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PAPR Analysis in SC FDMA for Uplink System

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Abstract

High peak-to-average power ratio (PAPR) is one of the major drawbacks in the orthogonal frequency division multiple access (OFDMA) systems which increases the complexity of Analogue to Digital (A/D) and Digital to Analogue (D/A) converters and also reduces the efficiency of High Power Amplifier (HPA), for that, the LTE (Long Term Evolution) network has proposed DFT-spreading OFDMA technique for reducing this problem in the Uplink system. In this work we show the PAPR performance of DFT-spreading technique, where the impact of the radio resource allocation , the RC filter pulse shaping with different Roll Off factor , the number of subcarrier system and the number of subcarrier per user on the PAPR are simulated.

Key words: LTE , OFDM, OFDMA, HPA, PAPR,CCDF, DFT-Spreading.

Résumé

Le PAPR est l'un des inconvénients majeurs dans les systèmes d'accès multiples par répartition de fréquences orthogonales (OFDMA). Car il augmente la complexité des convertisseurs analogique-numérique (A/N) et numérique-analogique (N/A) et aussi réduit l'efficacité de l'amplificateur haute puissance (HPA). Le LTE propose une technique de DFT-Spreading afin de réduire ce problème dans la voie montante. Dans ce mémoire nous présentons les performances de PAPR pour la technique DFT-Spreading où l'impact de l'allocation de ressource radio, le filtre RC (Raise Cosine) avec différent valeurs de facteur Roll Off, le nombre de sous porteuses de système et le nombre de sous porteuses par utilisateur sur le PAPR sont simulé.

Mots clés : LTE, OFDM, OFDMA, HPA, PAPR, CCDF, DFT-Spreading.

ملخص

يعد PAPR احد العيوب الرئيسية لنظام الارسال المتعدد للتضاعف باستعمال التقسيم المتعامد للتواترات OFDMA الذي يزيد من تعقيد المحولات التماثلية - رقمية (A/D) و الرقمية – تماثلية (D/A) .و كذالك يخفض من فعالية المضخمات العالية الطاقة (HPA) ، من هنا اقترحت شبكة التطور الطويل الامد (LTE) تقنية-DFT Spreading لتخفض هذا العيب في نظام الربط العلوي (Uplink). في هذه المذكرة سنعرض اداء PAPR في هذه التقنية اين سنقوم بمحاكات تاثير كل من توزيع موارد الراديو ، المصفاة RC مع قيم مختلفة للمعامل Roll Off، عدد نظام الحوامل الفرعية و كذالك عدد الحوامل الفرعية لكل مستخدم على PAPR.

الكلمات المفتاحية : LTE، OFDM، OFDMA، PAPR، CCDF،HPA، DFT-Spreading .

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List of abbreviations

3GPP	Third Generation Partnership Project.
ACK	ACKnowledge.
BCH	Broadcast CHannel.
CCDF	Complementary cumulative distribution function
CDMA	Code Division Multiple Access.
CP	Cyclic Prefix
DFDMA	Distributed Frequency Division Multiple Access
ECC	Error Correction Codes.
ENB	Enhanced Node B
EPS	Evolved Packet System.
ESM	Eps Session Management.
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network.
FDD	Frequency Division Duplex
FEC	Forward Error Correction.
FFT	Fast Fourier Transform
GBR	Guaranteed Bit Rate.
GGSN	Gateway Gprs Support Node.
GPRS	General Packet Radio Service.
HLR	Home Location Registrar.
HPA	High Power Amplifier
HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber Server
ICI	Inter Carriers Interference
IDFT	Inverse Discrete Fourier Transform
IFDMA	Interleaved Frequency Division Multiple Access
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol.
ISI	Inter Symbol Interference

LFDMA	Localized Frequency Division Multiple Access
LTE	Long Term Evolution
LOS	Line of Sight
MIMO	Multiple Input Multiple Output.
MME	Mobility Management Entity.
MSC	Mobile Switching Centre
OFDM	Orthogonal Frequency Division Multiple
OFDMA	Orthogonal Frequency Division Multiple Access.
PAPR	Peak to Average Power Ration
PCRF	Policy and Charging Rules Function.
PDCCH	Physical Downlink Control CHannel.
PDCP	Packet Data Convergence Protocol.
PDN GW	Packet Data Network Gate Way.
PDP	Packet Data Protocol.
PDU	Protocol Data Unit.
PHICH	Physical Hybrid ARQ Indicator CHannel.
PS	Pulse shaping
PSD	Power Spectral Density
PSTN	Public Switched Telephone Network.
PUCCH	Physical Uplink Control CHannel.
QAM	Quadrature Amplitude Modulation.
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying.
RAB	Radio Access Bearer.
RAN	Radio Access Network.
RF	Radio Frequency.
RLC	Radio Link Control.
RN	Request Number.
RNC	Radio Network Controller.
RRC	Radio Resource Control.
SAE	System Architecture Evolution.
SC-FDMA	Single Carrier - Frequency Division Multiple Access.

SCH	Synchronization CHannel.
SN	Sequence Number.
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
TE	Terminal Equipment
ARQ	Automatic Repeat reQuest.
EPC	Evolved Packet Core.
GSM	Global System for Mobile communications.
HARQ	Hybrid Automatic Repeat reQuest.
IEEE	Institute of Electrical and Electronics Engineers.
MAC	Medium Access Control.
UE	User Equipment.
UMB	Ultra Mobile Broadband

General introduction

The significant expansion seen in mobile and cellular technologies over the last two decades is a direct result of the increasing demand for high data rate transmissions. So, in recent years, the existing and the incoming wireless mobile communication systems are occupying more and more transmission bandwidths than the conventional ones to support broadband multimedia applications with high data rates for mobile users [1]. In addition, wireless mobile technologies are also moving rapidly toward small and low cost devices. However, broadband wireless channels suffer from a severe frequency-selective fading, which causes ISI [2,3]. As the bit rate increases, the problem of ISI becomes more serious. Conventional equalization in the time domain has become impractical, because it requires one or more transversal filters with a number of taps covering the maximum channel impulse response length [4,5].

Orthogonal frequency division multiplexing (OFDM) and OFDMA systems have received a lot of attention in the last few years due to their abilities to overcome the frequency-selective fading impairment by transmitting data over narrower subbands in parallel [6–8]. However, they have several inherent disadvantages such as the high Peak-to-average power ratio (PAPR) and the sensitivity to frequency offset [9–13]. To solve the problems encountered in the uplink of these systems, much attention has been directed recently to another system, namely the single-carrier with frequency domain equalization (SC-FDE) system [2–5], because it has a lower PAPR. To provide multiple access in broadband wireless networks, the SC-FDE system has been naturally combined with frequency division multiple access (FDMA), where different orthogonal subcarriers are allocated to different user equipment, and the new system is referred to as the SC-FDMA system [10,14,15].

In this work we will investigate the PAPR performance of DFT-SC FDMA signal compared with OFDMA where this work is organized as follows:

Chapter one gives an overview of LTE network and shows some performance requirements for LTE such as peak data rate, spectrum efficiency, reduced latency and mobility. The network architecture, protocols, quality of service, LTE handover and LTE advantages will be investigated in this chapter.

Chapter two introduces OFDM and OFDMA systems where the principal advantage in broadband radio systems is the strong reduction in inter-symbol interference ISI. In this chapter, we introduce also SC-FDMA signal processing operations described the two approaches to assigning mobile terminals to subcarriers: localized FDMA (LFDMA) and interleaved FDMA (IFDMA). Pulse-shaping filters are used to restrict the bandwidth of the transmitted signals, while minimizing the likelihood of decoding errors. Two pulse-shaping filters will be considered in this chapter: the raised cosine RC and the root raised-cosine RRC filters.

Chapter three investigate the PAPR performance of DFT-SCFDMA signal compared with OFDMA. The CCDFs of the PAPR for the DFT-IFDMA, DFT-LFDMA and the OFDMA system will be evaluated and compared for different modulation formats, also, the impact of the pulse shaping (RC filter), the impact of the number of subcarrier system and the impact of the number of subcarrier per user on the CCDF of the PAPR for DFT-IFDMA and DFT-LFDMA will be evaluated for different modulation formats. Finally, we will terminate this work by a conclusion.

Chapter 1
Long Term Evolution

1 Introduction

The LTE (Long Term Evolution) and LTE-Advanced are the latest mobile communications standards developed by the Third Generation Partnership Project (3GPP). These standards represent a transformative change in the evolution of mobile technology. Within the present decade, the network infrastructures and mobile terminals have been designed and upgraded to support the LTE standards. As these systems are deployed in every corner of the globe, the LTE standards have finally realized the dream of providing a truly global broadband mobile access technology.

2 Requirements for the 3GPP Long Term Evolution

The 3GPP (Third Generation Partnership Project) has set the requirements for LTE (Long Term Evolution), following is a brief summary of the main targets of LTE.

- ✓ **Peak data rate:** a peak data rate of 100 Mbps in the downlink and 50 Mbps in the uplink within 20 MHz bandwidth (BW). This is equivalent to a 5 bits/s/Hz spectral efficiency in the downlink and 2.5 bits/s/Hz in the uplink.
- ✓ **Reduced latency:** the control-plane latency requirement is 100 ms for the transition from *IDLE* state to *ACTIVE* and 50ms for the transition from *STANDBY* state to *ACTIVE* state. On the other hand, the user-plane latency requirement, the time required for an IP packet from the *user equipment* (UE) to reach the IP layer of the radio access network, is 5 ms.

- ✓ **Spectrum flexibility:** LTE can be deployed in the available spectrum ranging from 1.25 - 20 MHz this enables more spectrum flexibility. It is also a requirement for LTE to be deployed in both paired and unpaired spectrum (FDD/ TDD modes).
- ✓ **Co-existence and interworking with other 3GPP technologies:** LTE is required to co-exist and interwork with other 3GPP technologies like GSM, and WCDMA.
- ✓ **High user throughput:** an average user throughput of 3-4 times in the downlink and 2-3 times in the uplink compared to the Release 6 High Speed packet Access (HSPA).
- ✓ **Spectrum efficiency:** spectrum efficiency (in bits/s/Hz/cell) of 3-4 times in the downlink and 2-3 times in the uplink compared to the Release 6 HSPA.
- ✓ **Mobility:** UE speeds of 0 - 15 km/h are supported with maximum performance, 15 - 120 km/h supported with high performance, and connection maintained for speeds up to 350 km/h or even up to 500 km/h.
- ✓ **Enhanced support for end-to-end Quality of Service.**
- ✓ **Reduced cost and system complexity** [16].

3 Multiple access techniques

3GPP LTE have selected different transmission schemes in uplink and downlink due to certain characteristics. OFDMA (Orthogonal Frequency Division Multiple Access) has been selected for downlink (from eNodeB to UE) and SC-FDMA has been selected for uplink (from UE to eNodeB).

3.1 Orthogonal Frequency Division Multiple Access (OFDMA)

The LTE downlink radio technology called OFDMA is simply a multiuser version of Orthogonal Frequency-Division Multiplexing (OFDM).OFDM is a multiplexing technique that works by dividing the available spectrum resources into a large number (usually hundreds) of smaller narrow-band subcarriers. The carrier is divided in a way that the sub-carriers are orthogonal to each other. Because of this OFDM can eliminate the need for non-overlapping sub-carriers in order to avoid interference. The eNodeB basically splits the high data rate downlink stream into a large number of low data rate narrow-band streams and puts each of them on a different sub-carrier. The UE receives the multiple narrowband streams over different sub-carriers and multiplexes them to form the original high data rate stream, OFDMA has the following advantages that make it well suited for use as the preferred technology for use in LTE downlink [17]:

- ✓ It is capable of providing high data rates
- ✓ It has high spectral efficiency
- ✓ It allows multiple users to use the radio link simultaneously.
- ✓ It uses lower maximum transmission power for low data rate users
- ✓ It can easily be deployed across various frequency bands with very small changes to the air interface.
- ✓ It provides very good frequency diversity since it spreads out the carriers throughout the available spectrum.

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

SC-FDMA (Single Carrier – Frequency Division Multiple Access) has been selected as 3GPP LTE uplink transmission technique (MS to eNodeB). It is a modified form of OFDMA and has similar throughput performance and essentially the same overall complexity as OFDMA. Like OFDM, SC-FDMA also consists on subcarriers but it transmits on subcarriers in sequence not in parallel which is the case in OFDM , which prevents power fluctuations in SC-FDMA signals low PAPR .

In a cellular system with severe multipath propagation environment, SC-FDMA signals might cause inter symbol interference when they reach at the base station. The base station uses the adaptive frequency domain equalization to cancel the inter symbol interference. As most mobile terminals are empowered with a battery, it is a good idea to perform some complex operations like frequency domain equalization at base station rather putting any burden like linear power amplification, on mobile terminal because more resources are available on base station[18].

3.3 Time Division Duplex (TDD) and Frequency Division Duplex (FDD)

In Time Division Duplex (TDD), a frame is divided into uplink sub-frame and a downlink sub-frame as shown in the Figure 1.1. Base station to subscriber station transmission happens in the downlink sub-frame and subscriber station to base station transmission happens in the uplink sub-frame. This division of a frame into downlink and uplink sub-frames in TDD can be static or dynamic-adapted to transmission load in either direction. In Frequency Division Duplex (FDD), the uplink and downlink transmissions occur on separate carrier frequencies and this division between uplink and downlink is static [19].

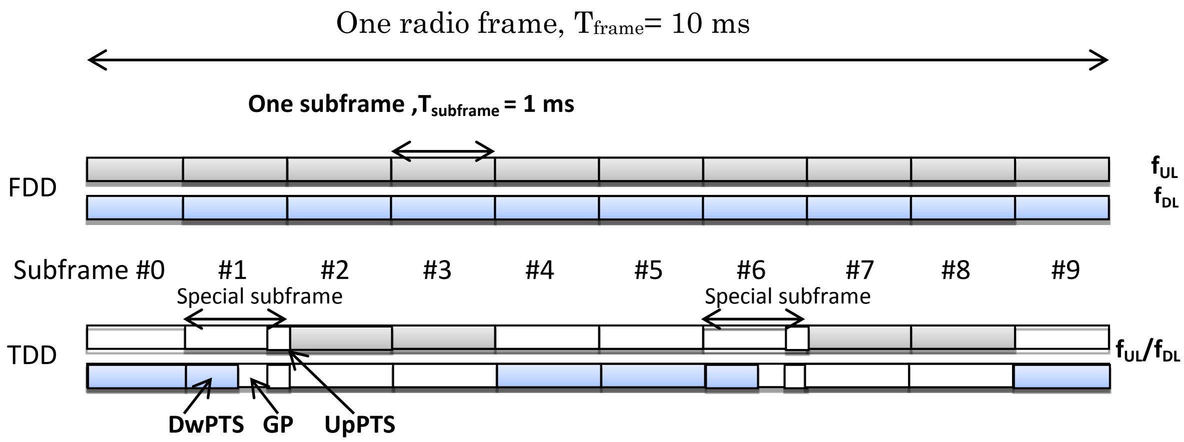

Figure 1.1 LTE generic frame structure.

4 LTE Network Architecture

The LTE system is designed for the packet switched services providing IP connectivity between the Packet Data Network (PDN) and the User Equipment (UE) without service interruption even during mobility. The LTE system can be divided into two main branches: Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and System Architecture Evolution (SAE).

The E-UTRAN evolved from the UMTS radio access network; it is sometimes also referred to as LTE. The SAE supports the evolution of the packet core network, also known as Evolved Packet Core (EPC). The combination of both the E-UTRAN and the SAE compose the Evolved Packet System (EPS).

EPS bearer is defined to be an IP packet flow between the PDN-GW and the UE with predefined Quality of Service (QoS) characteristics. Both the EPC and the E-UTRAN are responsible for setting and releasing such a bearer depending on the application QoS requirements. In LTE multiple bearers can be established for users with multiple services, e.g., a user can have a voice call using the Voice over Internet Protocol (VoIP) and at the same time be downloading a file using File Transfer Protocol (FTP), or browse the web using the Hypertext Transfer Protocol (HTTP). Each of these services can be mapped to a different bearer [20].

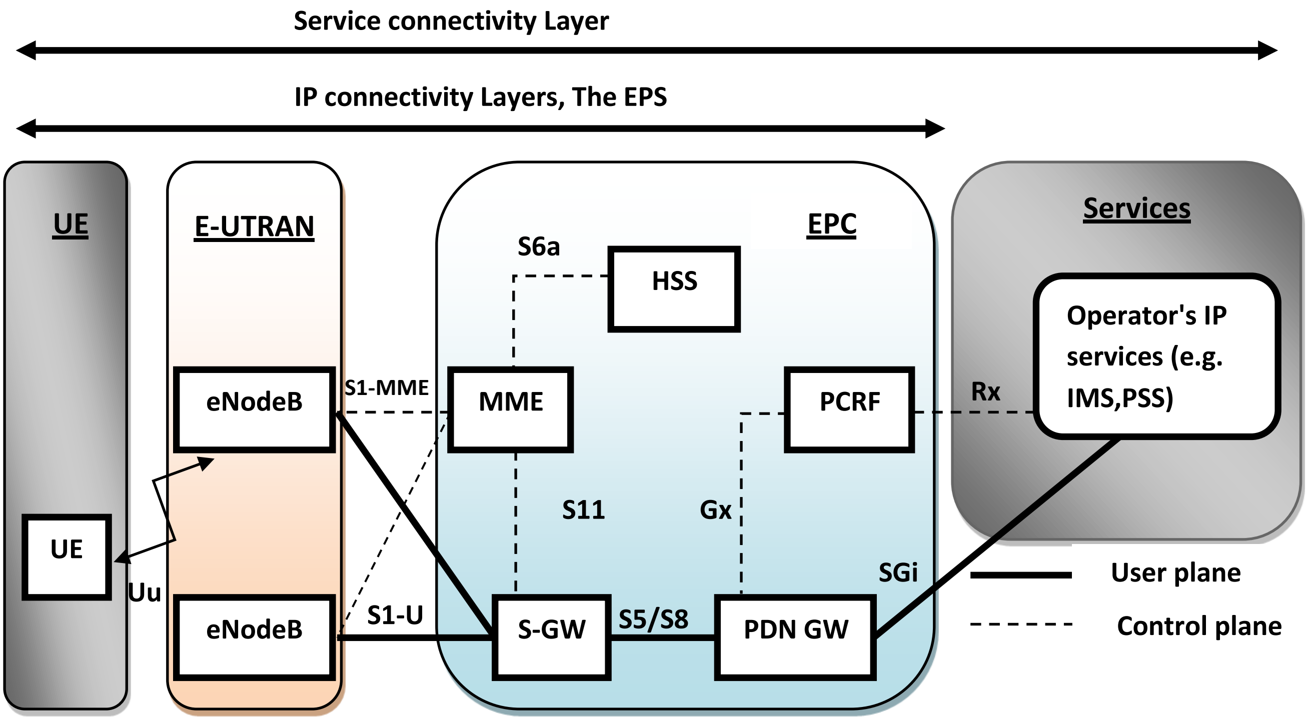

Figure 1.2 LTE EPS network architecture.

4.1 User Equipment (UE)

The term User Equipment (i.e. UE) is the joint name for all devices which enable a user to utilise the services of mobile communication networks (e.g. voice calls, text messaging, mobile internet browsing, etc.). These devices can be stand-alone equipment (such as mobile phones and internet tablets) or additional hardware equipment (e.g. LTE-internet sticks). Even though the function and application of these devices may be different; their architecture is comprised of the same elements: the Mobile Equipment (ME) and the Universal Integrated

Circuit Card (UICC). The ME consists of the Mobile Terminal (MT), which is responsible for all communications of an UE, and the Terminal Equipment (TE), which manages the directing and steering of data streams. The UICC is the key element for user identification and authentication in LTE systems, as it contains the Universal Subscriber Identity Module (USIM) in which a user's mobile number and other specific identification information is stored. Figure 1.3 shows architecture of the UE [21].

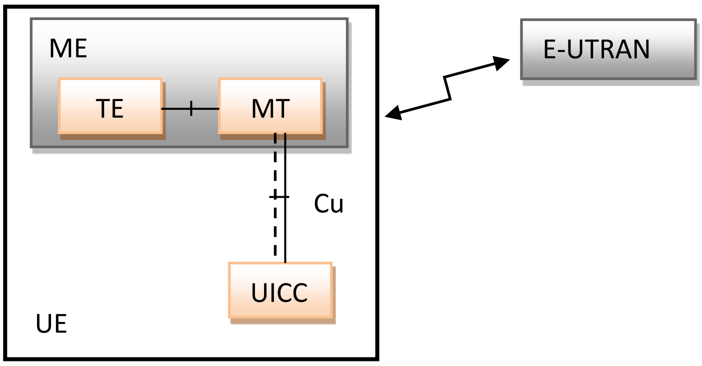

Figure 1.3 Architecture of the UE.

To enable an optimal network environment for data transmission and the utilisation of internet-based services, the RAN (i.e. the base station) requires every UE's capabilities and characteristics, such as the maximum allowed data rate or supported radio access technologies. Therefore, UEs with similar abilities are grouped together into so called LTE UE Categories and Classes (CC), which simplify the mentioned process. These classes, defined by the Third Generation Partnership Project (3GPP), are shown in Table 1.1.

UE class	Peak data rate [Mbps]		Soft buffer size [Gbits]	Multiple antenna streams	Highest downlink modulation	Highest Uplink modulation
	Downlink	Uplink				
1	10	5	0,25	1		
2	50	25	1,24	2		16QAM
3	100	50	1,24	2	64QAM	
4	150	50	1,83	2		
5	300	75	3,67	4		64QAM

Table 1.1 UE classes set by 3GPP.

4.2 Evolved UTRAN (E-UTRAN)

The E-UTRAN in LTE consists of directly interconnected eNodeBs which are connected to each other through the X2 interface and to the core network through the S1 interface. This eliminates one of the biggest drawbacks of the former 3GPP systems (UMTS/HSPA): the need to connect and control the NodeBs through the Radio Network Controller (RNC), which make the system vulnerable against RNC failures. The LTE E-UTRAN architecture can be seen in Figure 1.4.

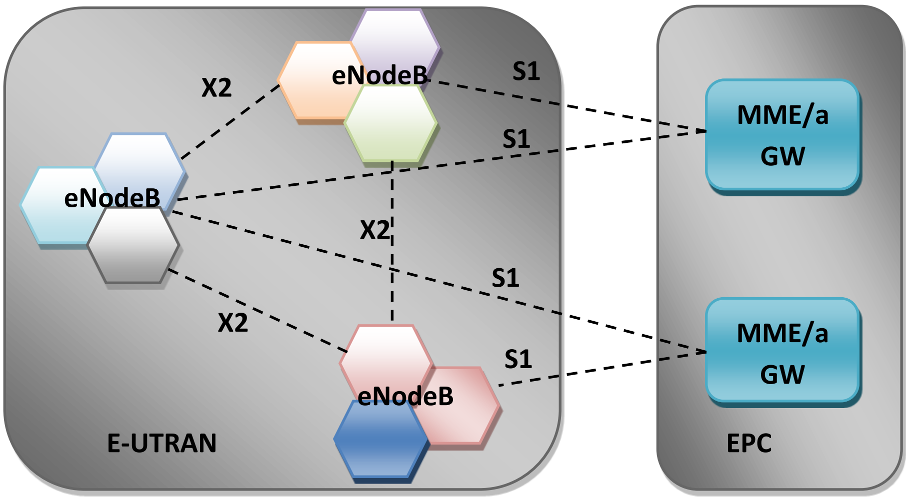

Figure 1.4 LTE E-UTRAN architecture.

The enhanced NodeB (eNodeB) entity works as a bridge between the UE and the EPC. It provides the necessary radio protocols to the user equipment, so as to be able to send and receive data and it tunnels the users data securely over the LTE transport to the PDN-GW and vice versa. The GTP tunneling protocol is used, which works on top of the UDP/IP protocols. The eNodeB is also responsible for the scheduling which is one of the most important radio functions. The eNodeB schedules the frequency spectrum resources among the different users by exploiting both the time and frequency, while guaranteeing different quality of service for the end users. In addition, the eNodeB also has some mobility management functionalities, e.g., radio link measurements and handover signaling for other eNodeB [18].

4.2.1 Evolved-Node B (e-Node-B or eNB)

It merges the functionality of the RNC and Node B in a 3G mobile network to achieve higher latency with fewer hops in data path as well as distribution of RNC processing load into multiple eNBs. It is responsible for header compression, ciphering and reliable delivery of packets. The control plane functions such as admission control and radio resource management are also incorporated into the eNB. The EPC is made up of the MME and the gateways (S-GW and P-GW) [20].

4.2.2 E-UTRAN Interfaces

One of the objectives of E-UTRAN is to simplify and reduce the number of interfaces between different network elements. Interfaces between different network elements are S1 (eNodeB-aGW) and X2 (inter ENodeB) as shown in figure 1.4 (in the section 1.4.2).

S1 is the interface between eNB and MME. This interface can be subdivided into two parts [11]:

- ✓ Control plane: S1-C is the interface between eNB and MME function in EPC
- ✓ User plane: S1-U is the interface between eNB and UPE function in EPC

From the S1 perspective, the E-UTRAN access point is an eNB and the EPC access point is either the control plane MME node or the user plane SAE gateway logical node. S1 access point shall independently fulfill the requirements of the relevant S1 specifications. S1 interface supports many functions which include initial context setup, UE context management and mobility functions. Initial context setup function supports the establishment of overall initial UE context plus SAE bearer context, security context, roaming restriction, UE capability information, etc. in the eNB to enable idle-to-Active transition. S1 interface also establishes and releases the UE contexts in eNB and in EPC to support user signaling. Moreover, S1 also provide mobility functions for handover. This can be intra-LTE handover or inter-3GPP handover (with a system other than LTE) [23].

X2 interface allows the interconnection between eNBs. X2 has the status of an open interface. It supports the signal information exchange between two eNBs, along with the forwarding of PDUs to their destination. In terms of logical point of view, X2 is a point-to-point interface within E UTRAN. Therefore, it is possible to create an X2 interface between two eNBs even if there is no physical and direct connection between them [24].

X2 facilitates the interconnection between eNBs of different vendors and offers a continuation of the services offered via S1 interface for a seamless network. In addition, it makes possible the introduction of new future technologies by clearly separating radio network and transport network functionalities. With significant improvements in the radio interface and other components, enabling a lower data access cost per megabyte, as well as several potentially important new services, 3G Long Term Evolution (LTE) will bring substantial technological improvements. These efforts are expected to deliver economic benefits to operators, and therefore provide a decisive advantage over alternative wireless technologies, keeping the mobile cellular systems competitive during the next decade.

4.3 The Evolved Packet Core (EPC)

In addition to the new and improved technology the LTE networks were also designed to be connected to a completely new packet core network called the Evolved Packet Core (EPC).The main goals for defining the Evolved Packet Core network were as follows:

- ✓ Improve performance over previously defined 3GPP packet core network
- ✓ Minimize the number of user plane nodes
- ✓ Allow the integration of other access technologies (fixed, CDMA etc.) in order to create a truly converged network
- ✓ Provide network based mobility support
- ✓ Allow optimized handovers from previous generation 3GPP radio technologies as well as selected non-3GPP radio technologies [25].

The evolved packet core network consists of 4 main different types of nodes. Two data-plane nodes called the Serving Gateway (S-GW) and PDN Gateway (P-GW) and two control plane nodes called the Mobility Management Entity (MME) and the Policy and Charging Rules Function (PCRF).

4.3.1 Mobility Management Entity

The Mobility Management Entity (MME) is a nodal element within the LTE EPC. It performs the signaling and control functions to manage the User Equipment (UE) access to network connections, the assignment of network resources, and the management of the mobility states to support tracking, paging, roaming and handovers. MME controls all control plane functions related to subscriber and session management.

MME manages thousands of eNodeB elements, which is one of the key differences from requirements previously seen in 2G/3G (on RNC/SGSN platforms). The MME is the key element for gateway selection within the EPC (Serving and PDN). It also performs signaling and selection of legacy gateways for handovers for other 2G/3G networks. The MME also performs the bearer management control functions to establish the bearer paths that the UE/ATs use. The MME supports the following functions:

- ✓ Security procedures: End-user authentication as well as initiation and negotiation of ciphering and integrity protection algorithms.
- ✓ Terminal-to-network session handling: All the signaling procedures used to set up packet data context and negotiate associated parameters like QoS.
- ✓ Idle terminal location management: The tracking area update process used to enable the network to join terminals for incoming sessions [26].

4.3.2 Serving Gateway

Another element of the EPC, which serves as a router for tunnelling and management of user data is known as the Serving Gateway (S-GW). It forwards all connected-state UE originated and terminated data between the eNodeB and

P-GW. Moreover, if the UE is currently in the idle state, the S-GW buffers all incoming data in its internal memory and initiates a UE state-change request to the respective MME, continuing the transmission when the UE reconnects to the connected state. Each active UE is connected to one S-GW, which can be changed in the event of handovers.

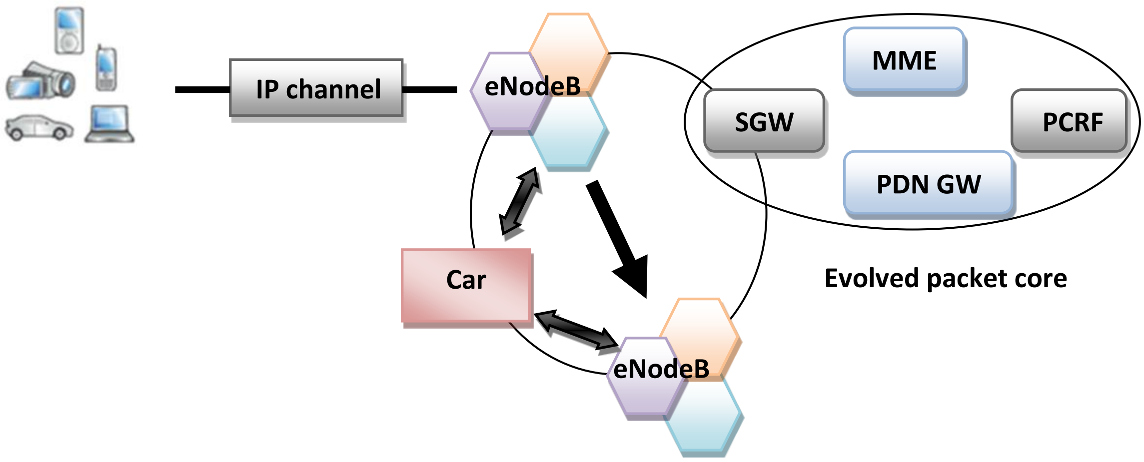

Figure 1.5 Serving Gateways.

The S-GW is also responsible for the setup of the Bearer Binding and Event Reporting Function (BBERF) and hence partially for policy and charging settings, as well as for bearer management, which is based on the information computed by the PCRF. Furthermore, since all traffic is routed through this interface, it also represents the optimal point for lawful interception [26].

4.3.3 Packet Data Network Gateway

The interface which enables the EPC and its elements to interact with and connect to the services of the Service Domain (i.e. to Packet Data Networks) is called the Packet Data Network Gateway (in further text P-GW). It is the main router that performs traffic directing and filtering functions required by some external services, and through which a UE obtains an IP address at start-up, enabling its always-on connectivity and allowing it to browse the web or use IMS operation. Furthermore, to enable the UE to establish simultaneous connections to multiple PDNs, it can also connect to more than one P-GW. At the same time, each P-GW can only be connected to one S-GW, if it is used for data exchange between an UE and a PDN. The P-GW is also partially responsible for policy and charging settings, as it contains the Policy and Charging Enforcement Function (PCEF) and applies the changes determined by the PCRF [28].

4.3.4 Policy and Charging Resource Function

The process responsible for the Policy and Charging Control of the elements in the EPC is called Policy and Charging Resource Function (PCRF). This function addresses all services in terms of QoS, setting up the most suitable signal bearers and appropriate policing, and hands the information to BBERF (S-GW) and PCEF (of the P-GW). This information is formed into so called PCC Rules which are sent on request of the S-GW, P-GW and Service Domain (i.e. as part of a service, subsystem or application, collectively called Application Function), each time a new bearer is set up. Even though each PCRF can be connected to one or more S-GWs, P-GWs and Afs, only one PCRF is associated for each PDN connection of the UE [23].

4.3.5 Home Subscription Server (HSS)

The Home Subscription Server (HSS) is in its essence a database or data repository which stores the master copy of all permanent data received from a subscriber (i.e. user). Its main element is the so called Authentication Centre (AuC), where a UE's permanent root key K is stored. Based on the received data, the HSS creates a user profile for each subscriber, which contains information about the UE's capabilities, allowed PDN connections, roaming restrictions and the UE's current location. Therefore, the HSS is allowed to connect to any UE (through the MME) in its range, but can only be connected to one MME per UE. In handover scenarios (i.e. if the serving MME of an UE is changed) all connections to this MME are terminated and the HSS automatically connects to the new serving MME [28].

4.4 Roaming architecture

A network run by one operator in one country is known as a public land mobile network (PLMN) Roaming, where users are allowed to connect to PLMNs other than those to which they are directly subscribed is a powerful feature for mobile networks, and LTE/SAE is no exception. A roaming user is connected to the E-UTRAN, MME and S-GW of the visited LTE network. However, LTE/SAE allows the P-GW of either the visited or the home network to be used, as shown in Figure 1.6. Using the home network's P-GW allows the user to access the home operator's services even while in a visited network. A P-GW in the visited network allows a local breakout to the Internet in the visited network [26].

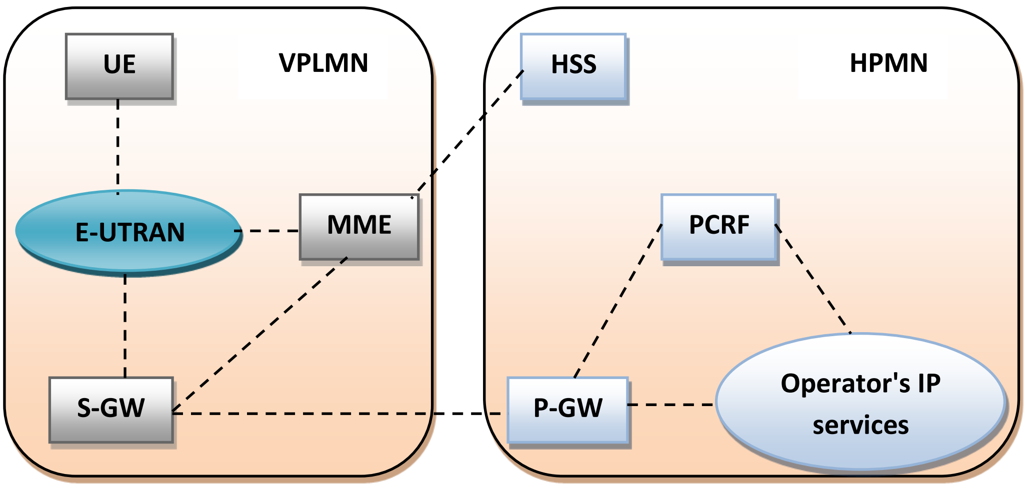

Figure 1.6 Roaming architecture for 3GPP accesses with P-GW in home network.

4.5 Interworking with other networks

EPS also supports interworking and mobility (handover) with networks using other Radio Access Technologies (RATs), notably Global System for Mobile Communications (GSM), UMTS, CDMA2000 and WiMAX. The architecture for interworking with 2G and 3G GPRS/UMTS networks is shown in Figure 1.7. The S-GW acts as the mobility anchor for interworking with other 3GPP technologies such as GSM and UMTS, while the P-GW serves as an anchor allowing seamless mobility to non-3GPP networks such as CDMA2000 or WiMAX. The P-GW may also support a Proxy Mobile Internet Protocol (PMIP) based interface [26].

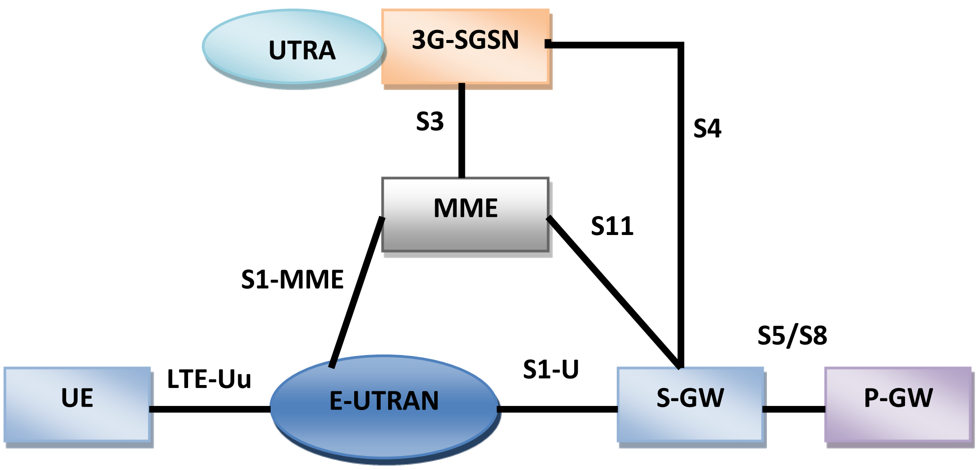

Figure 1.7 Architecture for Interworking with other networks.

5 E-UTRAN Protocol Architecture

The E-UTRAN protocols consist of both user plane and control plane. The user plane consists of a set of protocols used to transfer the actual user data through the LTE network, whereas the control plane consists of protocols which are used to control and establish the user connections and bearers within the E-UTRAN. Figure 1.8 shows the user plane protocol stack.

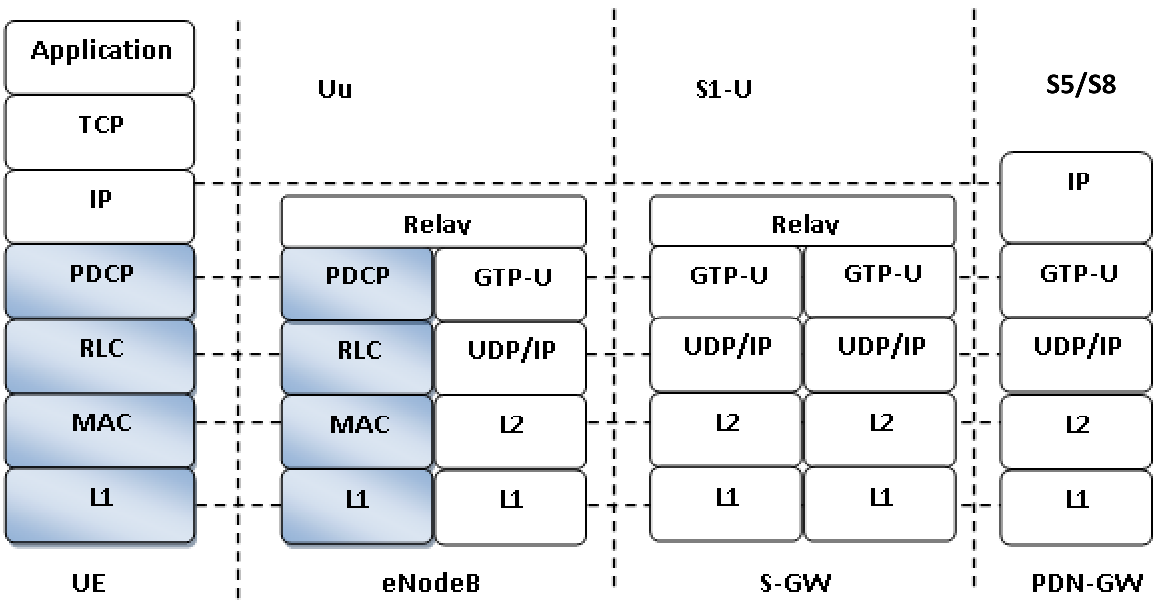

Figure 1.8 LTE E-UTRAN user plane protocol stacks.

The LTE radio access architecture is mainly the eNodeB which is an enhanced version of the original NodeB of the UMTS system. Since the RNC was removed from the LTE architecture some of its functions have been moved to the eNodeB [29].

- ✓ Radio Resource Control (RRC): is responsible for the handover functions, like handover decisions, transfer of UE context from serving eNodeB to target eNodeB during handover. In addition, it controls the periodicity of the Channel Quality Indicator (CQI) and is also responsible for the setup and maintenance of the radio bearers [30].

- ✓ Packet Data Convergence Protocol (PDCP): is responsible for compressing the IP header, i.e., reduces the overall overhead which in turn improves the efficiency over the radio interface. This layer also performs additional functionalities, e.g., ciphering and integrity protection.

- ✓ Radio Link Control (RLC): is responsible for the segmentation and concatenation of the PDCP packets. It also performs retransmissions and guarantees in-sequence delivery of the packets to the higher layers. The RLC also performs error corrections using the well-known Automatic Repeat Request (ARQ) methods.

- ✓ Medium Access Channel (MAC): is responsible for scheduling air interface resources in both uplink and downlink. It is also responsible for satisfying the users' QoS over the air interface. In addition, the MAC layer also performs the Hybrid Automatic Repeat Request (HARQ).

- ✓ Physical Layer (PHY): is responsible for the radio related issues: e.g., modulation/ demodulation, coding/decoding, Multi Input Multi Output (MIMO) techniques.

5.1 Radio Link Control (RLC)

The radio link control protocol is responsible for the concatenation and segmentation process. It segments the packets that come from the PDCP layer (i.e., the IP packets after compressing the header) into smaller RLC packets, and concatenates the RLC packets on the receiver side into the PDCP packets. In addition to the above functionality, the RLC protocol provides reliable communication between the eNodeB and the UE by the aid of packet retransmissions. The RLC uses sequence numbers to detect lost packets at the receiver side and inform the sender which packets to retransmit by using some selective repeat retransmissions. This is also known as Automatic Repeat Request (ARQ). The RLC protocol can operate in three different operational modes, these are [31]:

• Acknowledged Mode (AM): This is used to provide error-free transmission between sender and receiver. This mode is suitable for services that use the TCP transport protocol, like FTP and HTTP, where reliability and error free delivery is of the utmost importance.

• Unacknowledged Mode (UM): in this mode no retransmissions are performed and RLC only provides segmentation and concatenation functionalities. This mode is suitable for applications that does not require error-free transmission and can tolerate some losses, like VoIP and video conferencing.

• Transparent Mode (TM): this operation mode of RLC does not add any protocol overhead to the higher layer data. It can be used for example for random access.

The RLC segmentation and concatenation is done based on the MAC scheduler decision, where the scheduler informs the RLC layer on what Transport Block Size (TBS) to be used by a certain user/bearer. This tells the RLC the amount of bits to be sent down to the lower layer. In contrast to the RLC version used in UMTS/HSPA, in LTE the RLC Packet Data Unit (PDU) size is not fixed and is dynamically changed based on the scheduler decision. In addition to the retransmission and segmentation/concatenation functionalities of RLC there are a number of other functionalities supported by RLC [32]:

- ✓ Padding
- ✓ In-Sequence delivery of higher layer PDUs
- ✓ Duplicate detection
- ✓ Flow control
- ✓ SN check (unacknowledged data transfer mode)
- ✓ Protocol error detection and recovery
- ✓ Ciphering
- ✓ Suspend/resume function for data transfer

5.2 Medium Access Control (MAC)

It is among the most significant layers of the model. It ensures the mapping of data between the logical channels and the channels of transport by using a function of multiplexing of RLC.

On the level of this layer, measurements of the state of the traffic and correction of the errors are ensured by the method of retransmission HARQ (Hybrid Automatic Repeat reQuest).Moreover, the MAC layer offers the service of scheduling. In what follows, we will summarize the various functions of the MAC layer [33].

5.2.1 Scheduling

The eNodeB has a Schedule to control the resources like time and frequency for a given time. Dependently of the state of the channels, the Scheduler chooses the best multiplexing for the UE while always take into account:

- ✓ Parameters of quality of service (QoS).
- ✓ Useful data in the buffer memory.
- ✓ Capacity of the UE.
- ✓ Cycles of deactivation of the UE.
- ✓ Information of the system such as the band-width and the level of interference.

5.2.2 HARQ (Hybrid Automatic Repeat reQuest)

The hybrid ARQ is used by the MAC layer to provide reliable communication and to recover transmission errors. The HARQ mechanisms used in LTE are similar to the ones used before in HSPA. A multiple stop-and-wait process protocol is used for the HARQ , where the sender sends the packets and the receiver gets those packets and tries to decode them and check if they are corrupted or not. Then the receiver can report back to the sender; if the decoding was successful or not by sending either an Acknowledgment (ACK) or a negative Acknowledgment (NAK).

In LTE, two different protocols are used for the HARQ depending whether it's an uplink or downlink transmission. For the downlink an asynchronous protocol is used, where the retransmissions can happen at any time and that is why the process number has to be used so as to explicitly identify which process is being handled. As for the uplink, a synchronous protocol is used to handle the retransmissions without the need to have the explicit process number. The retransmission is done based on a fixed time interval that both the sender and the receiver know [29].

5.2 .3 The research of the cells

The user equipment (UE) research the cell, in order to have information necessary for its connection and its synchronization, namely: the identifier of the cell, the time and the frequency. During the search for the cell, two channels are detected either.

- ✓ Synchronization CHannel (SCH), it is to have information on the clock or the frequency of the downlink;
- ✓ Broadcast CHannel (BCH), the channel of diffusion indicates certain information on the cell like identifier of the cell, configuration of the antenna, etc [34].

6 LTE Quality of Service Bearers

Quality of service is a well-known concept within the 3GPP systems, it can be found in legacy 3GPP standards like UMTS/HSPA. Within these previous 3GPP releases many QoS attributes and parameters existed but in a partially disconnected manner from the application layer. This had led to some difficulties in setting and configuring these parameters in the correct manner to achieve the desired QoS targets.

Within today's mobile communication usage, people use multiple services at the same time each of which has different QoS requirements. Users can make a phone call using a VoIP service, and browse the Internet or download/upload a file at the same time. Looking at these services some have much higher strict requirements than others, VoIP for example needs a very low delay and jitter, whereas web browsing and FTP downloads/uploads can tolerate much higher delays than VoIP. In order to distinguish between these services and guarantee their QoS requirements different bearers are set up by the EPS each with a different QoS association.

From the literature, two main general categories are defined in classifying the bearers, depending on the type of QoS they need to satisfy and these are:

- ✓ Guaranteed Bit Rate bearers (GBR): these bearers, as the name suggests, guarantee a minimum bit rate for their services. These bearers carry an associated value that allows other units to reserve or allocate resources for them. Such bearers can be used for applications, like VoIP or video conferencing.
- ✓ Non-Guaranteed Bit Rate bearers (non-GBR): these bearers do not guarantee any bit rate and are a kind of best effort service. No resources are reserved for these bearers and they are served only if there are resources and bandwidth left for them. Such bearers can be used for applications like HTTP (web browsing) or file transfers like FTP downloads or uploads.

The eNodeB is the entity responsible for guaranteeing the QoS requirements of the bearers over the radio part. Each bearer is associated with two QoS parameters, and these are:

- ✓ QoS Class Identifier (QCI): this is an index that identifies predefined values for priority, delay budget and packet loss rate. Each bearer carries this value and the eNodeB reads this value and determines how to handle this bearer.
- ✓ Allocation and Retention Priority (ARP): this parameter defines the importance of bearer request establishment. It is used to determine whether to accept or reject a bearer establishment in case of radio congestion. This parameter is only used during bearer setup and doesn't influence other decisions once the bearer has been established, it does not affect scheduling or rate control [21].

7 The Handover in LTE

In LTE the management of mobility is distributed, the eNodeBs make the decision of Handover in an autonomous way without implication of the elements: MME and S-GW. Information necessary to Handover are exchanged between the eNodeBs to an interface called X2. MME and S-GW will receive a notification with a complete message of Handover after which new connection will have been allotted between the UE and the new eNodeB. After receive of the message, Gateways carry out the way of commutation. During Handover there is a lay die during which the UE is not connected to the system. To solve that a temporary solution of Forwarding of the data loss of old the eNB towards new the eNB is proposed, In this case there is no memorizing of the data on the level of Gateways. The interest of this solution is to minimize the load of indication on the level of the interface between the eNB and MME/S-GW.

The principal stages of Handover are:

- ✓ Handover is started by the UE which sends a report of measurement to the eNB source which will decide while being based on the received report and information relating to management radio resources.

- ✓ The phase of preparation of Handover starts with the sending of a request of Handover (HO Request) on behalf of the eNB source towards the eNB target. This message contains all the relevant information on Handover (UE - RAN, PDP Context, etc).
- ✓ The eNB target records the context, prepares layers 1 and 2 (L1/L2) for Handover and answers the eNB source by a payment (HO Ack Request) which will provide them information on the establishment again radio operator bond.
- ✓ The eNB source will transfer all information necessary to the UE, and this moment, the eNB source stops sending and receiving data with the UE. It will then make follow data with the eNB target.
- ✓ The UE informs the eNB target of the success of Handover with a message of confirmation until this moment the eNB target memorizes the data received of the eNB source. After having receives the message of confirmation it starts to send the data to the UE.
- ✓ The eNB target initiates the change of way of data by sending a "Handover Complete "with the footbridges. Information of localization of the UE will be then put up to date on the level of the footbridges which will carry out the change of way so that the data are sent directly towards the eNB target. MME/S-GW confirm the way by a message "Handover Complete Ack", and as of that the eNB target receives this message, it sends an indication to the eNB source so that it definitively releases connection with the UE [34].

8 The Advantages of LTE

LTE based networks have upload and download speeds unheard of in the past. LTE opens the gate for many new, exciting, and more robust public safety applications. For example:

- ✓ Real-time video will become more robust and widely available in the field on mobile terminals, tablet devices, and smartphones, resulting in increased situational awareness for first responders.

- ✓ Police officers will be able to view and exchange digital photographs and fingerprint technology, greatly improving on-the-spot suspect identification and resulting in savings of time and resources.
- ✓ Fire personnel will have digital access to building drawings and mapping programs in real time to improve fire ground situational awareness.
- ✓ Incident commanders and emergency managers will communicate through enhanced incident management software that will bridge the gap from the incident to the emergency operations center, greatly improving decision-making.
- ✓ Applications such as automated license plate recognition (LPR) systems and GPS-enabled navigation systems will provide real time notifications and alerts, including emerging hazards and geographically specific be-on the-look-out (BOLO) transmissions, all contributing to improvements in officer and civilian safety.

With LTE and the nationwide network, first responders will gain access to innovative tools to assist them with their critical missions. They will be in a better position to take advantage of fast changing digital technology. LTE will revolutionize the way public safety responds to emergencies [28].

9 Conclusions

In this chapter, we gave an overview about LTE and its important features such as high speed data, peak data rate, spectrum efficiency, reduced latency. LTE uses SC-FDMA in Uplink and OFDMA in downlink, in the next chapter , we will study why 3GPP proposes SC-FDMA in Uplink transmission.

Chapter 2

DFT-spreading SC FDMA

1 Introduction

This chapter will explain the Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiplexing Access (OFDMA). OFDMA has a problem which significantly degrades the power efficiency, this problem calls the Peak to Average Power Ration (PAPR) causes nonlinear distortions. The DFT-spreading technique is to spread the input signal with DFT, which can be subsequently taken into IFFT. This can reduce the PAPR of OFDM signal to the level of single-carrier transmission. This technique is particularly useful for mobile terminals in uplink transmission. It is known as the Single Carrier-FDMA (SC-FDMA), which is adopted for uplink transmission in the 3GPP LTE standard is investigated in this chapter.

2 OFDM technology system

Orthogonal frequency division multiplexing (OFDM) is based on multicarrier communication techniques. The idea of multicarrier communications is to divide the total signal bandwidth into number of subcarriers and information is transmitted on each of the subcarriers. Unlike the conventional multicarrier communication scheme in which spectrum of each subcarrier is non-overlapping and band pass filtering is used to extract the frequency of interest, in OFDM the frequency spacing between subcarriers is selected such that the subcarriers are mathematically orthogonal to each other's. The spectra of subcarriers overlap each other but individual subcarrier can be extracted by baseband processing. This overlapping property makes OFDM more spectral efficient than the conventional multicarrier communication scheme.

2.1 OFDM using Inverse DFT

The use of Discrete Fourier Transform (DFT) in the parallel transmission of data using Frequency Division Multiplexing was investigated in 1971 by Weinstein and Ebert [31].Consider a data sequence $d_0, d_2 \ldots d_{N-1}$, where each d_n is a complex symbol. (The data 8 sequence could be the output of a complex digital modulator, such as QAM, PSK, etc). Suppose we perform an IDFT on the sequence $2d_n$ (the factor 2 is used purely for scaling purposes), we get a result of N complex numbers S_m $(m = 0,1 \ldots, N-1)$ as:

$$S_m = 2\sum_{n=0}^{N-1} d_n \exp\left(j2\pi \frac{nm}{N}\right) = 2\sum_{n=0}^{N-1} d_n \exp(j2\pi f_n t_m)$$

$$[m = 0,1,..N-1] \qquad (2.1)$$

Where,

$$f_n = \frac{n}{NT_s} \text{ and } t = mfs \qquad (2.2)$$

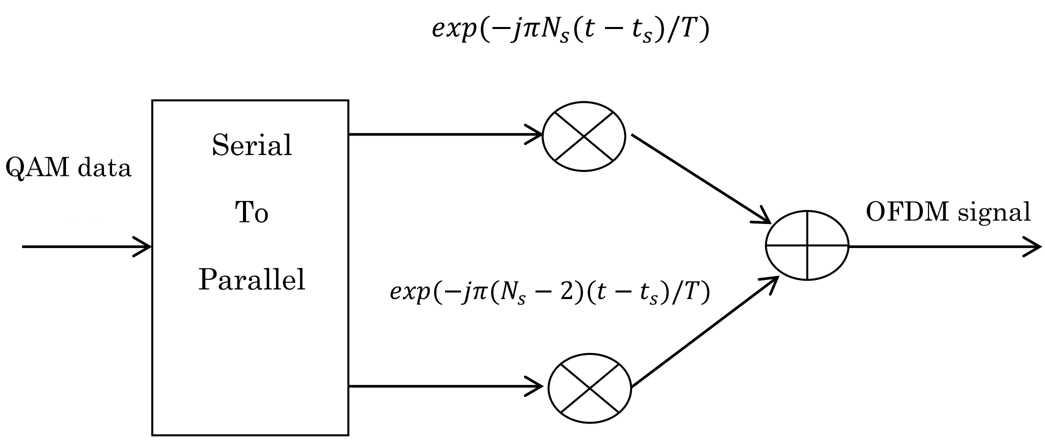

Figure 2.1 A OFDM Modulator.

T_s represents the symbol interval of the original symbols. Passing the real part of the symbol sequence represented by equation (2.1) thorough a low-pass filter with each symbol separated by duration of T_s seconds yields the signal.

$$y(t) = 2R_e\left\{\sum_{n=0}^{N-1} d_n \exp\left(j2\pi\frac{n}{T}t\right)\right\} \quad for \quad 0 \le t \le T \tag{2.3}$$

Where, T is defined as NTs. The signal y(t) represents the baseband version of the OFDM signal.

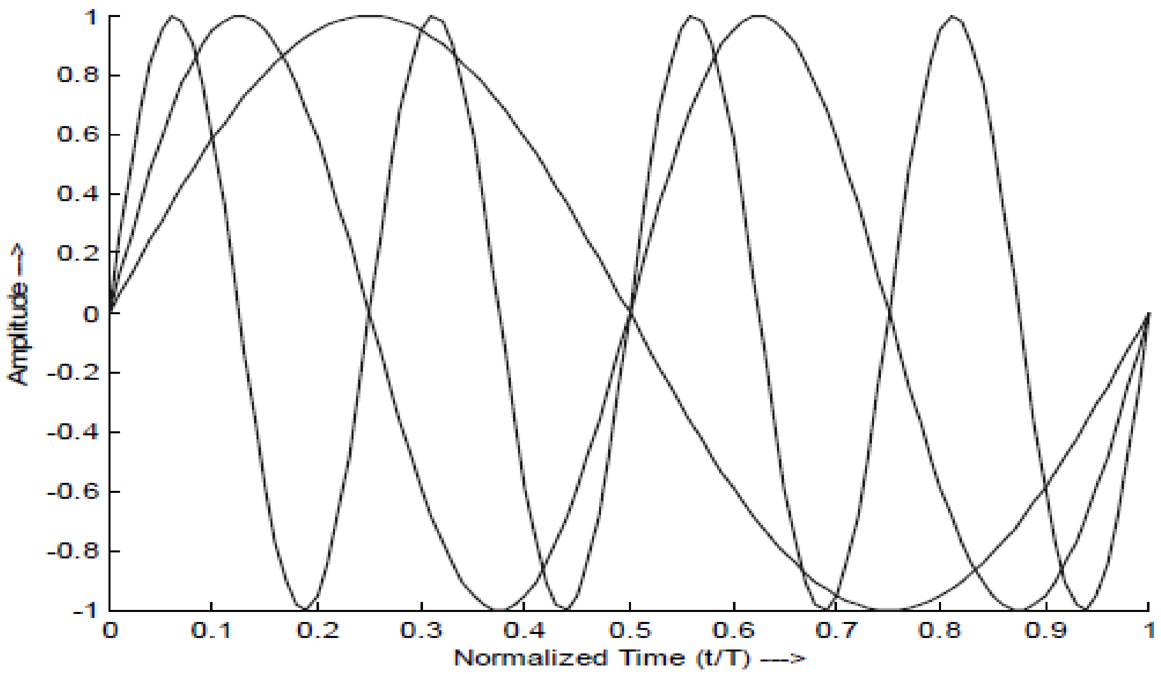

Figure 2.2 Three Subcarriers within an OFDM symbol.

It is easy to note from figure 2.3 that:

- ✓ The length of the OFDM signal is T.
- ✓ The spacing between the carriers is equal to 1/T.
- ✓ The OFDM symbol-rate is N times the original baud rate.
- ✓ There are N orthogonal sub-carriers in the system.
- ✓ The signal defined in equation (2.3) is the basic OFDM symbol.

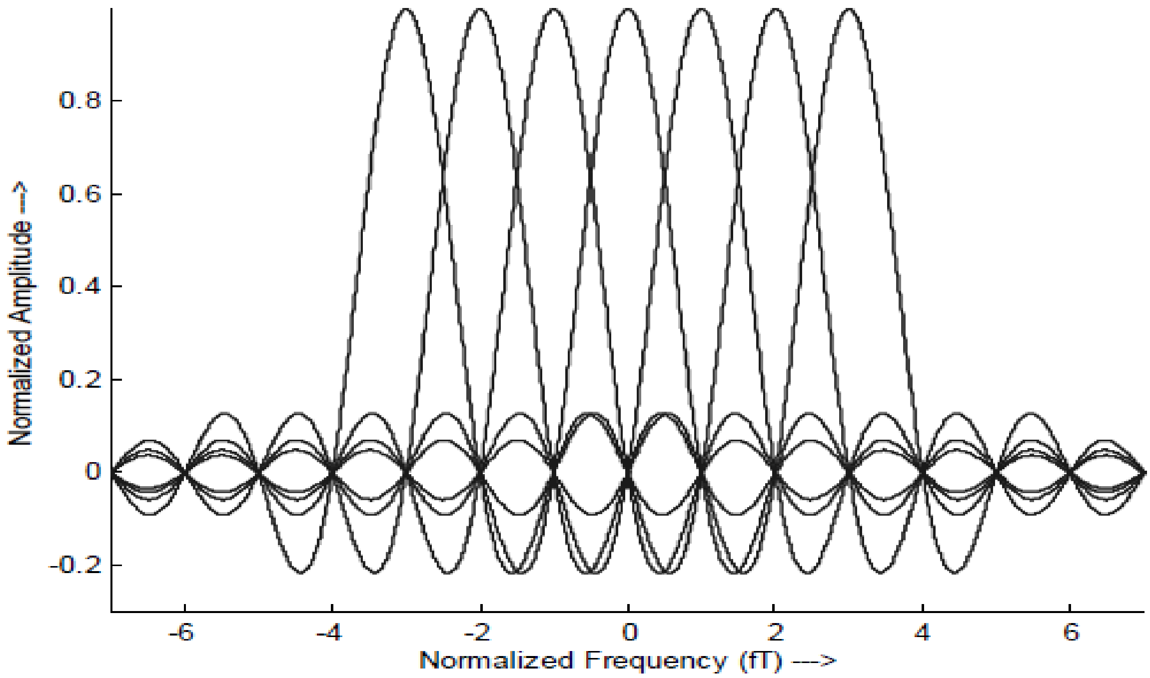

Figure 2.3 Spectra of Individual Sub-Carriers.

2.2 Guard time and cyclic extension

One of the most important problems in for wireless communications is the multipath delay spread. OFDM deals with it very efficiently. The parallel transmission implies that the input data stream is divided in N_S subcarriers and the symbol duration is made N_S times smaller, which also reduces the relative multipath delay spread, relative to the symbol time, by the same factor.

The inter symbolic interference is almost completely eliminated by introducing a guard time for a each OFDM symbol. The guard time is chosen larger than the expected delay spread such that multipath components from one symbol cannot interfere with the next symbol. This guard time could be no signal at all but the problem of inter carrier interference (ICI) would arise. Then, the OFDM symbol is cyclically extended in the guard time. Using this method, the delay replicas of the OFDM symbol always have an integer number of cycles within the FFT interval, as long as the delay is smaller than the guard time. Multipath signals with delays smaller than the guard time cannot cause ICI.

If multipath delay exceeds the guard time by a small fraction of the FFT interval (for example 3%), the subcarriers are not orthogonal anymore, but the interference is still small enough to get a reasonable constellation. Considering that the multipath delay exceeds the guard time by 10% of the FFT interval, the constellation is seriously affected and an unacceptable error rate is obtained [36].

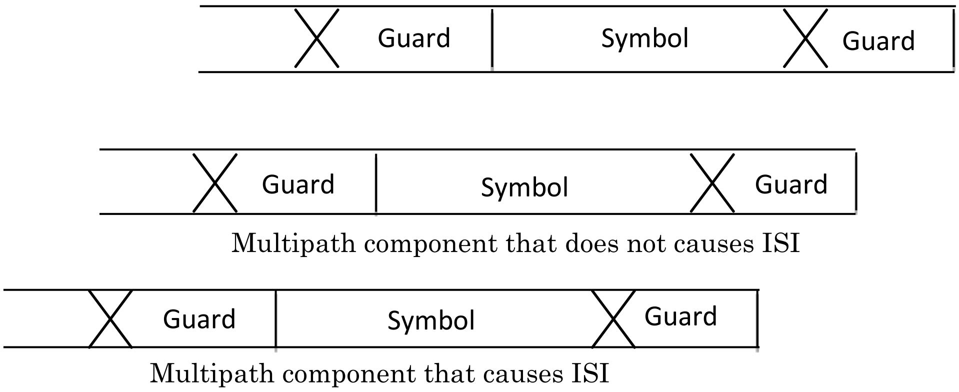

Figure 2.4 Guard Time and Cyclic Extension - Effect of Multipath.

2.3 OFDM Generation

Based on the previous discussions, the method for generating an OFDM symbol is as follows.

- ✓ First, the N input complex symbols are padded with zeros to get N_s symbols that are used to calculate the IFFT. The output of the IFFT is the basic OFDM symbol.
- ✓ Based on the delay spread of the multi-path channel, a specific guard-time must be chosen (say T_g). A number of samples corresponding to this guard time must be taken from the beginning of the OFDM symbol and appended at the end of the symbol.
- ✓ Likewise, the same number of samples must be taken from the end of the OFDM symbol and must be inserted at the beginning.
- ✓ The OFDM symbol must be multiplied with the raised cosine window to remove the power of the out-of-band sub-carriers.

- ✓ The windowed OFDM symbol is then added to the output of the previous OFDM symbol with a delay of T_r, so that there is an overlap region of βT_r between each symbol [37].

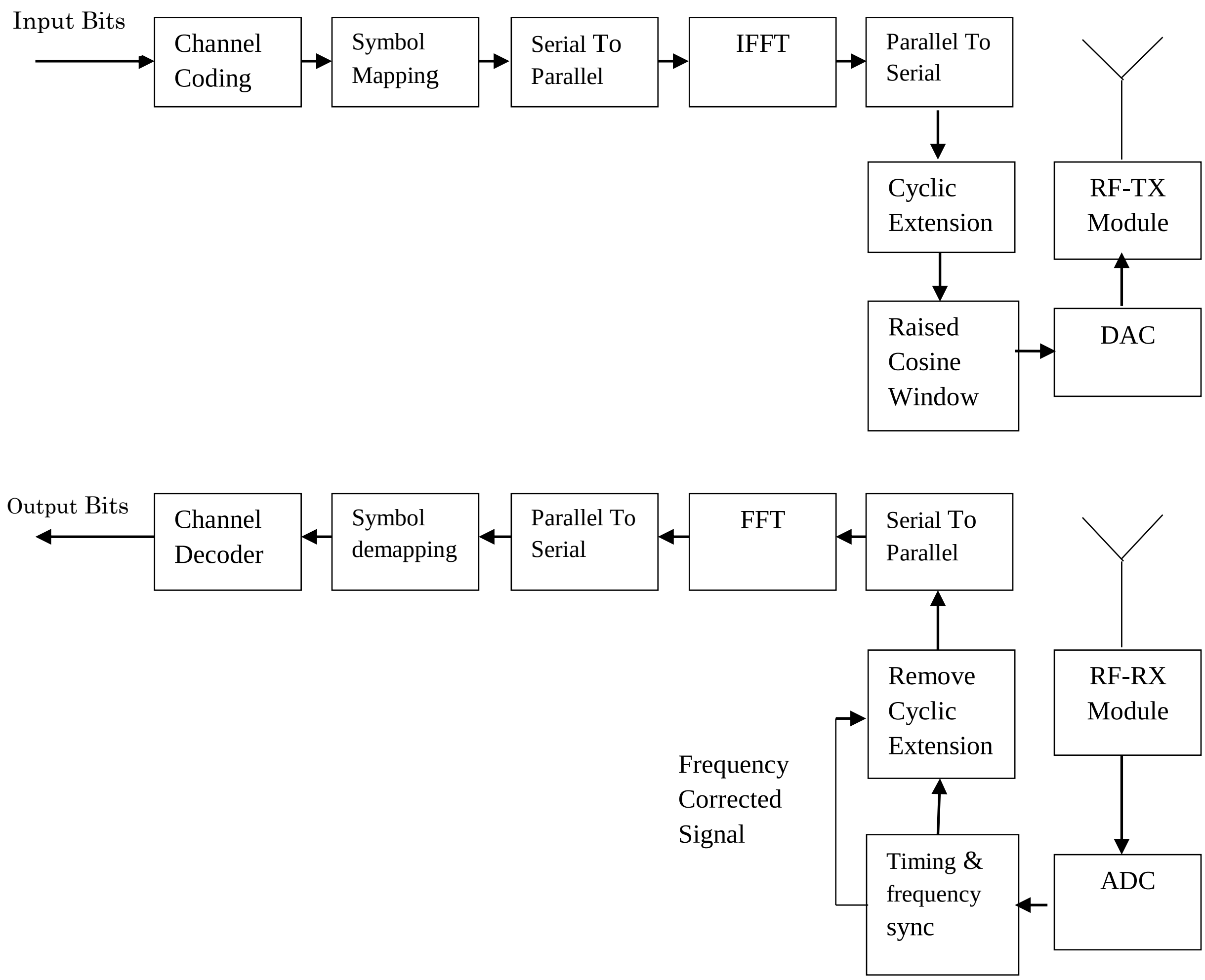

Figure 2.5 block diagram of an OFDM transmitter and receiver.

2.4 Cyclic Prefix

When a signal passes through a time dispersive channel the timing of the modulated symbols will be distorted and they will start to overlap and interfere with the subsequent symbols. This phenomenon is usually referred to as Inter Symbol Interference (ISI). ISI can reduce the effectiveness of the decision making mechanism at the receiver which will lead to an increase in the Bit Error Rate (BER) and a parallel decrease in the throughput of the system. The effect of ISI in time domain can be seen in Figure 2.6.

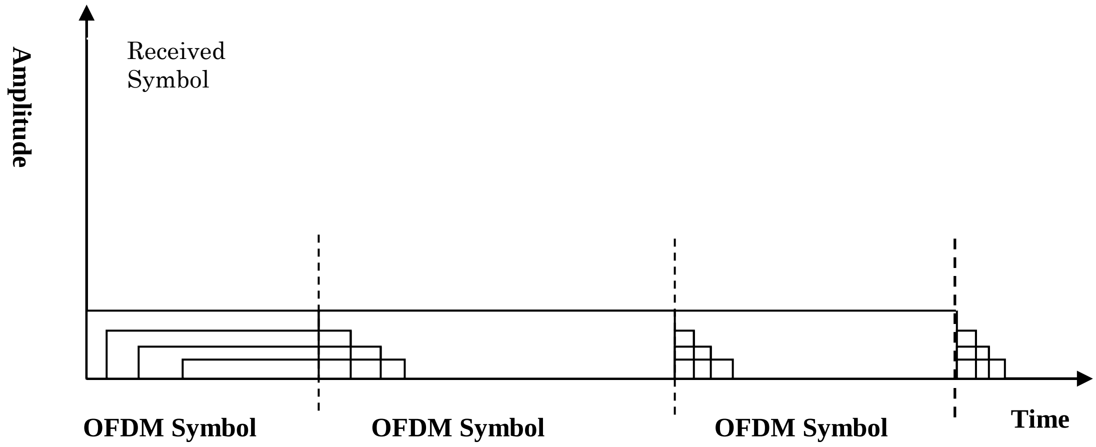

Figure 2.6 Effect of ISI on Symbols.

In wireless channels, signal fading is mainly caused by multi-path propagation. The presence of multi-path is either due to atmospheric reflections/refractions or reflections/scattering from buildings, trees and geographical structures. Multi-path implies that many copies of the transmitted signal will reach the receiver and each copy will have a different amplitude and delay.

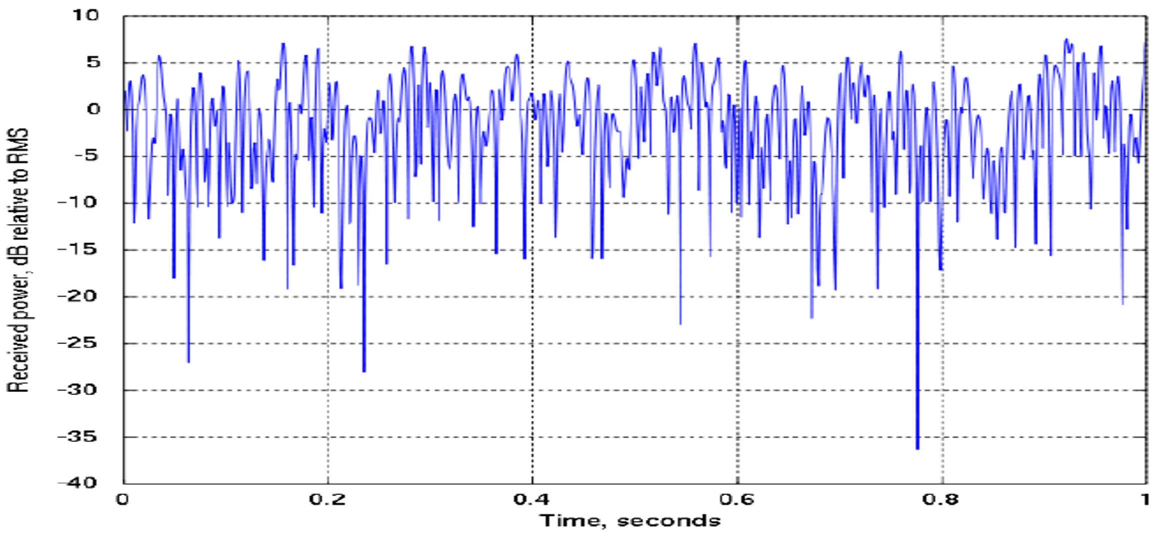

Figure 2.7 Frequency response of the fading channel under 100Hz.

It is possible for the received copies of the signals to add constructively or destructively. When they add destructively this will cause deep fades in the frequency response of the channel and cause severe attenuation of the transmitted signal [38].

Cyclic prefix is a copy of the last part of the symbol which has been added to the beginning of the symbol. This part works as a guard period for the symbol to eliminate the effect of interference from previous symbol. Cyclic prefix will be added to the transmitted signal after modulation (IFFT block) and will be discarded in the receiver before demodulation (FFT). For cyclic prefix to be effective the length of it should be longer than experienced impulse responds of the channel($\Delta\tau$).

2.5 Advantages and disadvantages of OFDM

2.5.1 Advantages

- ✓ For a given channel delay spread, the implementation complexity is much lower than that of a conventional single carrier system with time domain equalizer.
- ✓ Spectral efficiency is high since it uses overlapping orthogonal subcarriers in the frequency domain.
- ✓ Modulation and demodulation are implemented using inverse discrete Fourier transform (IDFT) and discrete Fourier transform (DFT), respectively, and fast Fourier transform (FFT) algorithms can be applied to make the overall system efficient.
- ✓ Capacity can be significantly increased by adapting the data rate per subcarrier according to the signal-to-noise ratio (SNR) of the individual subcarrier. Because of these advantages, OFDM has been adopted as a modulation of choice by many wireless communication systems.

2.5.2 Disadvantages

- ✓ High peak-to-average power ratio (PAPR): The transmitted signal is a superposition of all the subcarriers with different carrier frequencies and high amplitude peaks occur because of the superposition.

- ✓ High sensitivity to frequency offset: When there are frequency offsets in the subcarriers, the orthogonality among the subcarriers breaks and it causes intercarrier interference (ICI).
- ✓ A need for an adaptive or coded scheme to overcome spectral nulls in the channel: In the presence of a null in the channel, there is no way to recover the data of the subcarriers that are affected by the null unless we use rate adaptation or a coding scheme [19].

3 OFDMA (Orthogonal Frequency Division Multiple Access)

OFDMA is a multiple access scheme based on OFDM. In OFDMA the OFDM signal will be generated from signals of many users. OFDMA divides frequency domain into parts called sub-channel. Each sub-channel is a set of sub-carriers, in downlink each sub-channel might be allocated to a user or group of users and in uplink one or more sub-channel may be intended for one transmitter. So each user will have a time and sub-channel allocated (burst) for each one of their requests, An Example of OFDMA has been shown in Figure 2.8[39].

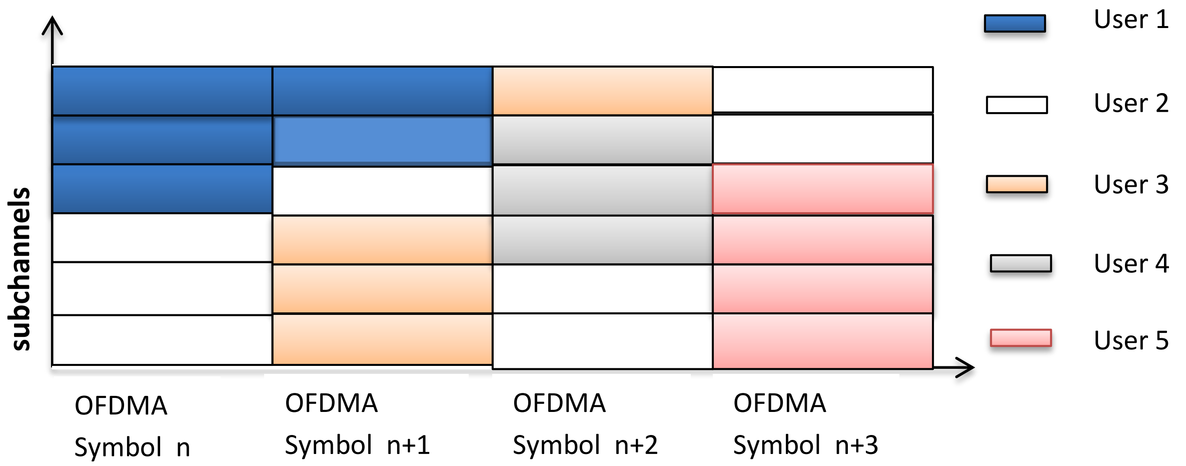

Figure 2.8 Example of OFDMA.

3.1 OFDMA symbol Structure and sub channelization.

Both OFDM and OFDMA symbols are structured in similar way. In OFDMA each symbol consists of sub-channels that carry data sub-carriers carrying information, pilot sub-carriers as reference frequencies and for various estimation purposes, DC sub-carrier (frequency zeros) as the center frequency, and guard sub-carriers or guard bands for keeping the space between OFDMA signals as shown in figure 2.9.

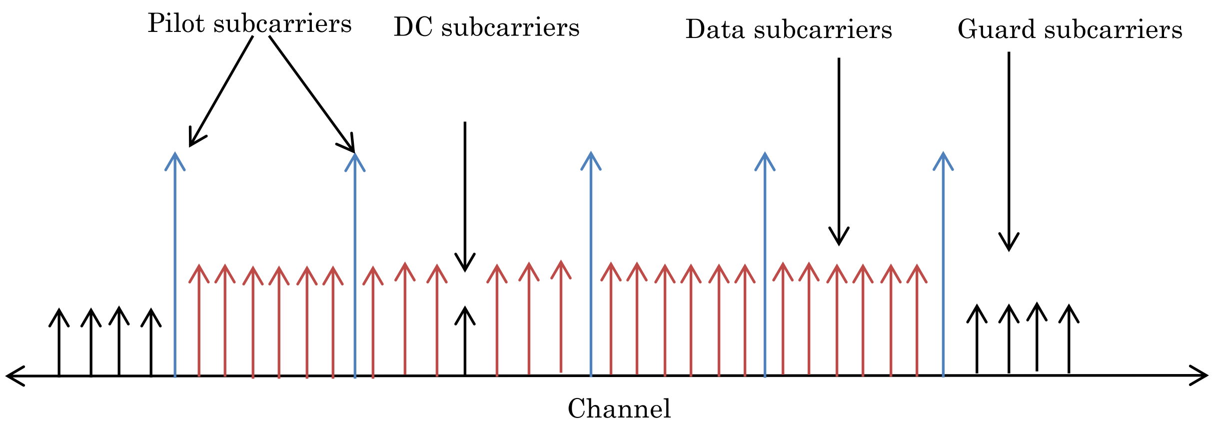

Figure 2.9 Structure of sub-carriers in OFDMA.

3.2 Sub-channelization

Active (data and pilot) sub-carriers are grouped into subsets of sub-carriers called Sub-channelization defines sub-channels that can be allocated to subscriber stations (SSs) depending on their channel conditions and data requirements. Using sub-channelization, within the same time slot, a BS (Base station) can allocate more transmit power to SSs with lower SNR and less power to user devices with higher SNR. Sub-channelization also enables the BS to allocate higher power to sub-channels assigned to indoor SSs resulting in better in-building coverage. Sub-channelization in the uplink can save a user device transmit power because it can concentrate power only on certain sub-channel(s) allocated to it.

This power-saving feature is particularly useful for battery-powered user devices. The concept of sub-channelization is explained in figure 2.10[39].

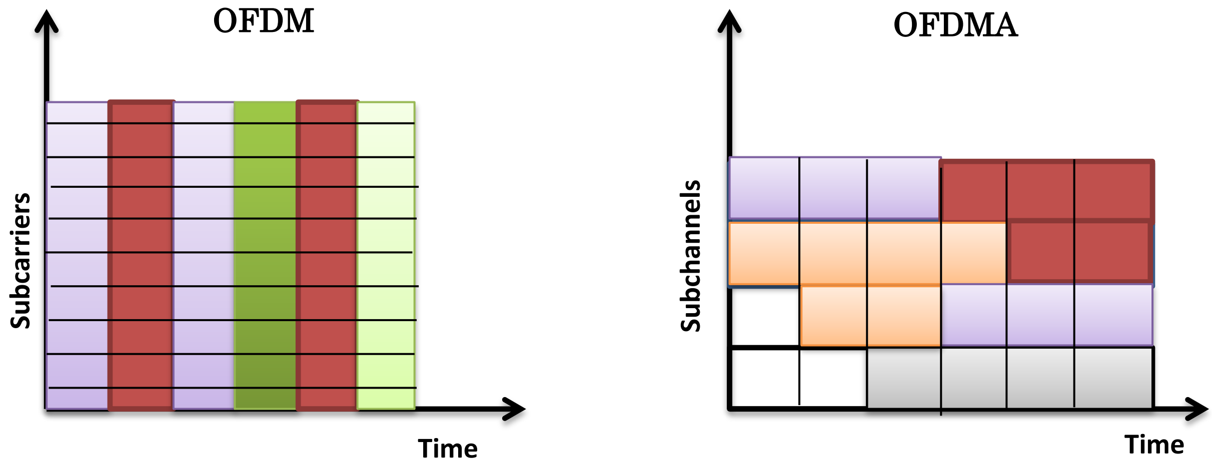

Figure 2.10 Sub-Channelization in OFDM and OFDMA.

4 PAPR peak to average power ratio

Peak to average power ratio (PAPR) is a performance measurement that is indicative of the power efficiency of the transmitter. In the case of an ideal linear power amplifier where we achieve linear amplification up to the saturation point, we reach the maximum power efficiency when the amplifier is operating at the saturation point. A positive PAPR in dB means that we need a power back off to operate in the linear region of the power amplifier. We can express the theoretical relationship between PAPR [dB] and transmit power efficiency as follows [40]:

$$\eta = \eta_{max}.10^{\frac{-PAPR}{20}} \quad (2.4)$$

Where η is the power efficiency and η_{max} is the maximum power efficiency. For class A power amplifier, η_{max} is 50% and for class B, 78.5%. Figure 2.11 shows the relationship graphically and it is evident from the figure that high PAPR degrades the transmit power efficiency performance.

A salient advantage of SC-FDMA over OFDMA is the lower PAPR because of its inherent single carrier structure. The lower PAPR is greatly beneficial in the uplink communications where the mobile terminal is the transmitter.

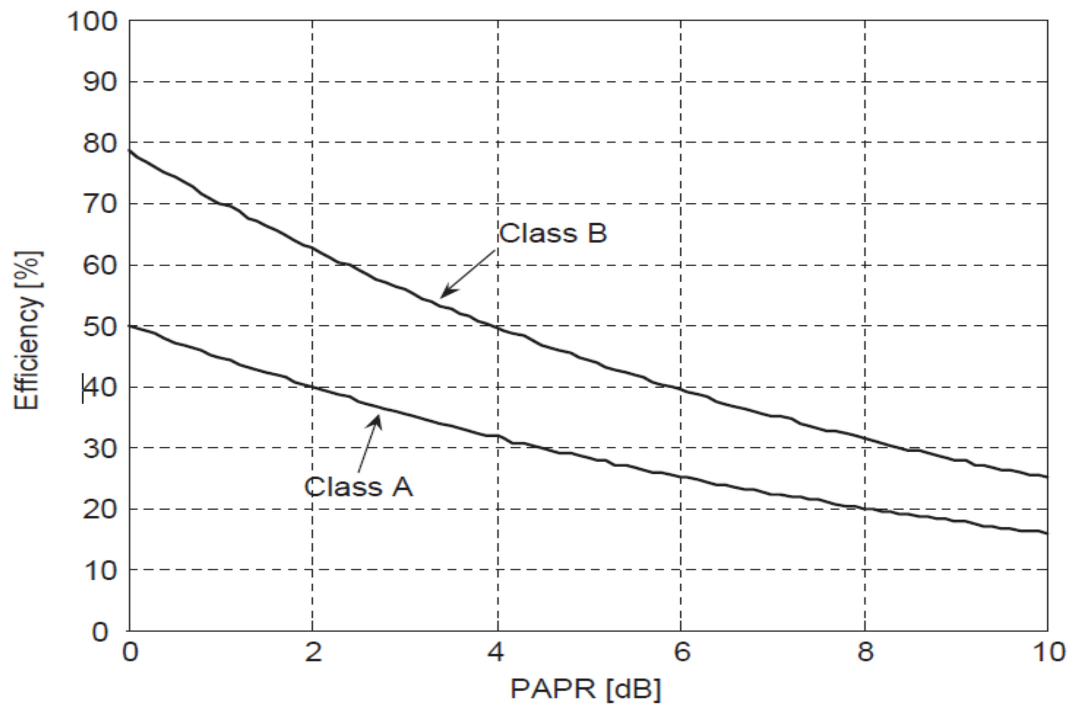

Figure 2.11 A theoretical relationship between PAPR and transmit power efficiency for ideal class A and B amplifiers.

Presence of large number of independently modulated sub-carriers in an OFDM system the peak value of the system can be very high as compared to the average of the whole system. This ratio of the peak to average power value is termed as Peak-to-Average Power Ratio. Coherent addition of N signals of same phase produces a peak which is N times the average signal.

The major disadvantages of a high PAPR are:

- ✓ Increased complexity in the analog to digital and digital to analog converter.
- ✓ Reduction is efficiency of RF amplifiers.

4.1 PAPR of a multicarrier signal

Let the data block of length N be represented by a vector $= [X_0, X_1, \dots . X_{N-1}]^T$. Duration of any symbol X_K in the set X is T and represents one of the sub carriers $\{f_n, n = 0,1, \dots . N-1\}$ set. As the N sub carriers chosen to transmit the signal are orthogonal to each other, so we can have $f_n = n\Delta f$ where $n\Delta f = 1/NT$ and NT is the duration of the OFDM data block X. The complex data block for the OFDM signal to be transmitted is given by:

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n \,.\exp(j2\pi n \Delta f t)\,, 0 \leq t \leq NT \qquad (2.5)$$

The PAPR of the transmitted signal is defined as

$$PAPR = \frac{\max\limits_{0 \leq t \leq NT} |x(t)|^2}{1 \,/\, NT \int_0^{NT} |x(t)|^2 dt} \qquad (2.6)$$

Reducing the max|x(t)| is the principle goal of PAPR reduction techniques. Since, discrete- time signals are dealt with in most systems, many PAPR techniques are implemented to deal with amplitudes of various samples of *x(t)*. Due to symbol spaced output in the first equation we find some of the peaks missing which can be compensated by oversampling the equation by some factor to give the true PAPR value.

4.2 Cumulative distribution function

The Cumulative Distribution Function (CDF) is one of the most regularly used parameters, which is used to measure the efficiency of any PAPR technique. Normally, the Complementary CDF (CCDF) is used instead of CDF, which helps us to measure the probability that the PAPR of a certain data block exceeds the given threshold.

By implementing the Central Limit Theorem for a multi carrier signal with a large number of sub-carriers, the real and imaginary part of the time domain signals have a mean of zero and a variance of 0.5 and follow a Gaussian distribution. So Rayleigh distribution is followed for the amplitude of the multi carrier signal, where as a central chi-square distribution with two degrees of freedom is followed for the power distribution of the system. The CDF of the amplitude of a signal sample is given by [40]:

$$F(z) = 1 - \exp(z) \tag{2.7}$$

The CCDF of the PAPR of the data block is desired is our case to compare outputs of various reduction techniques. This is given by:

$$p(papr > z) = 1 - p(papr \leq z) = 1 - F(z)^N = 1 - (1 - \exp(z))^N \tag{2.8}$$

4.3 Non-linear amplifiers

It is a well-known fact that OFDM comprises of large envelope fluctuations as compared to single carrier systems with same modulation and same spectral characteristics. This is because OFDM is nothing but sum of multitude of digitally modulated signals with Gaussian like probability density function (PDF). Hence the peak to average power ratio (PAPR) of OFDM is quite large which results in an inefficient usage of the high power amplifier (HPA) at the transmitter [41]. The high PAPR causes the HPA to enter into the non-linear region and thus we get distortions due to non-linearities at the output of the HPA. Normally non-linear regions are prevented by "backing off" the amplifier from the saturation region thus keeping it in the active or linear region of operation. This back off would however affect the efficiency of the HPA. Hence it is desired to maintain low back off values but this would cause an additional interference as non-linear distortions and peak value limitations produced as a result would result in inter-modulation between different carriers. It is thus desired to keep the back off values low but at the same time prevent the non-linearities caused by the HPA.

4.3.1 System degradation by HPA Non-linearity

The distortions produced by a non-linear amplifier are dependent on envelope fluctuations. A non constant envelope signal when modulated by a non-linear amplifier would be distorted in different ways. The non-linearities in the HPA would cause additional interference in the receiver. We would get interference between the in-phase and quadrature components due the AM/PM conversion. Moreover the power spectral density (PSD) of the modulated signal with fluctuating envelope would be broadened by the non-linear effects of the HPA that would cause spectral spreading of the signal and hence adjacent channel interference would be introduced in the amplifier output. Finally it should be noted that when several channels are amplified in the same HPA, there would be inter- modulation effects in the amplifier output signal. In other words the orthogonality in OFDM would be completely destroyed by the non-linear distortions in the HPA. As mentioned earlier one way of preventing these effects is to make the amplifier operate in the linear region which would require introduction of "output back off" (OBO) of the HPA which is given by [42]:

$$OBO = 10log_{10}\left(\frac{P_0}{P_s}\right)\ in\ dBs \tag{2.9}$$

Where the reference power Po is the saturating power of HPA and Ps is the mean output power of the transmitted signal. It is however unfortunate that the efficiency of the HPA is very low at high values of OBO so there is a tradeoff between maximizing output power on one side and avoiding degradations due to non-linear distortions on the other side The figure below shows Idealized amplifier AM-to-AM characteristic .

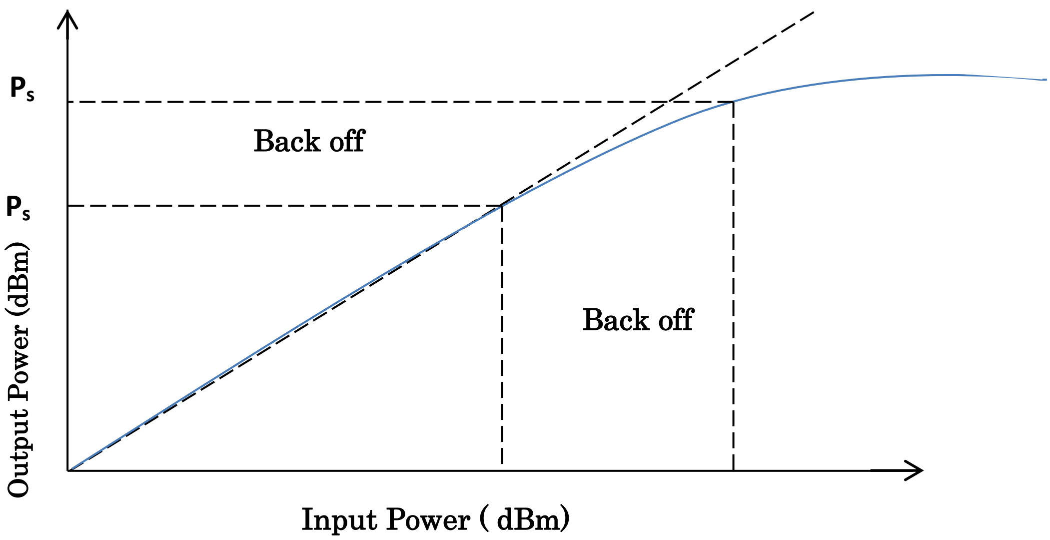

Figure 2.12 Idealized amplifiers AM-to-AM characteristic.

5 SC-FDMA (Single carrier frequency division multiple access)

Single carrier frequency division multiple access (SC-FDMA), which utilizes single carrier modulation and frequency domain equalization, is a technique that has similar performance and essentially the same overall complexity as those of orthogonal frequency division multiple access (OFDMA) system. SC-FDMA is an extension of single carrier modulation with frequency domain equalization (SC/FDE) to accommodate multiple-user access. One prominent advantage over OFDMA is that the SC-FDMA signal has lower peak to average power ratio (PAPR) because of its inherent single carrier structure. SC-FDMA has drawn great attention as an attractive alternative to OFDMA, especially in the uplink communications where lower PAPR greatly benefits the mobile terminal in terms of power efficiency. It is currently a working assumption for uplink multiple access scheme in 3GPP Long Term Evolution (LTE) [42].

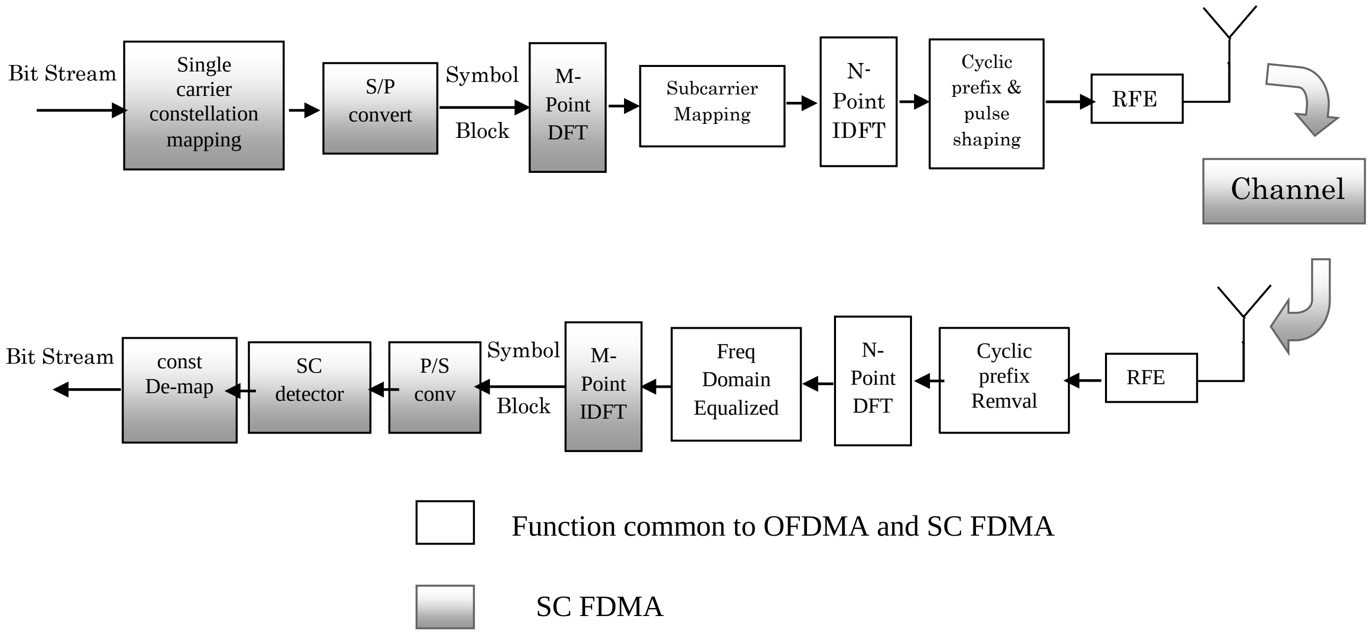

Figure 2.13 block diagram of an SC-FDMA system.

5.1 Overview of SC-FDMA System

Figure 2.13 shows a block diagram of an SC-FDMA system. SC-FDMA can be regarded as DFT-spread OFDMA, where time domain data symbols are transformed to frequency domain by DFT before going through OFDMA modulation. The orthogonality of the users stems from the fact that each user occupies different subcarriers in the frequency domain, similar to the case of OFDMA. Because the overall transmit signal is a single carrier signal, PAPR is inherently low compared to the case of OFDMA which produces a multicarrier signal. The transmitter of an SC-FDMA system converts a binary input signal to a sequence of modulated subcarriers. At the input to the transmitter, a baseband modulator transforms the binary input to a multilevel sequence of complex numbers x_n in one of several possible modulation formats. The transmitter next groups the modulation symbols $\{x_n\}$ into blocks each containing N symbols. The first step in modulating the SC-FDMA subcarriers is to perform an N-point DFT to produce a frequency domain representation X_k of the input symbols. It then maps each of the N DFT outputs to one of the $(M > N)$ orthogonal subcarriers that can be transmitted. If $N = M/Q$ and all terminals transmit N symbols per block, the system can handle Q simultaneous transmissions without co-channel interference where Q is the bandwidth expansion factor of the symbol sequence. The result of the subcarrier mapping is the set $X\ (l = 0, 1, 2 \ldots, M-1)$ of complex subcarrier amplitudes, where N of the amplitudes are non-zero. As in OFDMA, an M-point IDFT transforms the subcarrier amplitudes to a complex time domain signal x_m . Each x_m then are transmitted sequentially.

The transmitter performs two other signal processing operations prior to transmission. It inserts a set of symbols referred to as a cyclic prefix (CP) in order to provide a guard time to prevent inter-block interference (IBI) due to multipath propagation. The transmitter also performs a linear filtering operation referred to as pulse shaping in order to reduce out-of band signal energy[44][45].

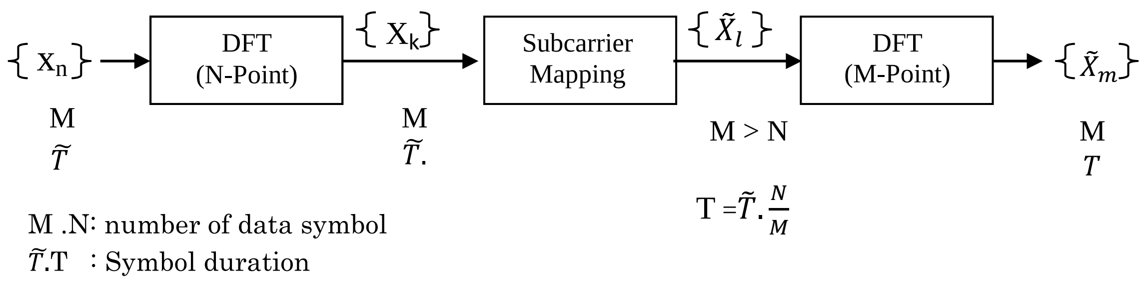

Figure 2.14 The generation of SC-FDMA transmit symbols.

Figure 2.14 details the generation of SC-FDMA transmit symbols. There are M subcarriers, among which $(N < M)$ subcarriers are occupied by the input data. In the time domain, the input data symbol has symbol duration of T seconds and the symbol duration is compressed to $\tilde{T} = (N/M) \times T$ seconds after going through SC-FDMA modulation.

The receiver transforms the received signal into the frequency domain via DFT, de-maps the subcarriers, and then performs frequency domain equalization.

Because SC-FDMA uses single carrier modulation, it suffers from inter-symbol interference (ISI) and thus equalization is necessary to combat the ISI. The equalized symbols are transformed back to the time domain via IDFT, and detection and decoding take place in the time domain.

5.2 Subcarrier Mapping

There are two methods to choose the subcarriers for transmission as shown in Figure 2.15; distributed subcarrier mapping and localized subcarrier mapping. In the distributed subcarrier mapping mode, DFT outputs of the input data are allocated over the entire bandwidth with zeros occupying the unused subcarriers, whereas consecutive subcarriers are occupied by the DFT outputs of the input data in the localized subcarrier mapping mode.

We will refer to the localized subcarrier mapping mode of SC-FDMA as localized FDMA (LFDMA) and distributed subcarrier mapping mode of SC-FDMA as distributed FDMA (DFDMA). The case of $M = Q \times N$ for the distributed mode with equidistance between occupied subcarriers is called Interleaved FDMA (IFDMA). IFDMA is a special case of SC-FMDA and it is very efficient in that the transmitter can modulate the signal strictly in the time domain without the use of DFT and IDFT [44].

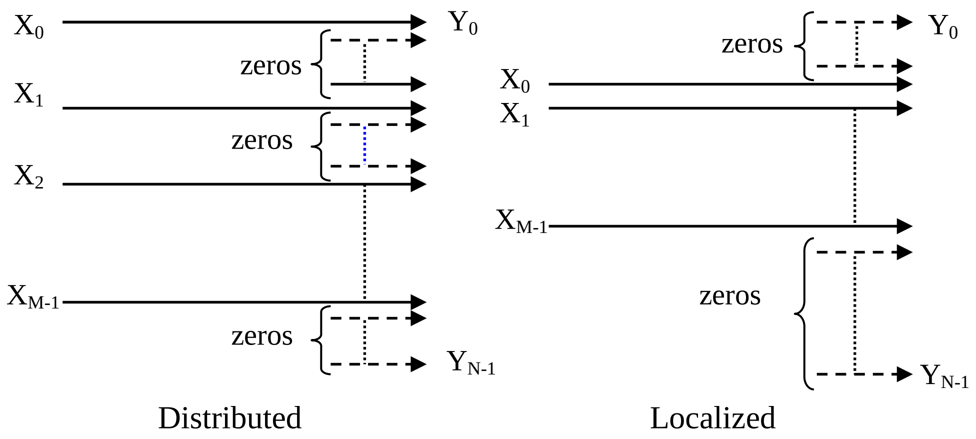

Figure 2.15 Subcarrier mapping modes; distributed and localized.

5.3 Time Domain Representation of SC-FDMA Signals

For IFDMA, LFDMA, and DFDMA, the three operations in Figure 2.16 can be viewed as one linear operation on the sequence of modulation symbols $\{x_m: m = 0, 1, 2, \ldots, M - 1\}$. Therefore each element of the output sequence $\{y_n: n = 0, 1, 2, \ldots, N - 1\}$ is a weighted sum of the elements of the input sequence, where the weights are complex numbers. In the case of IFDMA, the weights are zero for all but one element of the input sequence.

The set of operations reduces to multiplying each input symbol by a complex number with unit magnitude and repeating the input sequence with proper phase rotation Q times, where Q is the bandwidth expansion factor [36].

5.3.1 Time Domain Symbols of IFDMA

For IFDMA, the combination of the DFT and IDFT in the transmitter of Figures 2.13 and 2.14 reduce to the simple signal processing operations of multiplying each input symbol by a complex number with unit magnitude and repeating the input sequence with proper phase rotation Q times. The multiplication is equivalent to a rotation of each complex modulation symbol in the transmission block.

To verify that this is true, we observe two properties of the DFT and its inverse: (a) equally spaced nonzero samples in one domain correspond to a periodic sequence in the other domain; and (b) a shift of r in the frequency domain corresponds to a phase rotation of each time sample. The phase rotation is accomplished by multiplying each sample by $exp(j2\pi rn/N)$, where N is the number of points in the inverse transform, r is the amount of the frequency shift, and n is the output sample number in the time domain.

The following paragraph is a detailed mathematical demonstration of this property. Figure 2.16 is an illustration for our example of $M = 4$ symbols per block, $Q = 3$ terminals, and $N = Q \times M = 12$ subcarriers. For one input signal, $\{Y_l: l = 0, 1, 2, \ldots, N - 1\}$ is the spectrum of the transmitted SC-FDMA sequence representing the block of data$\{x_m: m = 0, 1, \ldots, M - 1\}$. In IFDMA, the spectrum has M uniformly-spaced nonzero components, with adjacent samples separated by $Q - 1$ samples in the frequency domain. The corresponding time domain signal $\{y_n: n = 0, 1, 2, \ldots, N - 1\}$is periodic with Q replicas distributed over times $n = 0, 1, 2, .., M - 1 (= N/Q - 1)$ and with phase rotation of $exp(j\ 2\pi rn/N)$.

Consider the input signal $\{x_m: m = 0, 1, ., M - 1\}$ that occupies subcarriers $l = 0, Q, 2Q, .., (M - 1)Q$. The periodic transmitted time signal corresponding to the spread spectrum of this signal has the sequence $\{x_{0/Q}, x_{1/Q}, \ldots, x_{M-1/Q}\}$, repeated Q times (rotation of 0 radian). Now consider the signal from another terminal $\{u_m: m = 0, 1, \ldots\ldots, M - 1\}$ that modulates the next set of equally spaced subcarriers $n = 1, Q + 1, 2Q + 1, \ldots\ldots\ldots, (M - 1)\,Q + 1$. The spectrum of this signal $\{V_l: l = 0, 1, 2, ., N - 1\}$ is similar to the spectrum of Y_l, but with nonzero components shifted by one subcarrier. This shift in the frequency domain corresponds to multiplication in the time domain by $exp(j2\pi n/N)$.

Therefore, the transmitted time domain sequence is $u_0/Q\ , u_1 exp(j2\pi/N)\ / Q \ldots.., u_{M-1}\, exp(j2\pi(M - 1)/N)/Q$, repeated Q times with appropriate phase rotations. In general, we have for the input signal $\{x_m : m = 0, 1, ., M - 1\}$ that modulates subcarriers $n = r,\ Q + r, 2Q + r, \ldots.., (M - 1) + r,$ the transmitted signal $\{x_m : m = 0,1,\ldots,M-1\}$ repeated Q times with phase rotation of $exp(j2\pi rn/N)$.

The mathematical formulas corresponding to this description begin with frequency domain symbols Y_l[45].

$$Y_1 = \begin{cases} X_{1/Q} & , \ l = Q \cdot K \quad 0 \leq K \leq M-1 \\ 0 & , \quad otherwise \end{cases} \tag{2.10}$$

Where $0 \leq l \leq N-1 \; and \; N = Q.M$

Let $n = M.q + m \, (0 \leq q \leq Q-1, 0 \leq m \leq M-1)$. Then,

$$y_n = (y_{Mq+m}) = \frac{1}{N}\sum_{l=0}^{N-1} y_1 \exp\left(j2\pi\frac{n}{N}l\right) = \frac{1}{N}\sum_{l=0}^{N-1} \boldsymbol{X_{1/Q}} \exp\left(j2\pi\frac{n}{N}l\right)$$

$$= \frac{1}{Q.M}\sum_{K=0}^{M-1} X_K \exp\left(j2\pi\frac{n}{Q.M}Q.K\right)$$

$$= \frac{1}{Q.M}\sum_{K=0}^{M-1} X_K \exp\left(j2\pi\frac{Mq+m}{M}K\right) = \frac{1}{Q}.\left(\frac{1}{M}\sum_{K=0}^{M-1} X_K \exp\left(j2\pi\frac{m}{M}K\right)\right)$$

$$= \frac{1}{Q}\mathrm{X_m} = \frac{1}{Q}\mathrm{x(n)_{mod\,M}} \tag{2.11}$$

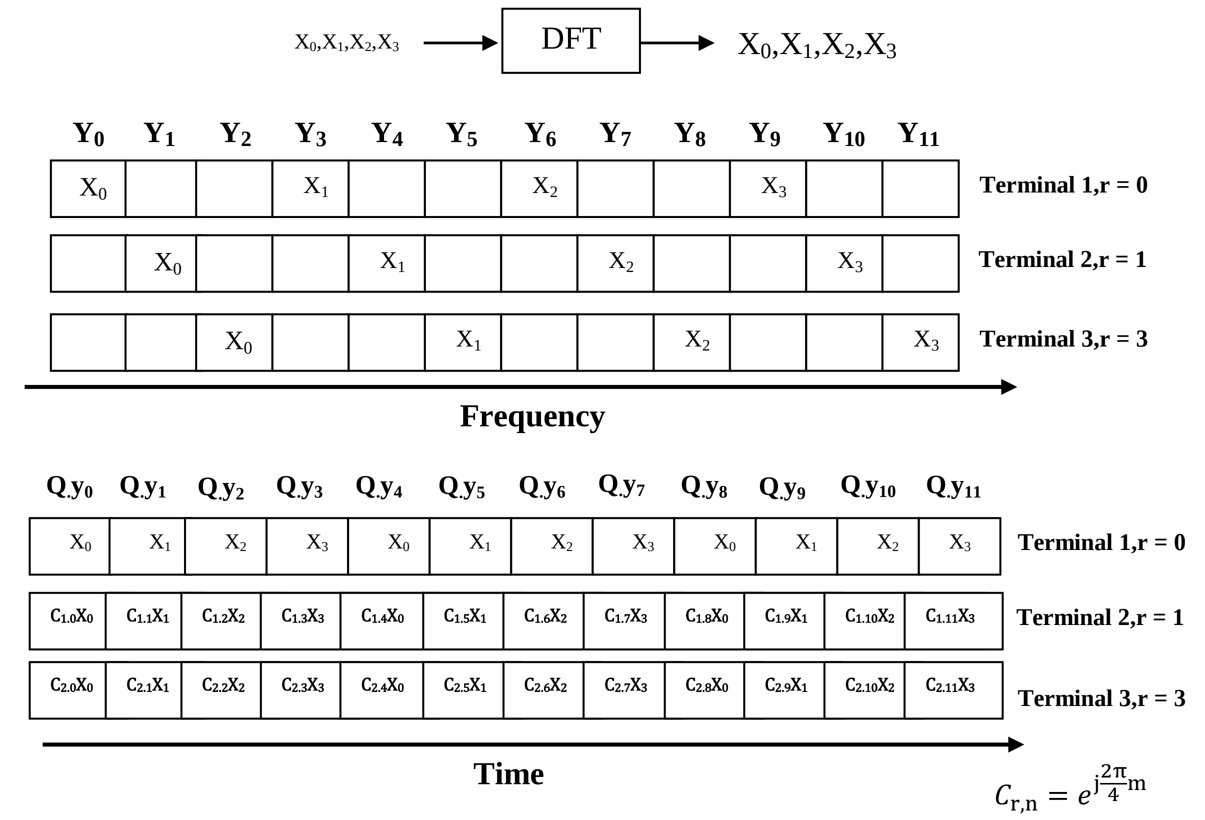

Figure 2.16 Illustration of IFDMA subcarrier mapping for $M = 4$ symbols per block, $Q = 3$ terminals, and $N = Q \times M = 12$ subcarriers.

The resulting time symbols $\{y_n\}$ are simply a repetition of the original input symbols $\{x_m\}$ with a scaling factor of 1/Q in the time domain just as we described. When the subcarrier allocation starts from the **r**th subcarrier $(0 < \boldsymbol{r} \leq Q - 1)$, then,

$$Y_1 = \begin{Bmatrix} X_{1/Q-r} & , & l = Q \cdot K + r \quad 0 \leq K \leq M-1 \\ 0 & , & otherwise \end{Bmatrix} \tag{2.12}$$

Corresponding to equation (2.12), the time symbols $\{y_n\}$ can be derived as:

$$y_n = \frac{1}{Q} x(n)_{mod\,M} . \exp\left(j2\pi \frac{rn}{N}\right) \tag{2.13}$$

As can be seen from equation (2.13), there is an additional phase rotation of $exp(j2\pi rn/N)$ as noted earlier when the subcarrier allocation starts from r^th subcarrier instead of subcarrier zero. This phase rotation will also apply to the other subcarrier mapping schemes.

5.3.2 Time Domain Symbols of LFDMA

Figure 2.17 is a diagram of the LFDMA subcarrier mapping. It shows the modulation symbols that occupy the 12 subcarriers $\{Y_1\}$ in the example.

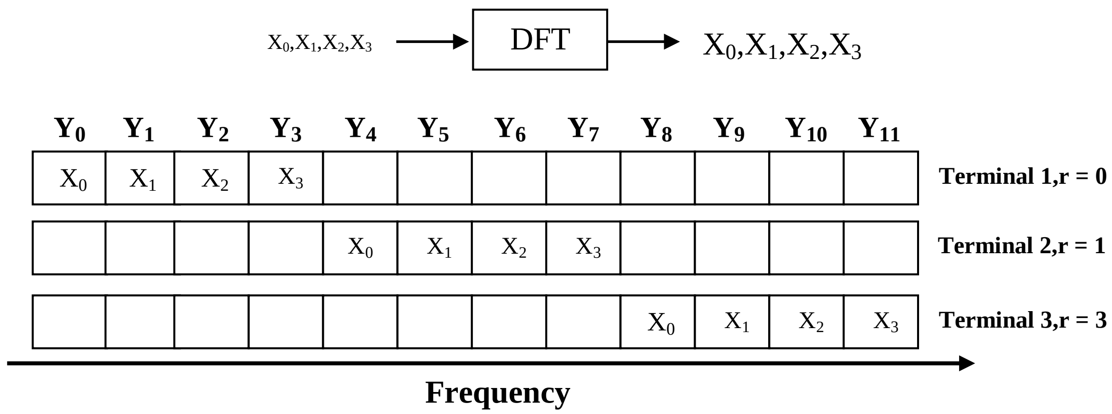

Figure 2.17 Illustration of LFDMA subcarrier mapping for $M = 4$ symbols per block, $Q = 3$ terminals, and $N = Q \times M = 12$ subcarriers.

The time domain samples of the LFDMA signal can be expressed as follows [44]:

$$Y_n = y_{Q.m+q} = \left\{ \begin{array}{ll} \frac{1}{Q} x(n)_{mod\ M}, & q = 0 \\ \frac{1}{Q} . \left(1 - e^{j2\pi\frac{q}{Q}}\right) . \frac{1}{M} \sum_{p=0}^{M-1} \frac{X_p}{1 - e^{j2\pi\left\{\frac{(m-p)}{M} + \frac{q}{QM}\right\}}} & , q \neq 0 \end{array} \right\} \quad (2.14)$$

The LFDMA signal in the time domain has exact copies of input time symbols with a scaling factor of $1/Q$ at sample positions that are integer multiples of Q. Intermediate values are weighted sums of all the time symbols in the input block [46].

5.3.3 Time Domain Symbols of DFDMA

Figure 2.18 is a diagram of the DFDMA subcarrier mapping. It shows the modulation symbols that occupy the 12 subcarriers, $\{Y_1\}$ in the example. The time domain samples of the DFDMA signal can be expressed as follows:

$$Y_n = y_{Q.m+q} = \begin{cases} \frac{1}{Q} X_{(\tilde{Q}(n)_{mod\,M})_{mod\,M}}, & q = 0 \\ \frac{1}{Q}\cdot\left(1 - e^{j2\pi\frac{\tilde{Q}}{Q}q}\right)\cdot\frac{1}{M}\sum_{p=0}^{M-1}\frac{X_p}{1 - e^{j2\pi\left\{\frac{(m\tilde{Q}-p)}{M}+\frac{\tilde{Q}q}{QM}\right\}}}, & q \neq 0 \end{cases} \qquad (2.15)$$

Where $(1 \leq \tilde{Q} < Q)$ is the actual spreading factor. The time domain samples of DFDMA have the same structure as those of LFDMA.

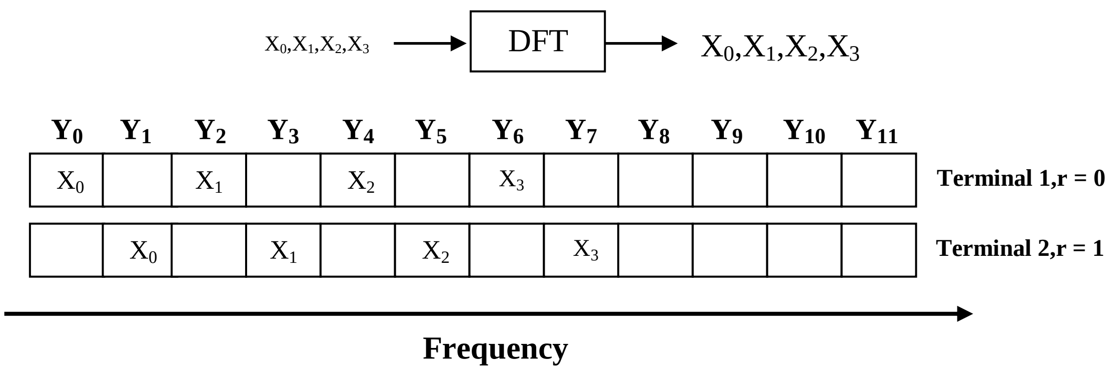

Figure 2.18 Illustration of DFDMA subcarrier mapping for M = 4 symbols per block, Q = 3 terminals, and N = $Q \times M$ = 12 subcarriers.

5.3.4 Comparison of Subcarrier Mapping Schemes

Figure 2.19 shows the time domain samples for each subcarrier mapping described earlier. The IFDMA signal maintains the input time symbols in each sample whereas LFDMA and DFDMA have more complicated time samples because of the complex-weighted sum of the input symbols. This implies that higher peak power is expected for LFDMA and DFDMA signals.

Figure 2.20 shows one instance of the amplitude of the samples for each subcarrier mapping for $N = 64$ subcarriers, $M = 16$ subcarriers per block, $Q = 4$ spreading factor for IFDMA with four terminals, and $\tilde{Q} = 3$ spreading factor for DFDMA with three terminals. In Figure 2.19 there is no pulse shaping.

For comparison Figure 2.20 also shows the corresponding OFDMA waveform. These particular input symbols for the SC-FDMA modulation used QPSK. For IFDMA, we can observe the constant amplitude that comes from maintaining the constant envelope property of QPSK. For LFDMA and DFDMA, we can see more fluctuation and higher peaks [46].

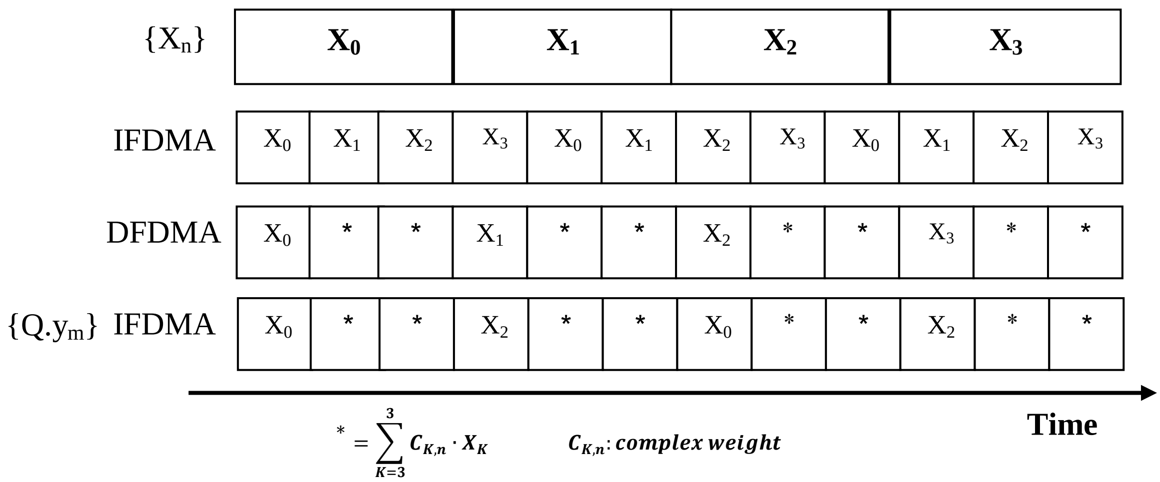

Figure 2.19 Time domain samples of different subcarrier mapping schemes.

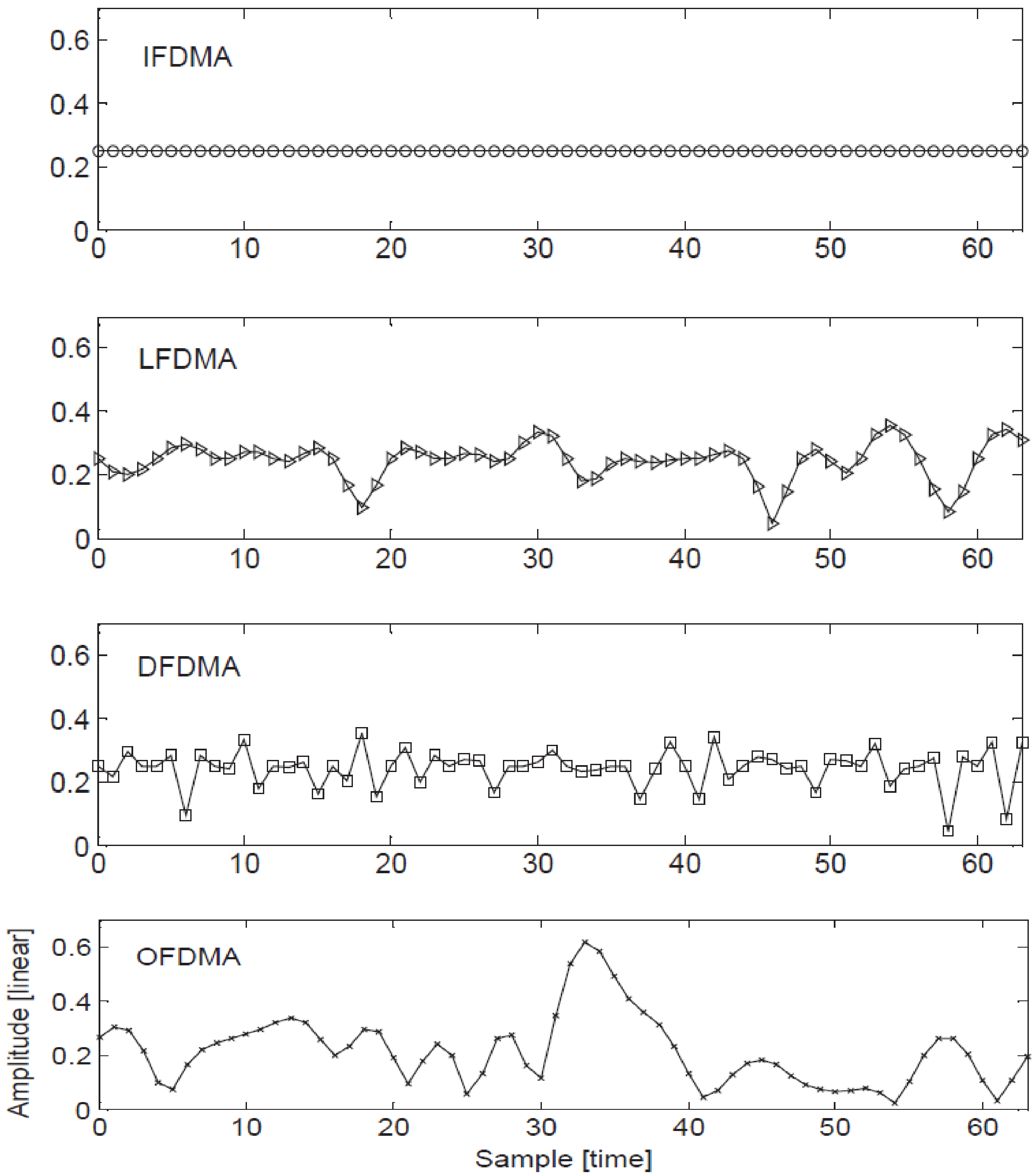

Figure 2.20 Amplitude of SC-FDMA and OFDMA samples for QPSK input modulation without pulse shaping with $N = 64$ subcarriers, $M = 16$ subcarriers per block, $Q = 4$ spreading factor for IFDMA with four terminals, and $\tilde{Q} = 3$ spreading factor for DFDMA with three terminals.

Overall, all three single carrier subcarrier mapping schemes exhibit lower peak power than OFDMA.

5.4 Pulse Shaping

Bandwidth is a scarce resource obliging data transmission systems to constrain the bandwidth of their transmitted signals. But the drawback is the increase in the likelihood of decoding errors.

Pulse shaping is a technique used to restrict the bandwidth of the transmitted signals while minimizing the likelihood of decoding errors.

To better clarify the importance and the mechanism behind pulse-shaping, one should examine the most basic information unit in digital transmission, and the same concept will be valid on more sophisticated systems. Starting with the time domain representation of a rectangular pulse as shown in figure 2.21, we can see that the spectrum or frequency domain representation is nothing but the *sinc* response where the null points occur at integer multiples of f_0 which is the pulse rate. In theory, the spectrum of a rectangular pulse is infinite but in this figure, the spectrum from $-5f0\ to\ +5f0$ is shown [47].

This infinite bandwidth associated with the rectangular pulse can be limited by applying a low-pass filter. The well know pulse-shaping filter is known as the raised cosine filter with its frequency and the root raise cosine.

The raised-cosine filter is an implementation of a low pass Nyquist filters i.e. one that has the property of vestigial symmetry. This means that its spectrum exhibits odd symmetry about 1/2T, where T is the symbol-period of the communications system.
Its frequency response is a piecewise function given by:

$$H_{RC}(f) = \begin{cases} \tau, & |f| \leq \dfrac{1+\alpha}{2\tau}\ ; \\ \dfrac{\tau}{2}\left[1+\cos\left(\dfrac{\pi\tau}{\alpha}\left(|f| - \dfrac{1-\alpha}{2\tau}\right)\right)\right], & \dfrac{1-\alpha}{2\tau} \leq |f| \leq \dfrac{1+\alpha}{2\tau}; \\ 0, & otherwise; \end{cases} \quad (2.16)$$

Where f is the frequency, τ is the pulse period, and α is the roll off factor and the impulse response given by:

$$h_{RC}(f) = \operatorname{sinc}\left(\frac{t}{\tau}\right)\left[\frac{\cos\left(\frac{\pi\alpha t}{\tau}\right)}{1-\left(\frac{2\alpha t}{\tau}\right)^2}\right] \tag{2.17}$$

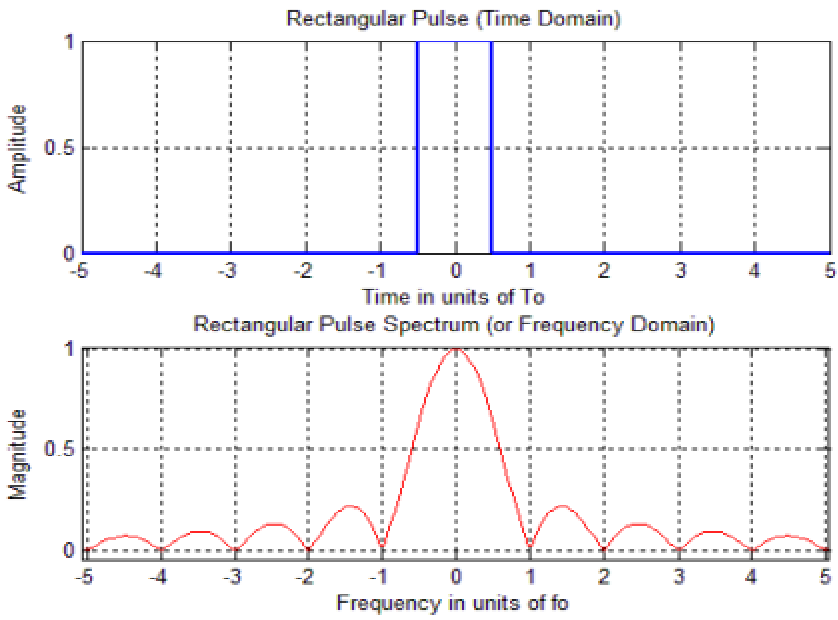

Figure 2.21 Rectangular Pulse Time and Frequency Domain Representation.

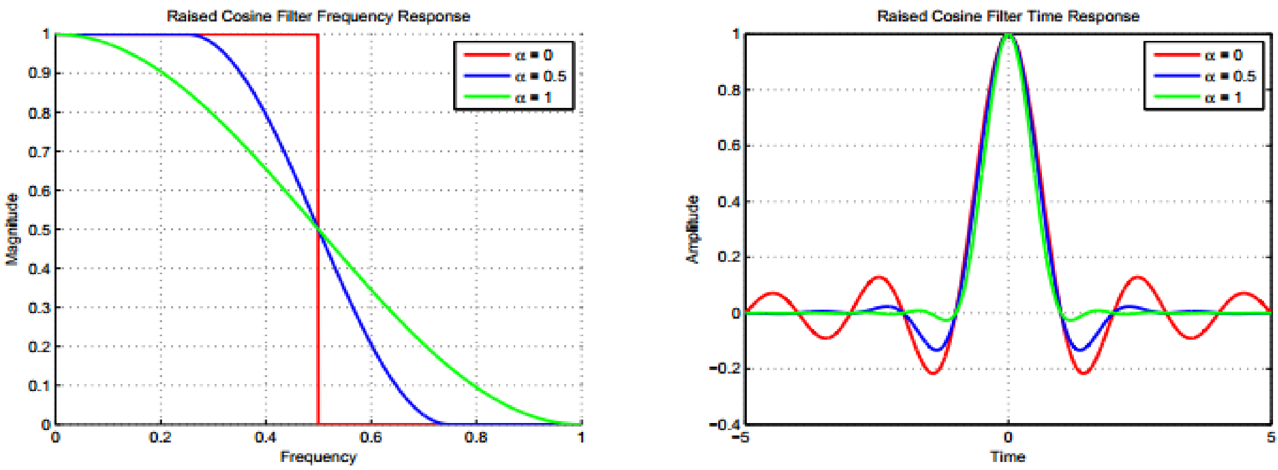

Figure 2.22 Frequency and Time of RC Filter.

Based on the roll-off factor, the response characteristics of the raised cosine filter will change, and this will be reflected in the different oscillations observed in the impulse response (time domain) as presented in figure 2.21.

The root raised cosine filter is generally used in series pairs, so that the total filtering effect is that of a raised cosine filter. The advantage is that if the transmit side filter is stimulated by an impulse, then the receive side filter is forced to filter an input pulse shape that is identical to its own impulse response, thereby setting up a matched filter and maximizing signal to noise ratio while at the same time minimizing ISI [47].

Mathematically, the frequency response may be written as:

$$H_{RRC}(f) = \begin{cases} \sqrt{\tau}, & |f| \leq \frac{1+\alpha}{2\tau} \\ \sqrt{\frac{\tau}{2}\left[1+\cos\left(\frac{\pi\tau}{\alpha}\left(|f|-\frac{1-\alpha}{2\tau}\right)\right)\right]} & \frac{1-\alpha}{2\tau} \leq |f| \leq \frac{1+\alpha}{2\tau} \\ 0, & otherwise \end{cases} \quad (2.18)$$

And the impulse Response given by:

$$h(t) = \frac{2\alpha}{\pi\sqrt{\tau}} \frac{\cos[(1+\alpha)\pi t/\tau] + \frac{sin\left[\frac{(1+\alpha)\pi t}{\tau}\right]}{4\alpha t/\tau}}{1-\left(\frac{4\alpha t}{\tau}\right)^2} \quad (2.19)$$

6 Conclusion

The single-carrier frequency division multiple access (SC-FDMA) system is a well-known system that has recently become a preferred choice for mobile uplink channels. This is attributed to its advantages such as the low peak-to-average power ratio (PAPR) and the use of frequency domain equalizers. Low PAPR allows the system to relax the specifications of linearity in the power amplifier of the mobile terminal, which reduces cost and power consumption. Moreover, it has a similar throughput performance and essentially the same overall complexity as the orthogonal frequency division multiple access (OFDMA) system. Due to these advantages, SC FDMA has been chosen as the uplink transmission method in the long-term evolution (LTE) system. The next chapter shows the simulation results for the PAPR values of OFDMA and SC FDMA in Uplink transmission.

Chapter 3

Simulation and results

1 Introduction

This chapter gives a simulation study for the peak to average power ratio (PAPR) in the DFT-SCFDMA and OFDMA system and comparing between them in the Uplink transmission. The impact of the radio resource allocation, the RC filter pulse shaping, the number of subcarrier system and the number of subcarrier per user on the PAPR is investigated in this chapter.

2 Simulation Model

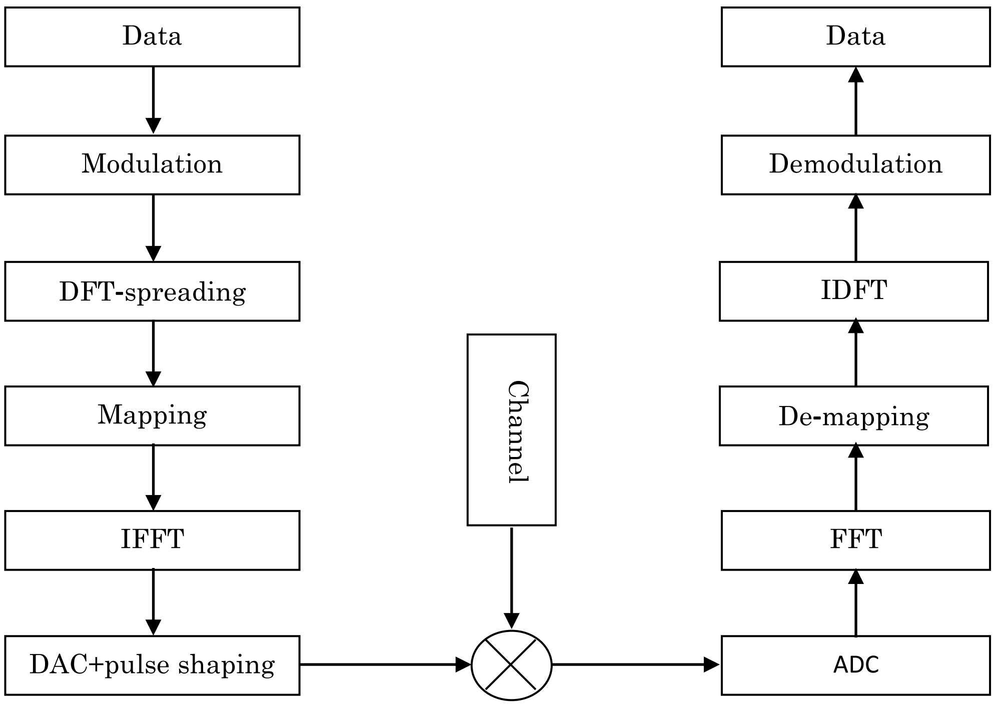

Figure 3.1 Simulation model.

2.1 The impact of the radio resource allocation on the PAPR of DFT-SC-FDMA with-out pulse shaping

The CCDFs of the PAPR for the DFT-IFDMA, DFT-LFDMA and the OFDMA system have been evaluated and compared for different modulation formats. 5.10^3 data blocks have been generated to calculate the CCDFs of the PAPR. No pulse shaping was applied in this case. Simulation parameters are tabulated in table 3.1.

Parameters	Values
Channel bandwidth	5Mhz
Oversampling factor	4
User subcarriers	16
System subcarriers	512
Spreading	DFT
Modulation schemes	QPSK, 16-QAM and 64-QAM
Subcarrier mapping scheme	Interleaved and Localized
pulse shaping	No

Table 3.1 Simulation parameters with out pulse shaping.

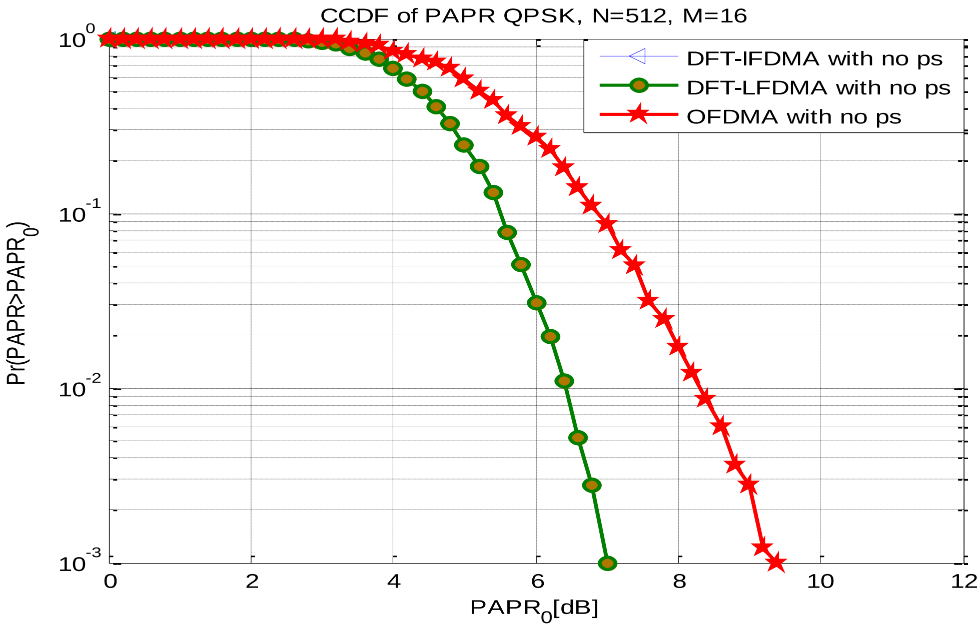

Figure 3.2 Comparison between the CCDFs of the PAPR for the DFT-IFDMA, the DFT-LFDMA and OFDMA systems with-out pulse shaping (QPSK).

The CCDFs of the PAPR for the DFT-IFDMA, the DFT-LFDMA and the OFDMA systems with QPSK modulation are shown in Figure 3.2. It is clear that with out pulse shaping, the DFT-IFDMA system has a lower PAPR than that of the OFDMA system by about 9.4 dB, while the PAPR of the DFT-LFDMA system is lower than that of the OFDMA system by about 2.4dB, but higher than that of the DFT-IFDMA system by about 7dB.

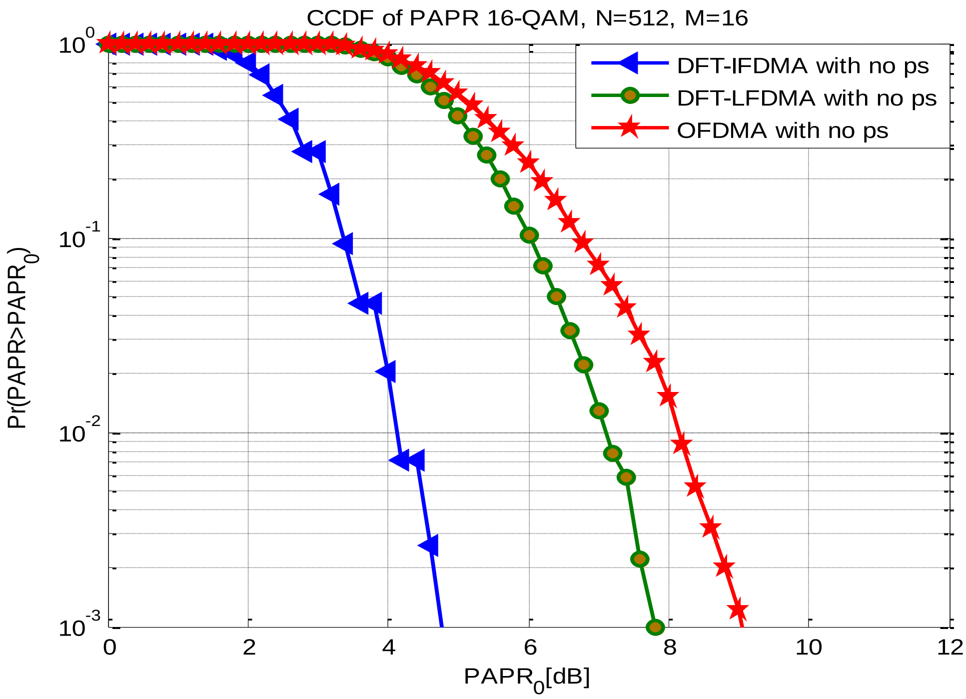

Figure 3.3 Comparison between the CCDFs of the PAPR for the DFT-IFDMA, the DFT-LFDMA and OFDMA systems with-out pulse shaping (16-QAM).

The CCDFs of the PAPR for the DFT-IFDMA, the DFT-LFDMA and the OFDMA systems with 16-QAM modulation are shown in Figure 3.3. It is clear that with out pulse shaping, the DFT-IFDMA system has a lower PAPR than that of the OFDMA system by about 4.4dB, while the PAPR of the DFT-LFDMA system is lower than that of the OFDMA system by about 1.3 dB, but higher than that of the DFT-IFDMA system by about 3.1dB.

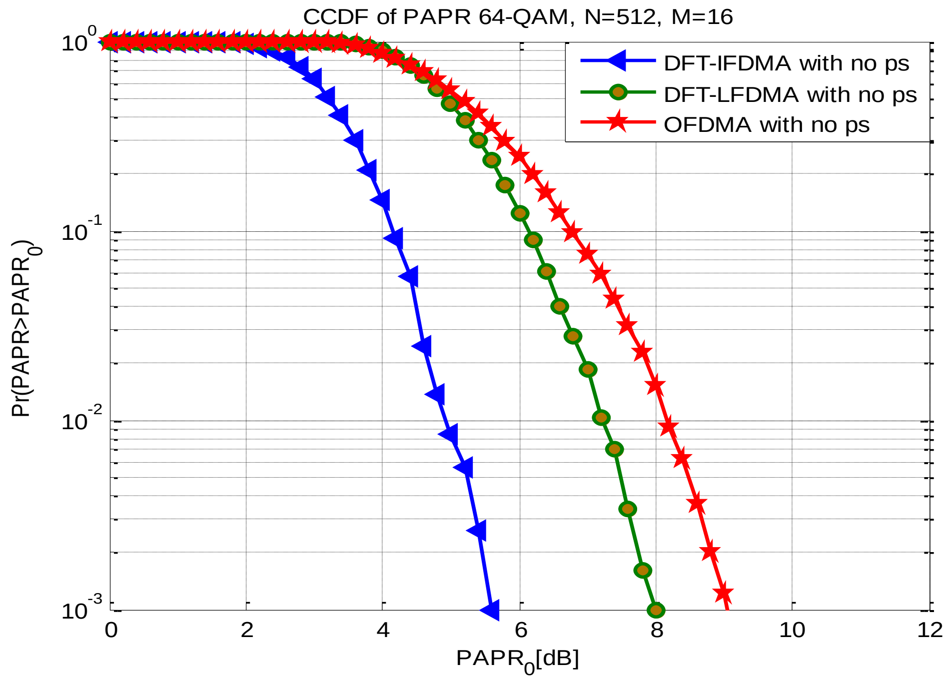

Figure 3.4. Comparison between the CCDFs of the PAPR for the DFT-IFDMA, the DFT-LFDMA and OFDMA systems with-out pulse shaping (64-QAM).

The CCDFs of the PAPR for the DFT-IFDMA, the DFT-LFDMA and the OFDMA systems with 64-QAM modulation are shown in Figure 3.4. It is clear that with out pulse shaping, the DFT-IFDMA system has a lower PAPR than that of the OFDMA system by about 3.4dB, while the PAPR of the DFT-LFDMA system is lower than that of the OFDMA system by about 1dB, but higher than that of the DFT-IFDMA system by about 2.4dB.

A full comparison of the PAPR for the different modulation formats at a CCDF = 10^{-3} is given in Table 3.2. It is clear that the DFT-IFDMA and the DFT-LFDMA systems have lower PAPR values than the OFDMA system.

Schemes	PAPR (dB)		
	QPSK	16 QAM	64 QAM
OFDMA with no PS	9.4	9.1	9
DFT-IFDMA with no PS	0	4.7	5.6
DFT-LFDMA with no PS	7	7.8	8

Table 3.2 PAPR values at a CCDF = 10^{-3} for the different schemes.

2.2 The impact of the RC filter pulse shaping on the PAPR of DFT-SC-FDMA

The impact of the pulse shaping (RC filter) on the CCDF of the PAPR for DFT-IFDMA and DFT-LFDMA is evaluated in this section for different modulation formats (QPSK, 16-QAM and 64-QAM). The number of data blocks generated is 5.10^3. Simulation parameters are tabulated in Table 3.3.

Parameters	Values
Channel bandwidth	5Mhz
Oversampling factor	4
User subcarriers	16
System subcarriers	512
Spreading	DFT
Modulation schemes	QPSK, 16-QAM and 64-QAM
Subcarrier mapping scheme	Interleaved and Localized
RC pulse shaping factors	Alpha=0, 0.4, 0.8

Table 3.3 Simulation parameters with in pulse shaping.

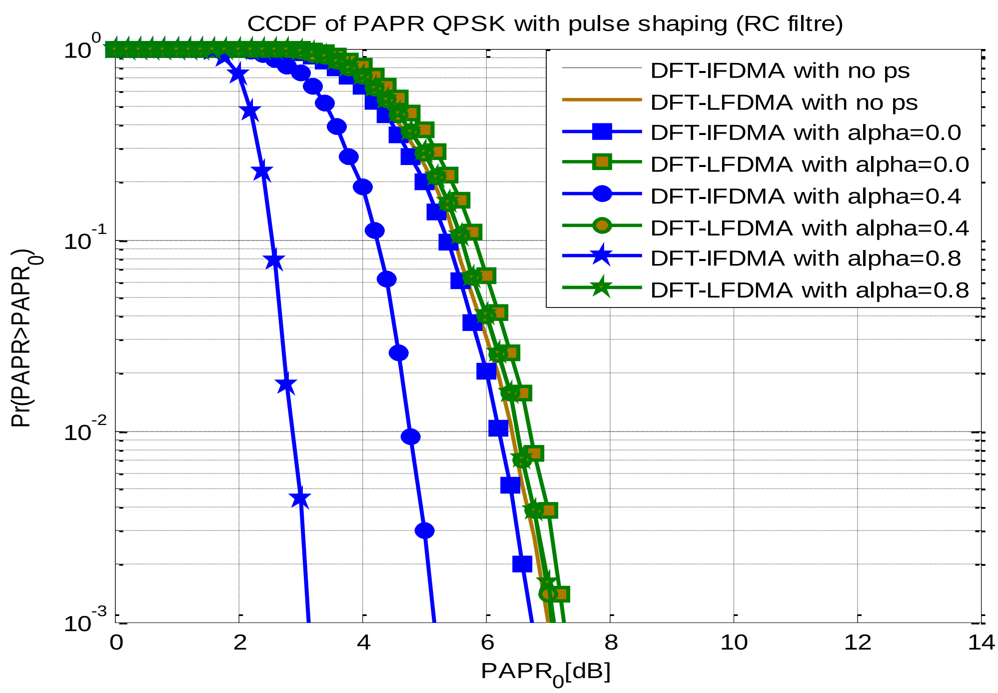

Figure 3.5 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using RC pulse shaping with different roll-off factors (QPSK).

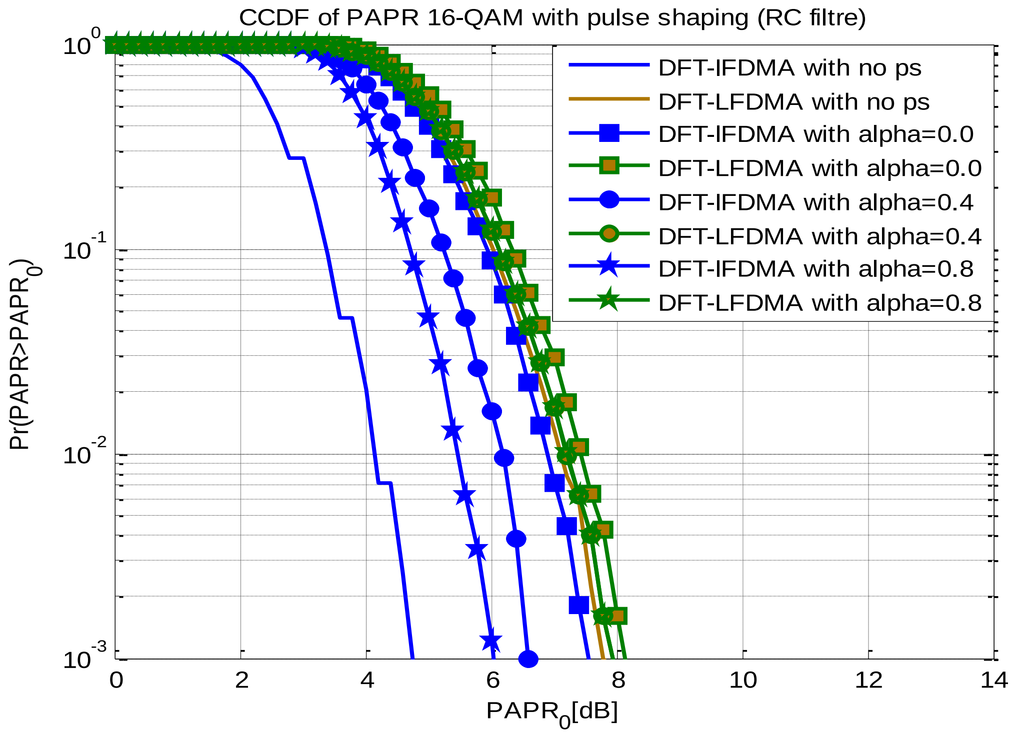

Figure 3.6 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using RC pulse shaping with different roll-off factors (16-QAM).

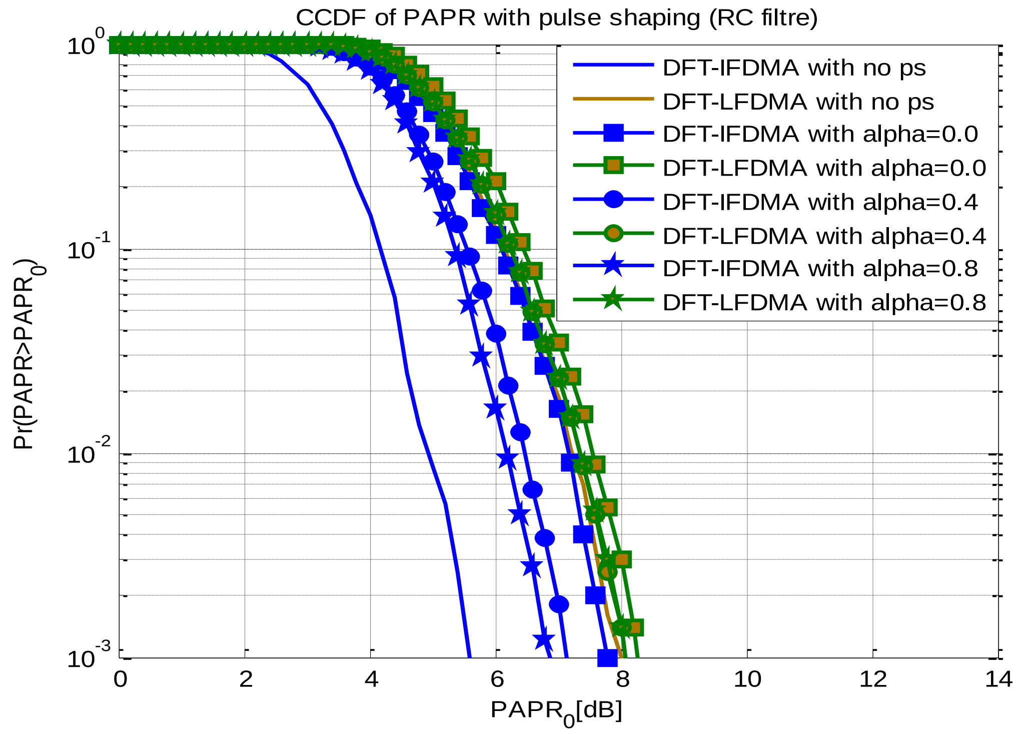

Figure 3.7 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using RC pulse shaping with different roll-off factors (64-QAM).

Figure 3.5, 3.6 and 3.7 show the CCDFs of the PAPR for DFT-IFDMA and DFT-LFDMA using pulse shaping at α=0.0, 0.4 and 0.8 with different modulation formats QPSK, 16-QAM and 64-QAM respectively. It can be seen from figures that the PAPR is reduced as α increases. This is because as α increases (large excess bandwidth), the RC filter ripples decay faster. Thus, the peak value of the transmit signal waveform will reduce appropriately. This implies that there is a trade off between PAPR performance and out of band radiation since out of band radiation increases with increasing roll-off factor.

A full comparison of the PAPR for the different modulation formats using pulse shaping at a CCDF = 10^{-3} is given in Table 3.2. It is clear that the PAPR of DFT-IFDMA and DFT-LFDMA is decreased as roll off factor increases.

Schemes	PAPR (dB)		
	QPSK	16 QAM	64 QAM
DFT-IFDMA with no ps	0	4.7	5.6
DFT-LFDMA with no PS	7	7.8	8
DFT-IFDMA (alpha=0)	6.8	7.5	7.8
DFT-LFDMA (alpha=0)	7.3	8.2	8.3
DFT-IFDMA (alpha=0.4)	5.2	6.6	7.2
DFT-LFDMA (alpha=0.4)	7.2	7.9	7.8
DFT-IFDMA (alpha=0.8)	3.2	6.1	6.8
DFT-LFDMA (alpha=0.8)	7.2	7.9	8

Table 3.4 PAPR Values at a CCDF = 10^{-3} for the DFT-IFDMA and the DFT-LFDMA schemes with different roll-off factors.

2.3 The impact of the number of subcarrier system on the PAPR of DFT-SC-FDMA with in pulse shaping

The impact of the number of subcarrier system on the PAPR of the DFT-IFDMA and DFT-LFDMA system has been studied for different modulation formats. M=16 and an RC filter with α=0.22 have been considered. 5.10^3 data blocks has been generated to calculate the CCDF of the system. Simulation parameters are tabulated in table 3.5.

Parameters	Values
Channel bandwidth	5Mhz
Oversampling factor	4
User subcarriers	16
System subcarriers	512, 256 and 128
Spreading	DFT
Modulation schemes	QPSK, 16-QAM and 64-QAM
Subcarrier mapping scheme	Interleaved and Localized
RC pulse shaping factors	Alpha=0.22

Table 3.5 Simulation parameters with different number of subcarrier system.

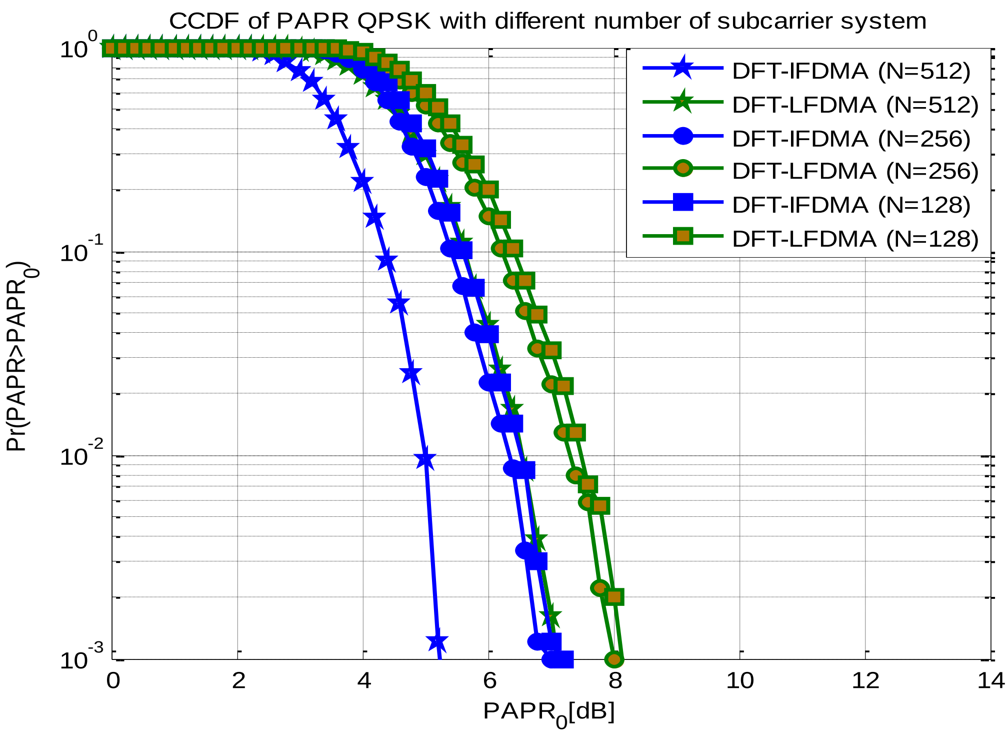

Figure 3.8 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using different number of subcarrier system (QPSK).

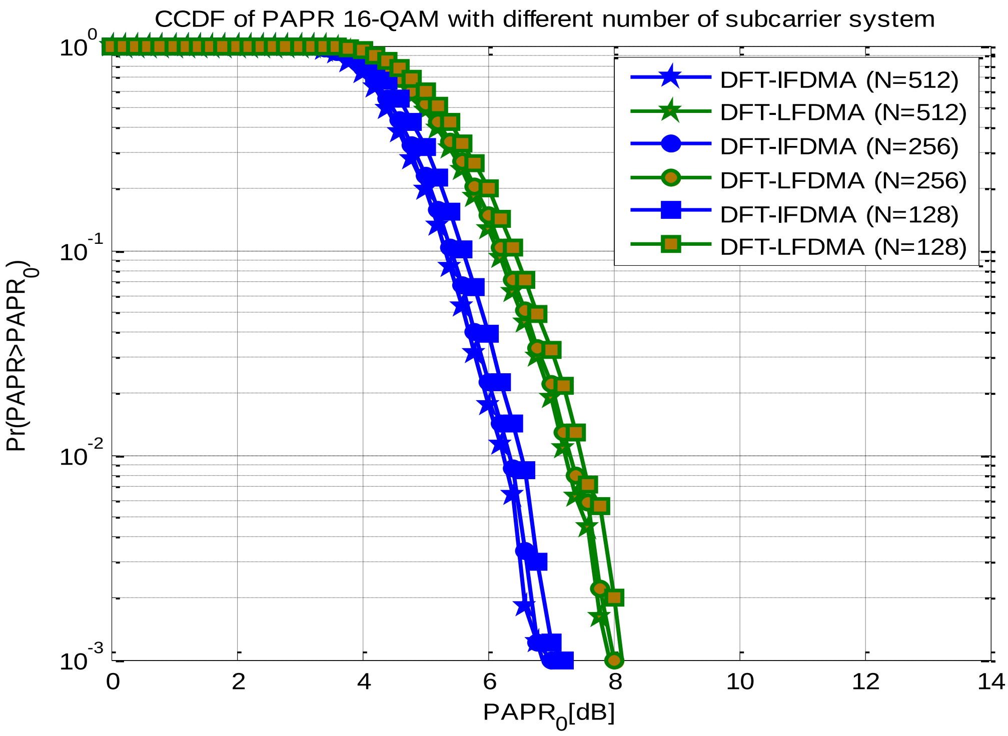

Figure 3.9 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using different number of subcarrier system (16-QAM).

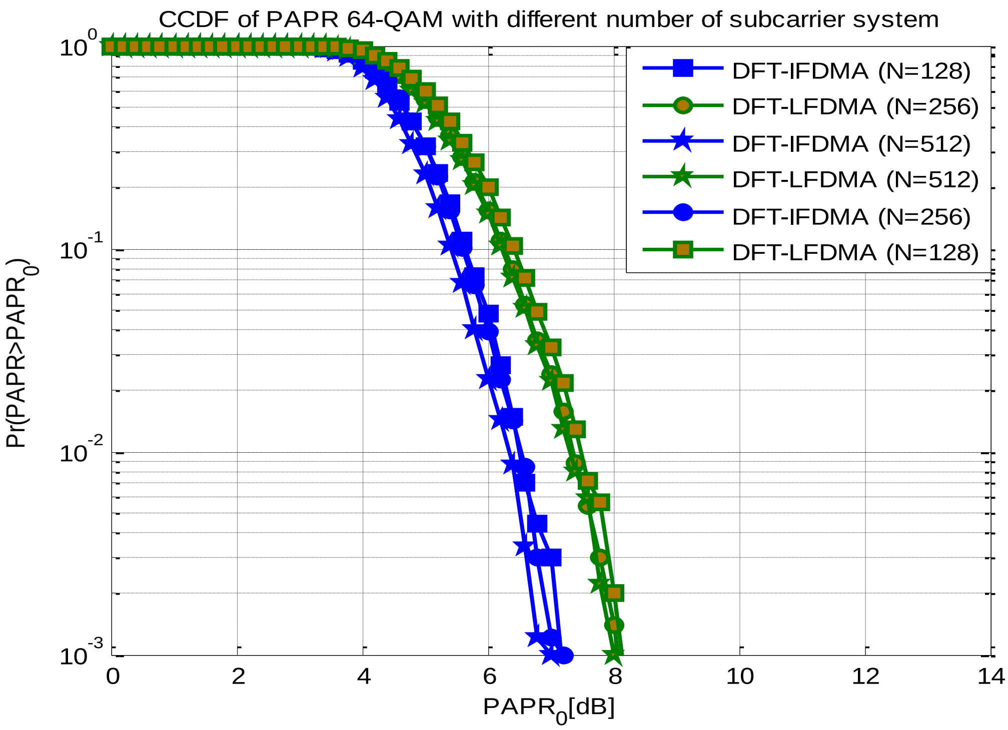

Figure 3.10 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using different number of subcarrier system (64-QAM).

The impact of the number of subcarrier system on the PAPR for the DFT-IFDMA and DFT-LFDMA with different modulation formats QPSK, 16-QAM and 64-QAM has been studied and shown in Figure 3.8, 3.9 and 3.10 respectively. M=16 and an RC filter with α=0.22 have been considered. It is observed that the PAPR of DFT-IFDMA and DFT-LFDMA depends on the number of subcarrier system. On the other hand, the higher number of subcarrier system correspond at the smaller PAPR value. As a result, improvements in the PAPR performance can be achieved by increasing the number of subcarrier system. This indicates that the number of subcarrier system must be chosen carefully in order to provide a good PAPR performance for the system.

To illustrate the impact of the number of subcarrier system on the PAPR of the DFT-LFDMA and the DFT-IFDMA systems, the measured PAPR values are tabulated in Table3.6. It is clear that the PAPR of the DFT-LFDMA and the DFT-IFDMA system decreases as the number of subcarrier system N increases.

Schemes	PAPR (dB)		
	QPSK	16 QAM	64 QAM
DFT-IFDMA (N=512)	5.3	6.8	7
DFT-LFDMA (N=512)	7.2	7.9	8
DFT-IFDMA (N=256)	7	7	7.2
DFT-LFDMA (N=256)	8	8	8.1
DFT-IFDMA (N=128)	7.2	7.2	7.2

Table 3.6 PAPR Values at a CCDF = 10^{-3} for the DFT-IFDMA and the DFT-LFDMA schemes with different number of subcarrier system.

2.4 The impact of the number of subcarrier per user on the PAPR of DFT-SC-FDMA with in pulse shaping

The impact of the number of subcarrier per user on the PAPR of the DFT-IFDMA and DFT-LFDMA system has been studied for different modulation formats. N=512 and an RC filter with α=0.22 have been considered. 5.10^3 data blocks has been generated to calculate the CCDF of the system. Simulation parameters are tabulated in table 3.7.

Parameters	Values
Channel bandwidth	5Mhz
Oversampling factor	4
User subcarriers	16, 32 and 64
System subcarriers	512
Spreading	DFT
Modulation schemes	QPSK, 16-QAM and 64-QAM
Subcarrier mapping scheme	Interleaved and Localized
RC pulse shaping factors	Alpha=0.22

Table 3.7 Simulation parameters with different number of subcarrier per user.

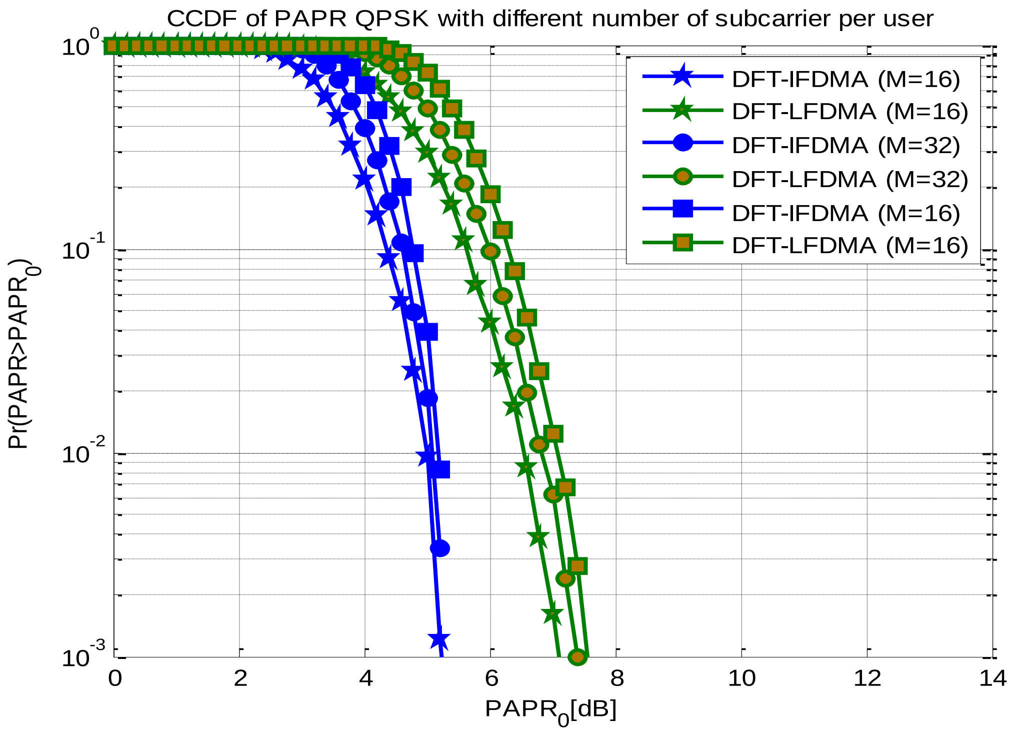

Figure 3.11 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using different number of subcarrier per user (QPSK).

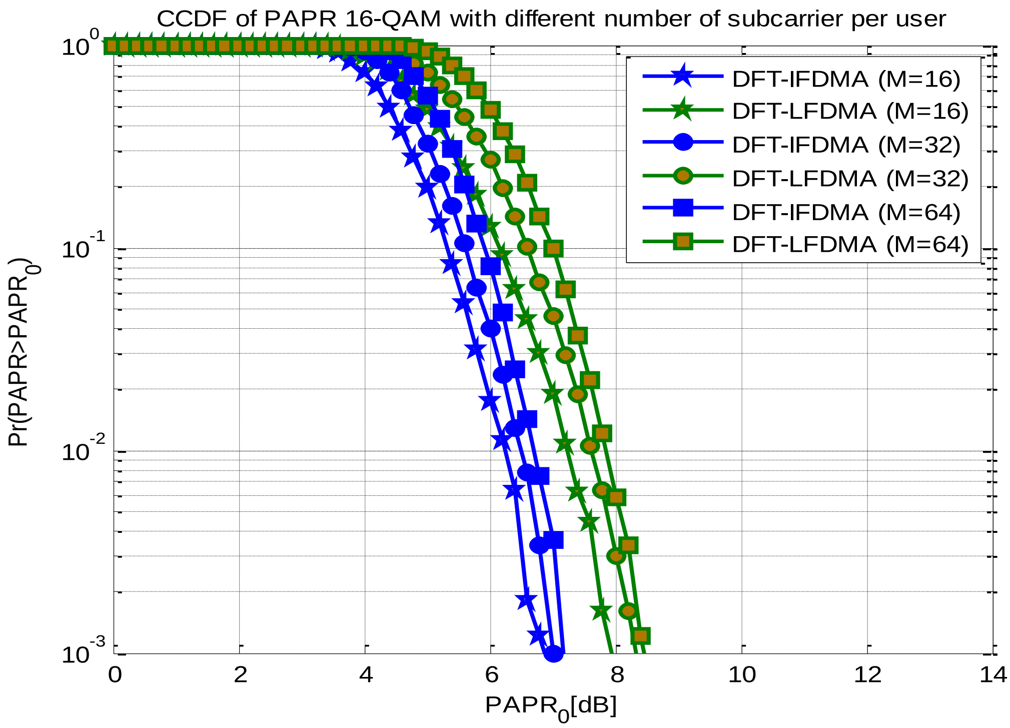

Figure 3.12 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using different number of subcarrier per user (16-QAM).

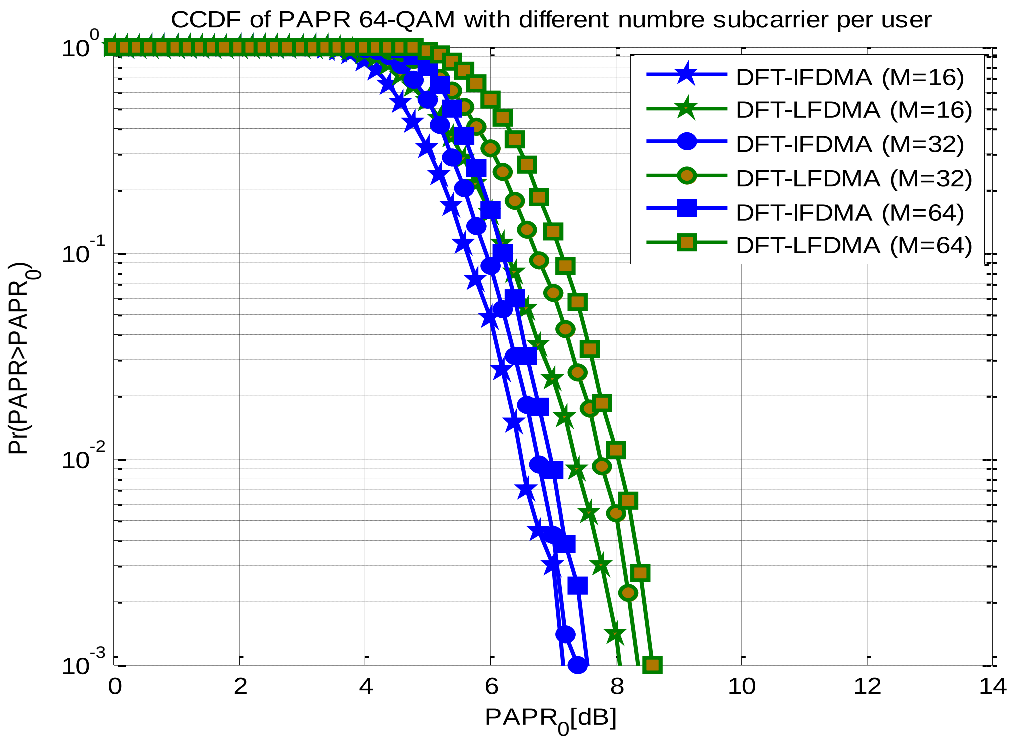

Figure 3.13 Comparison between the CCDFs of PAPR for the DFT-IFDMA and the DFT-LFDMA systems using different number of subcarrier per user (64-QAM).

The impact of the number of subcarrier per user on the PAPR for the DFT-IFDMA and DFT-LFDMA with different modulation formats QPSK, 16-QAM and 64-QAM has been studied and shown in Figure 3.11, 3.12 and 3.13 respectively. N=512 and an RC filter with α=0.22 have been considered. It is observed that the PAPR of DFT-IFDMA and DFT-LFDMA depends on the number of subcarrier per user. On the other hand, the higher number of subcarrier per user corresponds at the higher PAPR value. As a result, improvements in the PAPR performance can be achieved by decreasing the number of subcarrier per user.

To illustrate the impact of the number of subcarrier per user on the PAPR of the DFT-LFDMA and the DFT-IFDMA systems, the measured PAPR values are tabulated in Table3.8. It is clear that the PAPR of the DFT-LFDMA and the DFT-IFDMA system increases as the number of subcarrier per user M increases.

Schemes	PAPR (dB)		
	QPSK	**16 QAM**	**64 QAM**
DFT-IFDMA (M=16)	5.3	6.8	7
DFT-LFDMA (M=16)	7.2	7.9	8.1
DFT-IFDMA (M=32)	5.3	7	7.4
DFT-LFDMA (M=32)	7.4	8.3	8.3
DFT-IFDMA (M=64)	5.5	7.2	7.5

Table 3.8 PAPR Values at a CCDF = 10^{-3} for the DFT-IFDMA and the DFT-LFDMA schemes with different number of subcarrier per user.

3 Conclusion

In general, we can conclude the following points:

- ✓ The PAPR of the DFT-LFDMA system is lower than that of the OFDMA system but higher than that of the DFT-IFDMA system.
- ✓ The PAPR is reduced as α increase. This implies that there is a tradeoff between PAPR performance and out of band radiation since out of band radiation increases with increasing roll-off factor.

- ✓ The PAPR of DFT-IFDMA and DFT-LFDMA depends on the number of subcarrier system. This indicates that the number of subcarrier system must be chosen carefully in order to provide a good PAPR performance for the system.
- ✓ The PAPR of DFT-IFDMA and DFT-LFDMA depends on the number of subcarrier per user. The higher number of subcarrier per user corresponds at the higher PAPR value. As a result, improvements in the PAPR performance can be achieved by decreasing the number of subcarrier per user.

General conclusion

Broadband mobile wireless channel suffers from severe frequency-selective fading which causes the variation of received signal strength. OFDM is a multicarrier technique that overcomes the frequency-selective fading impairment by transmitting data over narrower sub bands in parallel but despite the many benefits, OFDM has a major drawbacks which is called the PAPR as we known in this work that the peak to average power ratio (PAPR) of OFDM is quite large which results in an inefficient usage of the high power amplifier (HPA) at the transmitter. The high PAPR causes the HPA to enter into the non-linear region and thus we get distortions due to non-linearities at the output of the HPA. For that 3GPP LTE has proposed DFT-spreading for reducing this problem of OFDMA.

In the first chapter, we gave an overview of LTE network and showed some performance requirements for LTE such as peak data rate, spectrum efficiency, reduced latency and mobility. The network architecture, protocols, quality of service, LTE handover and LTE advantages are investigated in this chapter.

In the second chapter, we first introduced OFDM and OFDMA systems where the principal advantage in broadband radio systems is the strong reduction in inter-symbol interference ISI. One disadvantage of OFDMA is the high peak-to-average power ratio PAPR, which raises the cost and lowers the power efficiency of a transmitter's power amplifier. With a lower PAPR, the power amplifiers at mobile terminals employing SC-FDMA can be simpler and more power-efficient than they would be with OFDMA transmission. On the other hand, with its high signaling rate, the frequency domain equalizer of an SC-FDMA link is far more complicated than an OFDMA equalizer. With SC-FDMA transmission confined to the LTE uplink, complicated equalizers are required only at base stations and not at mobile terminals. In this chapter, we introduced also SC-FDMA signal processing operations described the two approaches to assigning mobile terminals to subcarriers: localized FDMA

(LFDMA) and interleaved FDMA (IFDMA). Pulse-shaping filters are used to restrict the bandwidth of the transmitted signals, while minimizing the likelihood of decoding errors. Two pulse-shaping filters are considered in this chapter: the raised cosine RC and the root raised-cosine RRC filters.

In the last chapter, we investigated the PAPR performance of DFT-SCFDMA signal compared with OFDMA. The CCDFs of the PAPR for the DFT-IFDMA, DFT-LFDMA and the OFDMA system have been evaluated and compared for different modulation formats, also, the impact of the pulse shaping (RC filter), the impact of the number of subcarrier system and the impact of the number of subcarrier per user on the CCDF of the PAPR for DFT-IFDMA and DFT-LFDMA are evaluated for different modulation formats.

Finally, we can conclude that:

- ✓ The PAPR of the DFT-LFDMA system is lower than that of the OFDMA system but higher than that of the DFT-IFDMA system.
- ✓ The PAPR is reduced as α increase. This is because as α increases (large excess bandwidth), the RC filter ripples decay faster. Thus, the peak value of the transmit signal waveform will reduce appropriately. This implies that there is a tradeoff between PAPR performance and out of band radiation since out of band radiation increases with increasing roll-off factor.
- ✓ The PAPR of DFT-IFDMA and DFT-LFDMA depends on the number of subcarrier system. The higher number of subcarrier system correspond at the smaller PAPR value. As a result, improvements in the PAPR performance can be achieved by increasing the number of subcarrier system. This indicates that the number of subcarrier system must be chosen carefully in order to provide a good PAPR performance for the system.

- ✓ The PAPR of DFT-IFDMA and DFT-LFDMA depends on the number of subcarrier per user. The higher number of subcarrier per user corresponds at the higher PAPR value. As a result, improvements in the PAPR performance can be achieved by decreasing the number of subcarrier per user.

Bibliography references

[1] F. Khan, "**LTE for 4G Mobile Broadband Air Interface Technologies and Performance**", Cambridge University Press, Cambridge, U.K., 2009.

[2] D.Falconer, S. Ariyavisitakul, A. Benyamin-Seeyar, and B. Eidson, "**Frequency domain equalization for single-carrier broadband wireless systems**", IEEE Commun. Mag., 40(4), 58–66, April 2002.

[3] J. Coon, S. Armour, M. Beach, and J. McGeehan, "**Adaptive frequency domain equalization for single-carrier multiple-input multiple-output wireless transmissions**", IEEE Trans. Signal Process., 53(8), 3247–3256, August 2005.

[4] F. S. Al-kamali, M. I. Dessouky, B. M. Sallam, and F. E. Abd El-Samie, "**Performance evaluation of Cyclic Prefix CDMA systems with frequency domain interference cancellation**", Digital Signal Process., 19(1), 2–13, January 2009.

[5] A. Gusmao, P. Torres, R. Dinis, and N. Esteves, "**A reduced-CP approach to SC/FDE block transmission for broadband wireless communications**", IEEE Trans. Commun., 55(4), 801–809, April 2007.

[6] Y. Yoshida, K. Hayashi, H. Sakai, and W. Bocquet, "**Analysis and compensation of transmitter IQ imbalances in OFDMA and SC-FDMA systems**", IEEE Trans. Signal Process., 57(8), 3119–3129, August 2009.

[7] I. Koffman and V. Roman, "**Broadband wireless access solutions based on OFDM access in IEEEE 802.16**", IEEE Commun. Mag., 40(4), 96–103, April 2002.

[8] H. Schulze and C. Luders, "**Theory and Applications of OFDM and CDMA**", John Wiley & Sons, Ltd., Chichester, U.K., 2005.

[9] H. G. Myung and D. J. Goodman, "**Single Carrier FDMA: A New Air Interface for Long Term Evaluation**", John Wiley & Sons, Ltd., Chichester, U.K., 2008.

[10] Y. Wu and W. Y. Zou, "**Orthogonal frequency division multiplexing: A multicarrier modulation scheme**", IEEE Trans. Consum. Electron., 41(3),392–399, August 1995.

[11] N. Parasad, S. Wang, and X. Wang, "**Efficient receiver algorithms for DFT spread OFDM systems**", IEEE Trans. Wireless Commun., 8(6), 3216–3225,June 2009.

[12] Y. Zhu and K. B. Lataief, "**CFO estimation and compensation in single carrier interleaved FDMA systems**", in Proceedings of the IEEE GLOBECOM 2009, Honolulu, HI, pp. 1–5, 2009.

[13] Z. Cao, U. Tureli, and Y. Yao, "**Low-complexity orthogonal spectral signal construction for generalized OFDMA uplink with frequency synchronization errors**", IEEE Trans. Vehic. Technol., 56(3), 1143–1154, May 2007.

[14] H. G. Myung, J. Lim, and D. J. Goodman, "**Single carrier FDMA for uplink wireless transmission**", IEEE Vehic. Technol. Mag., 1(3), 30–38, September 2006.

[15] Z. Lin, P. Xiao, and B. Vucetic, "**Analysis of receiver algorithms for LTE SC-FDMA based uplink MIMO systems**", IEEE Trans. Wireless Commun., 9(1), 60–65, January 2010.

[16] Tariku temesgen mehari"**frequency hopping in lte uplink**" blekinge institute of technology ,sweden march 2009

[17] Suresh krishnan "**connecting a sensors to lte suresh krishnan**" university concordia montréal, québec, canada march 2012

[18] Sajid hussain "**dynamic radio resource management in 3gpp lte**" blekinge institute of technology january 2009

[19] Hyung g, j. lim, and david j " **single carrier FDMA for Uplink wireless Transmission** "-. ieee vehicular technology magazine | september 2006.

[20] Akanbasiam, apigagua Joshua "**the technical and cost assessment of some bwa technologies - a case study of knust**" kwame nkrumah university of science and technology may, 2012

[21] Yasir zaki "**future mobile communications: lte optimization and mobile network virtualization**" the faculty of physics and electrical engineering, university of bremen ,germany may 2012

[22] Mateo šoša "**the challenges of lte technologies**" polytechnic of zagreb professional study in electrical engineering zagreb, june 2013

[23] 3gpp technical report ts 36.410,"**E-utran; S1 general aspects and principles**"

[24] 3gpp technical report ts 36.420 "**E-utran; X2 general aspects and principles**"

[25] 3gpp ts 23.402, "**architecture enhancements for non 3gpp accesses**",dec 2007

[26] 3gpp technical specification 23.402, "**architecture enhancements for non- 3gpp accesses (release 8)**", www.3gpp.org.

[27] Flore, Dino; "**LTE RAN Architecture Aspects**", 3GPP, Beijing, 2009

[28] Holma, Harry;Toskala, Antti; "**LTE for UMTS – Evolution to LTE- Advanced**", Second Edition, John Wiley & Sons Ltd, Chichester, 2011

[29] E. Dahlman. "**3G evolution: HSPA and LTE for mobile broadband. Electronics & Electrical.**" Elsevier Academic Press, 2007.

[30] 3GPP Technical Specification TS 36.322. "**Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Link Control protocol specification**". Technical Report Version 10.0.0, 3rd Generation Partnership Project, December 2010.

[31] 3GPP Technical Specification TS 36.323. "**Evolved Universal Terrestrial Radio Access (E-UTRA); Packet Data Convergence Protocol (PDCP) specification**". Technical Report Version 10.1.0, 3rd Generation Partnership Project, March 2011.

[32] 3GPP Technical Specification TS 36.321."**Evolved Universal Terrestrial RadioAccess (E-UTRA); Medium Access Control (MAC) protocol specification**".Technical Report Version 10.2.0,3rd Generation Partnership Project, June 2011.

[33] H. Holma and A. Toskala. "**LTE for UMTS: OFDMA and SC-FDMA based radio access**". Wiley, 2009.

[34] Merah hocine ,"**conception d'un modem de la quatrième génération (4g) des réseaux de mobiles à base de la technologie mc-cdma**". universite ferhat abbas – setif 09 / 2012.

[35] Weinstein.S. B, Ebert P.M, "**Data Transmission by Frequency Division Multiplexing using the Discrete Fourier Transform**", *IEEE Transactions on Communications,* Vol- COM-19, pp. 628-634, Oct 1971.

[36] Richard Van Nee, Ramjee Prasad, "**OFDM for Wireless Multimedia Communications**", *Artech House Publishsers.*

[37] Ahmad R. S. Bahai, Burton R. Saltzberg, "**Multi-Carrier Digital Communications – Theory and Applications of OFDM**", *Kluwer Academic/Plenum Publishers.*

[38] M. Ruder"**Multiuser MIMO Receiver for the Uplink of Long Term Evolution (LTE)**", Nov. 2008.

[39] F. Khan, '**LTE for 4G Mobile Broadband: Air Interface Technologies and Performance**". New York, USA: Cambridge University Press, 2009.

[40] Miller, S.L . and O'Dea , R.J ., "**Peak Power and Bandwidth Efficient linear Modulation** " *IEEE Transactions on Communications,. Vol .46,no,12 dec* 1998.

[41] Sari Hikmat. "**OFDM Peak Power Reduction Techniques PerformanceAnalysis for WiMAX Systems**". Presentation Slides. 4th Annual Wireless Broadband Forum. Cambridge; 2005.

[42] Rapp Christoph. "**Effects of HPA-non-linearity on a 4-DPSK/OFDM signal for a digital sound broadcasting system**". 2nd European Conference on Satellite Communications. Liege; 1991

[43] H. G. Myung, J. Lim, and D. J. Goodman, "**Peak-to-Average Power Ratio of Single Carrier FDMA Signals with Pulse Shaping**," The 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '06), Helsinki, Finland, Sep. 2006.

[44] Sorger, U., De Broeck, I., and Schnell, M., "**Interleaved FDMA - A New Spread- Spectrum Multiple-Access Scheme,**" *Proc. IEEE ICC '98*, Atlanta, GA, Jun. 1998, pp. 1013–1017.

[45] Frank, T., Klein, A., and Costa, E., "**IFDMA: A Scheme Combining the Advantages of OFDMA and CDMA,**" *IEEE Wireless Commun.*, vol. 14, no. 3, June 2007, pp. 9–17.

[46] Myung, H.G., "**Single Carrier Orthogonal Multiple Access Technique for Broadband Wireless Communications**," Ph.D. Dissertation, Polytechnic University, Jan. 2007. Available online at http://hgmyung.googlepages.com/Hyung G Myung PhD thesis.pdf.

[47] Ifeachor, E. C., Jervis, B. W.,"**Digital Signal Processing: A Practical Approach**," Addisson-Wesley Publishing Co., 1996.