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PAPR In LTE Uplink: problem and improvement

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LIST OF ACRONYMS

2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Project Partnership
4G	Fourth Generation
ADC	Analog-to-Digital Converter
BPF	Bandpass Filter
BS	Base Station
CCDF	Complementary Cumulative Distribution Function
CDMA	Code Division Multiple Access
CM	Cubic Metric
CP	Cyclic Prefix
CSCF	Call Session Control Function
DAC	Digital-to-Analog Converter
DFDMA	Distributed Frequency Division Multiple Access
DFT	Discrete Fourier Transform
DL	Downlink
ENodeB	Enhanced NodeB
EPC	Evolved Packet Core
E-UTRA	Evolved -UMTS Terrestrial Radio Access
EV-DO	Evolution-Data Optimized
FDD	Frequency Division Multiplexing

FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
GSM	Global System for Mobile Communications
GTP	GPRS Tunnel Protocol
HD	High Definition
HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber Server
IFDMA	Interleaved FDMA
IFFT	Inverse FFT
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISI	Inter-symbol Interference
ITU-R	International Telecommunication Union Radio Section
LFDMA	Localized FDMA
LPF	Low Pass Filter
LTE	Long-Term Evolution
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-to-Average Power Ratio
PCRF	Policy Charging and Rules Function
PDN	Packet Data Network

PGW	PDN Gateway
P/S	Parallel-to-Serial
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RF	Radio Frequency
RSRP	Reference Signal Received Power
S/P	Serial-to-Parallel
SAE	System Architecture Evolution
SC-FDMA	Single Carrier- FDMA
SGW	Serving Gateway
SON	Self-Organizing Network
TDD	Time Division Multiplexing
TDMA	Time Division Multiple Access
UE	User Equipment
UL	Unlink
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband CDMA
WiMAX	Worldwide Interoperability for Microwave Access

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Abstract

LTE-Advanced is one of the most competing and widely adopted families of standards that will meet the 4G broadband wireless mobile communications requirements recommended by the IMT-Advanced for the terrestrial radio interface specifications. Pre-commercial deployments have proved that LTE-Advanced will ensure the competitiveness of the 4G mobile networks by providing a high-data-rate , low latency and optimized system.

Unlike the IEEE802.16m WiMAX which uses OFDMA in both downlink and uplink multiple access schemes, LTE and its advanced version systems continue to use different multiple access transmissions in which OFDMA and SC-FDMA are supported in the downlink and the uplink, respectively. The idea to use OFDMA in the LTE uplink communications invoked discord among the members of the 3GPP standardization body because of the growing concern over the signal peakiness which degrades the efficiency of mobile station power battery consumption. The dire consequence of the peak amplitudes generated by the superposition of several subcarriers of identical phases led 3GPP to adopt SC-FDMA as an uplink multiple access method.

Thus in this paper , the effect of pulse shaping on the performance of the uplink PAPR of distributed FDMA and localized FDMA will be dealt deeply. The performance improvement will be done by varying the roll-off factor of the raised-cosine filter for pulse shaping after IFFT.

KEYWORDS: LTE-Advanced, SC-FDMA, PAPR, DFDMA ,LFDMA

1. INTRODUCTION

In pre-industrial age, information was transmitted over line-of-sights distances using smoke signals, torch signaling, flashing mirrors, signal flares or semaphore flags. To convey complex messages with these elementary signals over large distances, observation stations were usually built on hilltops and along roads before these early communications were replaced by the telephone line. A few decades after the telephone was developed, the idea to relay information signals in free space was conceived leading to a rapid breakthrough of radio communications which enable transmissions over large distances with better quality , less power and smaller , cheaper devices (Goldsmith 2005: 1-3). In connection with this advancement of the radio technology, public and private radio communications, television broadcasts and wireless networking have gained a worldwide popularity and become inseparable from the daily lives of human beings.

In the last decade, there have been many advances in physical-layer wireless communication theory and their implementation in systems such as GSM, CDMA2000, 1x EV-DO and other wireless standards. The interplay between the theoretical concepts and their implementation in these systems have remained to be of great interest to engineers who are devoted their time and energy improving the performance of the wireless communications since the wireless technology is obviously one of the most dynamic areas in the field of radio communication which has been around for over a century.

The successful implementation of a theoretical concept requires an understanding of how the system as a whole reacts to the transmission channels. One of these challenging problems is *fading* —the time variation of the channel strengths due to small-scale effect of multi-path transmissions, as well as large-scale effect due to long-distance signal peak attenuation/path loss and shadowing by obstacles, while the other problem is the *interference* between the transmitter and the receiver in both the uplink and the downlink cellular systems as wireless users communicate over the air (Tse & Viswanath 2005: 24). Thus, to encounter these challenges, the design of wireless systems has traditionally focused on increasing the reliability of the air interface which has recently been superseded by the shift of the design more towards increasing spectral efficiency.

According to Garg (2007: 11-12), the link spectral efficiency of some common wireless communication systems is summarized as bellow.

Table 1.1. Spectral efficiency comparison for wireless technologies.

Service	**Standard**	**Link spectral efficiency (bits/s/Hz)**
2G	GSM	0.45
2.75G	CDMA200	0.0078/mobile
3G	WCDMA	0.077/mobile
3G	1x EV-DO	2.5/mobile
3.5G	HSDPA	8.44/mobile
3.9G	LTE	16.32/mobile
4G	LTE-Advanced	30.12/mobile

It is observed in the above table that mobile broadband wireless communications field is growing at a dramatically explosive rate, simulated by a host of important emerging applications like 4G.

The 4G mobile communications provide wireless broadband services at anytime and anywhere. Not only high quality voice and high data rates, 4G supports HD videos in very high speed. However, since the projections of rapidly escalating demand for these wireless services will present some challenges, network planners and designers should concentrate on finding sustained technical solutions to meet these challenges.

According to Nakamura (2009), the IMT-Advanced requirements for the radio interface technologies and core networks for 4G mobile broadband communications include the following:

- improvement of spectral efficiency ;
- different traffic support for real-time and non-real-time applications;
- re-use of existing cell site infrastructure ;
- flexible spectral allocation;
- lower cost per bit;
- improved Quality of Service;
- increasing coverage;
- improvement of latency ,capacity and throughput;
- simplified core network; and
- optimized IP traffic and services.

In the meantime, like in other cellular networks, all 4G the base stations in a given coverage area are connected via a high-speed communications link to a mobile switching center which acts as a central controller for the network, allocating channels within each cell, coordinating handovers between cells when a mobile traverses a cell boundary, and routing calls to and from mobile users, as well as can route voice calls through the PSTN or provide Internet access.

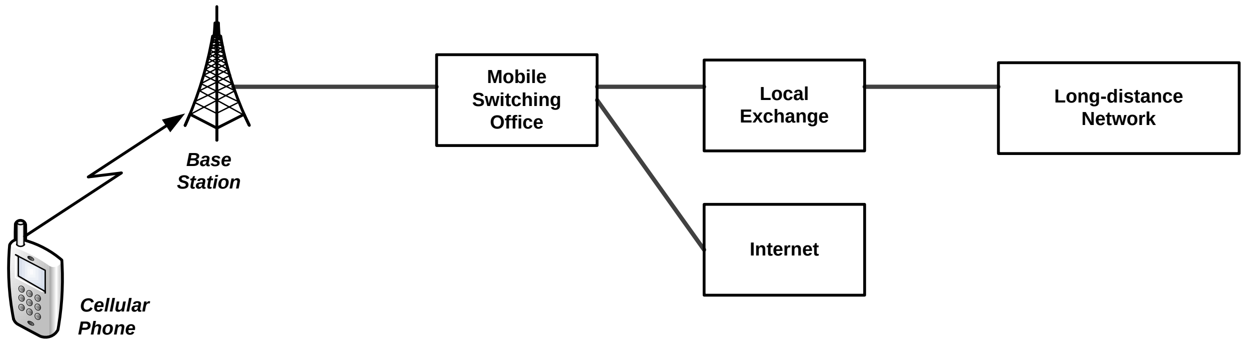

Figure 1.1. General cellular network architecture.

1.1. Overview of Mobile Wireless Standards

There is no doubt that standardization is required for communication systems to effectively interoperate with each other. Nationally or internationally recognized telecommunications committees usually adopt standards that are developed by other organizations so that competing companies will be able to innovate and differentiate their products from other standardized systems. The drawback of standardization is that the standards process is not perfect as frictions arising from own agendas and best interests of the customers of the company participants can lead to unrevitalized failure in technologies. It can also hinder innovations and improvements to the existing standards.

GSM and cdmaOne were the most prevalent 2G mobile wireless communication standards, evolved to UMTS with CDMA-2000 in close contention as two of the most competing 3G technologies. One of the most challenging problems to all radio access technologies is to divide the finite RF spectrum among the multiple users as efficiently as possible.GSM uses TDMA and FDMA for user and cell separation while UMTS, cdmaOne and CDMA-2000 use CDMA. Different from these standards are WiMAX which uses OFDMA in both UL and DL transmissions, and LTE system which uses OFDMA in the DL transmission and SC-FDMA in UL transmission. (Grag 2007: 5-10.)

1.2. Introduction to LTE-Advanced

LTE-Advanced standardization within the 3GPP has reached a mature state to be commercially deployed within the next few months. It is a natural evolution of 2G GSM and 3G UMTS, and an advanced version of LTE.

In September 2009, the 3GPP partners made a technical report to the ITU proposing LTE-Advanced requirements in the technical Specification Group Radio Access Network in LTE Release 10 & Beyond (Nakamura 2009). The radio interface technologies that were included in the ITU requirements for IMT-Advanced systems are given below:

- a high degree of commonality functionality worldwide;
- compatibility of services within IMT and with fixed networks;
- capability of interworking with other radio access systems;
- high quality mobile services;
- user equipment suitable for worldwide use;
- user-friendly applications, services and equipment;
- worldwide roaming capability; and
- enhanced peak date rates (100 Mb/s for high and 1Gb/s for low mobility).

The details of these requirements are summarized in the following table as according to Rohde and Schwarz (2010).

Table 1.2. LTE- Advanced radio interface specifications.

Parameters	**LTE-Advanced** **Release 10**
Peak Date Rate	UL: 500 Mb/s
	DL: 1 Gb/s
Control Plane Latency	Idle mode to connected mode < 50 ms
	Dormant mode to connected mode < 10 ms
User Plane Latency	< 1 ms
Spectrum Efficiency (bps/Hz)	UL 4×4 MIMO: 15
	DL 8×8 MIMO: 30
Average Spectrum Efficiency (bps/Hz/cell)	UL 1×2 MIMO : 1.2 UL 2×4 MIMO: 2.0
	DL 2×2 MIMO : 2.4 DL 4×2 MIMO : 2.6 DL 4×4 MIMO : 3.7
Cell Edge User Throughput (bps/Hz/cell/user)	UL 1×2 MIMO : 0.04 UL 2×4 MIMO: 0.07
	DL 2×2 MIMO : 0.07 DL 4×2 MIMO : 0.09 DL 4×4 MIMO : 0.12
Mobility	up to 500 km/hr
Spectrum Flexibility	450 –470 MHz band 698 –862 MHz band 790 –862 MHz band 2.3 –2.4 GHz band 3.4 –4.2 GHz band 4.4 –4.99 GHz band

1.3. Wireless Spectrum Allocation in LTE-Advanced

It is known that government agencies in most countries are responsible for allocating and controlling the commercial and military use of the radio spectrum. The spectrum allocation is done by the Federal Communications Commission, the European Telecommunications Standards Institute, the International Telecommunications Union Radio Communications Group in USA , Europe and for global use ,respectively (Goldsmith 2005: 17).

LTE-Advanced will be operating in spectrum allocations wider than 20 MHz bandwidth to support FDD and TDD for existing paired and unpaired frequency bands, respectively. To reach the high data rates requirements, multiple LTE system carriers are aggregated so that wider transmission bandwidths up to 100 MHz will be supported. According to Rohde & Schwarz (2010), the operating bands of LTE-Advanced will include the LTE Release 8 operating bands and possible IMT bands identified by ITU-R. Some of these operating bands are given in the following table.

Table 1.3. Operating bands of LTE-Advanced.

Operating Band	UL Operating Band BS receive/UE transmit	DL Operating Band BS transmit/UE receive	Duplex Mode
1	1920–1980 MHz	2110–2170 MHz	FDD
2	1850–1910 MHz	1930–1990 MHz	FDD
3	1710–1785 MHz	1805–1880 MHz	FDD
4	1710–1755 MHz	2110–2155 MHz	FDD
…			
15	Reserved	Reserved	-
16	Reserved	Reserved	-
…			
38	2570–2620 MHz	2570–2620 MHz	TDD
39	1880–1920 MHz	1880–1920 MHz	TDD
40	2300–2400 MHz	2300–2400 MHz	TDD
41	3400–3600 MHz	3400–3600 MHz	TDD

1.4. Goal and Scope of the Thesis

The primary objective of this thesis project is to study the effect of pulse shaping on the performance of LTE-Advanced uplink PAPR of distributed FDMA and localized FDMA. The idea to adopt OFDMA as an uplink multiple access scheme was so contentious at early stage of LTE development and thereby grabbed everybody’s attention because of the growing concern over the signal peakiness which impairs the efficiency of terminal battery consumptions. This led the 3GPP partners to have adopted SC-FDMA as a low signal peakiness uplink multiple access method as the performance improvement could be further enhanced by varying the roll-off factors of the raised-cosine filter for pulse shaping after IFFT.

1.5. Structure of the Thesis

Discussed in this chapter is the introduction which gets us familiar with 4G mobile wireless technologies and some radio interface parameters of LTE-Advanced, the subsequent chapters in this thesis are organized as follows.

Chapter 2 introduces the configuration of the LTE and its advanced version core network – a new system architecture which has improved the data transmission capacity of the wireless broadband communications.

Chapter 3 discusses the uplink multiple access transmission which is employed by subcarrier mapping and the implementation of FFT/IFFT. This is a unique feature of LTE and LTE-Advanced systems that the 3GPP standardization body was compelled to adopt in a bid to lower the signal peaking which derails the performance of the uplink communications.

Chapter 4 covers the measures of the uplink signal peakiness for different modulation sizes, low PAPR modulations and the raised-cosine pulse shaping techniques to reduce PAPR for SC-FDMA. This chapter is the main part of the thesis project, in which the roll-off factors of the pulse shaping will vary to investigate the levels of the uplink signal peakiness.

In chapter 5, conclusions which can summarize the findings in this paper are drawn, as well as some gaps which must be filled in the future works will be proposed.

2. SYSTEM ARCHITECTURE CONFIGURATION IN LTE-ADVANCED

In order that requirements for increased data capacity and reduced latency can be met, together with the move to an all-IP network, it is necessary for the cellular telecommunications to adopt a new approach to the network structure. Thus, one of the spectacular features of LTE system is the evolution of the core network, known as the System Architecture Evolution, which has been developed to provide a considerably higher level of performance that is in line with the requirements of LTE so that high data-rate can be handled. This new architecture has also been developed to fully support the 4G LTE-Advanced technology.

The SAE offers many advantages over the previous topologies and systems user for cellular core network. As a result of these privileges, LTE-Advanced is expected to be widely adopted by the cellular operators. According to Radio-Electronics.com (2012), some of these advantages are:

- improved data capacity;
- all IP architecture;
- reduced latency and;
- reduced capital expenditure and operational expenditure.

To enable simplified operations and easy deployment, this new architecture is based upon the existing core networks GSM/WCDMA. Nevertheless, the SAE network has brought in some changes to allow more efficient and effective transfer of data. The common principles used in the development of the LTE SAE network are listed below according to Radio-Electronics.com (2012); Holma & Toskala (2009: 23):

- a common gateway node and anchor point for all technologies;
- an optimized architecture for the user plane with only two node types;
- an all IP based system with IP based protocols used on all interfaces ;
- a split in the control/user plane between the MME and gateway ;

- a radio access network /core network functional similar to that used on WCDMA/HSPA;
- integration of non-3GPP access technologies using client as well as network based mobile-IP.

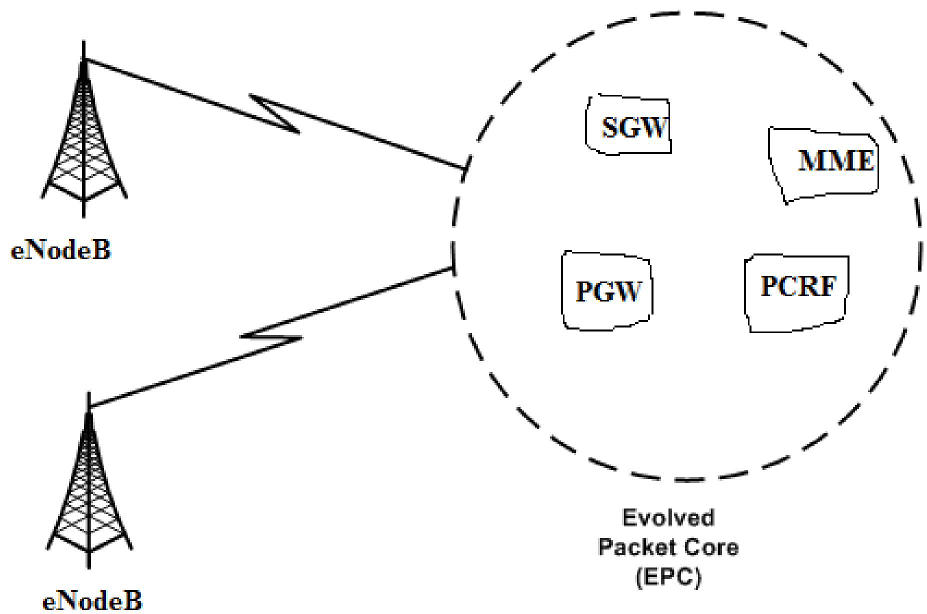

Figure 2.1. Elements of LTE SAE network.

As can be seen within the diagram, the main element of the LTE SAE network, the EPC which connects to the eNodeBs consists of four main components as described below.

1. *Mobility Management Entity* (MME): the main control node for the LTE SAE access network, handling the following activities
    - idle mode UE tracking ;
    - bearer activation/deactivation process;

- choice of SGW for a UE at the initial attach and at time of intra-LTE handover involving core network node location ;
- user authentication by interaction with Home Subscriber Server (HSS) and implementing roaming restrictions;
- provides temporary identities for UEs;
- supports lawful interception of signaling ;
- paging procedure; and
- provides the control plane function for mobility between LTE and 2G/3G access networks .

2. *Serving Gateway* (SGW): a data plane element within the LTE SAE, managing the user plane mobility and also acting as the main border between the RAN and the core network. It also maintains the data paths between the eNodeBs and PDN gateways so that when UEs move across areas served by different eNodeBs, the SGW serves as a mobility anchor ensuring that the data path is maintained.

3. *PDN Gateway* (PGW): provides connectivity from the UE to external packet data networks by being the point of exit and entry of traffic for the UE. The UE may have connectivity with more than one PGW for accessing multiple PDNs. The PGW performs policy enforcement, packet filtering for each user, charging support, lawful interception and packet screening.

4. *Policy and Charging Rules Function* (PCRF): is the node designated in real-time to detect the service flow, enforce charging policy in a multimedia network. Apart from its ability to be deployed as a standalone entity, PCRF can be integrated with different platforms like billing, rating, and charging and subscriber database.

2.1. LTE Self-Organizing Networks

The 4G LTE-Advanced radio core networks have become considerably complicated as the system requires smaller cell sizes to enable high data traffic to be handled. Thus, the need to reduce costs by implementing centrally self-organizing networks is seen as one of the major breakthroughs of the 4G wireless mobile communications. The SON development was adopted by the NGMN alliance as a result of the need within LTE system to deploy many more cells.

Accordingly, the 3GPP standardization body has generated the requirements for LTE SON system to sit alongside the basic functionality of LTE so that a SON-enabled broadband mobile network has been incorporated into useable 3GPP standards. The basic requirements of LTE self-optimizing networks will remain the same to any technology it will be applied. Then according to radio-electronics.com (2012), the primary areas over which LTE SON operates include the following:

- *Self-configuration* to reduce the operating cost by reducing the level of human intervention in the network design , build and operation;
- *Self-optimizing* to reduce capital expenditure by optimizing the use of available resource;
- *Self-healing* to protect revenue by reducing the number of human errors.

In self-configuring cellular networks, the base stations need as little manual intervention in the configuration process as possible, thereby saving costs while improving the reliability. In this manner, the major features within the overall self-configuring SON software are:

- ✓ automatic configuration of initial radio transmission parameters;
- ✓ automatic neighbor relation management;
- ✓ automatic connectivity management;
- ✓ self-test; and
- ✓ automatic inventory.

Once the system has been set up, the operational cost of the system should be optimized to best meet the demands of the overall network. Thus, the self-optimization routines are applied when the following events happen in the system:

- ✓ change in propagation characteristics;
- ✓ change in traffic patterns; and
- ✓ change in deployments.

Since faults which can cause major inconvenience to the users of the system network may occur, the self-healing aspects of the SON network will help the faults be detected and their effects masked to the users while the cellular network undergoes repairs. Then the number of areas that are addressed within the scope of self-healing includes the following:

- ✓ self recovery of software;
- ✓ self-healing of board faults;
- ✓ cell outage detection;
- ✓ cell outage recovery;
- ✓ cell outage compensation; and
- ✓ return from cell outage compensation.

2.2. IMS Architecture

Since LTE system only supports packet switching which runs over the standard IP-network , telecom operators and service providers which have been providing the 2G and the 3G voice calls will have to re-engineer their voice call networks. The implementation of this new adoption is based on the IMS network which provides all the services the Internet provides.

In this way, IMS will help service providers control and charge both mobile and fixed multimedia services which the users are able to access when roaming and from their home networks as well. This architectural frame for delivering IP multimedia services uses the SIP protocols as a signaling mechanism to ease the integration with the internet, thereby allowing the voice, text and multimedia services to traverse all connected networks (3GPP IMS: 2012). The work has enabled the 3GPP to ensure maximum reusability of internet standards, preventing the fragmentation of IMS standards.

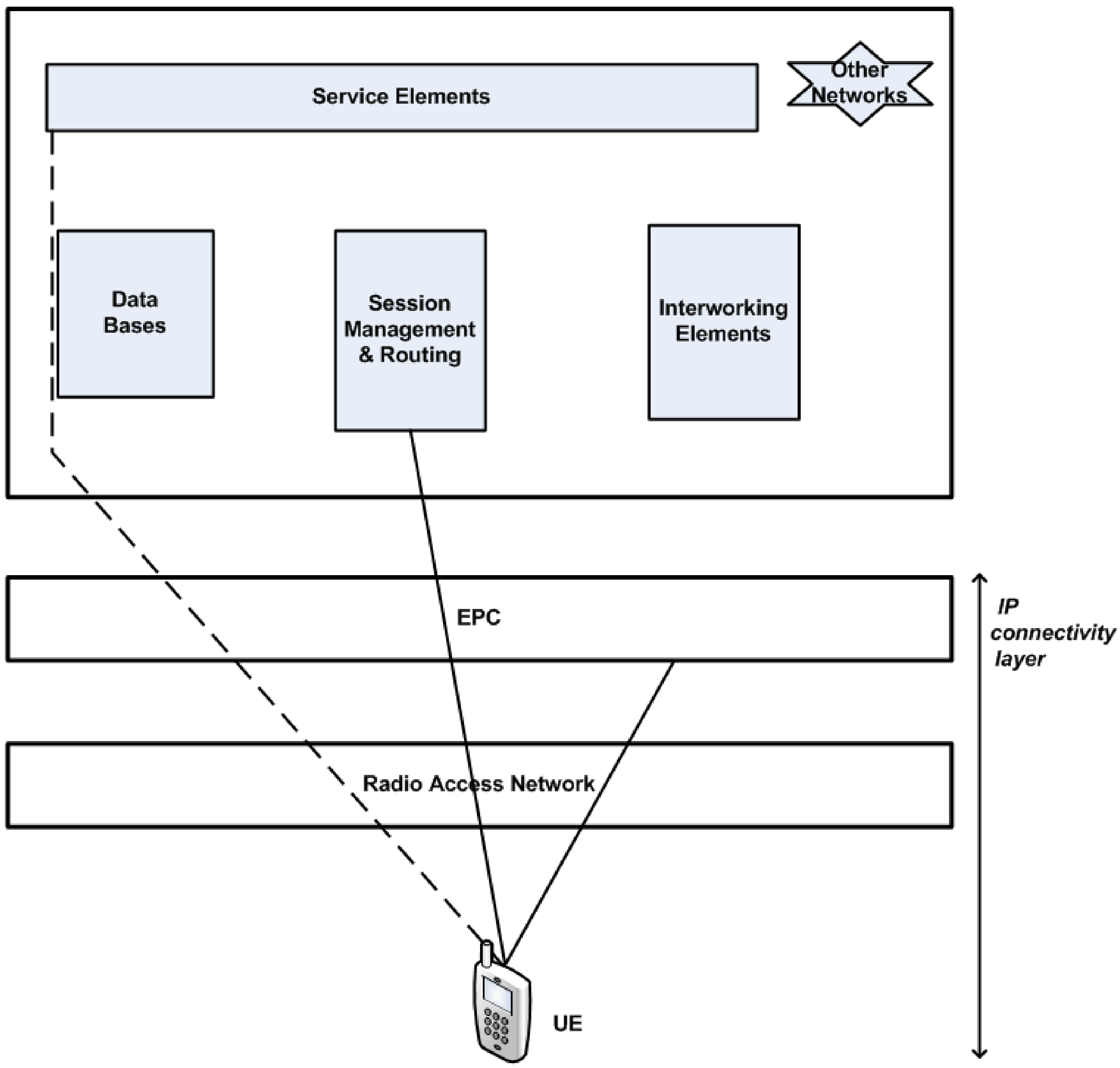

Figure 2.2. General IMS architecture.

2.3. Session Management and Routing

For a mobile station to use the services it needs, service signaling is directly run with the Application Servers. In session management and routing protocols, the CSCFs are in charge of the UE's registration in IMS and invoke the databases to gather appropriate information. Regarding the UE's service session in IMS, the CSCFs will signal the service elements to identify the type of connectivity needed for the services. The connection between the networks is controlled by the Interworking Elements. In addition, CSCF is playing an important role in handling an emergency call service in IMS, which has got its own dedicated channel.

2.4. Introduction to Mobility and Handover

Mobility offers a number of advantages to the user equipments as it enables the nomadic users to get connected anywhere within the providers network. Pre-commercial deployments of the 4G LTE-Advanced mobile communications have proved that delay-sensitive services such as voice calls or real-time video streams can be maintained while travelling by high-speed bullet trains.

Seamless mobility to guarantee a ubiquitous service has been a principal design focus for the cellular networks. Therefore, it is clear that stringent requirements should be set to avoid non-real time data loss during the service break in the handover procedure as tearing down and setting up new connections instead of seamless handovers may degrade the end-user data experience.

2.4.1. Mobility Scenarios

In order to find a suitable cell for initial camping with the best radio conditions based on cell RSRP measurements—measures signal power from a specific sector while potentially excluding noise and interference from other sectors, an LTE mobile station is powered on so that it scans all E-UTRA RF bands and starts to listen to the broadcast channels for synchronization. When the serving cell is selected, the mobile station accesses the network to measure intra-frequency neighbor's candidates for better cell reselection. The mobile station can also do the inter-frequency measurements of the neighboring cell received from the broadcast channel. The neighboring cell list contains system neighboring cells and their frequency carriers, and the end-user's parameters used in the measurements.

2.4.2. Handover Characteristics in LTE-Advanced

Handover is an important part of cellular communication system as it is used to providing continuity in cellular architectures of mobile services to a user travelling over cell boundaries in cellular infrastructure. For a user crossing the cell edge, it is more favorable to use the radio resources of the new target cell because the signal strength of the old cell decreases as the user approaches the target cell. The ability of a cellular network to perform efficient handovers in crucial to offer attractive services as real-time applications or streaming media are the merits of the 4G mobile networks.

The existence of the radio network connection to only one base station at a time makes handovers within an LTE and its advanced version tough even though the signaling connection and user plane tunnel are established to the target cell prior to switching the radio connection.

According to Holma et al. (2010: 167-171), the handover procedure in LTE system consists of three components, namely handover preparation, handover execution and handover completion. In the preparation process, data flows between the mobile station and the core network. At this stage, measurement control which includes UE measurement parameters is taken. The UE sends the measurement report to the serving eNodeB which establishes the signaling connection and GTP tunnel to the target cell which ensures the connectivity of the network connection by performing handover and admission control according to the availability of the radio resources. In the execution phase, the source eNodeB sends a handover command to the UE. If there is available resource at the target cell, the UE will switch the radio connection from the station to the target station. Finally in the handover completion, the target cell informs the MME that the user plane path has changed. The core network connection is updated in order for the data start flowing on the new path to the target cell.

3. INRODUCTION TO UPLINK MULTIPLE SCHEME

Mainly because of the many-to-one uplink transmissions, it is more challenging on the uplink than on the downlink to design an efficient multiple access and multiplexing scheme. One of the most important requirements for uplink transmission is to have low signal peakiness as high signal peakiness degrades the efficiency of transmission power at the mobile station.

There are reasons why the downlink OFDM was ruled out at the infant development of LTE systems as the uplink transmission scheme when compared to single-carrier systems. First, a large number of subcarriers in the system create a high peak-to-average power ratio that will impair the performance of the amplifiers. If we allow the peaks to distort, spectral regrowth develops in the adjacent channels; and if we try to modify an amplifier to avoid the distortions from degrading our system, we will incur additional cost, size and power battery consumption.

The other problem is that the tight spacing of subcarriers in the OFDM systems causes them to lose their orthogonality due to frequency errors which will in turn cause energy from one subcarrier's symbol to interfere with the next in the receiver.

However the 3GPP partners have, of course, solved some of these problems by introducing separation between the subcarriers. For example, to avoid the orthogonality loss caused by close subcarrier spacing when using long symbols, LTE system has adopted 15 kHz spacing, with a narrower 7.5 kHz chosen for Multimedia Broadcast Multicast Services.

3.1. Introduction to SC-FDMA

The two big disadvantages of OFDM system discussed in the preceding section led the 3GPP partners to choose a different modulation format for the LTE uplink transmission. Unlink the WiMAX which has continued to use OFDM in both the uplink and downlink multiple access methods, LTE in the uplink has preferred to use SC-FDMA, a new hybrid modulation method which smartly combines the low-PAPR of single-carrier systems with multipath resistance and flexible subcarrier frequency allocation. SC-FDMA is modified form of OFDMA and a promising technique for high data rate uplink communications in the future cellular systems. A principal advantage of SC-FDMA which got the attention of the 3GPP partners to cement its strong candidacy for the uplink multiple access scheme in the LTE of cellular systems is the ability to suppress a high PAPR that dries up the battery power of an end user.

3.2. Implementation of FFT/IFFT in uplink transmission

In the LTE system uplink transmissions, the input data is mapped on a signal constellation mapping and QPSK/QAM symbols are sequentially fed into an S/P converter and then fed into an FFT block which transforms the time-domain signal to a corresponding frequency-domain signal. This unique feature helps the uplink transmission method keep PAPR at a lower value so that mobile stations will have durable and efficient power batteries. In SC-FDMA, there could be some problems like ISI due to its single-carrier nature, but we have equalization techniques implemented at the receiver to deal with it. As a result, burdens loaded on mobile terminals will drop.

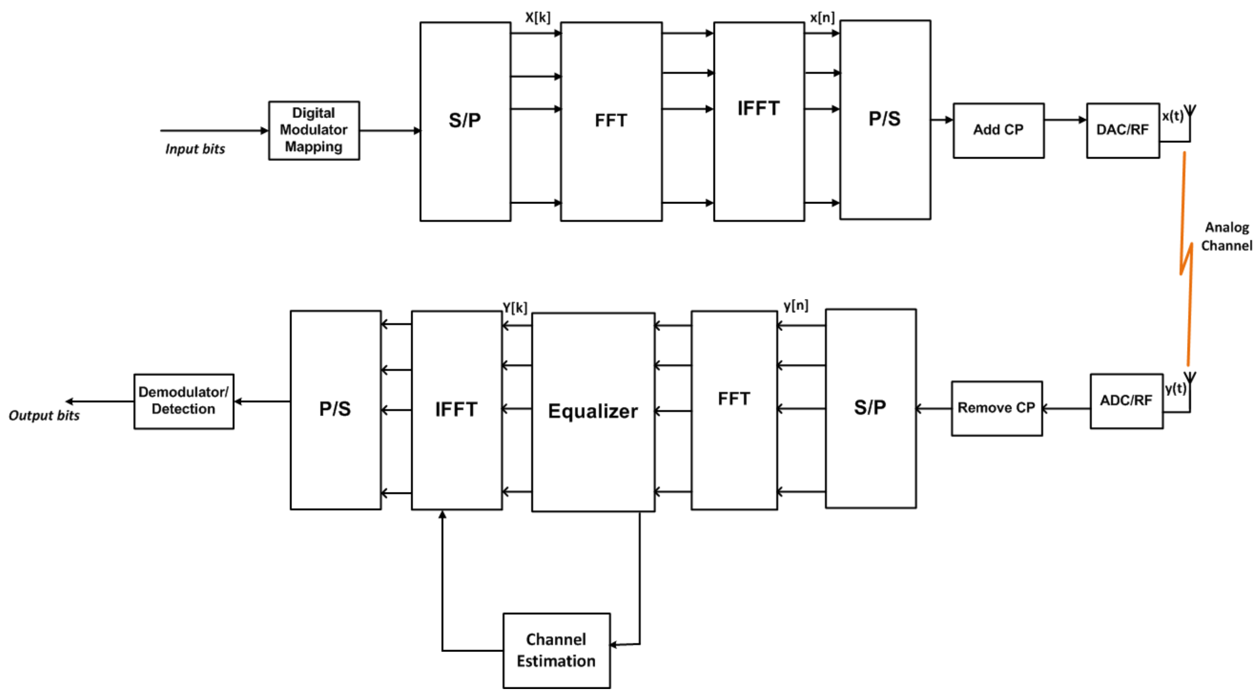

Figure 3.1. A block diagram of SC-FDMA transmitter and receiver.

3.3. Uplink Subcarrier Mapping

Two of the best approaches to mapping transmission symbols to SC-FDMA subcarriers are DFDMA and IFDMA. In DFDMA mapping scheme, FFT outputs of the input data are allocated over the entire bandwidth with zero occupying the unused subcarriers resulting in a non-continuous comb-shaped spectrum, whereas in IFDMA mapping mode, consecutive subcarriers are occupied by the FFT outputs of the input data in the localized subcarrier mapping mode resulting in a continuous spectrum that occupies a fraction of the total available bandwidth (Cho, Kim, Yang & Kang 2010: 242; Myung, Lim & Goodman 2006: 1-9).

Let us take the following values for a practicality show because with the number of subcarriers in system M=1024 in a practical LTE-Advanced, the number of possible mappings of the N symbols in each block onto the M>N transmission subcarriers will be too large to consider.

- M=12 the number subcarriers in the system
- N=4 the data block size
- S=3 the number of users

x_0	x_1	x_2	x_3

FFT: $X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi nk/N}$

X_0	X_1	X_2	X_3

X_0	0	0	X_1	0	0	X_2	0	0	X_3	0	0

X_0	X_1	X_2	X_3	0	0	0	0	0	0	0	0

Figure 3.2. SC-FDMA transmit symbols in frequency domain for M=12, N=4 and S=3.

It is worth noting in figure 3.1 that after subcarrier mapping, the frequency data is transformed back to the time domain by applying M-point IFFT.

In DFDMA symbol mapping, the input data $x[n]$ is FFT-spread to generate $X[k]$, and then mapped symbols are allocated as

$$\tilde{X}[k] \quad = \begin{cases} X[k/S], \ for\ k = S.m,\ m = 0,1,..,N-1 \\ \qquad\qquad 0,\ otherwise. \end{cases} \tag{3.1}$$

The IFFT output sequence $\tilde{x}[n]$, with n=$N.s$+q for s=0, 1,..., S and q=0,1,..,N-1 can be expressed as

$$\tilde{x}[n] = \frac{1}{M}\sum_{k=0}^{M-1}\tilde{X}[k]e^{j2\pi nk/M}$$

$$= \frac{1}{S}.\frac{1}{N}\sum_{m=0}^{N-1}X[m]e^{j2\pi nm/N}$$

$$= \frac{1}{S}(\frac{1}{N}\sum_{m=0}^{N-1}X[m]e^{j2\pi(N.s+q)m/N})$$

$$= \frac{1}{S}(\frac{1}{N}\sum_{m=0}^{N-1}X[m]e^{j2\pi\frac{n}{N}m})$$

$$= \frac{1}{S}x[n], \tag{3.2}$$

The above equation shows that the time-domain output of the IFFT block is the 1/S-scaled version of the original input data at the FFT block.

In IFDMA, the FFT-spread symbol can be expressed as

$$\widetilde{X}[k] \quad = \begin{cases} X\left[\frac{k-r}{S}\right], \ for\ k = S.m + r,\ m = 0,1,..,N-1 \\ \qquad\qquad\qquad 0,\ otherwise, \end{cases} \tag{3.3}$$

where r=0,1,…,S-1 is the position of the subcarriers where the mapping starts.

Then the corresponding IFFT output sequence is given as

$$\tilde{x}[n] = \frac{1}{M}\sum_{k=0}^{M-1}\widetilde{X}[k]e^{j2\pi nk/M}$$

$$= \frac{1}{S}.\frac{1}{N}\sum_{m=0}^{N-1}X[m]e^{j2\pi(\frac{nm}{N}+\frac{nr}{M})}$$

$$= \frac{1}{S}.\frac{1}{N}\sum_{m=0}^{N-1}X[m]e^{j2\pi(\frac{N.s+q}{N})m}e^{j2\pi\frac{nr}{M}}$$

$$= \frac{1}{S}(\frac{1}{N}\sum_{m=0}^{N-1}X[m]e^{j2\pi\frac{n}{N}m})e^{j2\pi\frac{nr}{M}}$$

$$= \frac{1}{S}x[n]e^{j2\pi\frac{nr}{M}}$$

$$= \frac{1}{S}e^{j2\pi\frac{nr}{M}}x[n], \tag{3.4}$$

It can be seen from the above equation that in IFDMA, time-domain symbols are simply the repetition of the original input symbols with a systematic phase rotation applied to each symbol in the time domain. This shows that the PAPR of IFDMA signal is the same as in the case of a conventional single-carrier signal.

In LFDMA FFT-spreading scheme, the IFFT input signal at the transmitter is given as

$$\tilde{X}[k] \quad = \begin{cases} X[k], \ k = 0,1,\ldots, N-1 \\ 0, \quad k = N, N+1, \ldots, M-1. \end{cases} \tag{3.5}$$

Then the IFFT output sequence for *n*=*S*.*m*+*s*, *s*=0, 1,..,*S*-1 is expressed as

$$\tilde{x}[n] = \tilde{x}[Sm+s]$$

$$= \frac{1}{S} \cdot \frac{1}{N} \sum_{k=0}^{N-1} X[k] e^{j2\pi(\frac{Sm+s}{N.S})k} \ , \tag{3.6}$$

If s=0, then equation (3.6) will be simplified as

$$\tilde{x}[n] = \tilde{x}[Sm]$$

$$= \frac{1}{S} \cdot \frac{1}{N} \sum_{k=0}^{N-1} X[k] e^{j2\pi(\frac{Sm}{N.S})k}$$

$$= \frac{1}{S} \cdot \frac{1}{N} \sum_{k=0}^{N-1} X[k] e^{j2\pi\frac{m}{N}k}$$

$$= \frac{1}{S} x[m], \tag{3.7}$$

If s≠0 and $X[k] = \sum_{p=0}^{N-1} x[p] e^{j2\pi\frac{pk}{M}}$, then equation (3.6) becomes

$$\tilde{x}[n] = \tilde{x}[Sm+s]$$

$$= \frac{1}{S}(1-e^{j2\pi s/S}).\frac{1}{N}\sum_{p=0}^{N-1}\frac{x[p]}{1-e^{j2\pi}(\frac{m-p}{N}+\frac{s}{SN})}$$

$$= \frac{1}{S}e^{j2\pi\frac{(N-1)s-Sm}{SN}}\sum_{p=0}^{N-1}\frac{\sin(\pi s/S)}{N\sin(\pi.\frac{Sm+s}{SN}-\frac{\pi p}{N})}.\hat{x}[p], \tag{3.8}$$

The equation (3.7) shows that the time-domain LFDMA signal is the 1/S-scaled copies of the original signal, while equation (3.8) depicts that the values in-between are obtained by summing all the input sequences with different complex weight factors.

4. TECHNIQUES TO REDUCE THE UPLINK SIGNAL PEAKINESS

In cellular systems, the downlink transmissions are one-to-many in which the base station transmits simultaneous signals to multiple UEs in its coverage area, while the uplink transmissions are many-to-one in a single UE has all its power transmission available to the base stations. The downlink communication requires a very high transmission power capability that should be shared among the mobile terminals to get the signals its destination. However, UEs may not be able to transmit high data rates in the uplink due a high peak transmission power limitation which would increase a data transmission time. This adds delays in the system and also a signaling overhead because of an increase in the number of scheduling grants as a result of the increased number of users requiring simultaneous transmissions.

One of the possible solutions to increase the data rates of the uplink cellular communications is to increase the size of the power amplifier. This would in fact be achieved at the expense of increased power amplifier cost and an end user batter consumption which is caused by the backoff required due to a high PAPR of the transmit signal. To achieve maximum power efficiency in the uplink with the same amplifier size, the signal peakiness needs to be reduced.

4.1. Introduction to PAPR

For amplifiers to avoid the introduction of signal distortion, the circuits must operate in a linear region so that maximum amplification will be achieved. Nevertheless if there is a high PAPR, the device is forced to run with lower amplification, thereof the peak power does not lie in the non-linear gain region. This will dry up batteries on mobile cell-phones more quickly and leads to increased power consumption. Hence, it is very important to keep a low PAPR on the uplink multiple access techniques.

Let us represent a baseband signal for a complex data sequence $x[n]$ as

$$\tilde{x}(t) = \sum_{k} x[n] g(t - kT_s) \ , \tag{4.1}$$

where $g(t)$ is a transmit pulse for each symbol ,and T_s is the symbol duration.

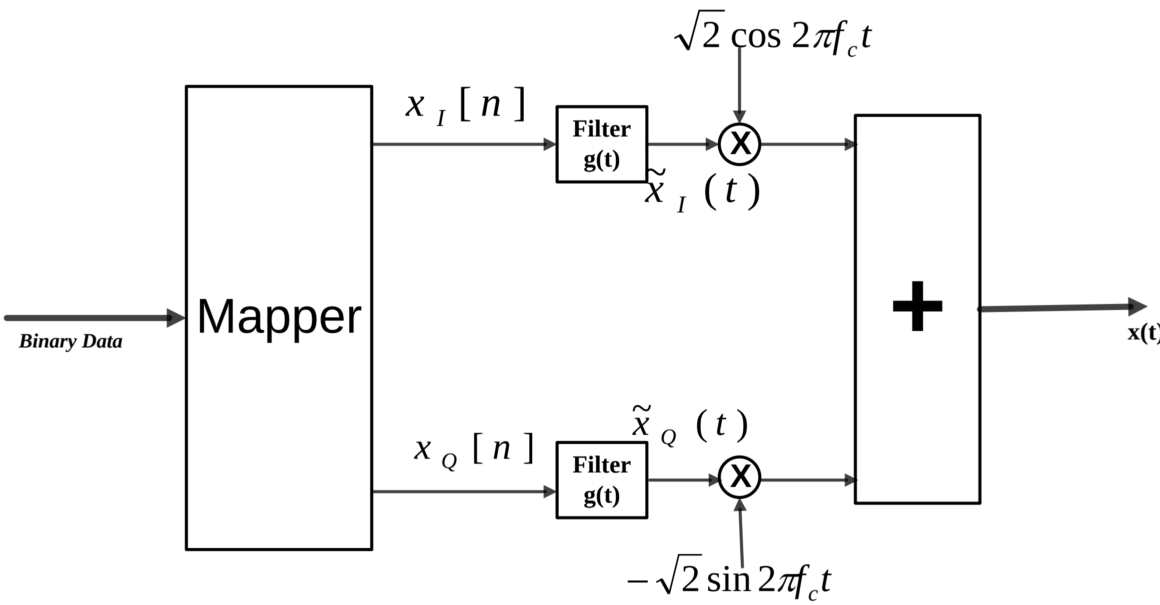

Figure 4.1. A baseband-passband transmitter.

As can be seen from the figure above, the output of the passband QAM modulator is given as

$$x(t) = \sqrt{2}\Re\{(\tilde{x}_I(t) + j\tilde{x}_Q(t))e^{j2\pi f_c t}\}$$

$$= \sqrt{2}\Re\{(\tilde{x}(t)e^{j2\pi f_c t}\}, \tag{4.2}$$

where $\tilde{x}_I(t)$ and $\tilde{x}_Q(t)$ are the in-phase and the Quadrature components of the complex baseband $\tilde{x}(t)$ signal. In the sequel, PAPR is the ratio between the peak power and the average of the complex passband signal, and expressed as

$$PAPR = \frac{\max\left|\Re(\tilde{x}(t)e^{j2\pi f_c t})\right|^2}{E[\left|\Re(\tilde{x}(t)e^{j2\pi f_c t})\right|]} = \frac{\max\left|x(t)\right|^2}{E[\left|x(t)\right|^2]}, \tag{4.3}$$

In the meantime, according to the Central Limit Theorem, the real and imaginary components of the transmitted signal in OFDMA system for a large number of subcarriers are Gaussian distributed. The superposition of this large number of parallel tones can be approximated by CCDF of a complex Gaussian random variable. This causes high PAPR that results in larger power back off in LTE and LTE-Advanced systems. Hence, the PAPR distribution can be approximated by CCDF of the complex Gaussian signal given as

$$\Pr(PAPR > x) = e^{-x}. \tag{4.4}$$

4.2. Measures of the uplink signal Peakiness

A closer look at the uplink signal peakiness is very important to consider the performance of a RF amplifier because low PAPR means an increased transmit power which provides higher data rates.

With one of the two best measures of the uplink signal peakiness, PAPR, discussed in the preceding section, the other measure will be studied here. In LTE standard performance evaluation, it was believed that PAPR may not be an accurate measure of an end user power amplifier backoff. A more effective measure of the actual reduction in power capability, referred as to cubic metric was developed as it was found to have a higher correlation with the measured power de-ratings and resulted in a tighter distribution of errors. The CM is expressed as

$$CM = \frac{20\log[(v_n^{\ 3})_{rms} / (v_{ref}^{\ 3})_{rms}]}{F}, \tag{4.5}$$

where v_n is the normalized voltage waveform of the input signal, v_{ref} the normalized reference voltage and F=1.85 is the empirical factor obtained by linear curve fit of CM of the reference power amplifier de-rating curve.

The main purpose of using CM is to model the impact of power amplifier non-linearity on the adjacent channel leakage which is caused by the third order non-linearity of the amplifier’s voltage gain characteristic. This amplifier voltage gain characteristic can be written as

$$v_0(t) = G_1 \times v_{in}(t) + G_3 \times [v_{in}(t)]^3, \tag{4.6}$$

where $v_{in}(t)$ is the input voltage to the amplifier , $v_0(t)$ is the output voltage ; G_1 and G_3 are the linear and the non-linear amplifier gains dependent on the amplifier design ,respectively.

4.3. Uplink transmission Coverage Gains due to Low PAPR

A small fraction of a dB transmit power gain can improve the transmission coverage with low signal peakiness in the uplink wireless communications. Let us look at the propagation analysis in the free space so as to deal with the coverage extension. Given P_t to be the radiated power of an isotropic radiator source, the power flux density at a distance *r* from the source is expressed as, according to Sklar (2001)

$$P_D = \frac{P_t}{4\pi r}. \tag{4.7}$$

If a receiving antenna is placed on a spherical wave front, then the received power is given as

$$P_r = P_D.A_r$$

$$= \frac{P_t}{4\pi r} A_r , \tag{4.8}$$

where A_r is the effective aperture area of the receiving antenna. The gain of the transmitter antenna of an isotropic radiator is given as

$$G_t = \frac{4\pi A_t}{\lambda^2}, \tag{4.9}$$

where A_t is the effective aperture of the transmitting antenna, and λ is the signal wavelength. The received power can be written and derived as

$$\begin{aligned} P_r &= \frac{G_t P_t}{4\pi r}.A_r \\ &= \frac{G_t P_t}{4\pi r}.\frac{G_r \lambda^2}{4\pi} \\ &= G_t G_r P_t (\frac{\lambda}{4\pi r})^2, \end{aligned} \tag{4.10}$$

where G_r is the receiver antenna gain. The total pathloss in free space is expressed as

$$\begin{aligned} L_{dB} &= 10\log_{10}(P_t / P_r) \\ &= 10\log_{10}[(1/G_t G_r)\times(4\pi r/\lambda)^2] \\ &= 20\log_{10}(4\pi r/\lambda) - \log_{10}(G_t G_r) \\ &= 32.44 + 20\log_{10} r + 20\log_{10} f - 10\log_{10}(G_t G_r), \end{aligned} \tag{4.11}$$

where r is in meters and f is in GHz.

It can be observed from the equation (4.11) that the pathloss is increased by 6 dB every time the distance doubles. This implies that for every 6 dB power gain, the distance at which the transmission is accessible in the free space is doubled.

In cellular system, however, the received power at the mobile station in the downlink or the base station in uplink as a function of distance r between them decreases more than in the free space. Thus, the received power is generally given as

$$P_r \propto (\frac{1}{r})^{1/\alpha}, \tag{4.12}$$

where α is the power attenuation factor and $2 \le \alpha \le 4$. The incremental transmission coverage due to power gains achieved through low signal peakiness is given as

$$\begin{aligned}
\Delta A = \frac{A_1 - A_0}{A_0} &= \frac{\pi r_1^{\ 2} - \pi r_0^{\ 2}}{\pi r_0^{\ 2}} \\
&= \frac{r_1^{\ 2} - r_0^{\ 2}}{r_0^{\ 2}} \\
&= (\frac{r_1}{r_0})^2 - 1, \\
&= (10^{(P_g/10)^{1/\alpha}})^2 - 1, \\
&= 10^{(P_g/10)^{2/\alpha}} - 1,
\end{aligned} \tag{4.13}$$

where r_1 and r_0 are the original range and the range with power gain of P_g dB, respectively.

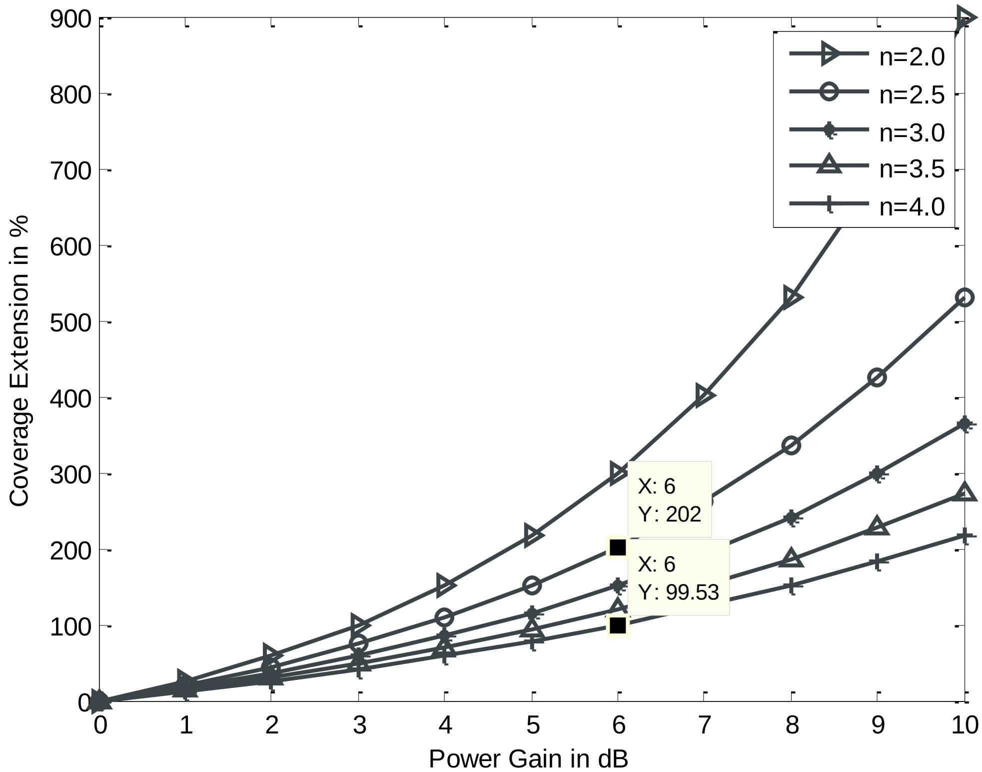

Figure 4.2. Transmission coverage area extensions as a function of transmit power gain P_g dB.

The above plot shows the coverage area improvements as a result of transmit power gain. It can be seen in the figure that, for example, a transmit power gain of 6 dB can extend the coverage area by 100 to over 200% for a pathloss exponent in the range of 3 to 4. This implies that a few number of transmitting base stations would be required to cover a geographical region resulting in a considerable amount of saving in system initial deployment cost.

4.4. PAPR Performance with Pulse Shaping

In addition to the adoption of SC-FDMA in the uplink system, pulse-shaping techniques can further reduce the signal peakiness of a single-carrier transmission. For time-domain processing of SC-FDMA, pulse shaping is used on the time-domain signal to reduce signal peakiness (Khan 2009: 98).

ISI is caused by a trail of the overall impulse response, which could impair the performance of a digital communication system. Hence, it should be minimized or completely eliminated by the transmit filter and receive filter. The severity on the system depends on symbol duration *T*, in which the shorter symbol period inflicts a larger influence of the ISI.

Given $g(t)$ the overall filter of the system, ISI can be eliminated by fulfilling the following time-domain condition on the overall impulse response:

$$g(nT) = \delta[n] = \begin{cases} 1, n = 0 \\ 0, n \neq 0. \end{cases} \tag{4.14}$$

The above equation is the Nyquist criterion which guaranteed ISI-free communication even with short symbol duration for high-data rate transmission in a single-carrier system. One of the filters that can satisfy Nyquist criterion is an idea LPF, which has a sinc function-type of impulse response and can be described in frequency-domain as

$$G_{LPF}(f) = \frac{1}{1W} rect(\frac{f}{2W}) = \begin{cases} T, |f| \leq 1/2T \\ 0, |f| > 1/2T \end{cases} , \tag{4.15}$$

where R and $W = \frac{R}{2} = \frac{1}{2T}$ are Nyquist rate and Nyquist bandwidth , respectively.

Even though the Nyquist bandwidth is the minimum possible bandwidth that is required to realize the data rate without ISI, the ideal filter is not physically realizable because its impulse response is not causal. Thus, we need to look for another physically realizable filter which is the raised-cosine filter. In frequency-domain, it is defined as

$$G_{RC}(f) = \begin{cases} T, |f| \le \frac{1-r}{2T} \\ T/2(1+\cos(\pi \mathrm{T}/r(|f| - \frac{1-r}{2T}))), \frac{1-r}{2T} < |f| \le \frac{1+r}{2T} \\ 0, |f| > \frac{1+r}{2T} \end{cases}, \tag{4.16}$$

where r is the roll-off factor that governs the actual bandwidth and $0 \le r \le 1$. The raise-cosine filters are usually used in wireless networks to produce a band-limited signal. A main feature of these filters is that they produce Nyquist pulse after matched filter to avoid any ISI that can damage the performance of the system.

In an ideal channel where a matched filter is used at the receiver, the frequency responses of the transmit and receive filters are equal, that is, $G_R(f) = G_T^*(f)$. Then the raised-cosine filter is re-evaluated as

$$\begin{aligned} G_{RC}(f) &= G_T(f) \times G_R(f) \\ &= G_T(f) \times G_T^*(f) \\ &= |G_T(f)|^2 . \end{aligned} \tag{4.17}$$

Equation (4.17) implies that $G_T(f) = \sqrt{G_{RC}(f)}$ .This is called a square-root raised-cosine typically used at the end of each communication system and represented as

$$G_{SRRC}(f)=\begin{cases}\sqrt{T}, |f| \le \frac{1-r}{2T} \\ \sqrt{T/2\{1+\cos\left(\frac{\pi \mathrm{T}}{\mathrm{r}}\left(|f|-\frac{1-r}{2T}\right)\right)\}}, \frac{1-r}{2T} < |f| \le \frac{1+r}{2T} \\ 0, |f| > \frac{1+r}{2T}\end{cases} . \tag{4.18}$$

Reduction techniques

There are different approaches to reduce PAPR, of which clipping, coding, scrambling and DFT-spreading techniques are those which commonly used. The clipping technique employs clipping or non-linear saturation to limit the maximum transmit signal to a pre-specified level so that PAPR will drop. This may cause in-band and out-of-band interferences which destroy the orthogonality among the subcarriers. However, filtering the clipped signal will reduce out-of-band interferences when clipping performed for sufficiently over-sampled signals in the discrete-time domain before a LPF and the signal passes through a BPF.

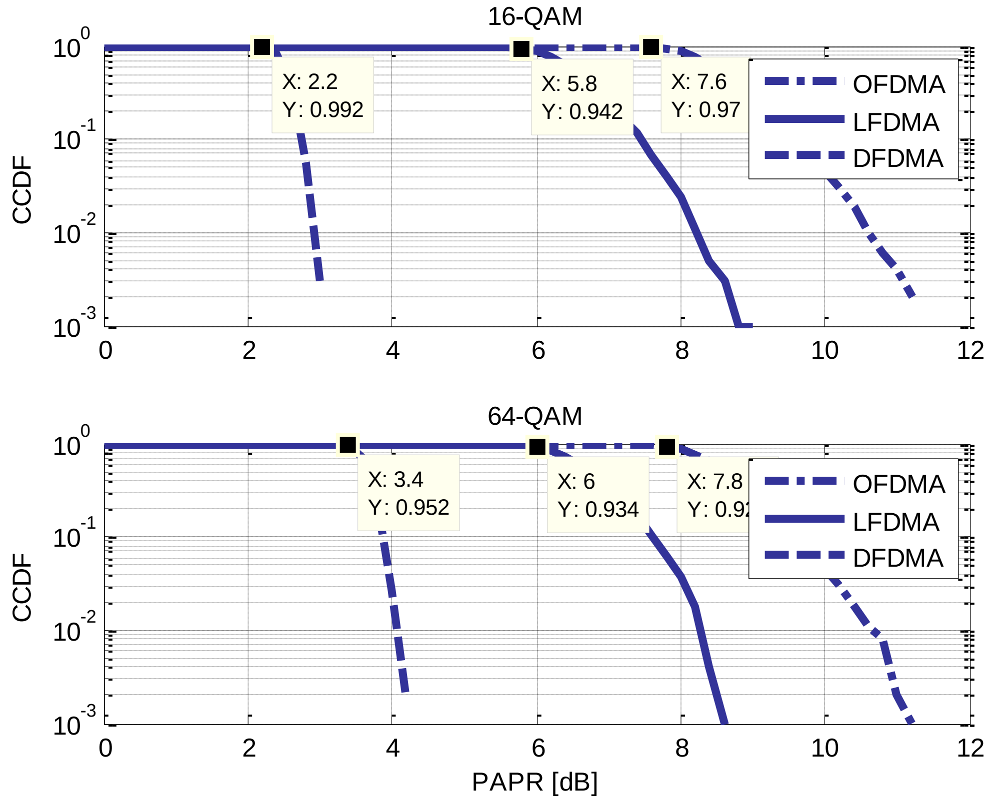

Figure 4.3. PAPR performance comparisons for OFDMA, DFDMA and LFDMA with *N*=256, *M*=1024.

The above figure shows the plots of CCDF of PAPR for OFDMA, DFDMA and LFDMA. For the sake of a simple comparison, the PAPR value that is exceeded with probability equal to 100%, i.e. pr ($PAPR>PAPR_0$) =1 will be considered. Then, it can be seen that DFDMA has lower PAPR than the case of OFDMA by 5.4 dB for 16-QAM and by 4.4 dB for 64-QAM, while the PAPR of LFDMA is lower than that of OFDMA by 1.8 dB for both modulation orders, but higher than that of DFDMA by 3.6 dB for 16-QAM and 3.6 dB for 64-QAM. This comparison clearly approves the reason which the 3GPP standardization body to have adopted SC-FDMA as an uplink transmission scheme. The following table can summarize the whole story of the above plots.

Table 4.1. PAPR comparison of OFDMA, DFDMA and LFDMA at CCDF=1.

Modulation order	DFDMA	LFDMA	OFDMA
16-QAM	2.2	5.8	7.6
64-QAM	3.4	6	7.8

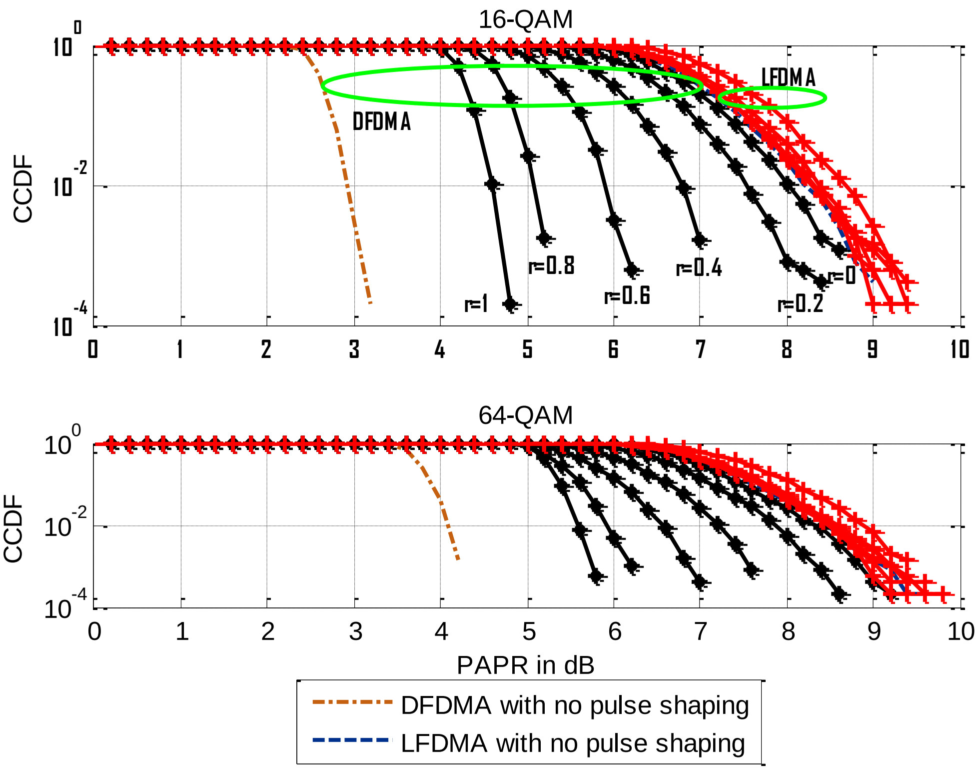

Figure 4.4. PAPR performance comparison between DFDMA and LFDMA with pulse shaping.

The plot shows the PAPR performance of DFT-spreading technique with DFMA and LFDMA, varying the values of the roll-off factor *r* of the raised-cosine filter for pulse shaping after IFFT. From the figure, it can be observed that the PAPR performance of DFDMA significantly improves as the roll-off factor increases from 0 to 1 even if DFDMA will have a trade-off between excess bandwidth and PAPR performance since the excess bandwidth increases as the roll-off factor becomes larger. However, the pulse shaping has no a significant effect on LFDMA subcarrier mapping.

Additionally, it has been seen from the above figure that modulation order does have a different effect on the performance of PAPR when there is no pulse shaping and DFDMA with pulse shaping is applied for the subcarrier mapping. Let us see a comparison for the two modulation formats at CCDF of 0.01 as in the following table.

Table 4.2. Comparison of PAPR for different modulation orders with roll-off factors *r*=0, 0.6,1.

Modulation type	**No pulse shaping**	**DFDMA with Pulse shaping**			**LFDMA with pulse shaping**		
		***r*=0**	***r*=0.6**	***r*=1**	***r*=0**	***r*=0.6**	***r*=1**
16-QAM	3	8	6	4.6	8.8	8.6	8.4
64-QAM	4.2	8.2	6.6	5.6	8.8	8.6	8.4

The table clearly shows DFDMA has a lower PAPR than LFDMA even though the LFDMA subcarrier mapping is usually preferred for its easy implementation as the DFDMA subcarrier allocation with equi-distance over the entire band requires guard band and pilot signals. In both DFDMA with pulse shaping and without pulse shaping, the performance of PAPR downgrades as the modulation order increases. However, it is observed that the modulation order does not have any effect on the performance of PAPR for LFDMA.

5. CONCLUSIONS AND THE FUTURE WORKS

It has been noted that reducing uplink signal peakiness by a few dBs could result in a significant amount of improvement in coverage area, which is particularly important in the uplink transmission where the coverage extension is very limited due to the impact of high battery consumption. This implies huge savings in deployments as SC-FDMA would require a fewer number of base stations to cover a rural geographical area than that required by OFDM. The SC-FDMA systems with DFDMA and LFDMA have a better performance than OFDMA systems. This unique feature has been adopted for uplink transmission in 3GPP LTE and LTE-Advanced, which has been evolved into one of the candidate radio interface technologies for the IMT-Advanced standards.

The main objective of this thesis project is to study the means to improve the uplink PAPR in 4G LTE-Advanced, specifically by varying the roll-off factors of raised-cosine for pulse shaping. In order to prove that the PAPR of SC-FDMA signals of the uplink transmission is lower than the case of OFDMA signals of the downlink transmission scheme , the PAPR characteristics of the time domain signals of DFDMA and LFDMA using CCDF of PAPR are numerically compared in the simulation analysis. The result shows that LFDMA incurs higher PAPR compared to DFDMA, but it has lower PAPR than that of OFDMA. Another noticeable fact is that pulse shaping increases PAPR and that roll-off factor of raised-cosine filter for pulse shaping has a significant impact on the performance of DFDMA. Nevertheless, with a roll-off factor of raised-cosine filter getting larger, it was seen that the performance of PAPR for DFDMA steadily increases, whereas that for LFDMA hardly does.

In conclusion, DFDMA subcarrier mapping is more desirable than LFDMA if you want to fully exploit the low advantage of SC-FDMA.

5.1. Future Works

In the future work of this paper, one should be trying to further reduce the impact of high PAPR on the uplink signal transmission by applying the same range of the raised-cosine roll-off factors after the signal has been clipped off the amplitude to a fixed level ,which improves the signal-to-quantization noise ratio of the system.

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