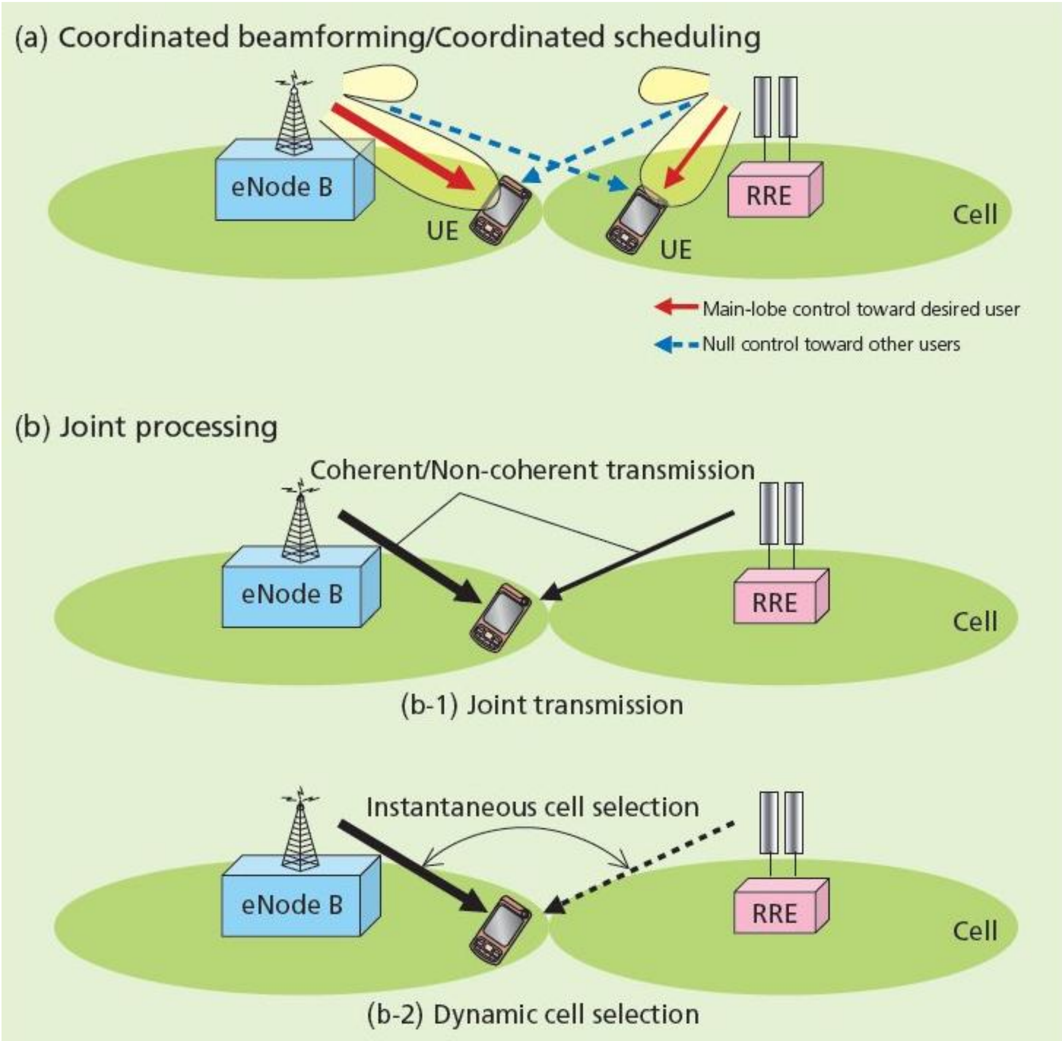


Figure 5.3.1: Downlink CoMP transmission(NTT Docomo 2011)

CoMP is a key technology of LTE-Advanced systems which effectively increases the signal-to-noise ratio for cell-edge users and the average capacity of cells. Although CoMP increases system complexity, its capacity and coverage advantages greatly outweigh its disadvantages.

5.4 FemtoCells

Various research results show that the majority of mobile users suffer from inadequate indoor signal penetration which leads to poor coverage provided to consumers. As a result they do not enjoy the full data capacity advertised by the operators. 4G systems are expected to provide high speed data services, but poor indoor coverage and interference will definitely lower the quality of real-time applications and will significantly slow down high speed data services.

The concept of 'home base station' was first studied by Bell Labs of Alcatel-Lucent in 1999. In 2002, Motorola announced the first 3G-based home base station product. In 2006, 'femtocell' as a term was coined. In February 2007, a number of companies demonstrated femtocells at the 3GSM World Congress (Barcelona), with operators announcing trials. In July 2007, the Femto Forum was founded to promote femtocell standardization and deployment worldwide(Zhang& de la Roche2010 pp1-12).

The femtocell enables users to access voice and broadband services over their own standard broadband Internet connection. A single femtocell supports usually at most four to eight simultaneous voice connections in any indoor environment, permitting many authorized users to be able to connect to the femtocell to utilize services other than voice, such as text or real time multimedia streaming etc. The user's subscription model (service and charging) for femtocell services may vary according to user needs and depends upon operators. There are various factors that affect peak data rates such as the air interface technology used, the user subscription and broadband link capacity. For supporting femtocell operations, the Home eNodeB Gateway (HeNB GW) and Home eNodeB Management System (HeMS) are new network elements that are introduced .

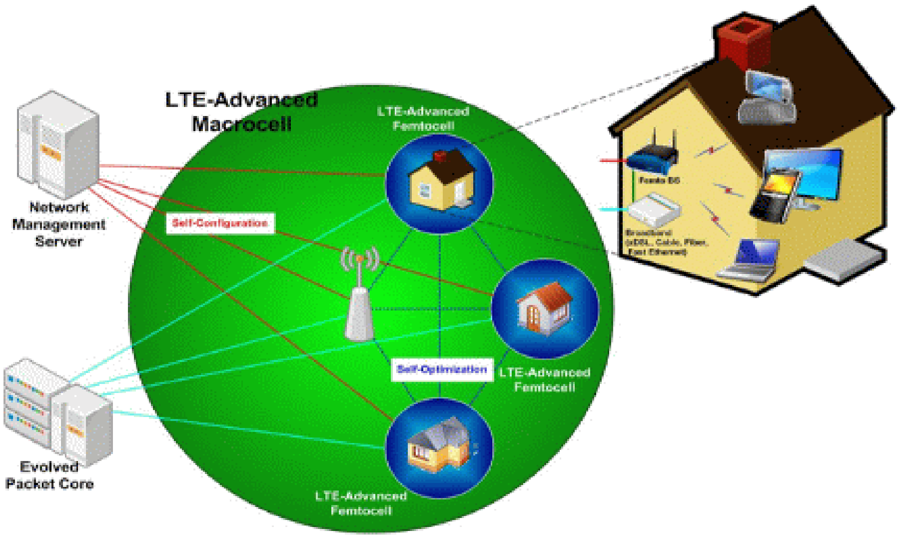


Figure 5.4.1. Femtocell deployment scenario

The HeNB GW is used as a concentrator for all traffic received from the HeNB. In the femtocell logical architecture designed by 3GPP, the HeNB GW is placed in the operator's premises.

The HeMS, on the other hand, is used to ensure that the services provided to the user are of high quality and sufficiently secured. Hence by analyzing the HeMS and HeNB GW functions, the HeNB is considered as an integral part of the operator network.

In order to utilize femtocell services, a user will buy a femtocell and will connect to it through its own fixed broadband access. Upon being connected to the broadband access, the HeNB will further connect to the operator's gateway; thereafter the HeNB will be authenticated and configured according to the user's subscription policy. Femtocell access is usually available to a restricted number of authorized users. This ensures that the coverage area which is provided by the femtocell is only accessible by the femtocell owner or by a trusted group of people **Figure 5.4.1**.

The HeNB is considered as a plug-and-play consumer device which is easily installed by the users in home and office environments. The HeNB uses the subscriber's broadband backhaul to connect to the operator's core network. HeNB uses the standard

3GPP S1 over-the-air interface to communicate with the mobile devices. Starting from 3GPP release 9 , RAN functionality is distributed between the HeNB and the HeNB GW. The HeNB supports radio management functions. The HeNB GW is used to provide various functions related to link security, control, and aggregation. the HeNB GW maintains the core network connectivity functions. The HeNB and HeNB GW work together to perform certain operations which cannot be fulfilled without each other's contribution. Paging is one kind of operation which needs HeNB and HeNB GW cooperation(Zhang& de la Roche2010 pp39-66).

5.5 Autonomous Component Carrier Selection

Local area deployment of low power eNBs such as femto cells calls for new features to facilitate high performance of uncoordinated installations . Femto-to-femto interference becomes an important issue for indoor performance, especially when femtocells are densely deployed. The interference footprint is significantly different in such local area environments from nicely planned macrocell scenarios, which consequently calls for new self-adjusting interference management techniques. There is a need for the ability to self-scale and self-adjust, which will lead to a new autonomic paradigm with fully "robotic" base stations. The optimal sharing of radio resources between low-power base stations depend on many factors such as the mutual interference coupling among them and the offered traffic for individual access nodes. Finding the optimal division of frequency resources between low-power base stations in a highly dynamic and leads to a hard optimization problem.

To overcome this problem , it has been proposed to have autonomous component carrier selection (ACCS) considered for LTE-Advanced. Autonomous component carrier selection is a fully distributed scheme, where each eNB dynamically selects a number of component carriers for its use. The selection by each eNB is dynamic according to the offered traffic in the cell, as well as based on how selection of component carriers impacts the performance in the immediately surrounding cells. This essentially means that the autonomous component carrier selection scheme provides an automatic mechanism for a dynamic frequency re-use on a component carrier resolution. The feature could also be used for managing the interference between local area and macro cells in heterogeneous environments. The basic concept is further illustrated in **Figure 5.5.1** with a simple example.

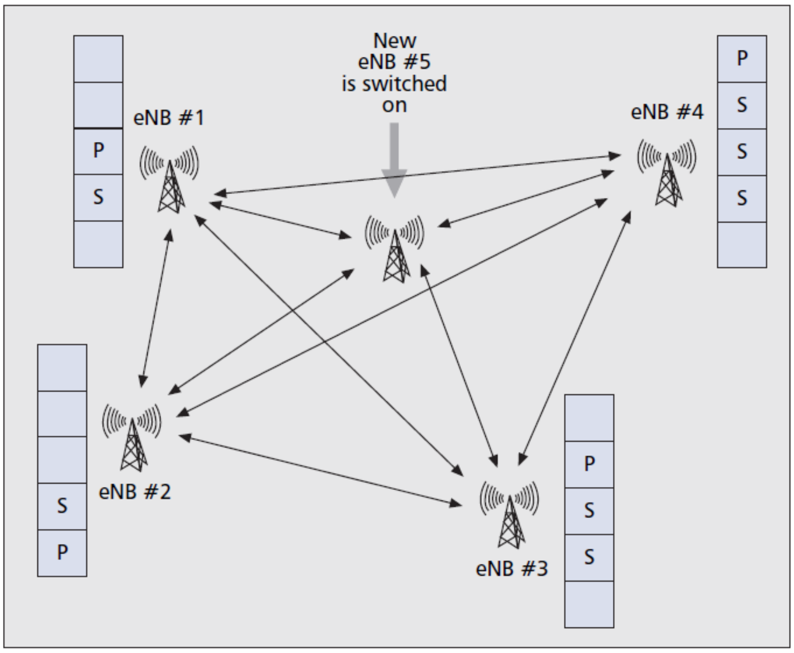


Figure 5.5.1 Basic principle of autonomous component carrier selection(Luis 2009).

Here each eNB has selected at least one primary component carrier (marked with P), and potentially multiple secondary component carriers (marked with S) depending on the offered traffic, interference conditions, etc. As a new eNB is powered on (eNB #5) it senses the environment and acquires information from the existing eNBs on which component carriers they have selected. Inter eNB communication could be realized via inband over-the-air signaling for cases without X2. Based on the later information, the new eNB selects one primary component carrier, and starts carrying traffic in its cell. As the offered traffic increases, eNB #5 may select additional secondary component carriers (Luis & etc. 2009).

5.6 Self-organizing network (SON)

In modern wireless networks, most of the network elements and associated parameters are manually configured. Planning, configuration, commissioning, integration and management of these parameters are vital for reliable and efficient operation of the network, but the associated operations costs are significant and time-consuming.

3GPP is the standardization of self-optimizing and self-organizing capabilities for LTE and beyond system - that will use network automation, intelligence and network management features to in order to automate the configuration and optimization of wireless networks. The aim of 3GPP standardize is to support SON options for multi-vendor network environments. 3GPP has proposed a number of LTE SON use cases and associated SON functions(3G Americas 2009).

An important source of LTE SON development is the industry forum NGMN (Next Generation Mobile Networks), which has established a set of initial requirements on Self-Organizing Networks, and since then several usage cases have been defined to cover multiple aspects of the network operations. These aspects may include planning, deployment, maintenance and optimization. Three mechanisms has been defined: Self-Configuration, Self-Optimization and Self-Healing.

Self-configuration mechanism is preferred during the pre-operational phases of the network elements, such as network planning and deployment. Some self-configuration can be used for the automatic neighbor ratio (ANR) feature, automatic configuration of the physical ID Cell (PCI), Self-establishment of a new eNB in the network as well as Self-configuration and self-healing of eNBs.

Self-optimization mechanism is attractive during the operational stage so that network operators get benefits of the dynamic optimization, e.g., mobility load balancing to make network more robust against environmental changes as well as the minimization of manual optimization steps to reduce operational costs. Self-optimization mechanism use cases are Coverage and capacity optimization, Interference reduction, Energy savings, Mobility load balancing optimization, Mobility robustness optimization, RACH optimization, Inter-cell interference coordination, Self-configuration and self-healing of eNBs, Self-establishment of a new eNB in the network.

The aim of the Self-healing functionality of SON is to mitigate the faults which could be solved automatically by activating corresponding recovery actions. For the fault management functionality, appropriate alarms shall be generated by the faulty network entity for each of the detected faults, regardless of whether it is an automatically detected/automatically cleared or an automatically detected/manually cleared fault(Siti& etc. , 3G Americas 2009).

6.SIMULATIONS AND RESULTS

6.1 Description of the transceiver model for downlink and uplink

OFDMA Transmitter

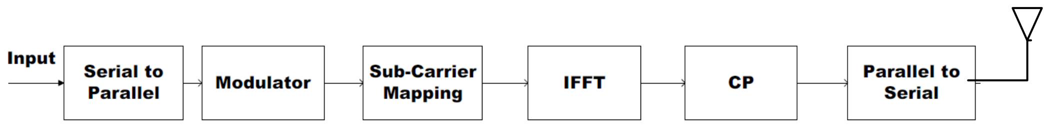


Figure 6.1.a. OFDMA Transmitter model

Transmitter

Random binary data is generated as a source data for this simulation. The first thing that should be considered in designing the LTE OFDM transmitter is the number of subcarriers required to send the given data. In LTE systems and beyond the number of subcarriers is fixed based on the Bandwidth used for transmission. As [1.25Mhz ; 2.5Mhz ; 5Mhz ; 10Mhz ; 15Mhz ; 20Mhz] bandwidths are used in LTE systems, the corresponding number of subcarriers are [72 ;180 ; 300 ; 600 ; 900 ; 1200]. Each subcarriers are centered at frequencies that are orthogonal to each other . The data has to be first converted from serial stream into parallel stream depending on the number of subcarriers (N). The Serial to Parallel converter takes the serial stream of input bits and outputs N parallel streams (indexed from 1 to N). **Figure 6.1.1.**

$$[a_1, a_2, \ldots \ldots a_n, \ldots \ldots a_{n+1}, \ldots \ldots a_{(x+1)n}] = \begin{bmatrix} a_1 & \cdots & a_{xn+1} \\ \vdots & \ddots & \vdots \\ a_n & \cdots & a_{(x+1)n} \end{bmatrix}$$

Figure 6.1.1. :Series to Parallel conversion

The second design parameter is the modulation format that is used. An LTE-OFDM signal can be constructed using any of the following digital modulation techniques namely QPSK, 16QAM, 64QAM.

After Serial to Parallel converter , the parallel streams are individually converted into the required digital modulation format (QPSK, 16QAM, 64QAM). In MatLab the conversion of parallel data into the digitally modulated data is usually achieved by function *modulate* from Communications System Toolbox.

The transmitter of an OFDMA system uses IFFT block to create the signal. The FFT operation moves the signal from time domain representation to frequency domain representation. The Inverse Fast Fourier Transform (IFFT) does the operation in the opposite direction. For the sinusoidal wave, the FFT operation's output will have a peak at the corresponding frequency and zero output elsewhere. The FFT operation can be carried out back and forth without losing any of the original information.

Modulated data feeds to the IFFT block. The IFFT stage converts these complex data symbols into time domain and generates OFDM symbols . For LTE the necessary FFT/IFFT lengths tend to be powers of two, such as 512, 1024, etc. From the implementation point of view it is better to have, for example, a FFT/IFFT size of 1024 even if only 600 outputs are used, than try to have another length for FFT/IFFT between 600 and 1024, thus the number of subcarriers should be extended until the number is a power of two.

In the Simulation case the process of extending the number of carriers are done by adding empty (filled with 0) rows to the modulated matrix. **Figure 6.1.2**

$$\begin{array}{c} \\ \\ \\ \Rightarrow \\ \Rightarrow \\ \Rightarrow \end{array}\begin{bmatrix} a_1 & \cdots & a_{xn+1} \\ \vdots & \ddots & \vdots \\ a_n & \cdots & a_{(x+1)n} \\ 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix}$$

Figure 6.1.2: Adding unused subcarriers

Each input for the IFFT block corresponds to the input representing a particular sub-carrier (or particular frequency component of the time domain signal) and can be modulated independently of the other sub-carriers (Holma & Toskala 2009).

In Matlab FFT/IFFT operations can be done by using fft() or ifft() functions. The functions Y = fft(x) and y = ifft(X) implement the transform and inverse transform pair given for vectors of length N by:

$$X(k) = \sum_{j=1}^{N} x(j)\omega_N^{(j-1)(k-1)}$$

$$x(j) = (1/N)\sum_{k=1}^{N} X(k)\omega_N^{-(j-1)(k-1)}$$

where

$$\omega_N = e^{(-2\pi i)/N}$$

is an *N*th root of unity(MatLab Help functions descriptions).

To avoid ISI, in the next step Cyclic Prefix is added. Which means that a copy of fixed number of last samples is appended to the start of the slot. In LTE systems the duration of a slot is approximately ~66.7us and the duration of a short CP is ~4.7us which is almost 1/14 part of a slot duration.

In the Simulaton CP is applied by coping 1/14 ending of the matrix to the beginning. **Figure 6.1.3**

$$\begin{bmatrix} {}^{1}/_{14}\begin{cases} a_{k+1} & \cdots & a_{(x+1)k+1} \\ \vdots & \ddots & \vdots \\ a_n & \cdots & a_{(n+1)k} \end{cases} \\ \begin{matrix} a_1 & \cdots & a_{xk+1} \\ \vdots & \ddots & \vdots \\ a_k & \cdots & a_{(x+1)k} \end{matrix} \\ {}^{1}/_{14}\begin{cases} a_{k+1} & \cdots & a_{(x+1)k+1} \\ \vdots & \ddots & \vdots \\ a_n & \cdots & a_{(n+1)k} \end{cases} \end{bmatrix}$$

Figure 6.1.2: Adding CP

Channel

In practice, there are losses in the transmission channel. To simulate the background noise of the channel, the Additive White Gaussian Noise must be considered in the simulation model.

A built-in Matlab function *awgn* is used in which the noise level is described by SNR per sample, which is the actual input parameter to the *awgn* function.

OFDMA Receiver

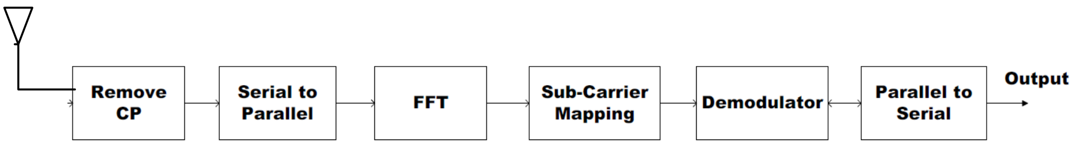


Figure 6.1.b. OFDMA Receiver model

Receiver

At receiver, the CP is removed first and then subcarriers are converted from parallel to serial sequence by using Matlab function reshape(). The FFT stage further converts the OFDM symbols into frequency domain followed by removing unused subcarriers and demodulation.

6.2 Parameters, Assumptions.

The Matlab simulation model have been developed using modular approach. Almost all blocks of the transmitter, receiver, channel as well as calculation and plot is written in separate ´m´ file. The main function calls each of the block in the manner a communication system works(Transmitter, channel, receiver, calculation and plot). The main procedure also contains initialization parameters, input data and delivers results with the help of plotting. The parameters that can be set at the time of initialization are the number of simulated OFDM symbols, CP length, modulation and sampling rate, range of SNR values and bandwidth for simulation. The input data stream is randomly generated. Each single block of the transmitter is tested with its counterpart of the receiver side to confirm that each block works perfectly.

The parameters used in this simulation are given in **Table 6.2.1**

Table 6.2.1 Parameters and assumptions used for simulations

PARAMETERS	**ASSUMPTION**
Model	SISO (Single input single output)
Number of Sub-carriers	300
CP Length	1/14
Range of SNR in dB	-10 to 30
FFT Length	512
Modulation	QPSK, 16-QAM, 64-QAM
Data Block Size	7 (Number of Symbols)
Channel	AWGN
System Bandwidth	5 MHz
Run times	50 times
Sampling Frequency	7.68 MHz

The objective behind simulating the physical layer in Matlab was to study BER performance under noisy channel conditions using different types of modulations for both downlink (OFDMA) and uplink (SCFDMA) and making comparisons with the theoretical values. Also Power Spectral Density and Peak-to-Average Power ratios were calculated for both OFDMA and SCFDMA.

6.3 BIT ERROR RATE calculations and simulations.

6.3.1 Bit Error Rate (BER) calculations

Bit error rate, also known as BER, is a key parameter used for assessing systems that transmit digital data from one location to another. Bit error rate, unlike many other forms of assessment, assesses the full end to end performance of a system including the transmitter, receiver and the channel between the two. In this way, it enables the actual performance of a system in operation to be tested, rather than testing the component parts and hoping that they will operate satisfactorily when in place.

As the name implies, a bit error rate is defined as the rate at which errors occur in a transmission system. The definition of bit error rate can be translated into a simple formula:

BER = number of errors / total number of bits sent

If the medium between the transmitter and receiver is good and the signal to noise ratio is high, then the bit error rate will be very small - possibly insignificant and having no noticeable effect on the overall system

The SNR is the ratio of bit energy (Eb) to the noise power spectral density (N0) and it is expressed in dB.

$$SNR = Eb / N0$$

For any modulation scheme, the BER is expressed in terms of SNR. BER is measured by comparing the transmitted signal with received signal, and compute the error counts over total number of bits transmitted.

The bit error rate, BER, can also be defined in terms of the probability of error or POE. The determine this, three other variables are used. They are the error function, erf, the energy in one bit, Eb, and the noise power spectral density (which is the noise power in a 1 Hz bandwidth), No.

The probability of error or error probability (Pe) is the rate of errors occurs in the received signal. For coherent detection, the symbol error probability of M-ary PSK and M-ary QAM in the AWGN channel is determined by following expressions;

For M-ary PSK the Pe is given by (Elmusrati 2009 lecture notes);

$$Pe \cong 2Q\left[\sqrt{\frac{2E_b log_2 M}{N_0}} Sin(\frac{\pi}{M})\right]$$

Where,

Eblog2M = E (Transmitted signal energy per symbol)

N0 = Noise density in AWGN

Q = Q-Function

Therefore;

$$Pe \cong 2Q\left[\sqrt{\frac{2E}{N_0}} Sin(\frac{\pi}{M})\right]$$

In the simulation, the complementary error function (erfc) is used instead of Q. Therefore, the symbol error probability in terms of erfc is given by (Elmusrati 2009 lecture notes)

$$Pe \cong erfc\left[\sqrt{\frac{2E}{N_0}} Sin(\frac{\pi}{M})\right]$$

Whereas, the relationship between erfc and Q is given by;

$$Q(x) = \frac{1}{2} erfc\left[\frac{x}{\sqrt{2}}\right]$$

For M-ary QAM the Pe is given by (Haykin 1998 pp317-321)

$$Pe \cong 4\left(1 - \frac{1}{\sqrt{M}}\right) Q\left[\sqrt{\frac{3E_{av}}{(M-1)N_0}}\right]$$

Similarly in terms of erfc, the Pe of M-ary QAM is given by

$$Pe \cong 2(1 - \frac{1}{\sqrt{M}}) erfc\left[\sqrt{\frac{3E_{av}}{2(M-1)N_0}}\right]$$

Where,

Eav = Average value of transmitted symbol energy in M-ary QAM

6.3.2 Bit Error Rate (BER) simulations and results

The BER vs SNR of OFDMA QPSK 16QAM and 64QAM are shown in **Figures 6.3.2.1 - 6.3.2.3** respectively.

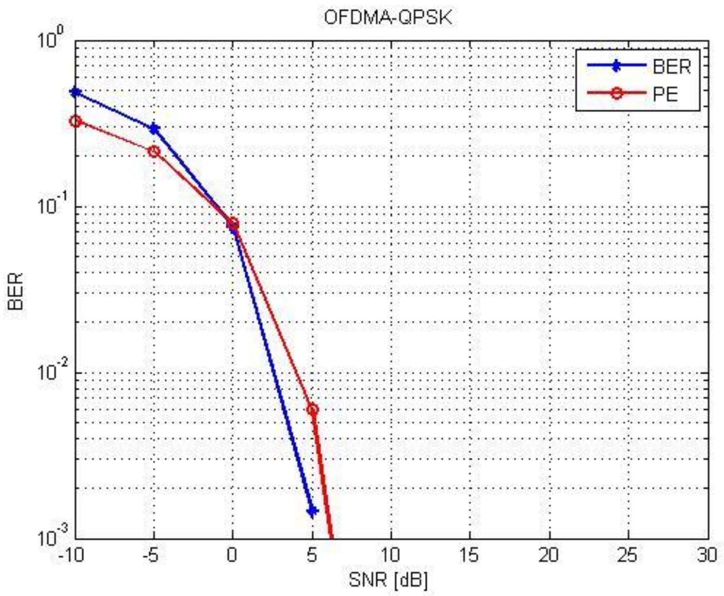


Figure 6.3.2.1 Relation between BER and Pe for OFDMA-QPSK

Table 6.3.2.1 OFDMA-QPSK: BER and Pe results for different SNR values

SNR	-10 dB	-5 dB	0 dB	5 dB	10 dB	15 dB	20 dB	25 dB	30dB
Pe	0.32	0.21	0.078	0.0095	0	0	0	0	0
BER	0.49	0.29	0.070	0.0017	0	0	0	0	0

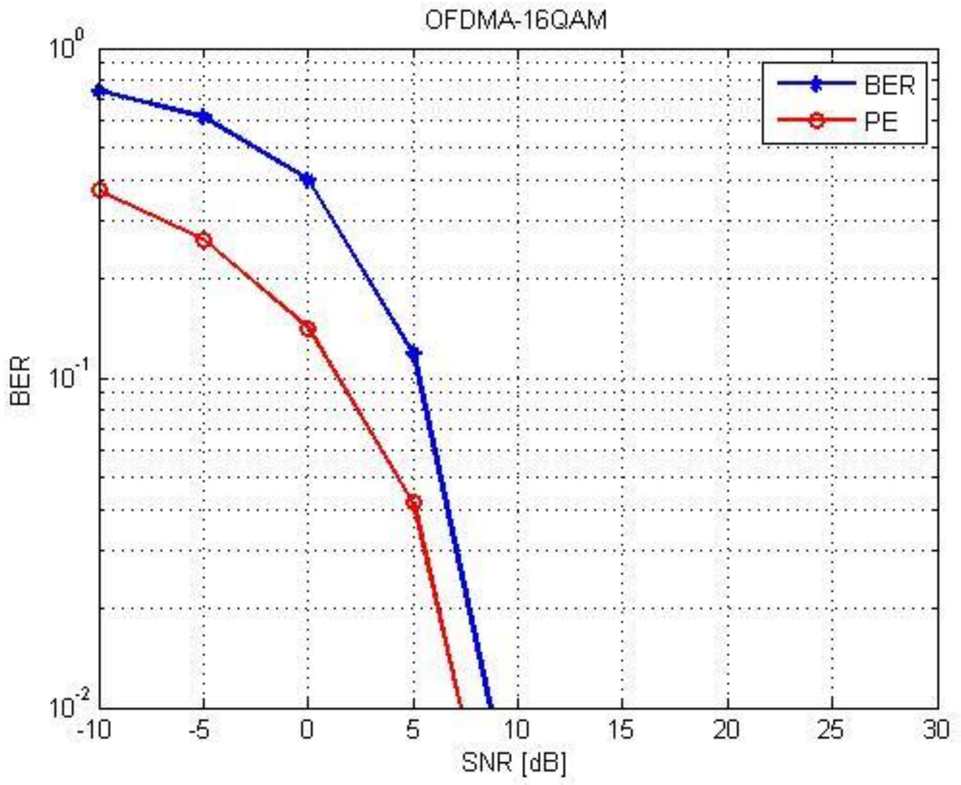


Figure 6.3.2.2 Relation between BER and Pe for OFDMA-16QAM

Table 6.3.2.2 OFDMA-16QAM: BER and Pe results for different SNR values

SNR	**-10 dB**	**-5 dB**	**0 dB**	**5 dB**	**10 dB**	**15 dB**	**20 dB**	**25 dB**	**30dB**
Pe	0.37	0.262	0.141	0.04	0	0	0	0	0
BER	0.73	0.61	0.39	0.116	0	0	0	0	0

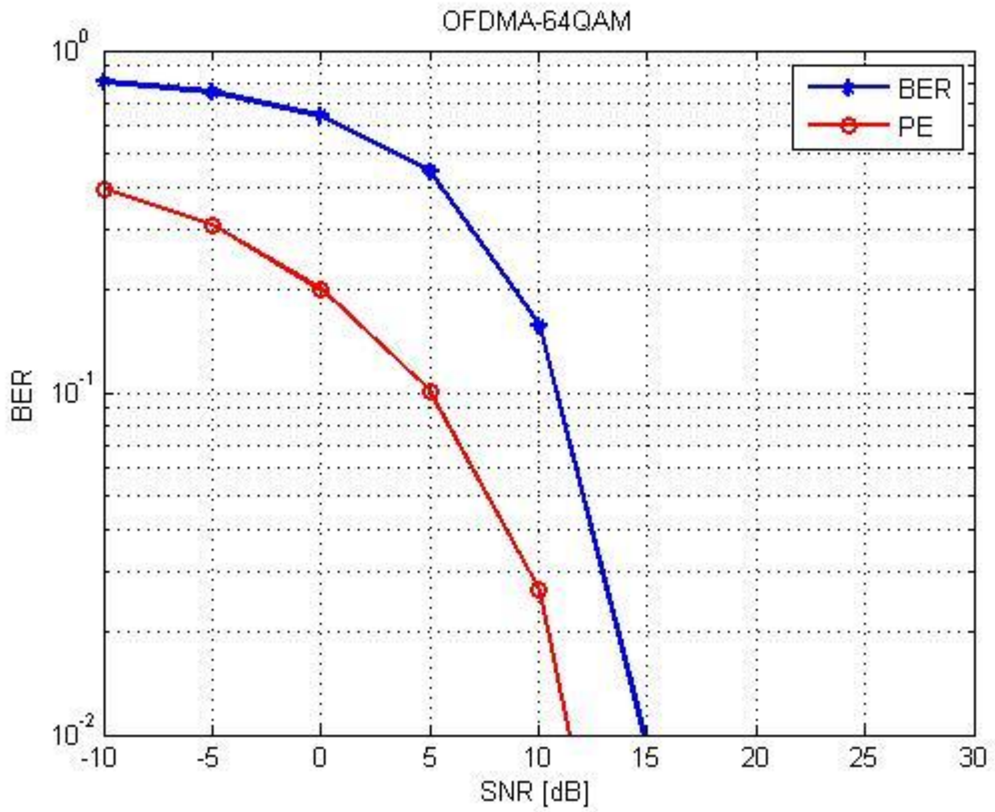


Figure 6.3.2.3 Relation between BER and Pe for OFDMA-64QAM

Table 6.3.2.3 OFDMA-64QAM: BER and Pe results for different SNR values

SNR	**-10 dB**	**-5 dB**	**0 dB**	**5 dB**	**10 dB**	**15 dB**	**20 dB**	**25 dB**	**30dB**
Pe	0.39	0.3	0.2	0.1	0	0	0	0	0
BER	0.808	0.75	0.44	0.16	0	0	0	0	0

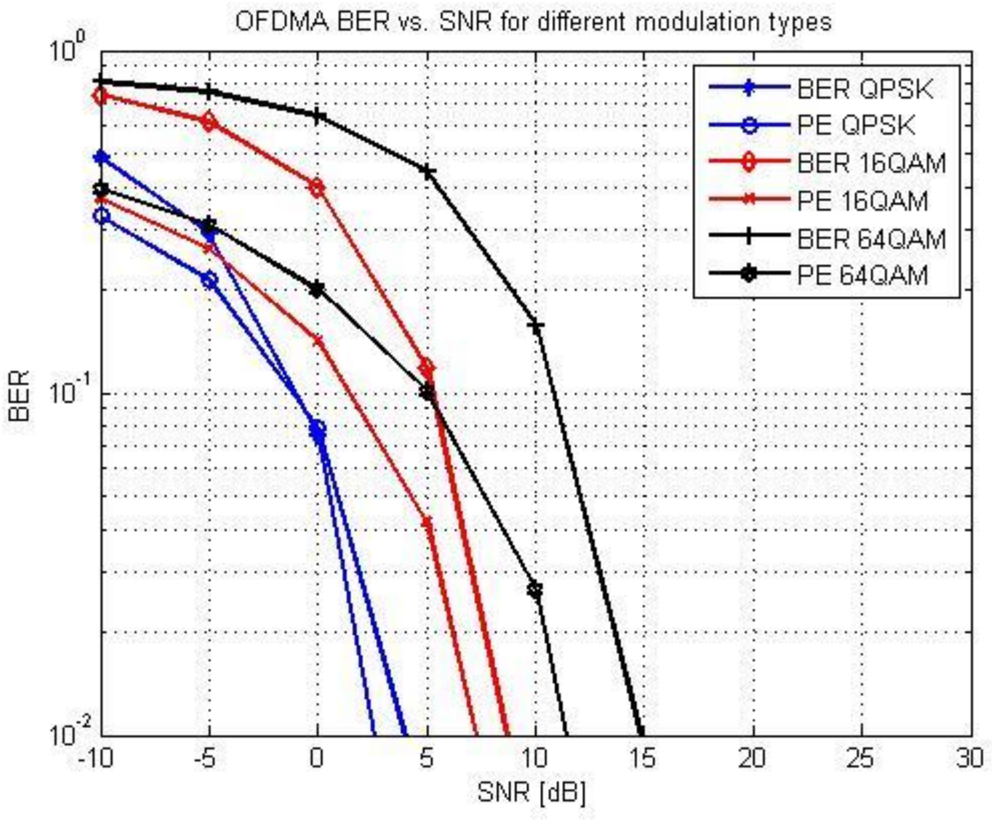


Figure 6.3.2.4 Relation between BER and Pe for OFDMA-All modulation types

The BER vs SNR of SC-FDMA QPSK 16QAM and 64QAM are shown in **Figures 6.3.2.5 - 6.3.2.7** respectively.

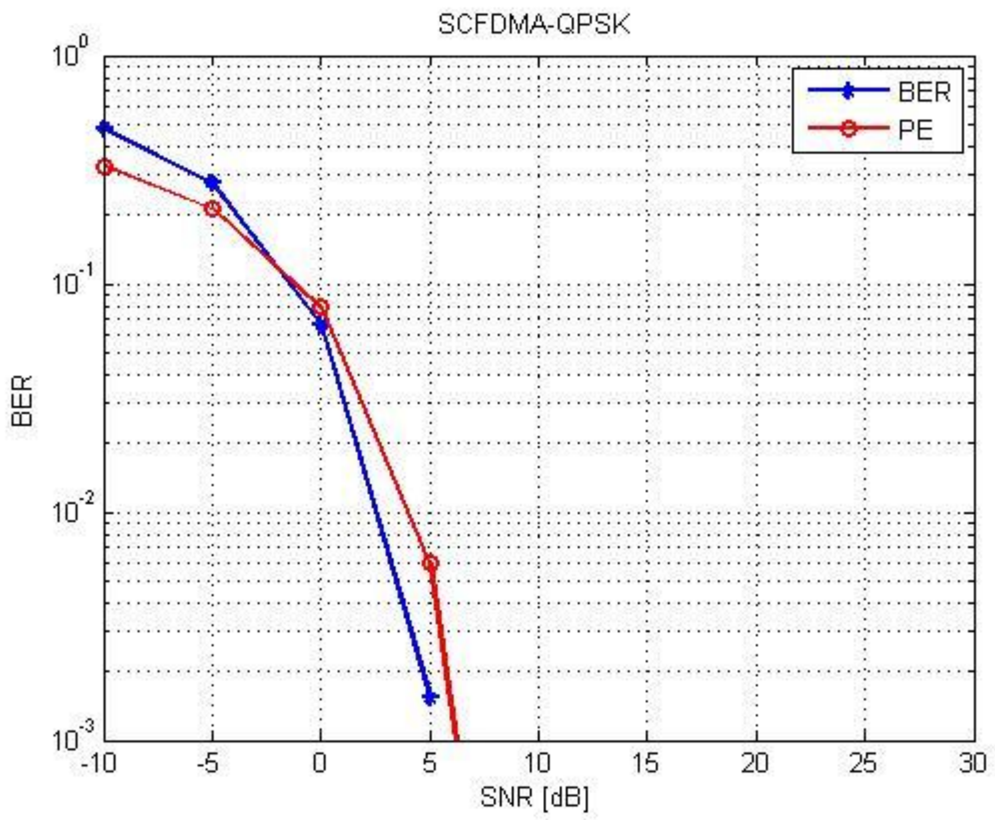


Figure 6.3.2.5 Relation between BER and Pe for SC-FDMA-QPSK

Table 6.3.2.4 SC-FDMA-64QPSK: BER and Pe results for different SNR values

SNR	**-10 dB**	**-5 dB**	**0 dB**	**5 dB**	**10 dB**	**15 dB**	**20 dB**	**25 dB**	**30dB**
Pe	0.32	0.21	0.07	0.005	0	0	0	0	0
BER	0.48	0.27	0.067	0.16	0	0	0	0	0

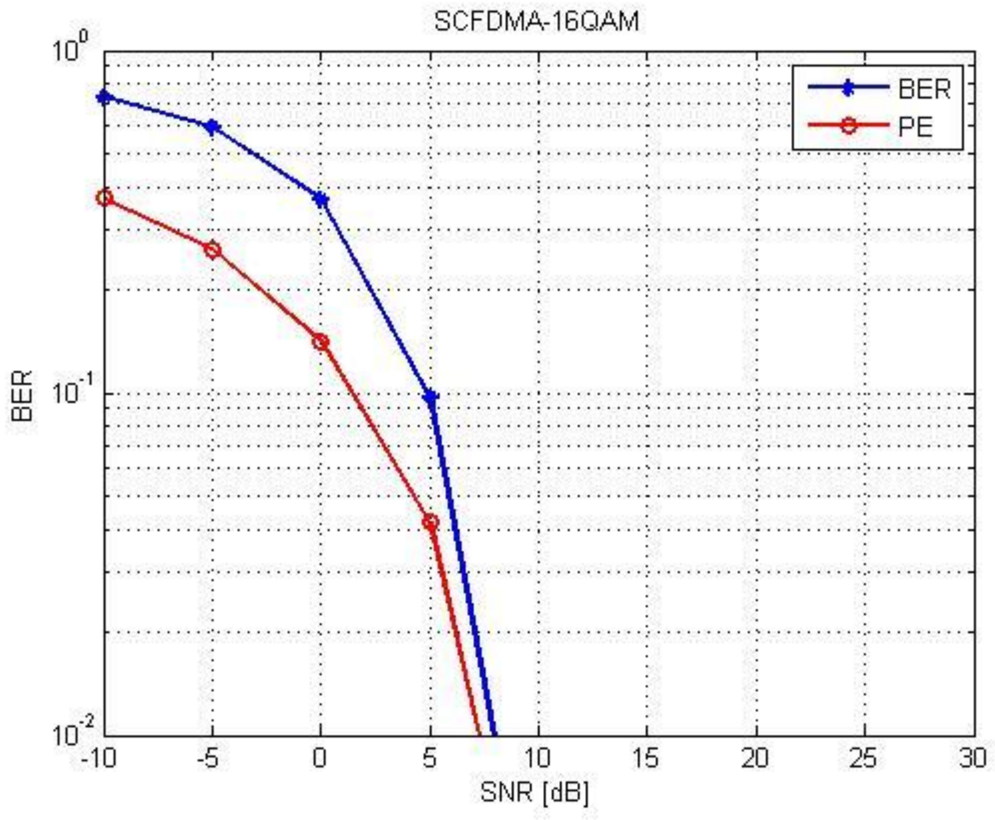


Figure 6.3.2.6 Relation between BER and Pe for SC-FDMA-16QAM

Table6.3.2.5 SC-FDMA-16QAM: BER and Pe results for different SNR values

SNR	**-10 dB**	**-5 dB**	**0 dB**	**5 dB**	**10 dB**	**15 dB**	**20 dB**	**25 dB**	**30dB**
Pe	0.37	0.26	0.14	0.04	0	0	0	0	0
BER	0.73	0.59	0.36	0.09	0	0	0	0	0

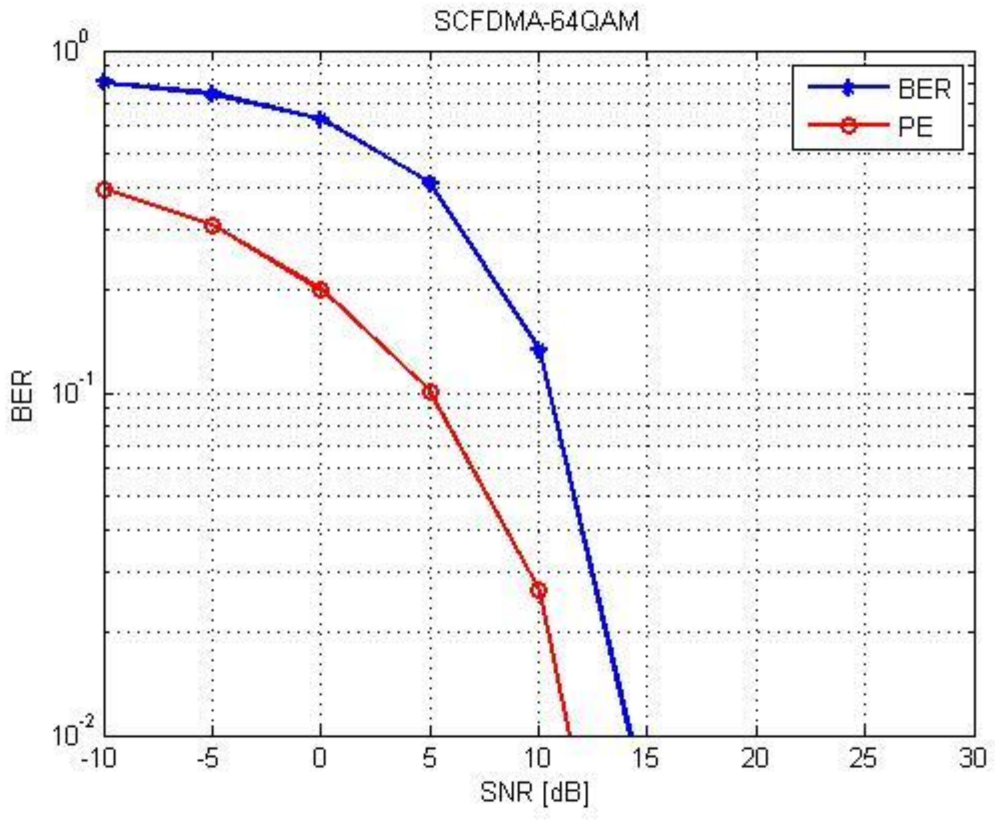


Figure 6.3.2.7 Relation between BER and Pe for SC-FDMA-64QAM

Table 6.3.2.6 SC-FDMA-64QAM: BER and Pe results for different SNR values

SNR	-10 dB	-5 dB	0 dB	5 dB	10 dB	15 dB	20 dB	25 dB	30dB
Pe	0.39	0.3	0.19	0.1	0.02	0	0	0	0
BER	0.8	0.74	0.63	0.41	0.13	0	0	0	0

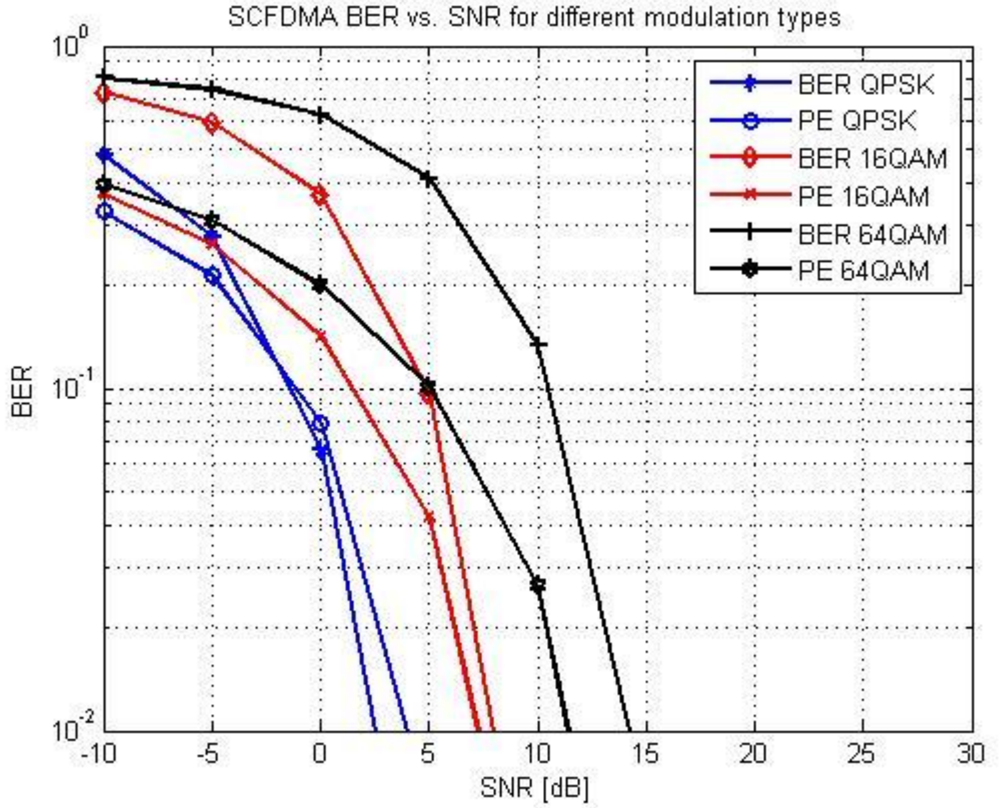


Figure 6.3.2.8 Relation between BER and Pe for SC-FDMA-All modulation types

Figure 6.3.2.4 shows the results of the BER and PE in OFDMA using different modulation types. By comparing this figure with **Figure 6.3.2.8**, that illustrates the results of the BER and PE in SC-FDMA again using different modulation types, it can be seen that the values for both access methods do not differ much from each other. In other words the performance of both access methods are almost the same in the presence of Noise (AWGN). However, when it comes to a channel with Frequency-Selective fading, though SC-FDMA effectively spreads each modulated symbol across the entire channel bandwidth and offers additional frequency diversity gain, the OFDMA is more robust with respect to frequency selective fading which transmits modulated symbols in narrow sub-bands (Ixia 2009: Myung &Goodman 2008 p66-67).

6.4. Power Spectral Density: calculations and simulations.

6.4.1. Power Spectral Density: calculations

Power spectral density function (PSD) shows the strength of the variations(energy) as a function of frequency. In other words, it shows at which frequencies variations are strong and at which frequencies variations are weak. The unit of PSD is energy per frequency and one can obtain energy within a specific frequency range by integrating PSD within that frequency range. Computation of PSD is done directly by the method called FFT or computing autocorrelation function and then transforming it(Irvine 2000).

In mobile communication, to perform the correct decision of radio resource management (RRM) at base station, the PSD plays a vital role, especially for the transmission format allocation including modulation and bandwidth. In the base station terminal, if PSD is unknown then it may cause to spent high transmission bandwidth as compared to the maximum UE power capabilities (Cygres Research International) .

In the simulation, a Matlab function spectrum is used to estimate the spectrum characteristics of a signal, along with psd (describes power characteristics of a signal). The average power of a signal in a given frequency band is determined by the integral of PSD over that frequency band. There are different types of spectral estimation methods used with psd. In this simulation a periodogram spectrum estimation method is used , which is a valid approach for discrete sinusoidal signals.

In the simulation, the average power distribution in OFDMA and SC-FDMA symbols over a 5 MHz bandwidth is analyzed using different modulation types. This 5 MHz bandwidth may exist in any LTE carrier frequency band (900 MHz, 1800 MHz, and 2600 MHz). For baseband modulation, the power characteristics of OFDMA and SC-FDMA symbols over a sampling frequency is estimated, where the sampling frequency is equal to twice of 3.84Mhz (7.68 MHz). The total power in the frequency band for the periodic signal with N period would be(Stensby class notes 2011)

$$Pxx(m) = \frac{1}{fs}\frac{1}{N}|DFTN\{x(n)\}|^2$$

Where,

fs= Sampling Frequency ((7.68 MHz)

N= Number of FFT points (512 = total subcarriers)

6.4.2. Power Spectral Density: simulation and results

The power spectral density of OFDMA are shown **in Figure 6.4.2.1 to Figure 6.4.2.3** respectively.

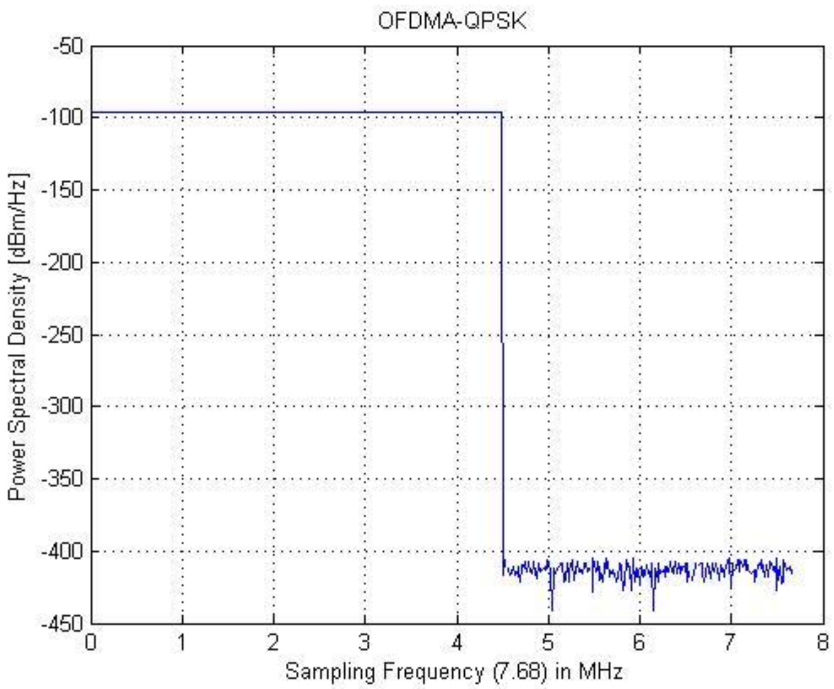


Figure 6.4.2.1: Power Spectral Density of OFDMA-QPSK

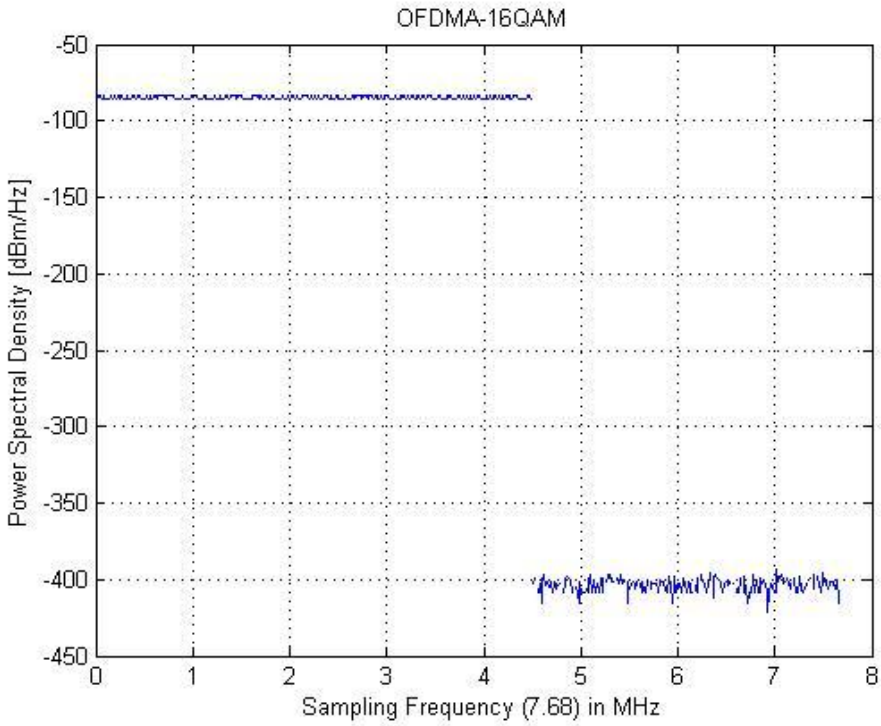


Figure 6.4.2.2: Power Spectral Density of OFDMA-16QAM

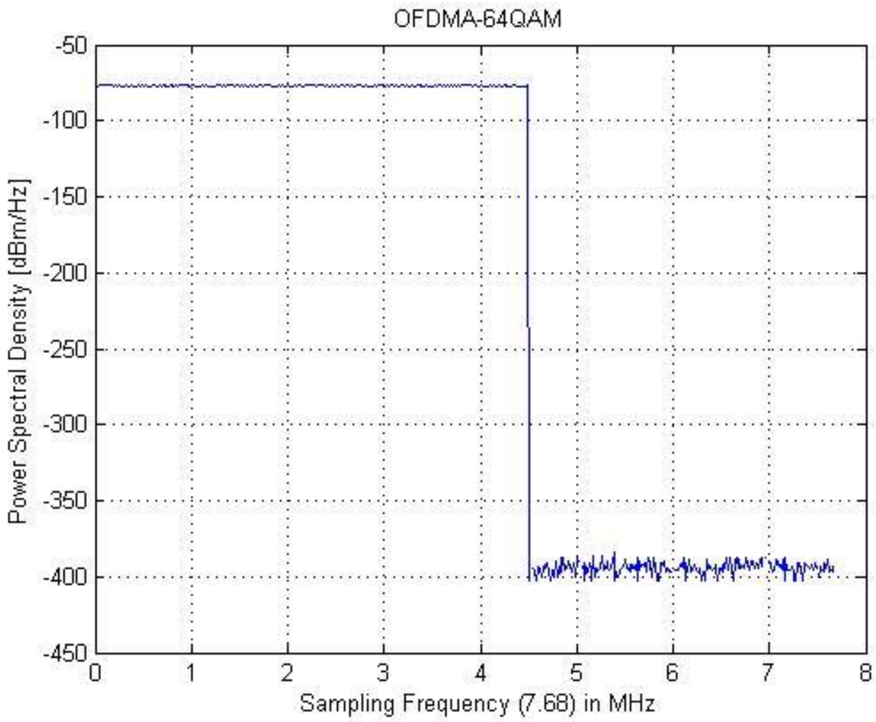


Figure 6.4.2.3: Power Spectral Density of OFDMA-64QAM

The power spectral density of SC-FDMA are shown in **Figure 6.4.2.4 to Figure 6.4.2.6** respectively.

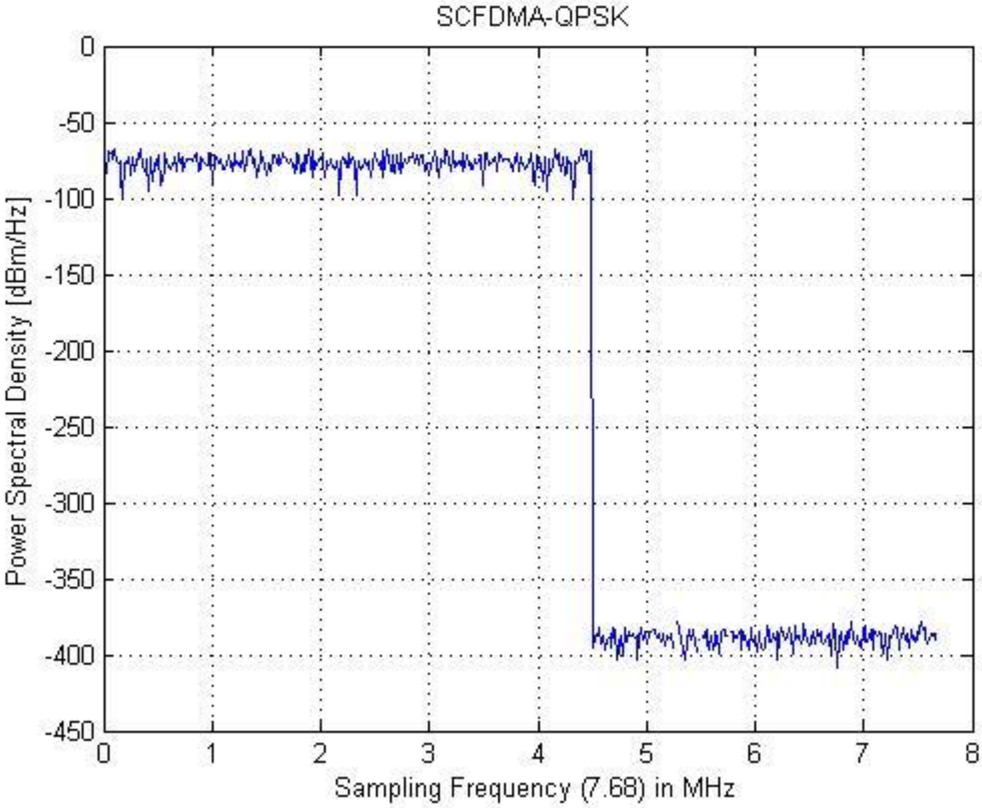


Figure 6.4.2.4: Power Spectral Density of SC-FDMA-QPSK

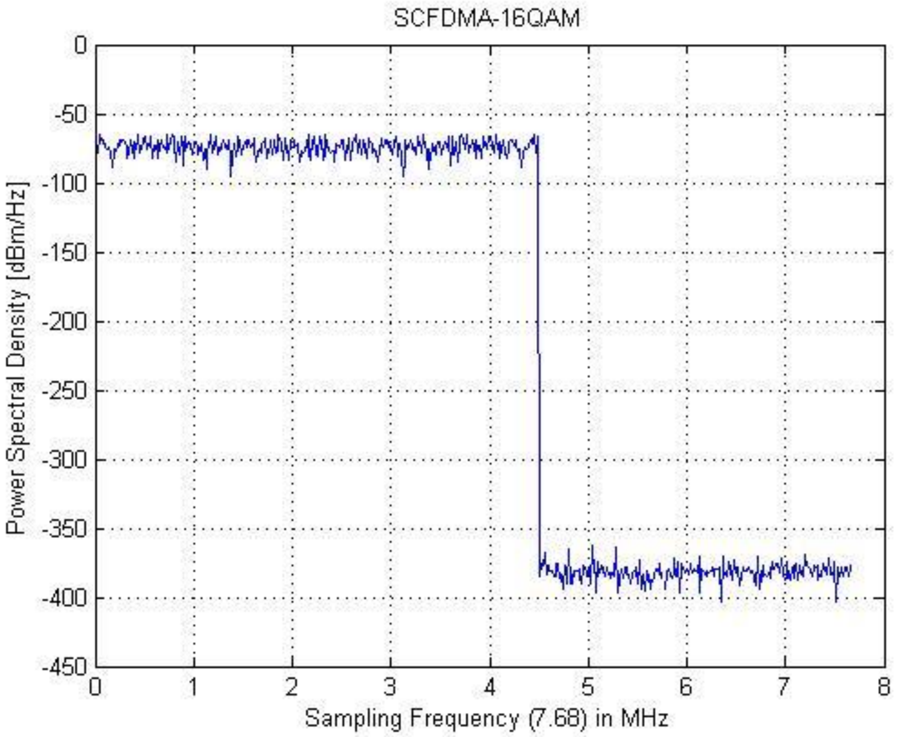


Figure 6.4.2.5: Power Spectral Density of SC-FDMA-16QAM

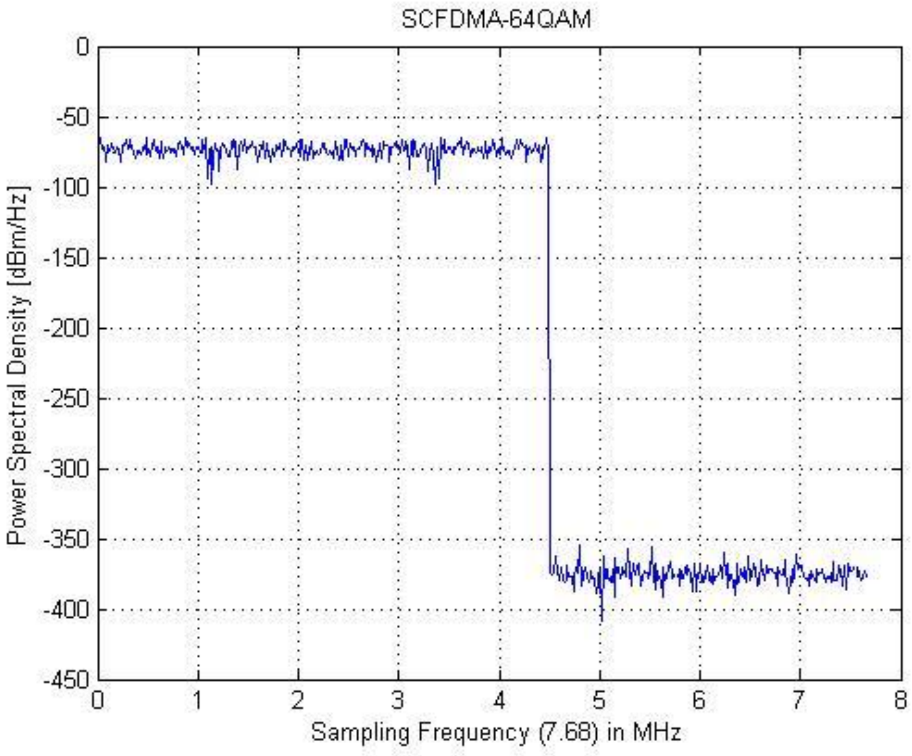


Figure 6.4.2.6: Power Spectral Density of SC-FDMA-64QAM

Figure 6.4.2.1 to Figure 6.4.2.6 illustrates the power spectral density of the OFDMA and SC-FDMA respectively using different types of modulation. One can observe that the average power of all SC-FDMA symbols is nearly (-370dB ,-380dB, -390db) based on the modulation type, whereas, in case of OFDMA the average power of all symbols is nearly (-415dB, -406dB, -398dB). This shows that the SC-FDMA symbols have inherently more average power as compared to OFDMA at all frequencies. This results also shows the transmit power requirements of OFDMA and SC-FDMA symbols which is covered in next section of PAPR.

6.5 Peak-to-Average Power Ratio: calculations and simulations

6.5.1 Peak-to-Average Power Ratio calculations

The Peak to Average Power Ratio (PAPR) is currently viewed as an important implementation issue in communication systems. Power saving in transmission is an extensive issue for the multiple access techniques used in LTE. This means that a limited PAPR can be supported. Therefore here an important transmission factor PAPR for both OFDMA and SC-FDMA is considered (Soltani2009).

The PAPR is calculated by representing a CCDF (Complementary Cumulative Distribution Function) of PAPR. The CCDF of PAPR is the probability that the PAPR is higher than a certain PAPR value PAPR0 (Pr {PAPR>PAPR0}) (Hyung G. Myung,2006). It is an important measure that is widely used for the complete description of the power characteristics of signals. The PAPR is defined as the ratio of peak power to average power of the transmitted signal in a given transmission block.

The peak to average power ratio for a signal $x(t)$ is defined as

$$papr = \frac{\max[x(t)x*(t)]}{\mathrm{E}[x(t)x*(t)]}$$

Where $()^*$corresponds to the conjugate operator.

6.5.2 Peak-to-Average Power Ratio simulations and results

The PAPR of OFDMA and SC-FDMA for QPSK, 16QAM and 64QAM modulations are shown in **Figure 6.5.2.1 to Figure 6.5.2.3** respectively.

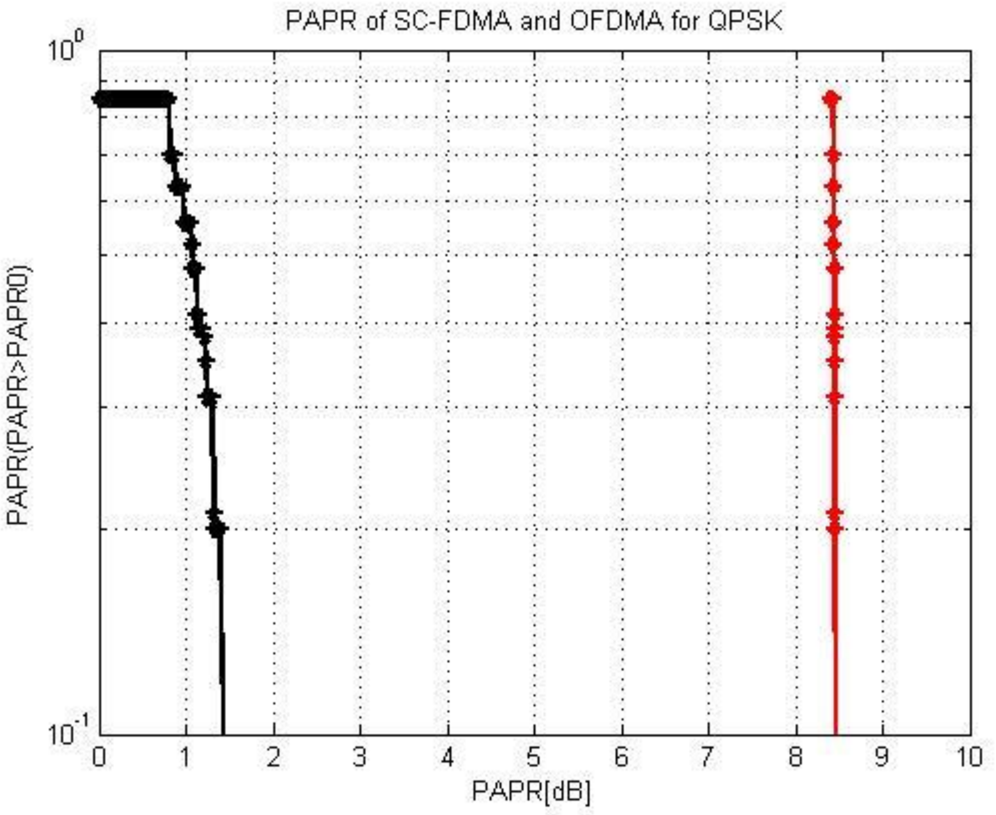


Figure 6.5.2.1: PAPR of OFDMA and SC-FDMA for QPSK

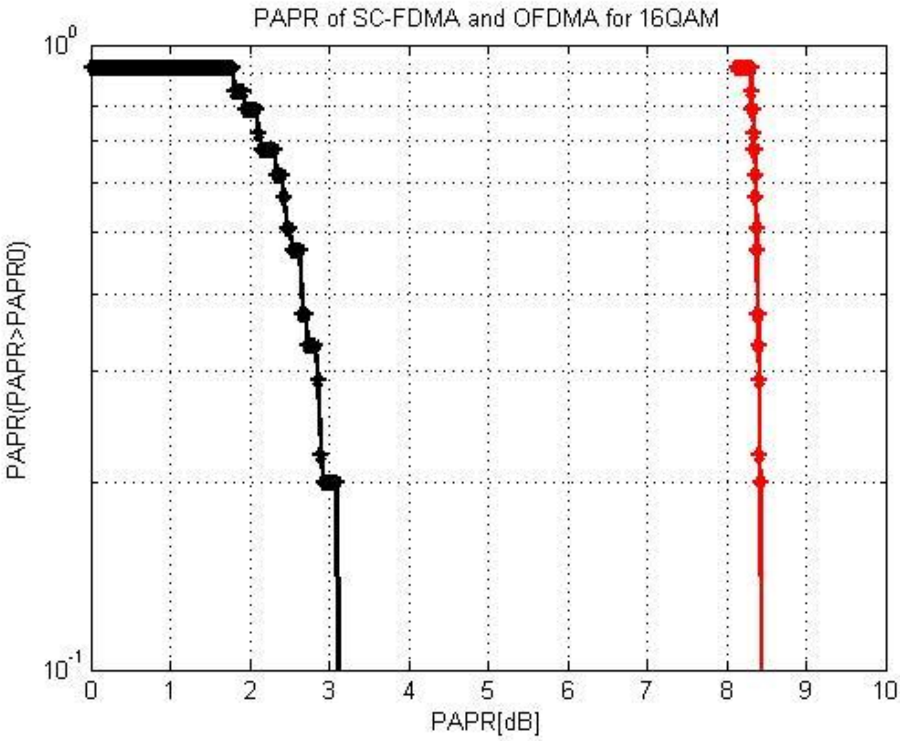


Figure 6.5.2.2: PAPR of OFDMA and SC-FDMA for 16QAM

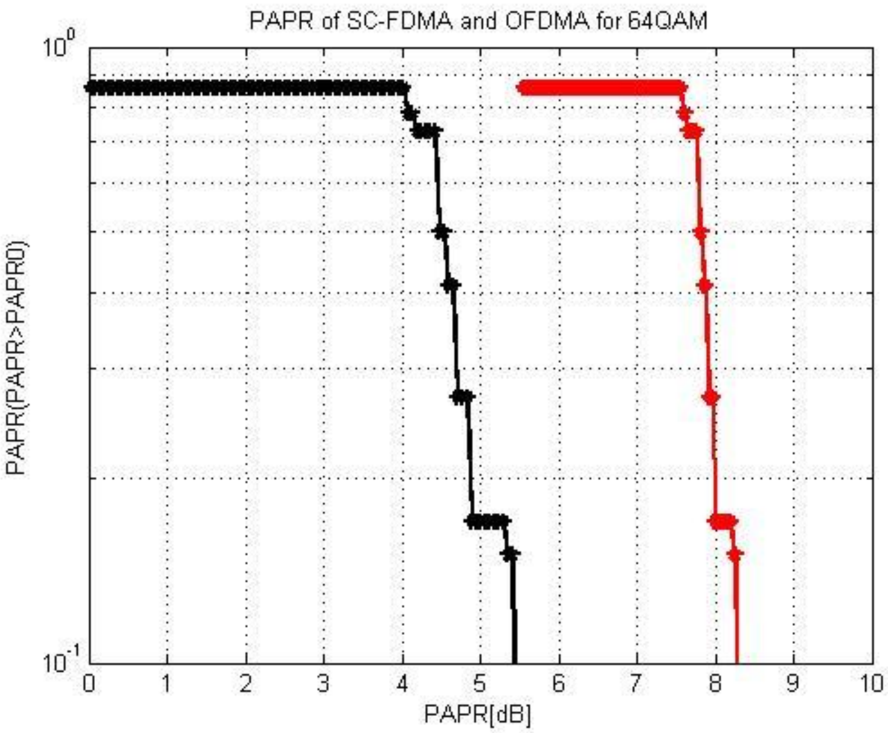


Figure 6.5.2.3: PAPR of OFDMA and SC-FDMA for 64QAM

From **Figure 6.5.2.1 to Figure 6.5.2.3,** one can observe that by increasing the order of modulation, the PAPR of SC-FDMA increases from 1.5 dB to 5.5 dB. Hence for SC-FDMA the PAPR increases for higher order modulation, whereas for OFDMA the PAPR slightly decreases from 8.4 dB to 8.2 dB for higher order modulation .

7.CONCLUSION AND FUTURE WORK

The ever changing and evolving cellular communication market demands for high speed broadband connectivity for mobiles and this future of mobile broadband market depends largely on the success of LTE technology. It is expected an increase in the data transfer speeds, both uplink and downlink, when all the new techniques mentioned in the 3GPP suite of specifications are developed and implemented. In this thesis an overall architecture of LTE-Advanced has been explored. This includes all four subsystems(EPC, E-UTRAN ,UE, Services Domain). Due to complete change in the radio part of the LTE, a special attention was given to the physical layer.

The key work of the author in this thesis was the implementation of the LTE-Advanced PHY layer using MATLAB in order to evaluate the PHY layer performance under noisy channel model for both downlink and uplink which use OFDMA AND SC-FDMA access methods respectively.

A key performance measure of a wireless communication system is the BER. In this research, BER was analyzed for different values of SNR. The BER curves were used to compare the performance of different modulations levels. All the result of the BER were compared with its theoretical values for the given SNR. The BER increases for the high order modulation (16-QAM and 64-QAM) in both the multiple access techniques (OFDMA and SC-FDMA) used in LTE system. On the other hand, the lower order modulation schemes (QPSK) experience less BER at receiver thus lower order modulations improve the system performance in terms of BER and SNR as expected. Considering the bandwidth efficiency of these modulation schemes, the higher order modulation accommodates more data within a given bandwidth and is more bandwidth efficient as compare to lower order modulation. Thus there exists a tradeoff between the BER and the bandwidth efficiency among these modulation schemes used in LTE.

The power consumption at the user end such as portable devices is again a vital issue for uplink transmission in LTE system. From the simulation results one can conclude that the values of PAPR in SC-FDMA are much lower than the ones in OFDMA, and that is why it has been adopted for uplink transmission in LTE system.

The conclusive remarks on PAPR are also supported by the results of PSD calculations. The average power distributed on all frequencies in SC-FDMA is greater than OFDMA. Therefore the peak transmits power requirements of SC-FDMA is relatively less as compare to OFDMA. Thus SC-FDMA is more power efficient.

The implemented PHY layer Simulation model still needs many improvements. To improve the model and making the model more practical and closer to the standards, turbo coding should be added. Furthermore, Frequency selective fading could be implemented. The assumed Simulation model is only suitable for SISO systems, hence it could be enhanced for MIMO models.

REFERENCES

Agilent (2009). *3GPP Long Term Evolution: System Overview, Product Development, and Test Challenges*. [online]. Available: http://cp.literature.agilent.com/litweb/pdf/5989-8139EN.pdf

Agilent technologies. *Bonus Material: Security in the LTE-SAE Network.* [online]. Available: http://www.home.agilent.com/upload/cmc_upload/All/Security_in_the_LTE-SAE_Network.PDF?&cc=FR&lc=fre

Alcatel-Lucent. (2009). *The LTE Network Architecture.* [online]. Available: www.alcatel-lucent.com

Beming P, Frid L, Hall G, Malm P, Noren T, Olsson M. & Rune G. (2007). *LTE-SAE architecture and performance*. [online]. Available: http://www.ericsson.com/ericsson/corpinfo/publications/review/2007_03/files/5_LTE_SAE.pdf

Bogineni K, Ludwig R, Mogensen P, Nandlall V, Vucetic V, Yi B.K. & Zvonar Z. (2009). *LTE PART I: CORE NETWORK*. [online]. IEEE Communications Magazine, February 2009, Pages 40-49.

Chen L., Chen W., Zhang X. & Yang. D. (2009). *Analysis and Simulation for Spectrum Aggregation in LTE-Advanced System.* [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5378825

Corici M, Vingarzan D. & Magedanz T. (2010) *3 GPP Evolved Packet Core-the Mass Wireless Broadband all-IP architecture.* [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=05755093

Dahlman E, Parkvall S. & Sköld J. (2011). *4G LTE/LTE-Advanced for Mobile Broadband.* First edition. Oxford. Elsevier Ltd. 431 P. ISBN: 978-0-12-385489-6

Elmusrati (2009). *DIJITAL COMMUNICATIONS*. lecture notes university of VAASA.

EventHelix.com Inc. (2009) *3GPP LTE Packet Data Convergence Protocol (PDCP) Sub Layer*. [online] Available from Internet: http://www.eventhelix.com/lte/presentations/3GPP-LTE-PDCP.pdf

Furth B. & Ahson S. A. (2009) *LONG TERM EVOLUTION 3GPP LTE Radio and Cellular Technology*. US. Taylor & Francis Group, Llc. 458 P. ISBN: 978-1-4200-7210-5

Garcia, L.G.U.; Pedersen, K.I. & Mogensen, P.E. (2009). *Autonomous Component Carrier Selection: Interference Management in Local Area Environments for LTE-Advanced.* [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5277463

Hanzo L, Akhtman Y, Wang L. & Jiang M. (2011). *MIMO-OFDM for LTE, Wi-Fi and WiMAX ; Coherent versus Non-coherent and Cooperative Turbo-transceivers.* First edition. Torquay, UK. John Wiley & Sons Ltd. P658. ISBN 978-0-470-68669-0

Haykin S. & Moher M. (2009). *Communication Systems.* 5th edition. USA. John Wiley & Sons, Ltd. 440P. ISBN: 978-0471697909

Helsinki University of Technology. *UTRAN Radio Interface protocols.* Lecture notes. [online] Available from Internet: http://www.comlab.hut.fi/opetus/238/lecture7_RadioInterfaceProtcols.pdf

Holma H. & Toskala A. (2009) *LTE for UMTS–OFDMA and SC-FDMA Based Radio Access.* First edition. Chippenham, UK. John Wiley & Sons, Ltd. 433 P. ISBN: 978-0-470-99401-6

Ian F. Akyildiz, David M. Gutierrez-Estevez & Elias Chavarria Reyes. (2010). *The evolution to 4G cellular systems: LTE-Advanced.* Elsevier. [online]. Available: http://www.ece.gatech.edu/research/labs/bwn/surveys/ltea.pdf

Iwamura M, Takahashi H. & Nagata S. *Relay Technology in LTE-Advanced.* NTT DOCOMO Technical Journal Vol. 12 No. 2. [online]. Available: http://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/rd/technical_journal/bn/vol12_2/vol12_2_029en.pdf

IXIA (2009). *SC-FDMA Single Carrier FDMA in LTE.* [online]. Available: http://www.ixiacom.com/pdfs/library/white_papers/SC-FDMA-INDD.pdf

Juan J. Sánchez, D. Morales-Jiménez, G. Gómez, J. T. Enbrambasaguas (2007). *Physical Layer Performance of Long Term Evolution Cellular Technology*. [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=4299090

Khan F. (2009). *LTE for 4G Mobile Broadband ; Air Interface Technologies and performance.* First edition. CAMBRIDGE UNIVERSITY PRESS. 492P. ISBN: 978-0-521-88221-7

Kreher R. & Gaenger K. (2011) LTE *Signaling, Troubleshooting and Optimization*, First Edition. Berlin. John Wiley & Sons, Ltd. 282 P. ISBN 978-0-470-68900-4

Lescuyer P. & Lucidarme T. (2008) *EVOLVED PACKET SYSTEM (EPS) THE LTE AND SAE EVOLUTION OF 3G UMTS.* Chippenham, England. John Wiley & Sons, Ltd. 338 P. ISBN: 978-0-470-05976-0

Lo & Niemegeers (2009). *Multi-hop Relay Architectures for 3GPP LTE-Advanced.* [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5431478

Maharum S. M. M., Ghafar A. S. A., Fisal N., Rashid R. A. & Saparudi F. A. *Challenges in Self-Optimizing Networks for LTE-Advanced Standards.* [online]. Available: http://trg.fke.utm.my/members/marwangi/SONforLTE_Advanced.pdf

Myung H. G. & Goodman D. J. (2008). *SINGLE CARRIER FDMA; A NEW AIR INTERFACE FOR LONG TERM EVOLUTION.* First edition. John Wiley & Sons, Ltd. 185 P. ISBN 978-0-470-72449-1

Myung H. G., Lim J. & Goodman D. (2006). *Single Carrier FDMA for Uplink Wireless Transmission.* [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=4099344

Nossenson R. (2009). *Long-Term Evolution Network Architecture*. [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5385947

Olsson M, Sultana S, Rommer S, Frid L. & Mulligan C. (2009) *SAE and the Evolved Packet Core Driving The Mobile Broadband Revolution*. First edition. Oxford. Elsevier Ltd. 440 P. ISBN: 978-0-12-374826-3

Parkvall S, Dahlman E, Furuskär A, Jading Y, Olsson M, Wänstedt S. & Zangi K. (2009). *LTE-Advanced – Evolving LTE towards IMT-Advanced.* [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=4657145

Qin-long Qiu, Jian Chen, Ling-di Ping, Qi-fei Zhang & Xue-zeng Pan (2009) *LTE/SAE Model and its Implementation in NS 2*. [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5401498

Ratasuk R., Tolli D & Ghosh A. (2010). Carrier Aggregation in LTE-Advanced. [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5493902

Rohde & Schwarz (2009) *LTE-Advanced Technology introduction Application note.* [online] Available from Internet: http://www2.rohde-schwarz.com/file_13924/1MA169_2E.pdf

Rohde & Schwarz. *UMTS Long Term Evolution (LTE) Technology Introduction.* [online]. Available: http://www2.rohde-schwarz.com/file_10948/1MA111_2E.pdf

Rumney M. (2008) *3GPP LTE: Introducing Single-Carrier FDMA.* Agilent. [online]. Available: http://cp.literature.agilent.com/litweb/pdf/5989-7898EN.pdf

Seidel E. (2008). *Progress on "LTE Advanced"* - *the new 4G standard.* [online]. Available: http://www.nomor.de/uploads/_c/V1/_cV1fTZl6MtFnAHVXltStg/LTEAdvanced_2008-07.pdf

Shah D.S. (2010). *LTE EVOLVED UTRAN (EUTRAN) AND LTE SELF ORGANIZING NETWORKS.* USA

Soltani N. (2009). *Comparison of Single-Carrier FDMA vs. OFDMA as 3GPP Long-Term Evolution Uplink*. [online]. Available: http://www.stanford.edu/~nsoltani/ee359project/project.pdf

Sorger U, Isabella De Broeck & Schnel M. (1998). *1nterleaved FDMA - A New Spread-Spectrum Multiple-Access Scheme.* [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=685165

Taoka H, Nagata S, Takeda K, Kakishima, She X. & Kusume K. *MIMO and CoMP in LTE-Advanced.* NTT DOCOMO Technical Journal Vol. 12 No. 2. [online]. Available: http://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/rd/technical_journal/bn/vol12_2/vol12_2_020en.pdf

Traian Andrei. *An Overview of Long Term Evolution Advanced.* [online]. Available: http://www.cs.wustl.edu/~jain/cse574-10/ftp/lte-adv/index.html

TS 24.301 3GPP. Technical Specification Group Core Network and Terminals. Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3, Release 8. TS 24.301; <http://www.3gpp.org/>

TS 23.401 3GPP. Technical Specification Group Core Network and Terminals. General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access; Release 8. TS 23.401; <http://www.3gpp.org/>

TS 23.402 3GPP. Technical Specification Group Core Network and Terminals. Architecture enhancements for non-3GPP accesses; Release 9. TS 23.402 <http://www.3gpp.org/>

TS 29.274 3GPP. Technical Specification Group Core Network and Terminals. 3GPP Evolved Packet System; Evolved GPRS Tunnelling Protocol for EPS (GTPv2); Stage 3, Release 8. TS 29.274 <http://www.3gpp.org/>

TS 29.303 3GPP. Technical Specification Group Core Network and Terminals. Domain Name System Procedures; Stage 3, Release 9. TS 29.303 <http://www.3gpp.org/>

TS 36.201 3GPP. Technical Specification Group Core Network and Terminals. Evolved Universal Terrestrial Radio Access (E-UTRA); Long Term Evolution (LTE) physical layer; General description; Release 8. TS 36.201 <http://www.3gpp.org/>

TS 36.321 3GPP. Technical Specification Group Core Network and Terminals. Evolved Universal Terrestrial Radio Access (E-UTRA) Medium Access Control (MAC) protocol specification. Release 8. TS 36.321 <http://www.3gpp.org/>

TS 36.322 3GPP. Technical Specification Group Core Network and Terminals. Evolved Universal Terrestrial Radio Access (E-UTRA) Radio Link Control (RLC) protocol pecification; Release 8. TS 36.322 <http://www.3gpp.org/>

TS 36.410 3GPP. Technical Specification Group Core Network and Terminals. Evolved Universal Terrestrial Access Network (E-UTRAN); S1 General aspects and principles. Release 8. TS 36.410; <http://www.3gpp.org/>

Xiaolong Huang, Ulupinar F, Agashe P, Ho D. & Gang Bao. (2010). *LTE Relay Architecture and Its Upper Layer Solutions*. [online]. Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5683640

Yuanye Wang (2010). *System Level Analysis of LTE-Advanced: with Emphasis on Multi-Component Carrier Management*. Aalborg, Denmark.

Zhang J. & Guillaume de la Roche (2010) *FEMTOCELLS Technologies and Deployment.* First edition. Singapore. John Wiley & Sons, Ltd. 297 P. ISBN: 978-0-470-74298-3

Zyren J. (2007) *Overview of the 3GPP Long Term Evolution Physical Layer*. White Paper. [online] Available from Internet: http://www.freescale.com/files/wireless_comm/doc/white_paper/3GPPEVOLUTIONWP.pdf

3G Americas. (2009). *The Benefits of SON in LTE; SELF-OPTIMIZING AND SELF-OPTIMIZING NETWORKS.* [online]. Available: http://www.slideshare.net/allabout4g/benefits-of-son-in-lte

APPENDIX

Matlab Code:

```
function [ SerialData, FS, Rows, SubCarierr, ModSelection,
inputData,ifftData  ] = OFDM_Transmitter(BwSelection, ModSelection)
%OFDM_TRANSMITTER Summary of this function goes here
%   Detailed explanation goes here

BwArray=[1.25e6  2.5e6 5e6 10e6 15e6 20e6];
SCarray=[72 180 300 600 900 1200];
FFTlengthArray=[128 256 512 1024 1024 2048];
FS_array=[1.92e6  3.84e6 7.68e6 15.36e6 23.04e6 30.72e6];
SubCarierr=SCarray(BwSelection);
FFTlength=FFTlengthArray(BwSelection);

FS=FS_array(BwSelection); %% sampling frequency

%%input generation
 inputData=rand(1,1*SubCarierr)>0.5 ;


ParData=series2parallel(inputData,SubCarierr);

switch ModSelection
    case 1
        %QPSK();
        modData=modulate(modem.pskmod(4),ParData);
    case 2
        %16QAM();
        modData=modulate(modem.qammod(16),ParData);
    case 3
        %64QAM();
         modData=modulate(modem.qammod(64),ParData);


end

 mappedData = SubMapping(modData,FFTlength,SubCarierr);

 %Apply IFFT
 ifftData=ifft(mappedData);
 CpData=CyclicPrefix(ifftData );
 Rows=size(CpData,1);

 %Parallel2Serial Conversion
 SerialData=reshape(CpData,1,size(CpData,1)*size(CpData,2));
 FFTlength
end


function [ rfData ] = Channel( FS,SerialData,ModSelection)
%CHANNEL Summary of this function goes here
```

```
%   Detailed explanation goes here
rfData=zeros(9,length(SerialData));
counter=1;
for i=-10:5:30
 switch ModSelection
     case 1
          i=i+3;
     case 2
          i=i+6;
     case 3
         i=i+8;

 end
 NoisyData=awgn(SerialData,i,'measured');
           rfData(counter,:)=NoisyData;
           counter=counter+1;
%% Adding noise
end
 %% Rayleighchan Fading
%  fading=rayleighchan(1/FS, 130 , [1e-7 1e-5],[0 0]);
%  rfData=filter(fading,NoisyData);


end


function [ Output ] = OFDM_Receiver( rfData,Rows, SubCarierr,
ModSelection )
%RECEIVER Summary of this function goes here
%   Detailed explanation goes here

Output=zeros(9,1*SubCarierr);
for i=1:1:9
parData=series2parallel(rfData(i,:), Rows);

DCPData= DeCyclicPrefix( parData );

%FFT transformation
FFTData=fft(DCPData,size(DCPData,1));
%

 deMappedData=DeSubMapping( FFTData, SubCarierr );

 switch ModSelection
    case 1
        %QPSK();
        DemodData=demodulate(modem.pskdemod(4),deMappedData);
    case 2
        %16QAM();
        DemodData=demodulate(modem.qamdemod(16),deMappedData);
    case 3
        %64QAM();
         DemodData=demodulate(modem.qamdemod(64),deMappedData);
```

```
    end
 serial=reshape(DemodData,1,size(DemodData,1)*size(DemodData,2));

Output(i,:)=serial;
end
Output
end


function mappedData = SubMapping(modData,FFTlength, SubCarierr)
%SERIES2PARALLEL Summary of this function goes here
%   Detailed explanation goes here
modData;
mappedData=zeros(FFTlength,size(modData,2));
mappedData(1:SubCarierr,:)=modData(1:SubCarierr,:);

end


function [ deMappedData ] = DeSubMapping( fftData, SubCarierr)
%DESUBMAPPING Summary of this function goes here
%   Detailed explanation goes here

deMappedData=zeros(SubCarierr,size(fftData,2));
deMappedData(1:SubCarierr,:)=fftData(1:SubCarierr,:);




end


function [ CpData ] = CyclicPrefix( ifftData )
%CYCLICPREFIX Summary of this function goes here
%   Detailed explanation goes here
cp=14;
LengthFFT=length(ifftData(:,1));
cpLength=floor(LengthFFT/cp);
CpData=[ifftData(LengthFFT-cpLength:LengthFFT,:);ifftData];
size(CpData,1)

end


function [ DCPdata ] = DeCyclicPrefix( parData )
%DECYCLICPREFIX Summary of this function goes here
%   Detailed explanation goes here
cp=14;
LengthparData=length(parData(:,1));
cpLength=floor(LengthparData/cp);
DCPdata=parData(cpLength-1:LengthparData,:);


end
```

```
function [ output,Eb_No ] = Calculations( inputData, Output )
%CALCULATIONS Summary of this function goes here
%   Detailed explanation goes here
%Compare input and output data
BERnum=0;
BER=zeros(1,9);


for j=1:9
for i=1:size(inputData,2)
    if inputData(i)~=Output(j,i)
    BERnum=BERnum+1;
    end
end

BER(j)=BERnum/size(inputData,2);
BERnum=0;
end

Eb_No=-10:5:30;

%BER=

    output=BER;
end


function [ avBER, Pe] = BER()
%BER Summary of this function goes here
%   Detailed explanation goes here
BwSelection=3;
loop=50;
avBER=zeros(3,9);
Pe=zeros(3,9);

for(ModSelection=1:3)

AV_Matrix=zeros(loop,9);

 for i=1:loop
     [SerialData, FS , Rows, SubCarierr,ModSelection,
inputData,ifftData] = OFDM_Transmitter( BwSelection,ModSelection);
     rfData=Channel( FS,SerialData,ModSelection);
      Output= OFDM_Receiver(rfData, Rows, SubCarierr, ModSelection);
      [output,Eb_No]=Calculations( inputData, Output );
      AV_Matrix(i,:)=output;
 end

 for i=1:9
     avBER(ModSelection,i)=mean(AV_Matrix(:,i))
 end
 Eb_No=-10:5:30;

 for k=1:9
```

```
 switch ModSelection
     case 1 %QPSK
Pe(ModSelection,k)= berawgn(Eb_No(k),'psk',4,'nondiff');
     case 2 %16 QAM
Pe(ModSelection,k)= berawgn(Eb_No(k),'qam',16);
    case 3 %64 QAM
Pe(ModSelection,k)= berawgn(Eb_No(k),'qam',64);
 end
 end
end
end
```

```
 function [OFDM_papr ] = OFDM_PAPR( )
%OFDM_PAPR Summary of this function goes here
%   Detailed explanation goes here
BwSelection=3;
ModSelection=1;
BwArray=[1.25e6  2.5e6 5e6 10e6 15e6 20e6];
SCarray=[72 180 300 600 900 1200];
FFTlengthArray=[128 256 512 1024 1024 2048];
FS_array=[1.92e6  3.84e6 7.68e6 15.36e6 23.04e6 30.72e6];
SubCarierr=SCarray(BwSelection);
FFTlength=FFTlengthArray(BwSelection);

mappedData=zeros(SubCarierr,1)

FS=FS_array(BwSelection); %% sampling frequency
times=100;
Symbols=7;
OFDM_papr=zeros(3,times);

for ModSelection=1:3
for Runs=1:times
%%input generation
 inputData=rand(1,1*SubCarierr)>0.5 ;

 ParData=series2parallel(inputData,SubCarierr);
 switch ModSelection
    case 1
        %QPSK();
        modData=modulate(modem.pskmod(4),ParData);
     case 2
        %16QAM();
        modData=modulate(modem.qammod(16),ParData);
    case 3
        %64QAM();
         modData=modulate(modem.qammod(64),ParData);

end
modData=modData/sqrt(mean(abs(modData).^2));
        temp=ceil(rand(Symbols,1)*7);
        for k=1:Symbols
        data(k)=modData(temp(k));
        end
```

```
 data=data';
 %FFTdata=fft(data);
 mappedData(1:Symbols)=data;

 ifftData=ifft(mappedData)


OFDM_papr(ModSelection,Runs)=10*log10(max(abs(ifftData).^2)/mean(abs(i
fftData).^2))
end
end
end


function [ output_args ] = PSD()
close all;
clc;
%PSD Summary of this function goes here
%   Detailed explanation goes here
FS_array=[1.92e6  3.84e6 7.68e6 15.36e6 23.04e6 30.72e6]
BwArray=[1.25e6  2.5e6 5e6 10e6 15e6 20e6];
SCarray=[72 180 300 600 900 1200];
FFTlengthArray=[128 256 512 1024 1024 2048];
Mytitle_OFDM=char('OFDMA-QPSK','OFDMA-16QAM','OFDMA-64QAM');
Mytitle_SCFDM=char('SCFDMA-QPSK','SCFDMA-16QAM','SCFDMA-64QAM');
for ModSelection=1:3
BwSelection=3;
[SerialData, FS , Rows, SubCarierr,ModSelection, inputData,ifftData] =
OFDM_Transmitter( BwSelection,ModSelection);
h = spectrum.periodogram;
figure()
HS =
psd(h,ifftData,'SpectrumType','twosided','NFFT',FFTlengthArray(BwSelec
tion),'FS',FS_array(BwSelection));
plot(HS);
axis auto;
xlabel('Sampling Frequency (7.68) in MHz')
ylabel('Power Spectral Density [dBm/Hz]')
title(Mytitle_OFDM(ModSelection,:))
[SerialData, FS , Rows, SubCarierr,ModSelection, inputData,ifftData] =
SCFDM_Transmitter( BwSelection,ModSelection);
k = spectrum.periodogram;
figure()
HS1 =
psd(h,ifftData,'SpectrumType','twosided','NFFT',FFTlengthArray(BwSelec
tion),'FS',FS_array(BwSelection));
plot(HS1);
axis auto;
xlabel('Sampling Frequency (7.68) in MHz')
ylabel('Power Spectral Density [dBm/Hz]')
title(Mytitle_SCFDM(ModSelection,:))
end
end
```