ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

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A Study on LTE to 3G Radio Access Technologies Handover in the Case of Ethiopia

A Thesis submitted in partial fulfilment of the requirement of degree of Master of Science in Communication Engineering

By

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‘A study on LTE to 3G Radio Access Technologies Handover in the case of Ethiopia’

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Declaration in lieu of oath

I hereby declare that the work presented in this thesis, titled "*A Study on LTE to 3G Radio Access Technologies Handover in the case of Ethiopia*," submitted to Adama Science and Technology University in partial fulfilment of the requirements of the degree of Master of Science in Communication Engineering, is the result of my own research carried out under the supervision of Dr. M V Raghavendra using solely the referred sources and support. I additionally assert that this thesis has not been part of another examination process.

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Abstract

Long Term Evolution (LTE) is a fourth-generation cellular network technology that provides improved network performance (spectrum efficiency, latency, and user data rates) compared to legacy cellular systems such as the third generation (3G) network.

Field test measurements are performed in real environmental conditions to study and analyze the performance of the network regarding handover from LTE to 3G networks in Addis Ababa, Ethiopia. Currently, LTE is deployed based on service hotspots covering only Addis Ababa area while the 3G network is deployed throughout the country. It is expected that full scale deployment of LTE takes a considerable amount of time which implies mobile users must primarily depend on legacy 3G and 2G networks for some future years. Therefore, it is important to study the handover mechanisms between LTE and legacy networks to provide seamless mobility and uninterrupted user services in the available LTE area.

In general, handover from LTE to 3G, and vice versa, is possible. However, LTE's higher priority over 3G allows a new user (LTE capable) to join LTE at first. When the user begins moving towards cell edge, LTE signal strength declines reaching a point where handover becomes a necessity. But, by design (few LTE sites), the coverages of neighboring LTE cells do not overlap with that of the serving LTE cell. Consequently, the service must be handed over to the 3G network which can be co-located with LTE or at a different cell.

On the other hand, a user accessing the 3G network can move seamlessly without the need for Inter-RAT handover as the 3G network has a full coverage. This thesis focuses on LTE to 3G handover because 3G service continuity can be assured without handovers from 3G to LTE, of course involving intra-technology handover (3G to 3G). That means, when a user equipment powers up, it accesses the preferred network (LTE) and then the service will be transferred to the next preferred network (3G) when the usermoves away from LTE coverage area. The reverse, 3G to LTE handover, takes place only when the user equipmentneeds to access high-speed data while it was using 3G's voice service in the case of Ethiopian network. As a result, user quality of experience (QoE) can be more affected by LTE to 3G handover than the opposite. Therefore, the most likely and the most network performance affecting scenario – LTE to 3G handover – is studied in this thesis.

Network parameters that are typically used to evaluate the performance of cellular networks are commonly referred to as Key Performance Indicators (KPI). In this thesis, KPIs including received signal level, handover success rate, downlink throughput, handover delay and service interruption are studied. Measurements are carried out at two different locations in Addis Ababa area – Bole and Kality sub-cities– with good radio conditions to study and demonstrate how KPIs and quality of service (QoS) are affected during the handover process.

Our Inter-RAT field tests and analysis of measurement results show that some data are lower and others are inconsistent with the Third-Generation Partnership Project (3GPP) recommendations and standard values. For example, we observed a good handover success rate. On the contrary, a handover delay of up to seven seconds was observed which is far from 3GPP's recommended value of half a second. Moreover, Handover triggering threshold values are set very low which is the primary reason for a perfect handover success rate. In general, our results show that further optimization and configuration changes are necessary to provide the desired QoS and to meet customer expectations.

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List of Abbreviations

1G	First Generation
2G	Second Generations
3G	Third Generations
3GPP	Third Generation Partnership Project
4G	Fourth Generations
ACK	Acknowledge Mode
AF	Application Function
AMPS	Advanced Mobile Phone System
APN	Access Point Name
AuC	Authentication Centre
ATM	Asynchronous Transfer Mode
AT&T	American Telephone & Telegraph
BCH	Broadcast Channel
BCCH	Broadcast Control Channel
BS	Base Station
BSS	Base Station Subsystem
CA	Carrier Aggregation
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CN	Core Network
CP	Control Plane
CP	Cyclic Prefix
CPICH	Common Pilot Channel
CQI	Channel Quality Indicator
CSFB	Circuit Switch Full Back
DCCH	Dedicated Control Channel
DFT	Discrete Fourier Transform
DHCP	Dynamic Host Control Protocol
DL	Downlink

DLSCH	Downlink Shared Channel
DSP	Digital Signal Processing
EDGE	Enhanced Data rates for GSM Evolution
ECM	EPS Connectivity Management
EIR	Equipment Identity Register
EMM	EPS Mobility Management
eNodeB	Evolved NodeB
EPC	Evolved packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
EUTRAN	Evolved UTRAN
FACH	Forward Access Channel
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
GGSN	Gateway GPRS Support Node
GI	Guard Interval
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GTP	GPRS Tunneling Protocol
HARQ	Hybrid Automatic Repeat Request
HLR	Home Location Register
HO	Handover
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed Downlink Shared Channel
HSPA	High Speed Packet Access
HSS	Home Subscription Server
HSUPA	High Speed Uplink Packet Access
HTTP	Hypertext Transfer Protocol
iDEN	integrated Digital Enhanced Network
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform

IMEI	International Mobile Equipment Identity
IMS	International Mobile System
IMSI	International Mobile Subscriber Identity
IP	Internet Protocol
IP-CAN	Internet Protocol Connection Access Network
ITU	International telecommunication union
IS	Interim-Standard
ISDN	Integrated Services Digital Network
ISI	Inter Symbol Interference
J-TACS	Japanese Total Access Communication System
KPI	Key Performance Indicator
LTE	Long Term Evolution
LAC	Location Area
LAI	Location Area Identity
LAU	Location Area Update
MAC	Medium Access Control
MCC	Mobile Country Code
MCH	Multicast Channel
MCCH	Multicast Control Channel
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MM	Mobility Management
MME	Mobility Management Entity
MMS	Multimedia Message Service
MNC	Mobile Network Code
MSISDN	Mobile Station Integrated Service Digital Network
MTCH	Multicast Traffic Channel
NACK	Non-Acknowledge Mode
NAS	Non-Access-Stratum
NMT	Nordic Mobile Telephone System

NSS	Network Switching Subsystem
NTT	Nippon Telephone and Telephone Company
O&M	Operation & Maintenance
OFDMA	Orthogonal Frequency Division Multiple Access
OLPC	Open Loop Power Control
PARP	Peak Average Power Ratio
PBCH	Physical Broadcast Channel
PCC	Policy and Charging Control
PCH	Physical Control Channel
PCCH	Paging Control Channel
PCFICH	Physical Control Indicator Channel
PCI	Physical Cell Identity
PCRF	Policy and Charging Resource Function
PDCCH	Physical Data Convergence Protocol
PDCP	Packet Data Convergence Protocol
PDC	Personal Digital Cellular Technology
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PGW	Packet Data Network Gateway
PHY	Physical Layer
PHICH	Physical Hybrid ARQ Indicator Channel
PLMN	Public Land Mobile Network
PMI	Precoding Matrix Indicator
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service

QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RAT	Radio Access Technology
RE	Resource Element
RLC	Radio Link Control
RF	Radio Frequency
RNC	Radio Network Controller
RRC	Radio Resource Connection
RRM	Radio Resource Management
RSCP	Received Signal Code Power
RSRP	Reference Signal Received Power
RSRQ	Received Signal Received Quality
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCTP	Stream Control Transfer Protocol
SFBC	Space Frequency Block Code
SGSN	Serving GPRS Support Node
SGW	Serving Gateway
SIB	System Information Block
SINR	Signal Interference Noise Ratio
SISO	Single Input Single Output
SIMO	Single Input Multiple Output
SMS	Short Message Service
SMPT	Simple Mail Transfer Protocol
SNR	Signal to Noise Ratio
TA	Tracking Area
TACS	Total Access Communication System
TAI	Tracking Area Identity
TAL	Tracking Area List
TAU	Tracking Area Update

TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TM	Transparent Mode
TTI	Transmission Time Interval
TTY	Tampereen Teknillien Yliopisto
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UP	User Plane
USIM	Universal Subscriber Identity Module
USCH	Uplink Shared Channel
UTRAN	Universal Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access
VAS	Value Added Service
VLR	Visitor Location Register
VMS	Voice Message Service
VoLTE	Voice over LTE

CHAPTER 1

Introduction

Due to the ever-increasing demand for broadband cellular data transfer, mobile operators need more efficient technologies to meet customer expectations and demands.In fact, cellular technologies have evolved over the last two decades in terms of efficiency, types of supported end user applications and availability. However, legacy cellular systems such as Global System for Mobile Communications (GSM) and its successor – Universal Mobile Telecommunications System (UMTS) – are designed and optimized for voice communication although the later supports high data rate communication, too. With the advent of applications that are demanding high speed data transfer, it became clear that next generation systems should be designed to meet such requirements. Mobile data traffic has already exceeded voice traffic in both volume and growth trend. There is no sign that mobile data traffic is going to saturate any time soon. As a result, mobile operators and standard organizations needed a technology solution that meets the overwhelmingly growing data traffic. Hence, the Third-Generation Partnership Project (3GPP) task force developed and standardized an evolutionary radio access technology called Long Term Evolution (LTE) [1].

LTE is a 4^{th} generation (4G) cellular mobile system standardized after the UMTS technology by 3GPP with several versions – starting from Release 8 and the latest being Release 12 – with several enhancements in each release. For this thesis, LTE release 8 is used as it is the currently deployed technology in Ethiopian capital Addis Ababa. In general, LTE is a fully-packet-switched technology as opposed to its predecessors which utilize circuit-switched technology for their voice traffic. LTE is designed for high performance air interface with other architectural and key technology differences from earlier generations of mobile systems. Compared to UMTS, LTE can provide higher data rates, lower latencies, higher spectral efficiency with backward compatibility to GSM, UMTS as well as non-3GPP networks.

With the fast-changing mobile landscape and convergence in all aspects of telecom, interoperability is an essential attribute for any technology to succeed. Operators and consumers both benefit from interoperability in terms of cost effectiveness, enhanced features, locationindependence and ease of use as costumers expect interrupted, efficient and stable service from mobile network while moving from one place to another.

At initial deployment, the coverage of LTE will be rather limited and concentrated on relevant traffic hotspot areas overlaying with legacy 3rd Generation (3G) coverage. Outside these areas, no LTE connection can be provided. To provide service continuity with a quality of service as good as that of existing 3G networks,handover mechanisms from LTE to 3G are necessary when user equipment (UE) leaves the LTE coverage area while having an active connection. Therefore, interoperability between different Radio Access Technologies – commonly referred to as Inter-RAT – accomplishes such service continuity. In other words, Inter-RAT mobility (handover) offers mobile operators the promise of extracting more value from their variety of different RATs and provides them with a powerful means for matching network resources to application requirements.

Inter-RAT handover is often forced by radio reason when one RAT has coverage limitation. User mobility while maintaining service connectivity for both voice and data traffic is an essential and core part of cellular networks. Hence, this thesis focuses on several aspects of the Inter-RAT Handover process from LTE to UMTS. These two technologies are chosen in this paper because bothsupport broadband data traffic and the high priority for LTE makesLTE to 3G handover the most common type of Inter-RAT handover when all technologies are available. The currently deployed LTE network in Ethiopia supports only data trafficwitha circuit-switched full-back support to voice users. Hence, this study focuses on Inter-RAT Handover for data traffic as explained in more detail in the following sections.

1.1. Background and Motivation

Global system for mobile communications (GSM) is the first type of mobile network deployed by Ethio telecom by the year 2000 where Ericsson and Nokia Networks provided the necessary equipment. Later in 2007, wideband code division multiple access (WCDMA) based 3G network and CDMA2000 network were implemented. Due to the growth in mobile data traffic and customer expectation for such services, Ethio telecom deployed high-speed packet access (HSPA) network and introduced LTE network in Addis Ababa since 2013. There are currently undergoing and other upcoming project activities which are related to 3G and 4G network expansions. The current LTE network in Ethiopia can be considered as a beginning towards a full-scale network coverage. As a result, network performance issues related to interoperability, user mobility, coverage, availability, reliability and quality of service (QoS) need to be properly planned and then optimized to improve system performance. Thus, the motivation for this thesis is the introduction of LTE network inside 3G networks with a limited number of studies conducted regarding interoperability and handover. Maintaining seamless user mobility at a descent QoS is an important feature of any mobile system. User mobility can face a series of challenges when new technologies are introduced to older, more stable and optimized networks. Therefore, this thesis is motivated by the introduction of LTE radio access technology to Ethiopia's telecom infrastructure. Consequently, one of the most important aspects when different technologies are co-operated – Inter technology handover – is chosen as study topic in this thesis. Formally, the topic is titled 'A Study on LTE to 3G radio access technologies (Inter-RAT) handover in the case of Ethiopia'.

1.2. Problem Statement

Ethio telecom is the sole operator and service provider offeringevery telecom service in Ethiopia. Currently, there are various telecom expansion projects underway to expand the network capacity and to introduce the latest cellular technologies. Despite such huge investment and deployments, there are still performance problems that customers keep reporting and complaining implying customer dissatisfaction. This paper's problem identification is based on those complaints and identifying the key quality of service (QoS) issue causing such problems. From the network management perspective, there are several call drops per second, voice cross talks, data throughput degradation and repetitive out of service issues. The ultimate effect of one or more of these problems is lowered QoS which in turn results in poor user experience.

The demand for high-quality voice, high-speed mobile data and multimedia services is very high in Addis Ababa and other major cities in Ethiopia. User mobility is an important performance parameter which can significantly affect the service quality provided by the operator. Therefore, handover is one method of analyzing the network performance of Ethio telecom.

The study topic of this thesis is to analyze and find out LTE to 3G radio access technologies handover performance based on KPI parameters. It is important to study and test Ethio telecom's network in real environmental scenarios in the newly LTE deployed network because upcoming network expansion and deployment projects should avoid persistent quality problems. Broadband data service that are supported and not supported by Ethio telecom shall be identified and consistency of KPI parameters against 3GPP specifications are must be analyzed.

LTE network is introduced and deployed in the same site as 3G networks which needs tests to be done appropriately to provide significant input to future network planning, design, optimization, configuration and scalability analysis.

1.3. Objectives

1.3.1. General Objectives

This thesis is all about studying inter radio access technologies (Inter-RAT) handover between LTE and 3G (UMTS) cellular networks. Filed measurement activities are conducted under good radio conditions at two different locations in Addis Ababa, namely Bole and Kality sub-cities.

1.3.2. Specific Objectivates

a) To measure key network parameters under realistic radio conditions.

b) To analyze measurement results to compare them with 3GPP's specifications.

c) To evaluate the impact of those network parameters on user services user connected mobility condition.

d) To provide exact methods for Inter-RAT field tests including route selection, test setup, interconnecting devices and applications, and recording measurement results.

e) To provide concrete suggestions for future works that could involve network planning, design, configuration and optimization.

f) To provide a clear and thorough documentation which can be used as a valuable resource in both the telecom industry and academia.

g) To make sure the outcome of this thesis uniquely contributes to knowledge base specifically to the area of Inter-RAT handover.

1.4. Forecasted Value of the Thesis

Cellular technology evolution shows that each generation of mobile network is standardized and made commercially available ten years later than the preceding cellular network technology. That means, ten years gap became the de facto technology gap in the mobile network industry. For example, 2G was commercialized in 1980, 3G in 2000, and 4G in 2010. Most network equipment vendors design equipment with estimated ten years life time.In the case of Ethiopia, LTE is implemented three years later than the developed countries.

LTE is predicted to serve as the state-of-art cellular technology for the upcoming five to six years in general. The next generation cellar network, 5G, is being studied at this time. Standardization, protocols development and implementation take at least the abovementioned five to six years. Considering deployment pattern in Ethiopia, LTE will remain as the latest and dominant radio access technology for the coming ten years in Ethiopia with further enhancements. Therefore, this thesis can serve as a valuable knowledge base and technical document at least for those ten years. However, the other legacy networks cannot just be taken off and replaced by a new technology. That means, the value period of this research goes beyond ten years.

1.5. Challenges and Limitations

- One major difficulty during this thesis research is finding the appropriate LTE and 3G sites and route during mobility.

- Another challenge was identifying how exactly the tests should be executed and what network element behaviors should be evaluated so that they can lead to KPI impacts related to handovers.

- Interferences originating from neighboring cells made site selection very complex in downtown areas such as Piazza. Hence Bole and Kality are selected as they exist at the edge of the current LTE network coverage with urban and sub-urban population and building density behaviors, respectively.

- This thesis addresses handover from LTE to 3G network systems which can be considered as the sole limitation of this study.

1.6. Literature Review

Different studies have been made on the handover and interoperability among various 3GPP mobile networks by different scholars. A few among many of recently published articles which are related to Inter-RAT handover from LTE to 3G, which is the focus of this thesis, are reviewed in this subsection as follows.

3GPP (v.19.0, 2012) provides feasibility study of LTE E-UTRAN network component. The article focuses on evolved core network called system architecture evolution (SAE). Backward compatibility with existing RAT systems was studied. Moreover, the requirements for Inter-RAT handovers between LTE and 3G networks were discussed in detail. The paper asserts such networks must support handover measurement capabilities. In other words, E-UTRAN is required to efficiently support Inter-RAT handover measurements with acceptable impact of terminal complexity and network performance. Furthermore, the paper states that the network must define the interruption during Inter-RAT handover [2].

Marilynn P. et al. (IEEE 2010)present a summary of 3GPP's LTE radio system performance during theexecution of a multi-site field trial. As the results indicate, the system boasts a peak downlinksingle-user throughput exceeding49 Mbps and a peak uplinksingle-user throughput observed of 19 Mbps. The latter result is quite close to the theoretical uplink limit of 21 Mbps. In addition, the paper states the system achieved a perfect handover with a success rate of 100% and a best case average user plane latency of 22 milliseconds [3].

A. Awada et al. (IEEE 2011)lookedin to the potential approaches to interoperability as well as inter-technology mobility between LTE system and other different generations of wireless communication. The paper shows that the 4G LTE network provides better interoperability performance than other generations of cellular networks [4].

Awada, A. (IEEE 2012) studied Inter-RAT mobility focusing on end-of-coverage-area considering LTE as a coverage limited deployment in a fully-covered 3G environment. It showed that there are radio link failure (RLF)-affected handovers and unnecessary handovers such as ping-pongs in case of inappropriate and inconsistent parameter configurations setting of two different RATs. Such undesired handovers can lead to packet loss and capacity reduction. The paper's results demonstrate that performance of the tested network highly depends on configuration of mobility parameters and KPIs [5].

J. Vehanen (2011)introduced a planfor Inter-RAT test execution. It then introduced the necessary tools and procedures required to perform such tests. The test was not conducted under measurement field environment with realistic radio conditions. However, the study clearly specified handover locations involving base station. The results provide a solid test bed for Inter-RAT measurement [6].

B. Abuhaij and M. Alwakeel (2013)discussed the deployment of LTE along with existing legacy cellular system such as Universal Mobile Telecommunications System (UMTS). The paper shows deploying LTE in the same cell site as UMTS enhances network resources available to operators. It also mentions that such deploymentsbringoperators and vendors to the forefront of many technology challenges. One important example is mobility.The paper discusses in detail the complexity of handover management due to the diversity of services and availability of several radio access technologies at the same time. The results also showed that operators will have a better utilization of their new deployed technologies if they speed up in the replacement of existing user equipment (UE) with more advanced and feature rich UEs. The authors also demonstrated the effect of traffic distribution on the system's blocking probability. A complete handover algorithm has been presented with various factors influencing the decision-making process. Some of the key factors mentioned are user mobility, UE capabilities and power consumption, and type of service the user is accessing. A similar algorithm proposed in the paper is used in this thesis and possible enhancements to the algorithm are also suggested. The authors suggest future studies shall focus on the link between resource allocation and the type of service as well as user throughput [7].

F. Afroz et al (2015) analyzedsome practical measurement results recorded from a live LTE network in Australia by using a commercialmeasurement tool NEMO Handy to verify the possible relationships among SINR,RSRP, RSSI and RSRQ. In addition, the effect of SNR on throughput is evaluated. The authors studied intra-eUTRAN and LTE-eUTRAN Inter-RAT handover events which occurred during the test period within the test area. The results showed that RSRP and SNR are proportional to each other on average. Furthermore, the paper illustrates the lesser the difference between RSSI and RSRP, the better is the RSRQ. The authors conclude that if the SINR is better for a measurement slot, achievable throughput becomes higher. The paper also showed when the RSRP/RSRQ of a serving cell drops below the respective RSRP/RSRQ of a neighbor cell, the handover process takes place to maintain ongoing data and/or voice call sessions[8].

1.7. Research Methods

Based on the aforementioned aims and objectives of this thesis, the study primarily includes review of various research papers related to the topic to gain a knowledge base and to identify important features to be studied. Once the initial literature review is complete, different documentations from both the vendor and the operator are collected. Among the documents I obtained, design specification, site layouts, site locations, radio frequency plan, low level design parameters are from Huawei Technologies Co. Ltd. Which deployed both UMTS and LTE networks in Addis Ababa.

Measurements were carried out in Bole and Kality areas of Addis Ababa by selecting appropriate routes. Drive tests are performed towards the cell edge to cause poor coverage of the 4G LTE network while the 3G channel condition remains good which triggers Inter-RAT handover to take place. For the field test, Nemo Outdoor is used to monitor and record the measurements. Then, Actix Analyzer is used to analyze the data which uses MS Excel for generating various data sheets. Finally, MATLAB is used to plot and extrapolate the results extracted from Actix Analyzer. Analysis based on results extracted or generated by using these tools is done considering both numerical and statistical comparisons to see the KPIs of the network performance. At the end, the handover process is discussed and analyzed in detail with suggestions for future studies.

1.8. Thesis Structure

This document is organized in five chapters. The first chapter introduces the thesis topic and it outlines study aims and objectives, motivations and the research methodology followed in this thesis. Chapter 2 provides a background information about mobile communication systems. It explains the cellular concept and discusses mobile network evolution towards LTE and UMTS. A short introduction of UMTS and LTE network architectures is also presented in Chapter 2. The third chapter provides a brief discussion of LTE's air interface technologies. The frame concept, interfaces and protocols, and the different layers of LTE and their functions are explained in detail. Chapter 4 deals with basic mobility concepts including system information messages, measurement events, and mobility management in idle and connected modes. The final chapter begins with a discussion of different KPIs and then continues to present measurement results and analyzing those results with various plots, tables and explanations. Finally concluding remarks and suggestions for future studies are provided.

CHAPTER 2

Mobile Communication Overview

2.1. Introduction

Communication system is a transfer of information from a transmitter to a receiver that are physically separated. The transmitter and receiver are connected via a variety of communication media such as copper wire, optical fiber and wireless medium (radio or microwave). Additionally, several intermediate devices are typically involved in setting up a path for the information transfer and to maintain adequate signal strength for the receiving end to effectively understand and extract the information sent by a transmitter. The information transfer must be established and maintained at acceptable levels in terms of certain key criteria such as speed of the transmission link, information transfer rate, response time, error detection and/or correction, and the associated cost. The type of information transmitted over a communication system can be voice, video, image or any combination of them (multimedia).

Data communication has now also become an integral part of the consumer need. People on the move with wireless appliances such as smart phones are demanding high speed data service along with voice service. Users always expect uninterrupted, efficient, stable and better-qualityservices from mobile network while moving from one place to another. Mobility supports user to move from one place to another without breakdown of ongoing service within coverage area.

This chapter presents an introduction of cellular mobile system and different access technologies used in wireless mobile communication. It then discusses the evolution of the mobile network technology starting from the 1st to the latest 4thgeneration networks. It also contains detailed description and technical concepts about network architecture and channel characteristics of today's 3G and 4G networks.

2.2. Cellular Systems

The concept of Cellular systems was first proposed in 1947 by Bell Laboratories. The purpose was to use a number of low power transmitters within a cell which allow frequency reuse and ensure full mobility within coverage area of the system.The idea is to partition the available spectrum among the cells and a given frequency is reused at the closest possible distance that the radio link will allow. Smaller cells have a shorter distance between reused frequenciesand these results in an increased spectral efficiency and traffic carrying capacity. In this mechanism, users in geographically separated cells simultaneously use the same carrier frequency. The cellular layout of a conventional macro-cellular system is quite often described by a uniform grid of hexagonal cells or radio coverage zones. The hexagon is an ideal choice for representing macro cell coverage areas. A tessellating reuse cluster of size of *N* can be constructed by using:

$$\mathbf{N} = \mathbf{i}^2 + \mathbf{ixj} + \mathbf{j}^2 \qquad (2.1)$$

Where *i* and *j* are non-negative integers and the cluster size *N* can be 1, 3, 4, 7, 9, 12 and so on.
A simplified 7-cell frequency reuse plan is shown in fig. 2.1, where cells marked with the same letters use identical sets of carrier frequencies.

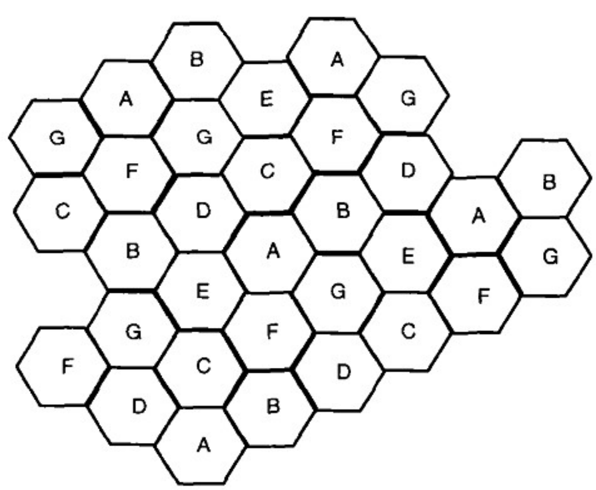


Figure 2.1 *Macro-cellular deployment using 7-cell reuse pattern [9]*

The co-channel reuse factoris defined as the ratio of the co-channel reuse distance *D* between cells using the same set of carrier frequencies to the radius of the cells *R*. For hexagonal cells, the reuse cluster size *N* and the co-channel reuse factor *D/R* are related by [9]:

$$\frac{\mathbf{D}}{\mathbf{R}} = \sqrt{\mathbf{3N}} \tag{2.2}$$

As the height of the base station decreases, the size of the cell becomes smaller. Smaller cell radius requires smaller transmit powers. This helps to reduce the mobile battery consumption. Base stations (BS) can be added to increase radio capacity from fixed radio spectrum to serve more users. However, the cellular concept has some drawbacks. To increase the capacity, several base stations are required which makes it expensive. It should also support seamless handoff between the cells as radio channel condition varies across the network. Resource management is required which also needs to track the user location to route incoming call or message [9].

2.3. Mobility Management

In cellular systems, Mobility Management (MM) is required for allowing a user equipment (UE) to be able to communicate from various locations while moving. The process of identifying and tracking a UE's current point of attachment to the network is called location management. This mechanism helps to locate incoming calls and packets to the UE regardless of where they are in the network. On the other hand, handover management enables seamless transition or handoff to maintain an ongoing session as the UE moves out of the coverage area of BS to that of another. Both location management and handover management constitute mobility management [1].

2.3.1. Location Management

Location management involves two processes: location update (registration) and paging.

- ***Location update.***This operation is performed by active mobile UE in which the UE periodically informs the network of its current location. This enables the network to authenticate the user and update its location profile in a database which is used to inform the network location of a mobile user. The process requires the device to register its new location with the current BS to allow the forwarding of incoming calls.

- ***Paging.*** It is always performed by cellular network that needs to be able to precisely determine the current cell location of a user to route an incoming call. This requires the network to send a paging query to all cells where the mobile device may be located to inform it of the incoming transmission.

2.3.2. Location Area (LA)

Location Area (LA) identifies the area where the UE can freely move without performing a location update. This is an approach widely used in GSM systems. The serving area is subdivided into location areas and each location area consists of several adjacent cells. Every LA is uniquely identified with a Location Area Identity (LAI). The LAI is a globally unique number and the UE listens to the LAI from the Broadcast Channel of the BS. A mobile station updates its location area and informs the network by sending Location Area Update (LAU) code whenever it enters into a cell which belongs to a new location area.

2.3.3. Routing Area (RA)

This approach is the equivalent of LA for the Packet Core network domain of GSM and UMTS. Routing area (RA) is sub-area of a location area. The UE stores the latest RA when carrying out RA update. The UE receives its current RA identity from the system information broadcast by a camped cell. Each user informs the Serving GPRS Support Node (SGSN) about RA to which the user resides. Each RA has its own Routing Area Identity (RAI) and is updated when a mobile station RA changes. This RAI consists of Location Area Code (LAC) and RAC message.

2.3.4. Tracking Area (TA)

This approach is an important in LTE networks. They are used to track mobile stations (MS) that are in idle or in power conservation modes. The network knows the location of the UE to the granularity of a few cells called the Tracking Area (TA).A tracking area generally covers multiple cells. Tracking Area Identity (TAI) indicates which TA a cell belongs to. A UE can detect changes in a TA when it receives a different TAI than in its current cell. The UE updates the

Mobility Management Entity (MME) with its new TA information by sending Tracking Area Update (TAU) message as it moves across tracking area list.A Tracking Area List (TAL) indicates the paging scope of the network where each cell belongs to only one TA but a UE can be registered to many TAs at the same time. These TAL is formed by the collection of TAs to which a single UE is registered.

2.3.5. Handover Management

Handover is one of the essential means to guarantee user mobility in a mobile communications network. Its role is to maintain the traffic connection for a moving UE when the UE moves from the coverage area of one cell to another. To do so, a new connection with a new target cell must be established while the connection to the old cell may be released. One reason behind the handover in any mobile network is the deterioration of the quality of received signal strength for the point of attachment. Other reasons include load balancing, better Quality of Service (QoS), cost, better bandwidthfrom a new network.

Handover can be of type hard, soft or softer. Hard handover is the break-before-make handover where the channel of the source cell is released before connecting to the channel of the target cell. Soft handover is the make-before-break handover in which the channel of the source cell is released only after connecting to the target cell. Softer handover is a type of soft handover where radio channels that are connected and released belong to the same site.The handover process can be divided into three main steps, namely:

- ***Handover Initiation Phase.*** MS or network initiates the handover process
- ***Handover Decision Phase.***Make the network to find the available resources for handover process and routing operations
- ***Handover Execution Phase.*** Anew connection is established to the target network.

Handover can be identified as intra-cell, inter-cell and Inter-RAT cell based on the technologies involved. Intra-cell handover occurs when the MS moves within a serving area of the same network. Inter-cell handover occurs when the UE moves into adjacent cell within a network and Inter-RAT handovers occurs when the MS moves from one technology to another [1].

2.4. Multiple Access Scheme

In wireless cellular systems, Access techniques allow multiple users to share a limited amount of radio spectrum at the same time. There are four major categories of multiple access technologies that are generally used in communication systems as shown in Figure 2.2. Namely, Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) and Orthogonal FDMA (OFDMA).

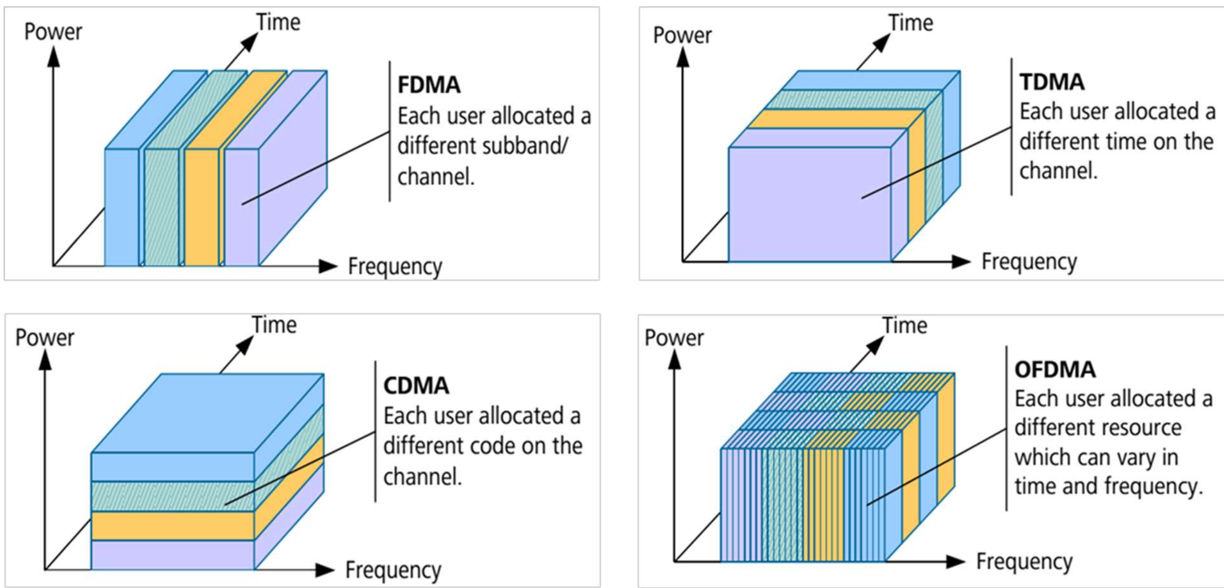


Figure 2.2 *Multiple Access scheme: FDMA,TDMA ,CDMA and OFDMA [10]*

FDMA divides the available spectrum into sub-bands or channels. Using this technique, a dedicated channel can be allocated to a user. In a cellular Mobile system, users occupy multiple channels where one for the downlink and the other for the uplink. This however makes FDMA less efficient since most data applications are downlink intensive.

In TDMA system, the channel bandwidth is shared in the time domain. The top right of Figure 2.2 shows how each device is allocated a time on the channel called a timeslot. Several timeslots are then grouped into a TDMA frame. The number of time slots in a TDMA frame is dependent on the system. For example, GSM utilizes 8 timeslots per TDMA frame. A combination of TDMA and FDMA schemes is used in GSM system.

In CDMA technique, the devices can use the system at the same time and using the same frequency or bandwidth. This is possible because each transmission is separated using a unique code. The narrowband signals are spread with a wide code by using spread spectrum techniques. The transmitter and the receiver are designed to extract the encoded signal and reject anything else as noise. Both UMTS and CDMA2000 use CDMA channel access scheme.

OFDMA is the latest addition to cellular systems. It provides a multiple access technique based on orthogonality where the bandwidth is broken into smaller orthogonal units known as subcarriers. These subcarriers are grouped together and allocated as a resource to a device. A device can be allocated resources both on time and/or frequency domains.

2.5. Evolution of Mobile Networks

In the old days, people used flag and written messages carried by a courier as a medium to convey the information. In 1792 C. Chappe invented telegraph for communication purpose for which the word telegraph was coined. To overcome geographical and weather barriers, electromagnetic waves were discovered. In 1857,J.C. Maxwell was the first to deduce mathematically the existence of electromagnetic waves. It then fell to Hertz in 1888 to prove their existence relating them to Maxwell's equations to see effects of radio waves in space. G. Marconi successfully demonstrated communications over increasing distances in 1901 by transmitting a signal across the Atlantic. He used huge transmitter stations with very high antennas where the system requires high power for transmission. In 1920 Marconi discovered short waves which overcame the requirement of huge transmitters and receivers. As time passed, radio telephony was used for military purposes during the Second World War. In the 1940's, hand held transmitters were available which were bulky and consume high power. After the war, mobile car telephones were introduced at first from AT&T in St. Louis, USA in1946.The service was very successful and soon spread to twenty-four other cities. Those early single cell systems were severely constrained by restricted mobility, low capacity, limited service and poor speech quality. The equipment was heavy, bulky, expensive and susceptible to interference [9].

2.5.1. First Generation (1G) Mobile systems

The first generation of mobile cellular telecommunications systems appeared in the 980s.These systems utilized analogue modulation techniques mainly designed for voice based on FDMA. The big uptake of subscribers and usage came when mobile communication became an international concern.The first international mobile communication system was the analog Nordic MobileTelephony (NMT) system which was introduced in Europe in the 1980s. At the same time, as analog Advanced Mobile Phone Service (AMPS) was introduced in North America. Other analog cellular technologies deployed were Total Access Communication Systems (TACS) in Japanese.

In 1979 Nippon Telephone and Telephone Company (NTT) launched commercially the so called 1st generation (1G) network in metropolitan areas of Japan. This analog system worked on 800–900 MHz frequency bands by using frequency modulation to transmit the signals. In the 1980s, a packet switched technology called X.25 was deployed for data networks while voice networks deployed circuit switched technology. In the 1990s, a new circuit based telephony system – Integrated Service Digital Network (ISDN) – was introduced to replace the circuit switched analog technology by the digital lines. ISDN standard was simple and supported both voice and data services [11].

2.5.2. Second Generation (2G) Mobile Systems

The development of 2nd generation (2G) cellular systems was driven by the need to improve transmission quality, system capacity, and coverage areas. 2Gcellular system utilize digital multiple access technologies such as TDMA and CDMA. It includes GSM, IS-95, Digital Advanced Mobile Phone System (D-AMPS), and Personal Digital Communication (PDC) where the first two being the most popular 2G technologies.

GSM is the most successful of all 2G technologies. It was initially developed by European Telecommunications Standards Institute (ETSI) for Europe. It was designed to operate in the 900MHz and 1800MHz frequency bands and later standardized to additionally support 850MHz and 1900MHz frequency bands. The original GSM technology is based on TDMA channel access employing eight timeslots on a 200 kHz radio carrier for voice service. Later, a new packet switched technology was launched to transfer data as short messaging service (SMS) with a speed of 9.6 kbps. The arrival of SMSservices gave rise to the use of internet and its protocols. UE battery life was improved and encryption techniques were implemented for security purposes and the system became more immune to noise. In the late 1990s, general packet radio service (GPRS) was introduced to support high data rate packets to the existing GSM networks supporting speeds up to 114 kbps. Following GPRS, Enhanced Data Rates for GSM Evolution (EDGE) was introduced. It uses eight Phase Shift Keying (8-PSK) modulation technique and combining EDGE with GPRS provides up to 200 kbps speed.Interim Standard (IS-95) is a CDMA system which uses spread spectrum (SS) technique. IS-95 utilizes a mixture of codes and timing to identify cells and channels operating at a bandwidth of 1.25 MHz[11, 12].

2.5.3. Third Generation (3G) Mobile Networks

Projections of increasing demand for wide area communications supporting new applications that are requiring high data rates led to the development of a new generation of cellular communication system in the late 1980s. These systems became known as 3rdGeneration (3G) systems which fulfill the requirements set out by the International Telecommunication Union (ITU) for the so-called IMT-2000 family of standards.A set of 3G standards developed includesUMTS, CDMA2000 and WiMAX. Among them, UMTS used a new paradigm in multiple access technology being based on CDMA access technology. The first release of the UMTS specifications became available in 1999 and is known as Release 99which contains all features needed to meet the IMT-2000 requirements as defined by ITU. Release 99 is also known as Wideband Code Division Multiple Access (WCDMA). WCDMA supports circuit-switched voice, video and data services over both packet-switched and circuit-switched bearers. It also offers different data rates providing up to 144 kbps for moving vehicles, up to 384 kbps for pedestrian users and up to 2 Mbps for stationary users.

In 2002, the SK Telecom from South Korea introduced another 3G technology called 1xEVDO which is based on CDMA. On the same year, the Monet Mobile Network from North America launched 1xEV-DO based on CDMA2000 standards. The completion of the first release of the UMTS specifications was followed by extensions known as high-speed packet access(HSPA).The main stimulus for HSPA was the rapid growth of packet data traffic which necessitated both much higher data rates and a switch from constant data-rate circuit-switched traffic(chiefly voice) toward Internet Protocol (IP)based packet-switched traffic. The first enhancement was to the downlink, where high-speed downlink packet access (HSDPA) was introduced in Release 5 of the UMTS specifications. It was driven predominantly by the growth of download traffic from the Internet. This was followed inRelease6 by high-speed uplink packet access (HSUPA) which focuses on services requiring a more symmetric uplink and downlink traffic such as e-mail, file sharing and interactive gaming.HSDPA offers data rates up to 14.4 Mbps in downlink whereas HSUPA offers 5.76 Mbps in uplink direction. On further development, HSPA+ was introduced in Release 7 to offer higher data traffic up to 84 Mbps in downlink and 22 Mbps uplink direction [13].

2.5.4. Fourth Generation Mobile Systems

The work towards 3GPPLTE started in 2004 with the definition of targets. LTE is introduced as 4G wireless mobile network in release 8. It is IP based technology with flat architecture providing data rates of up to 100Mbps in the downlink and 50Mbps in the uplink direction. Latency is one characteristics of LTE which improves the end user experience. Another key feature of LTE is its requirement for minimum terminal power consumption to enable more usage of the multimedia applications without recharging UE battery. LTE-Advanced (LTE-A) is another upgrade evolution from LTE. LTE-A is defined in Release 10 which are envisaged to handle a wide range of supported data rates according to economic and service demands in multi-user environments with target peak data rates of up to approximately 100 Mbps for high mobility users and up to 1 Gbps speeds for low mobility users [14].

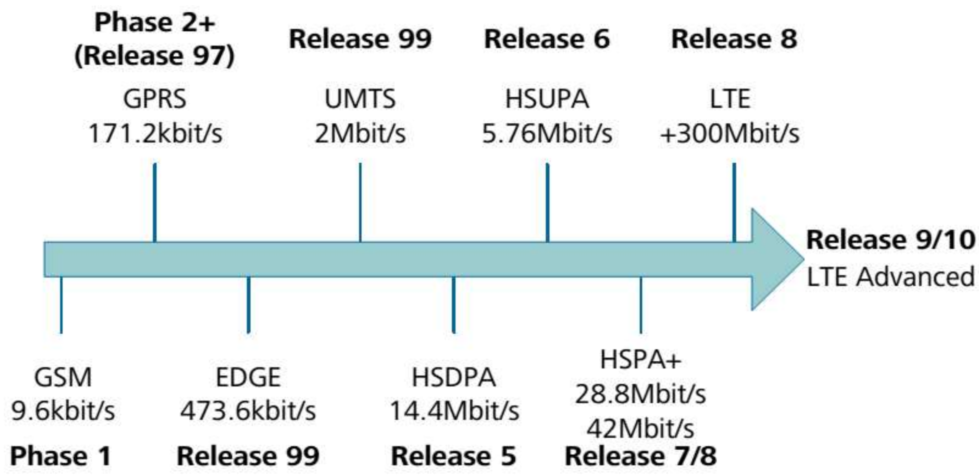


Figure 2.3*3GPP LTE Evolution path [10]*

2.6. Overview of UMTS System

The Universal Mobile Telecommunication System (UMTS) is a 3G cellular technology standardized by the 3GPP in Released 99 for voice and data. It uses WCDMA technique to offer high spectral efficiency and bandwidth. It offers data rate up to 2 Mbps, seamless handover to GSM/GPRS and high-quality speech.

2.6.1. UMTS Network Architecture

The UMTS network architecture is grouped into User Equipment (UE), Radio Access Network (RAN), UMTS Terrestrial RAN (UTRAN) and Core Network (CN) as shown in Figure 2.4.

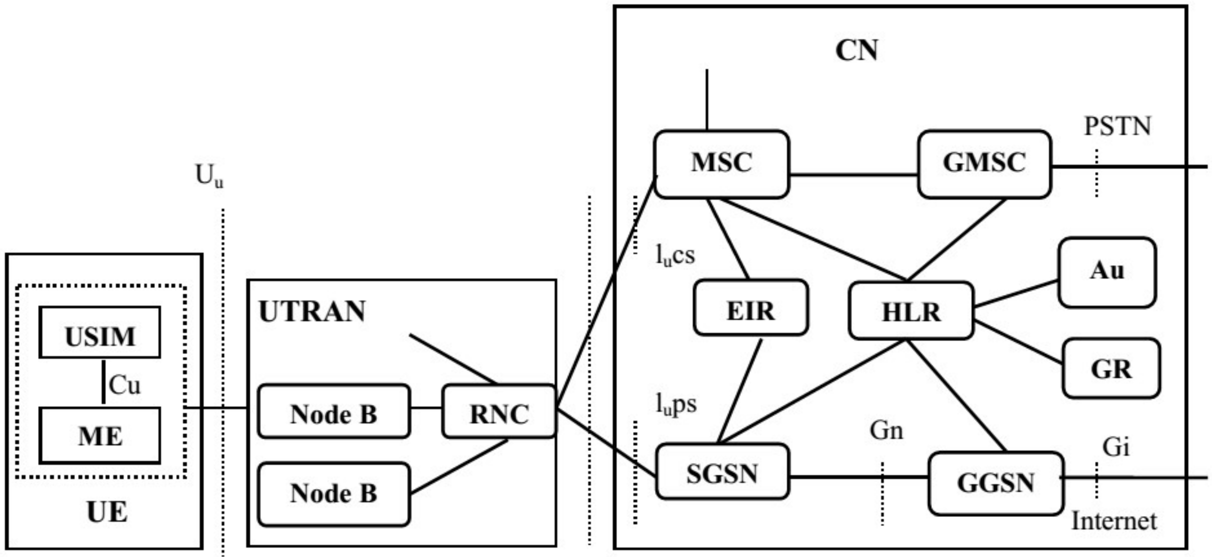


Figure 2.4 *UMTS Network architecture [14]*

2.6.1.1. User Equipment (UE)

User Equipment (UE) is the user device which interfaces the user with the radio network. UE contains UMTS Subscriber Identity Module (USIM) and Mobile Equipment (ME). Both are interconnected with each other by Cu interface. The USIM is a smart card that holds the subscriber identity to perform authentication, encryption. It also contains some subscription information which is needed at the terminal. The Mobile Equipment (ME) is the radio terminal used for radio communication over the Uu air interface [15].

2.6.1.2. UMTS Terrestrial Access Network (UTRAN)

UTRAN handles all radio-related functionality. It consists of two distinct elements: NodeB and the Radio Network Controller (RNC). The UTRAN is connected with the UE via Uu air interface for communication.

- ***NodeB.*** It is a base station responsible for converting the data flow between the Iub and Uu interfaces for handling the user physical data and signaling between the UE and the Radio Network Controller (RNC). It oversees controlling transmit power and system load. Other major functions of NodeB includes channel coding, error handling, modulation and demodulation.

- ***Radio Network Controller (RNC).***It is equivalent to the Base Station Controller (BSC) in GSM systems. RNC controls and serves the NodeBs. It is mainly responsible for radio resource management and controlling the radio channels. It also takes part in routing and switching the calls to Gateway Mobile Switching Center (GMSC). It interconnects with NodeB via Iub interface and with other RNCs via Iur interface.

2.6.1.3. Core Network (CN)

The core network is divided into three different groups according to the type of data they carry: Circuit switched, Packet switched and Shared elements [14].

- ***Circuit switched (CS) elements.***They provide circuit-switched connections like the existing telephony service such as ISDN and Public Switched Telephone Network (PSTN). The key elements are Mobile Switching Center (MSC) and Gateway MSC. The primary function of MSC is to route the voice and data traffic as well as other value-added services. It is also responsible for end to end connectivity between users, handling user mobility and charging. A database known as Visitor Location Register (VLR) is also included in the MSC. This database stores information about active users connected to the network. The GMSC forms a gateway to connect UMTS core network with external circuit switch networks like PSTN.

- ***Packet switched (PS) elements.***They provide connections for packet data services. The Internet is one example of a PS network.The key elements are Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). SGSN is responsible for carrying and delivering the data packets from one user to another user. It also takes part in mobility management, logical management, authentication and billing. The GGSN forms the gateway to connect the GPRS network with external packet switched networks like the Internet.

- ***Shared elements.*** This section comprises Home Location Register (HLR), Equipment Identity Register (EIR) and Authentication Centre (AuC). The HLR is a database which contains the information of registered users to the network (all active as well as non-active users). The EIR is responsible to decide whether UE is valid and authorized to access the network or not. Each UE has its unique International Mobile Equipment Identity (IMEI) code to check the validity of the device. The AuC is a database which stores the cipher text of each user for security purpose.

2.6.2. UMTS Interface Channels

Considering the protocol channel, the UMTS radio interface has three types of channels: physical channel, transport channel and logical channel.

2.6.2.1. Physical Channels

Table 2.1 shows physical channels which are the ultimate embodiment of all kinds of information when they are transmitted on radio interface to exchange the information between the user and UTRAN in UMTS. Each channel using a dedicated carrier frequency, a spreading code and a scramble and a carrier phase can be regarded as a physical channel.

Table 2.1*UMTS physical channels and their functions*

Channels	Functions
Synchronization Channel (SCH)	Used for cell search procedure. There are primary and secondary SCHs.
Common Control Physical Channel (CCPCH)	Used to carry common control information such as the scrambling code used in DL and secondary CCPCH.
Common Pilot Channels (P-CPICH and S-CPICH)	Used for coherent detection of common channels. They indicate the phase reference.
Dedicated Physical Data Channel (DPDCH)	Used to carry dedicated data coming from layer 2 and above (coming from DCH).
Acquisition Indicator Channel (AICH)	Used for coherent detection of common channels. They indicate the phase reference.

High Speed Physical Downlink Shared Channel (HS-PDSCH)	Used to carry subscribers BE service data (mapping on HSDPA) coming from layer 2
High Speed Shared Control Channel (HS-SCCH)	Used to carry control message to HS-PDSCH such as modulation scheme and UE ID.

2.6.2.2. Transport Channels

Table 2.2 shows the transport channels that define how and with which type of characteristics the data is transferred by the physical layer. The transport layers are interfaces between the physical and the Media Access Control (MAC) layer.

Table 2.2*UMTS transport channels and their functions*

Channels	Functions
Broadcast channel (BCH)	A downlink channel for broadcast of system and cell-specific information
Paging channel (PCH)	A downlink channel used for transmission of paging and notification messages
Random access channel (RACH)	Used for initial access or non-real-time dedicated control of data traffic
Dedicated Control Channel (DCCH)	Used to carry control information to particular UEs in uplink and downlink direction
Common Control Channel (CCCH)	Transfers control information in both directions
Dedicated Traffic Channel (DTCH)	Used to carry user data in uplink and downlink directions.
Common Traffic Channel (CTCH)	Used to broadcast the data to a group of UEs in downlink direction

2.6.2.3. Logical Channels

Table 2.3 shows UMTS Logical channels where they exist in the interface between the MAC and the RLC protocol layers. Logical channels are mapped into transport channels in the MAC layer. They describe what type of data is transferred between the user and the network.

Table 2.3*UMTS Logical channels and their functions*

Channels	Functions
Broadcast Channel (BCH)	Broadcasts system and cell-specific information in the downlink

	direction
Paging Channel (PCH)	Transfers paging information and some other notifications in the downlink direction
Dedicated Transport Channel (DCH)	Responsible to transport the data to the particular UE in both uplink and downlink directions
Synchronization Channel (SCH)	Responsible for synchronization between the UEs and NodeBs.
Forward Access Channel (FACH)	Mainly transmits the control data or user data to UE in the downlink direction
Random Access Channel (RACH)	Responsible to carry service request from UEs in uplink direction.
Downlink Shared Channel (DCH)	Shared by different UEs to transmit control information or user information in downlink.

2.6.3. High Speed Downlink Packet Data Access (HSDPA)

The introduction of High-Speed Downlink Packet Access (HSDPA) by 3GPP implies a major extension of the WCDMA radio interface. It enhances the WCDMA downlink packet-data performance and capabilities in terms of higher peak data rate, reduced latency and increased capacity.A key characteristic of HSDPA is the use of Shared-Channel Transmission. It implies that a certain fraction of the total downlink radio resources available within a cell which is a common resource in WCDMA is shared dynamically between users. The use of shared-channel transmission in WCDMA implemented through the High-Speed Downlink Shared Channel (HS-DSCH).This channel enables rapid allocation of a large fraction of downlink resources for transmission of data to a specific user. HSPA provides downlink and uplink data rates up to approximately 14 Mbps and 5.7 Mbps, respectively. Moreover, it significantly reduced round trip times and improved capacity as compared to WCDMA [15, 16].

2.7. LTE System Overview

LTE represents the next developmental step for the 3GPP standard groups ultimately towards a 4G solution in Release 8. It is the last step toward the 4^{th} generation of radio technologies designed to increase the capacity and speed of mobile telephone networks. LTE is designed to address growing global demand for anywhere, anytime broadband access by maintaining efficient provision of traditional telecommunication services and maximizing system coverage, performance and capacity. It provides high data rates, real-time voice and video telephony to high quality streamed TV and services to existing terminals at the same time. The 3GPP defined the requirements and key features for LTE development which are described below [16, 17].

- The LTE system is packet switched domain optimized. This means circuit switched elements are not really considered but everything is assumed to be based on a packet type of operation. The system was required to support IP Multimedia Sub-system (IMS) and further evolved 3GPP packet core.
- Higher peak data rate of 100 Mbps for downlink and peak 50 Mbps for uplink at 20 MHz band and increased cell edge bit rate while maintaining the same site location as are deployed for R99 and HSPA.
- Significantly improved spectral efficiency two to four times that provided by release 6 HSPA.
- Provide frequency allocation flexibility with 1.25, 2.5, 5, 10, 15 and 20 MHz allocations.
- Supports for interoperability with previous 3G or 2G systems and other non-3GPP technologies.
- Provides high quality of service. It has radio access network latency less than 10 milliseconds. The control plane latency from idle mode to active mode is less than 100 ms while for user plane latency is less than 50 ms for real time application and voice.

2.7.1. LTE Network Architecture

LTE has been designed to support only packet switched services in contrast to the circuit-switched model of previous cellular systems. Figure 2.5 shows the LTE network architecture and the elements associated with it. This figure also shows the division of the architecture into four main high level domains: User Equipment (UE), Evolved UTRAN (E-UTRAN), Evolved Packet Core Network (EPC) and the Services domain. UE, E-UTRAN and EPC together represent the Internet Protocol (IP) Connectivity Layer. This part of the system is also called the Evolved Packet System (EPS). The main function of this layer is to provide IP based connectivity. All services will be offered on top of IP and circuit switched nodes and interfaces seen in earlier

3GPP architectures are not present in E-UTRAN and EPC at all. IP technologies are also dominant in the transport where everything is designed to be operated on top of IP transport. Each of these network elements is interconnected by means of interfaces which are standardized in order to allow multi-vendor interoperability. This gives network operators the possibility to source different network elements from different vendors.In general, the architecture looks similar to that of UMTS system but holds distinct unique features that ensure the highest-level performance and requirements set by 3GPP.

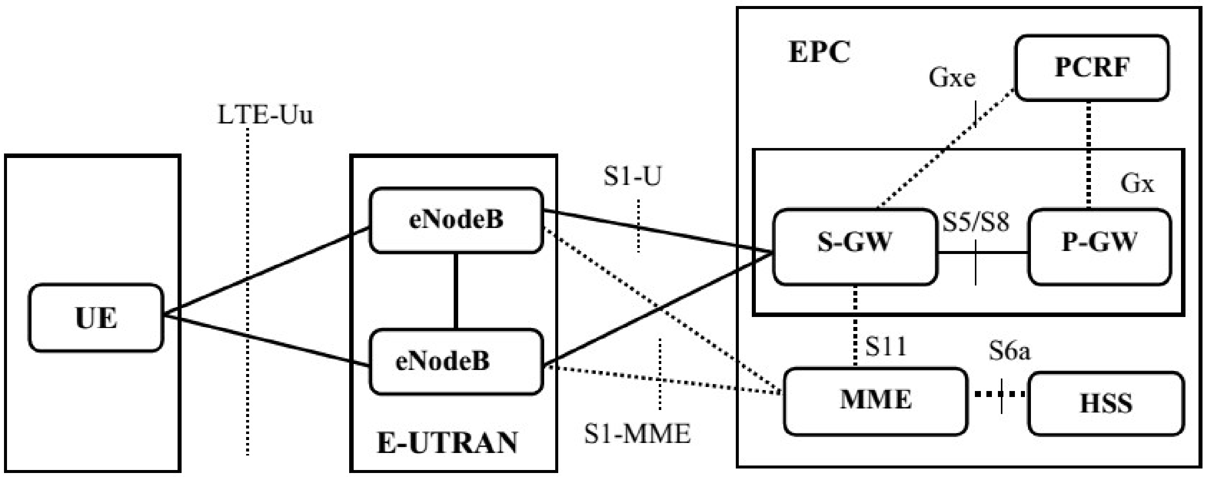


Figure 2.5 *LTE System Architecture [16]*

2.7.1.1. E-UTRAN NodeB (eNodeB)

The EUTRAN is a radio access network standard meant to be a replacement of UMTS NodeB and Radio Network Controller (RNC) to flatten the network architecture in LTE. It performs the functionalities of both NodeB and the Radio Network Controller (RNC). This simplifies the network structure and reduces the latency in the network as well. Each eNodeB is connected to their neighboring eNodeBs with the X2 interface and interconnects MME and SGW with S1-MME interface and S1-U interface respectively.

The eNodeB has the essential role of Mobility Management (MM) which controls and analyses radio signal level measurements (RSCP and E_c/N_0 value) carried out by the UE. It also performs decisions to handover UEs between cells, encryption and decryption of User Plane and Control Plane data and IP header compression and decompression as well to decrease the sending of redundant data in IP header.

The eNodeB is also responsible for Radio Resource Management (RMM). It sets Radio Resource Connection (RRC), allocate radio resource, prioritizing and scheduling traffic according to required QoS, monitoring of the resource usage situation, type of modulation used and retransmission of the data.

2.7.1.2. Evolved Packet Core (EPC)

Evolved Packet Core (EPC) is the core of the network. The main functions of EPC are to provide all IP based connectivity, seamless mobility, QoS and charging functions. The major change in the EPC compared to 3G core is that it does not contain circuit switched domain. The major elements of EPC are discussed below.

Mobile Management Entity (MME)

Mobility Management Entity (MME) is the main control plane element in the EPC. Figure 2.5 shows that the MME is connected to Home Subscription Server (HSS) via S6a interface and with eNodeBs via S1 interface. The major roles are mobility management, managing subscription Profile and service connectivity, tracking area management as well as user authentication and security related functions between the UE and the network. It performs activation and deactivation of the radio bearers with Serving Gateway (SGW) connected with S11 interface.The protocols running between the UE and the CN for processing the signaling between the UE and the CN is known as *Non-Access Stratum* (NAS) protocols.

The Non-Access-Stratum (NAS) forms the highest stratum of control plane between UE and MME at the radio interface. It is responsible for maintaining functionalities such as choosing the S-GW for a UE at cell attach and detach, tracking area management, authentication and session management for IP connection between UE and Packet Gateway (P-GW). MME also takes part in the intra-system handover, Inter-RAT handover performance in between the LTE and previous legacy 3G/2G networks via S3 interface (SGSN to MME).

Serving Gateway (S-GW)

The S-GW routes and forwards user data packets. It acts as the mobility anchor for the user plane during inter-eNodeB handovers. It also acts as mobility anchor between LTE and other 3GPP technologies and relaying the traffic between 2G/3G systems and PDN-GW. During the handover process, the MME commands the S-GW to switch data tunnel from current eNodeB to the target eNodeB. It relays the data transmission between the serving eNodeB and P-GW. When the UE goes to IDLE mode from the CONNECTED mode while receiving the data packets from the P-GW for a data path, S-GW holds the data packet in buffer. In the meantime, it also requests MME to page the particular IDLE UE. Once the UE resumes to the CONNECTED mode, the buffered packets are delivered and S-GW starts to relay the data from P-GW. When direct inter-eNodeB connection is not available for the handover, it performs the indirect forwarding of the downlink data. Indirect data forwarding case where UP data is forwarded between eNodeBs through the S-GWs. In addition, the S-GW performs some administrative functions in the visited network such as collecting information for charging and legal interception.

Packet Gateway (P-GW)

The P-GW provides connectivity to the UE to external packet data networks by being the point of exit and entry of traffic for the UE. It is the highest-level mobility anchor in the system. It performs traffic gating and filtering functions as required by the service in question. It also allocates the IP address to the UE and the UE uses that to communicate with other IP hosts in external networks. It is also possible that the external PDN to which the UE is connected allocates the address that is to be used by the UE and the P-GW tunnels all traffic to that network. It allocates the IP addresses to the UE attached to the EPS using the Dynamic Host Control Protocol (DHCP). It could also provide the requested IP via externally connected dedicated DHCP server. The PDN gateway assigns the temporary address to each connected UE based on IPv4 or IPv6 standard. P-GW interacts with via S7 interface the PCRF for appropriate policy control information.

Policy and Charging Resource Function (PCRF)

It is the network element that is responsible for Policy and Charging Control (PCC). PCC rule identifies the service data flow and specifies the parameters for charging control. Policy control includes controls the packet flow based on the Application Function (AF) reports of session events and authorization and enforcement of the maximum QoS that is authorized for a service data flow or an IP-Connectivity Access Network (IP-CAN) bearer. It also handles the PCC requests from the other elements in the network such as P-GW and S-GW. Apart from these, it also acknowledges the PCC requests from the external networks and provides decisions for the EPS bearer setup procedure. A bearer is a transmission path of defined capacity, delay and bit error rate.

Home Subscription Server (HSS)

The HSS is a database which contains user's data. It includes the subscriber information International Mobile Subscriber Identity (IMSI) and Mobile Station International Subscriber Directory Number (MSISDN) value used for user identification and addressing. It stores the master copy of the subscriber profile, available services to the user, roaming information etc. Authentication Centre (AuC) is integrated with HSS which holds the master key for all of the subscribers for security and encryption reasons. HSS also keeps track of the location information of UE with the assistance of MME.

CHAPTER 3

LTE Radio Access Technology

This chapter begins with a general discussion of air interface technologies used in LTE systems.Then LTE frame structure and radio interface protocols are addressed followed by a discussion of physical, logical and controls channels of LTE and the associated reference signals.

Finally, LTE's MAC and physical layer resource allocation mechanisms and functions are presented.

3.1. LTE Air Interface Technologies

Legacy technologies like UMTS and its predecessors (HSDPA, HSUPA and HSPA+) use CDMA access technology. On the other hand, GSM uses TDMA multiple access technique together with Frequency Division Multiplexing (FDM). CDMA access technique is used in both the uplink and downlink of UMTS systems. Similarly, GSM utilizes TDMA in both directions. However, it is somehow different in LTE for the two directions. The uplink of LTE is based on Single Carrier Frequency Division Multiple Access (SC-FDMA) while the downlink is based on OFDMA multiple access technique.

3.1.1. Orthogonal Frequency Division Multiple Access (OFDMA)

The 3GPP standard specification for LTE requires OFDMA technique to be used in the downlink. In OFDMA, the available spectral bandwidth is subdivided in to smaller units known as subcarriers. These subcarriers are make mutually orthogonal where the inner product of two subcarriers results in a zero value. In other words, in frequency domain, when one subcarrier is at its maximum, the other adjacent subcarrier is passing through its minimum (zero) as shown in Figure 3.1. Using orthogonal subcarriers allows overlapping spectra of subcarriers which in turn increases spectral efficiency of the system. Orthogonality of subcarriers can be affected by several environmental impairments such as electromagnetic interferences. To mitigate such issues, guard bands are provided both at the upper and lower part of a channel so that adjacent channel interferences are reduced. OFDM subcarriers can be modulated by using Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (16-QAM) and 64-QAM which are typical modulation techniques in LTE systems.

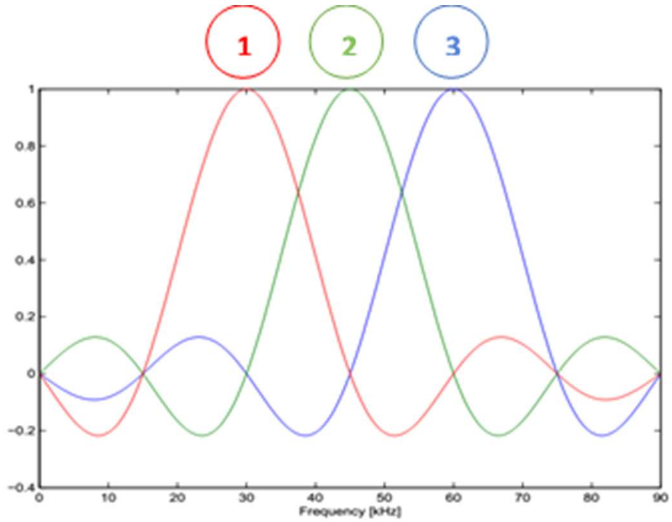
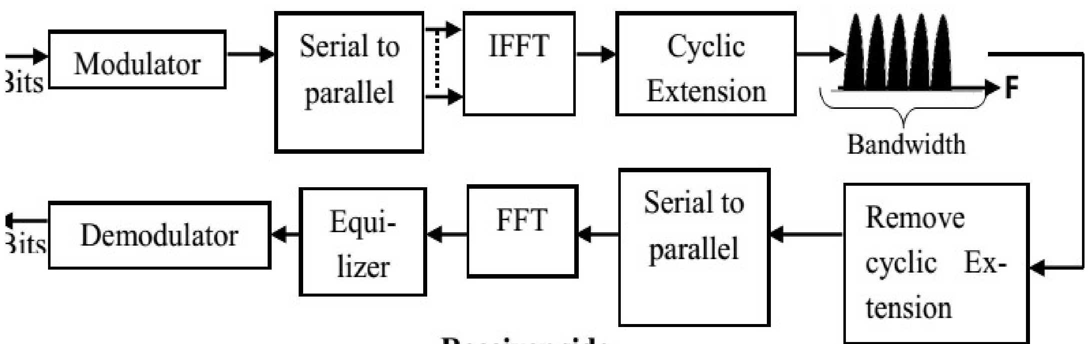


Figure 3.1 *Frequency spectra of three orthogonal subcarriers [17].*

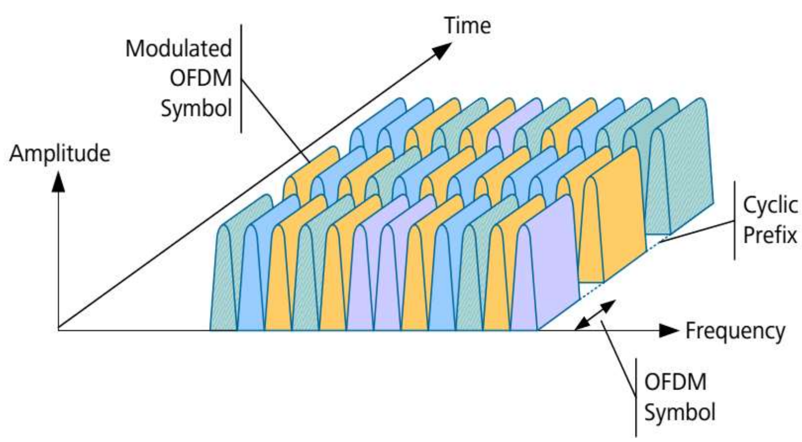
In OFDM systems, the center frequency of a subcarrier is selected from a set such that in frequency domain, the neighboring subcarriers must have zero values at the sampling instant of the desired subcarrier as illustrated in Figure 3.1. In general, OFDM subcarriers are generated and decoded by using mathematical functions called Fast Fourier Transform (FFT) and Inverse FFT (IFFT). IFFT is used at the transmitter side to generate the transmitted waveform and FFT is used at the receiver side to recover the original signal. Figure 3.2 (a) shows a complete block diagram of a generic OFDM transmission system.

OFDM subcarriers are spaced 15 kHz apart from each other which gives a symbol period of 66.7 μs (= 1/15 kHz). Users are assigned a resource block (RB) which is equivalent to 12 subcarriers in frequency and one Transmission Time Interval (TTI) corresponding to 1 millisecond in time. Since subcarriers are selected according to the orthogonality rule, the OFDM signal provides protection in frequency domain.

One typical challenge in OFDM systems is associated to maintaining orthogonality of subcarriers. Multipath interference, which arises from different components of a transmitted signal following different paths, causes spreading of received signal in time which is often expressed in terms of delay. The delayed signal manifests itself as Inter-Symbol Interference (ISI) where one symbol interferes with the next one. To mitigate problems related to delay, a Cyclic Prefix (CP) is utilized in most OFDM systems. A cyclic prefix effectively provides a guard period between successive OFDM symbols. Its size depends on the maximum delay spreading the system can tolerate. As a result, systems designed for macro coverages (large cells) should have long CPs with its normal value being 4.67 μs and extended value of 16.67 μs. The presence of CP indeed affects the system capacity since the number of information bits per second is reduced. The receiver removes the CP with FFT operation to extract the correct transmitted bits. Figure 3.2 (b) illustrates subcarrier allocation in OFDM system.



(a)



(b)

Figure 3.2 *(a) Block diagram of transmitter and receiver, and (b) subcarrier allocation of OFDM system [10, 16].*

3.1.2. Single Carrier FDMA (SC-FDMA)

Single Carrier FDMA (SC-FDMA) is the preferred uplink multiple access technology over OFDMA in LTE systems. The problem associated with the OFDMA in the uplink direction is its high Peak-to-Average Power Ratio (PAPR). That means, the operating point of the power amplifier must be lowered which in turn lowers amplifier efficiency. This is not a problem in the downlink direction because there is abundant power at the eNodeB compared to battery operated UEs. Hence, for a longer battery life, SC-FDMA is used for uplink (UE to eNodeB) transmission.

SC-FDMA utilizes a single carrier modulation scheme. It is also known as OFDM system with a Discrete Fourier Transform (DFT) mapped because frequency domain symbols are generated by using DFT. Thus, generated symbols are mapped to available subcarriers by sub-carrier mapping techniques and thenIFFToperation is performed in a similar was as OFDM. The frequency domain samples obtained after DFT are interleaved and placed in blocks of 12 subcarriers. The remaining vacant sub-carriers are filled with zeros. IFFT is performed to on frequency domain samples to obtain the time domain samples that are evenly spread throughout the subcarriers. There are two types of sub carrier mappings: localized and distributed. In localized mapping, modulated symbols are assigned to adjacent subcarriers whereas in distributed mapping, modulated symbols are equally spaced over the entire bandwidth [16, 17].

Figure 3.3 (a) shows block diagram of SC-FDMA transmitter and receiver.The main difference between OFDMA and SC-FDMA is that symbols are carried by individual subcarriers in OFDMA while they are carried by a group of subcarriers simultaneously.

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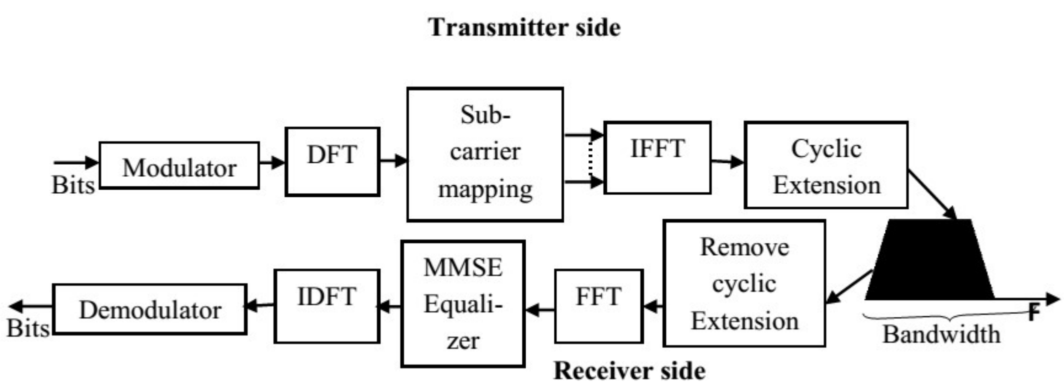
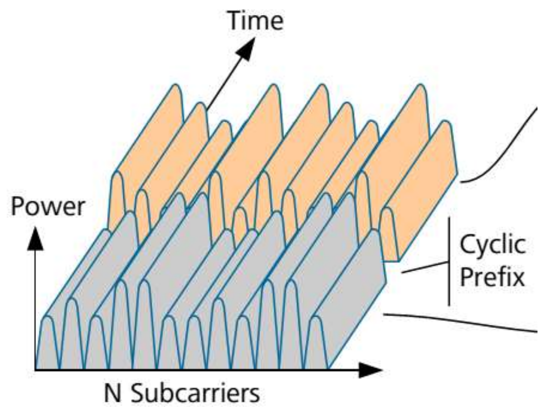


(a)



(b)

Figure 3.3 *(a) Block diagram of transmitter and receiver, and (b) subcarrier allocation of SC-FDMA system [10, 16].*

3.1.3. Multiple Input Multiple Output (MIMO)

One specification requirement of LTE release 8 as per 3GPP was the implementation of multiple input multiple output (MIMO) techniques in the radio environment. MIMO technique uses spatial multiplexing to send signals from two or more different antennas with different data streams so that the receiver can separate the streams by applying different signal processing techniques. Theoretically, MIMO increases the peak data rates by a factor of N for NxN antenna configurations. For example, a 2x2 MIMO system where two transmitting antennas and two receiving antennas are used, the peak data rate can be doubled. Therefore, to send *N* independent layers, both the transmitter and receiver need at least *N*different antennas.

Figure 3.4 shows a 2x2 MIMO and spatial multiplexing. The eNodeB sends data on two different layers from two different antennas. The receiver must be able to separate the two data layers using the independent channel characteristics produced by the two paths. In theory, a 2x2 MIMO system doubles the peak data rate and a 4x4 MIMO quadruples it.However, it is not always true that the peak data rate increases with MIMO size depending on the actual refence symbols (h_{ij} in Figure 3.4)that are in use. In general, some key advantages of using MIMO include coherent combing (power gain), spatial diversity and spatial multiplexing.

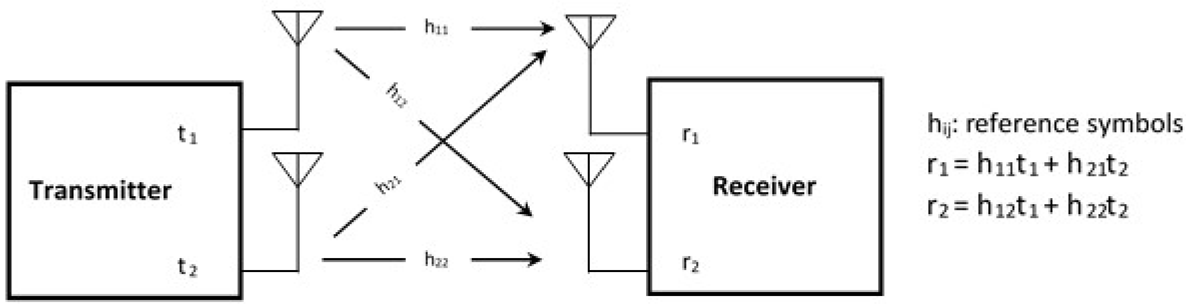


Figure 3.4*A 2x2 MIMO system [18].*

3.2. LTE Frame Structure

In LTE systems, devices are allocated blocks of subcarriers which are commonly referred to as Physical Resource Blocks (PRB). These resource blocks are contained inside the generic LTE frame structure. Resource blocks can be of Frequency Division Duplex (FDD) or Time Division Duplex (TDD) radio frames. The number of resource blocks is determined by the signal bandwidth. A single PRB is considered as the smallest unit in LTE frame which is allocated for a duration of half a millisecond (0.5 ms).

A single LTE frame can be considered as a two-dimensional grid of subcarriers and symbols. It consists of 12 subcarriers grouped together where each subcarrier has six or seven symbols depending on the length of the CP. The term Resource Element (RE) is used to describe one subcarrier lasting one symbol which can then be assigned to carry a modulated information, a reference information or nothing [13]. The basic time unit used in an LTE system (T_s) is calculated as follows.

$$\mathbf{T_s} = \frac{\mathbf{1}}{\mathbf{Subcarrier\ BW * FTT\ size}} \qquad (\mathbf{s}) \qquad (3.1)$$

For example, a typical LTE system with 15 kHz subcarrier bandwidth and 2048 FTT window size, the basic unit is 32.6 ns. Figure 3.5 shows the detail of LTE frame structure.

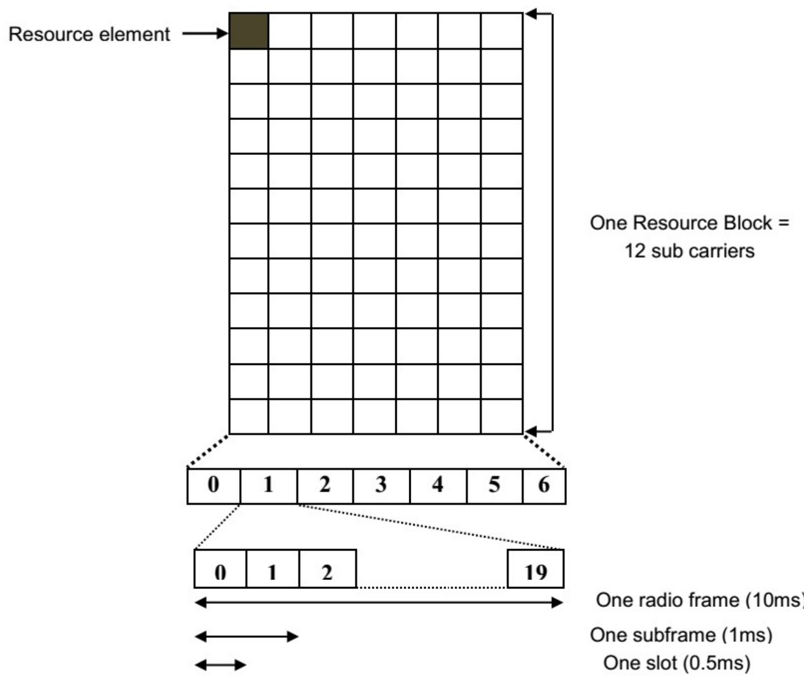


Figure 3.5 *LTE frame structure [19].*

A single PRB is also referred to as a slot in the LTE frame. Two slots make up a sub-frame with a duration of 1 ms. A group of 20 PRBs form a single frame with a 10 ms length. The frame structure is same for the downlink (OFDMA) and the uplink (SC-FDMA). Reference symbols are used for channel estimation where they are placed with a specific pattern in the PRBs estimate the channel condition efficiently. Table 3.1 shows a standard list of resource block configuration for different allowable bandwidths in LTE systems [12]. For example, a 20 MHz LTE system has 100 PRBs while a 1.4 MHz system has only 6 PRBs.

Table 3.1 *Resource block configuration in EUTRAN channel bandwidth.*

Channel bandwidth (MHz)	1.4	3	5	10	15	20
Number of resource blocks	6	15	25	50	75	100

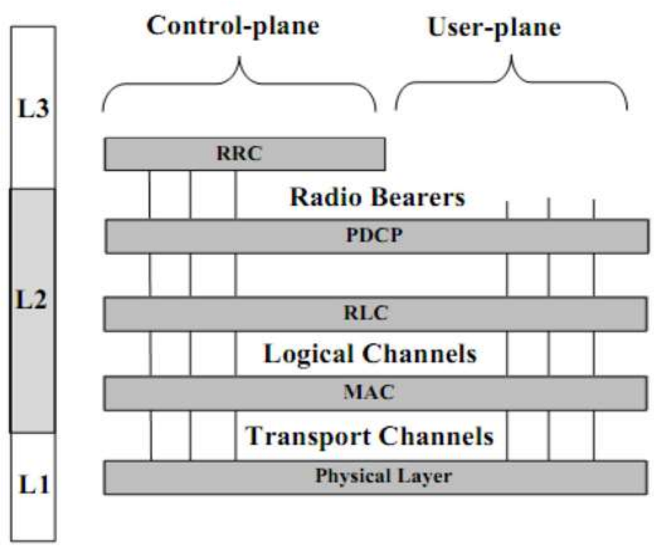


Figure 3.6 *LTE Radio Protocol Stacks [17].*

3.3. LTE Interface and Protocols

LTE interface defines connectivity between the user equipment and the eNodeB whereas protocols are a set of rules and requirements to connect and transmit the data between the two ends. The role of LTE radio interface protocols is to setup, reconfigure and release the radio bearer that provides the means for transferring the EPS bearer.

In general, the radio interface protocol architecture of LTE can be divided in to two groups of protocols: User Plane Protocols and Control Plane Protocols as shown in Figure 3.16. There are effectively two control planes protocols. The first is provided by Radio Resource Control (RRC) which carries the signaling message between the User Equipment and the eNodeB. The second carries Non-Access Stratum (NAS) signaling messages to the MME which are also carried by RRC. The user plane focuses on delivery of IP datagrams to and from the core network.

Figure 3.6 shows the EUTRAN layer classification in user plane and control plane. The protocol stack is used to organize the information and services for transmitting through logical channels. Logical channels carry control or traffic information and map these logical channels into transport channels. Transport channels define how and with what characteristic the information within each logical channel is transmitted over the radio interface.

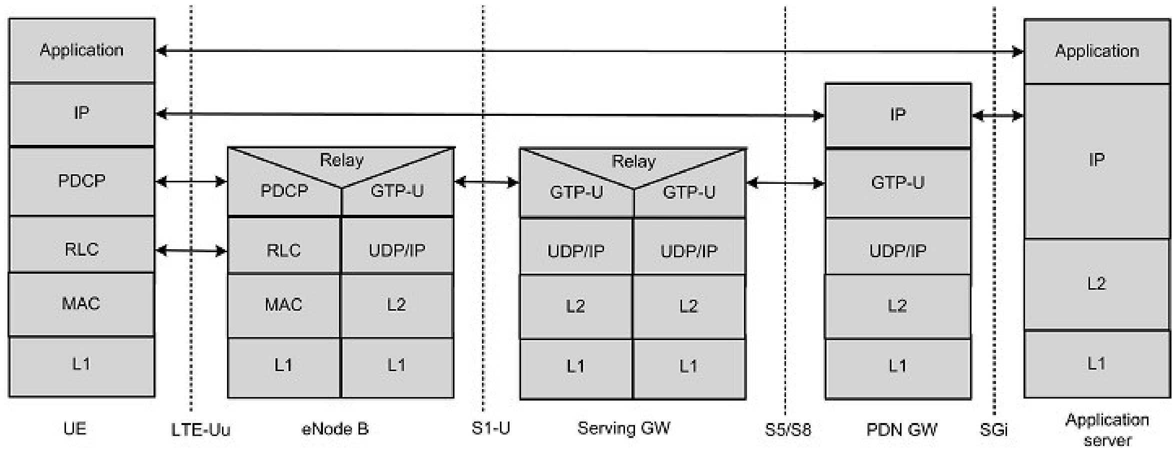


***Figure 3.7** User plane protocol stack [21].*

Figure 3.7 shows the protocol stack in user plane. The LTE-Uu denotes the interface between the UE and eNodeB. The eNodeBs are connected to the SGW S1-U and to the PGW by S5/S8 interfaces. Data packets are tunneled using GPRS Tunneling Protocol (GTP) across the S1 and S5/S8 interfaces. The eNodeB, SGW and PGW are responsible for transferring the application data from application server to users. The function of each layerand protocol in LTE-Uu is explained as follows.

- ***Physical Layer (Layer1).***It refers to the transmission medium which carries all information from the MAC transport channels over the air interface. It takes care of error detection, rate matching, mapping of physical channels, power weighting, modulation and demodulation, frequency and time synchronization, radio measurements, MIMO processing transmit, diversity beam forming and RF processing. This layer is available on the user equipment and eNodeBs.

- ***Medium Access Control (MAC) Layer.*** The MAC sublayer offers a set of logical channels to the RLC sublayer that it multiplexes into the physical layer transport channels. It also manages the HARQ error correction, handles the prioritization of the logical channels for the same UE and the dynamic scheduling between UEs.

- ***Radio Link Control (RLC) Layer.*** This layer transports Protocol Data Units (PDU) of the Packet Data Convergence Protocol (PDCP) layer. The main functions of RLC are segmentation and concatenation of PDUs, error detection and recovery of protocol. An RLC entity can be configured to perform data transfer in one of the following three modes: Transparent Mode (TM), Unacknowledged Mode (UM) or Acknowledged Mode (AM). The TM and UM modes RLC entities are defined to be unidirectional whereas the AM entities are described as bidirectional. This layer is also present in UE and eNodeB.

- ***Packet Data Convergence Protocol (PDCP).***The PDCP provides services both to the upper layer and to the lower layer. In the control plane, PDCP facilitates encryption and integrity checking of signaling messages. The user plane is slightly different since only encryption is performed. In the user plane IP datagrams can also be subjected to IP header compression techniques in order to improve the system's performance and efficiency. Finally, PDCP also facilitates sequencing and duplication detection. Both UE and eNodeB support this protocol.

- ***Internet Protocol (IP).***IP routes the user plane data across packet switched network. IP routers are used to forward the packets in the right direction. Each user is assigned with IP address by PDN gateway during data transfer.

- ***Application Layer.***This layer is available on both the UE and the application server. Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP) and Simple Mail Transfer Protocol (SMPT) are examples of application layer protocols that use TCP or UDP to transmit or receive data.

Figure 3.8 shows the protocol stack in the control plane. Control plane and User plane have common protocols which perform the same functions except that there is no header compression activity in control plane. In the access stratum protocol stack and above the PDCP, there is the RRC protocol which is considered as a Layer 3 protocol. It sends signaling messages between the eNodeB and UE for establishing and configuring the radio bearers of all lower layers in the access stratum. The Mobile Management Entity (MME) within Evolved Packet Core (EPC) is responsible to transfer those control messages. The function of control plane protocols is explained below.

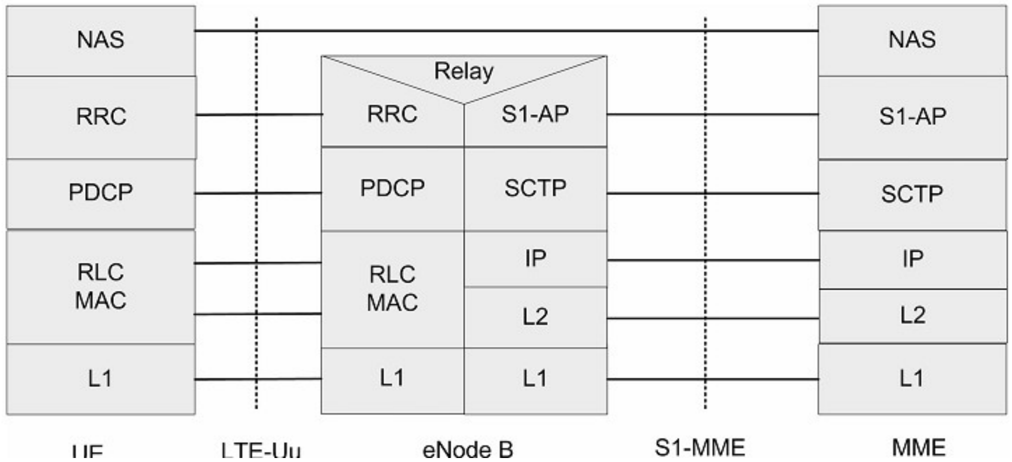


Figure 3.8 *Control plane protocol stack [21].*

- ***Radio Resource Control (RRC).*** The RRC layer is a key signaling protocol which supports many functions between the terminal and the eNodeB. It performs broadcast system information, establishes and reconfigures radio bearers, performs paging and mobility procedures functions as well as Measurement control. This layer resides on both UE and eNodeB.

- ***Stream Control Transmission Protocol (SCTP).***It is a transport layer protocol which transfer the user data and signaling message into different chunks. Chunks are the fragment of the message which is identified by chunk header. SCTP are alternatives to TCP and UDP.

- ***S1 Application Protocol (S1-AP).***They provide the signaling between eNodeB and MME. It is responsible for location reporting and NAS signaling functions.

- ***Non-Access-Stratum (NAS).*** It is responsible for handling session management procedure for IP connectivity between UE and PDN GW. It also supports UE mobility and Evolved Packet System (EPS) bearer management.

3.4. LTE Data Channels

LTE classified data channels into three different categories based on where they are located with respect to the information to be sent - physical, transport and logical channels [15, 22].

3.4.1. LTE Physical Channels

A physical channel corresponds to a set of time–frequency resources used for transmission of user data and control information from higher layers. They are classified as downlink physical channels and uplink physical channels as listed in Table 3.2.

Table 3.2*LTE Physical channels and their functions.*

Channels	**Functions**
Physical Broadcast Channel (PBCH)	It carries part of the system information, required by the terminal in order to access the network.
Physical Downlink Shared Channel (PDSCH)	It is used for unicast transmission, but also for transmission of paging information
Physical Control Format Indicator Channel (PCFICH)	Downlink channel that provides the terminals with information necessary to decode the set of PDCCHs. There is only one PCFICH in each cell
Physical Hybrid-ARQ Indicator Channel (PHICH)	Downlink channel which carries the hybrid-ARQ acknowledgement to indicate to the terminal whether a transport block should be retransmitted or not.
Physical Downlink Control Channel (PDCCH)	It is used for downlink controlling formation, mainly scheduling decisions, required for reception of PDSCH and for scheduling grants enabling transmission on the PUSCH
Physical Uplink Control Channel (PUCCH)	It is used by the terminal to send hybrid-ARQ acknowledgements for downlink channel dependent scheduling, and for requesting resources to transmit uplink.
Physical Random Access Channel (PRACH)	It is an uplink channel which transfers the random-access preambles send by UE to access the network in non-synchronized mode.
Physical Uplink Shared Channel (PUSCH)	It is responsible to transfer user data and contains the information of Signaling Radio Bearers (SRB) for RRC signaling

3.4.1.1. Downlink Physical Signals

Downlink Reference Signals

In order to acquire the LTE system, the eNodeB must broadcast various downlink signals. The method of finding the system needs to be consistent by reference signals since the downlink is scalable from 1.4MHz to 20MHz and the device may not be aware of the eNodeB configuration. LTE downlink reference signals are explained below [15].

- ***Cell specific downlink reference signals***are transmitted in every downlink subframe and span the entire downlink cell bandwidth. They can be used for channel estimation for coherent demodulation of any downlink transmission.

- ***UE specific reference signal***is specifically intended for channel estimation for coherent demodulation of downlink shared channel (DL-SCH) transmissions. The term *UE specific* relates to the fact that each such reference signal is typically intended to be used for channel estimation by one specific terminal. They are transmitted within the resource blocks assigned for DL-SCH transmission to that specific terminal.

- ***Multimedia Broadcast Single Frequency Network (MBSFN) reference signals***are used for channel estimation for coherent demodulation of signals being transmitted by means of MBSFN. The transmitted signals are received by many UEs. These signals may carry timing information, climate information and calendar information in a cell.

- ***Downlink Synchronization Signals***are used for initial synchronization, cell search and identify cell groups for all detected UEs and synchronization of neighbor cell during handover measurements. There are 504 physical cell identities divided into 168 groups of three identities. They always occupy 62 subcarriers of the channels.

3.4.1.2. Uplink Physical Signals

- ***Demodulation Reference Signals (DRS)***are multiplexed with user data and control transmission to provide the receiving eNodeB with a known signal element. They perform channel estimation and from which it can calculate time adjustments. They will always occupy the same allocated bandwidth as the user data which means the reference symbol sequence needs to be the same as the number of allocated subcarriers in the transmission bandwidth[15].

- ***Sounding Reference Signals (SRS)*** are allocated over multiples of four resources blocks and always transmitted in the symbol of a subframe. They are used by the base station to estimate the quality of the uplink channel that can be used to optimize uplink scheduling process.

3.4.2. Transport Channels

The transport channels are Service Access Point (SAP) between the MAC and Physical layers which are mapped in the physical layer to different physical channels. Transport channelsdefine how and with what characteristicsthe information is transmitted over the radio interface. The UE acquires the System Information Block (SIB) from BCH. It contains information for cell selection or reselection to make handover decisions. Table 3.3 lists different types of transport channel available in LTE.

Table 3.3*LTE Transport channels and their function*

Channels	Functions
Broadcast Channel (BCH)	broadcast the parameters required to access the system in the cell coverage area
Downlink Shared Channel (DL-SCH)	intended to carry dedicated user data and control information
Paging Channel (PCH)	carries data relevant to the paging procedure
Random Access Channel (RACH)	is used to carry control information from the terminal, such as requests to setup a connection
Uplink Shared Channel (UL SCH)	is an extension to the RACH channel that is intended to carry packet-based user data in the uplink direction

3.4.3. Logical Channels

The data transfer services of the MAC layer are provided on the logical channels. A set of logical channel types is defined for the different kinds of data transfer servicesoffered by the MAC layer.

LTE logical channels are grouped in to two general groups of channels:control channels and traffic channels. Control channels are used to transfer control plane information while traffic channels are used for user plane information.Logical channels are mapped from transport channels to transfer the user plane and control plane information offered by the MAC layer. Table 3.4 lists the different logical channels along with their functions.

Table 3.4*LTE Logical channels and their function*

Channels	**Functions**
Broadcast Control Channel(BCCH)	It sends System Information messages from the eNB to UEs.
Paging Control Channel (PCCH)	Used by the eNodeBs to send paging information
Common Control Channel (CCCH)	It is used to send random access information to start a new Radio Resource Control (RRC) connection
Dedicated Control Channel (DCCH)	It is used to send user specific control information for making handover decisions and power control mechanisms
Dedicated Traffic Channel (DTCH)	It is responsible to send the user specific data in uplink and downlink direction.

3.5. Scheduling

3.5.1. Link Adaptation

Link Adaptation is a crucial feature of the LTE air interface which involves the variation of modulation and coding schemes to maximize throughput on the air interface. LTE adjusts the transmitted information data rate by modulation scheme and channel coding rate dynamically to match the prevailing radio channel capacity for each user. Link adaptation is therefore very closely related to the design of the channel coding scheme used for forward error correction. It is included in LTE physical shared channels in downlink and uplink.

For the downlink data transmissions in LTE, the eNodeB typically selects the modulation scheme and code rate depending on a prediction of the downlink channel conditions. An important input to this selection process is CQI feedback transmitted by the UE in the uplink. CQI feedback is an indication of the data rate which can be supported by the channel by considering SINR and the characteristics of the UE’s receiver.

For Uplink, link adaptation in LTE is used to guarantee the required minimum transmission performance of each UE such as the user data rate, packet error rate and latency while maximizing the system throughput. For this purpose, uplink link adaptation should effectively utilize a combination of the adaptive transmission bandwidth accompanied with channel dependent scheduling, transmission power control and the adaptive modulation as well as channel coding rate [16, 22].

3.5.2. Hybrid Automatic Repeat Request (HARQ)

It provides a Physical Layer retransmission data from the source if erroneous data is collected at the receiver. This significantly improves performance and adds robustness. The retransmission protocol selected in LTE is known as Stop and Wait (SAW).

Automatic retransmission means the transmitter persists on the transmission of the current transport block until it has been successfully received before initiating the transmission of the next one. The physical layer in LTE supports HARQ on the physical downlink and uplink shared channels with separate control channels as well as physical hybrid indicator channel to send the associated acknowledgement feedback. If the mobile device identified an error in the transmission, it can send a Negative Acknowledgement(NACK) to the eNodeB. The eNodeB is then able to quickly reschedule the data. This ACK/NACK information is sent in PDCCH for downlink or PUCCH for uplink. HARQ in the downlink uses Asynchronous adaptive HARQ where retransmission can happen at any time. Uplink ACK/NAKs in response to downlink retransmissions are sent on PUCCH or PUSCH. The retransmissions are always scheduled through PDCCH. HARQ in the uplink uses Synchronous HARQ where retransmission of data takes place at predefined time. Downlink ACK/NAKs in response to uplink retransmissions are sent on PHICH [22].

3.5.3. Power Control

LTE like most other cellular systems requires power control to be implemented. This reduces interference and enables it to be managed or optimized by the eNodeB. Average powers to be used on different physical uplink channels are determined by the uplink power control. Only uplink power control is defined in LTE specifications. Uplink power control for LTE is the set of tools by which the transmit power for different uplink physical channels and signals are controlled to ensure that they are received at the cell site with an appropriate power. The uplink demodulation reference signals are always transmitted together with PUSCH or PUCCH with the same power as the corresponding physical channel.

Uplink power control improves system capacity, network coverage, attains improved quality of services, minimizes inter/intra cell interference and allow increased battery life. Both open-loop and closed-loop power control schemes are supported in LTE to mitigate deep fading, the near-far effect, multiuser and inter-cell interference. An open-loop mechanism implies that the terminal transmit power depends on estimates of the downlink path-loss. On the other hand, a closed-loop power control implies that the network can in addition directly control the terminal transmit power by means of explicit power-control commandstransmitted in the downlink. Power control is an effective mechanism to ensure a certain level of bit error rate (BER) regardless of channel conditions [22].

3.5.4. Radio Resource Management (RRM)

The purpose of RRM is to ensure efficient use of the available radio resources as well as to provide mechanisms that enable E-UTRAN to meet radio resource-related requirements. RRM in E-UTRAN provides mechanisms to assign, re-assign and release radio resources for both single and multi-cell scenarios [16, 22]. The RRM functions are represented by the following aspects.

- ***Radio Bearer Control (RBC).***It is concerned with the establishment, maintenance and release of radio bearers. It considers the overall resource situation in E-UTRAN like the QoS requirements of in progress sessions and the QoS requirement for the new service. RBC is located in the eNodeB which also involves in the release of radio resources associated with radio bearers at session termination and handover.

- ***Connection Mobility Control (CMC).*** It is concerned with the management of radio resources with regard to idle or connected mode mobility. In idle mode, the cell reselections are controlled by setting of parameters like thresholds and hysteresis values. In connected mode, the mobility of radio connections or handover decision are based on UE and eNodeB measurements.This takes other inputs such as neighbor cell load, traffic distribution, transport and hardware resources as well as operator-defined policies into account.

- ***Dynamic Resource Allocation (DRA) or Packet Scheduling (PS).***Itis used to allocate and de-allocate resources to user and control plane packets. DRA involves tasks for selection of radio bearers whose packets are to be scheduled and managing the necessary resources .PS otherwise takes into account the QoS requirements associated with the radio bearers, the channel quality information for UEs, buffer status and interference situation.

- ***Inter-cell Interference Coordination (ICIC).*** It is used to manage radio resources by controlling inter-cell interferences.It takes resource usage status and traffic load information from multiple cells to make decisions.

- ***Load Balancing (LB).***Ithas the task to handle uneven distribution of the traffic load over multiple cells for high utilization of radio resources and keeping of QoS.LB involves in handover or cell reselection with the purpose of redistributing traffic from highly loaded cells to underutilized cells.

- ***Inter-RAT Radio Resource Management.*** It is concerned with the management of radio resources in connection with Inter-RAT handover. At Inter-RAT handover, the handover decision may take into account the involved RAT resource situation as well as UE capabilities and operator policies.

CHAPTER 4

Mobilityin LTE Systems

Mobility is an essential component of mobile cellular communication systems because it offers clear benefits to the end users. Low latency services such as voice and/or real-time video connections can be maintained while moving even in high speed trains. Mobility is beneficial also for nomadic services such as laptop connectivity since it allows a reliable connection to be maintained in the areas between two cells where the best serving cell is changing.

One of the main goals of LTE or any wireless system is to provide fast and seamless handover from one cell to another while simultaneously keeping network management simple. This is especially true for LTE system because of the distributed nature of the LTE radio access network architecture which consists of just one type of base station known in LTE as the eNodeB.

This Chapter introduces the basic procedures of mobility in EPS. Two modes of mobility, idle mode and connected mode are discussed. Connected mode includes the handover process.Inter-RAT handovers are explained briefly with signal flow messages and diagram as well as measurement events and triggering conditions for the handover process. A short introduction about Circuit Switch Full Back (CSFB) is also given at the end.

4.1. EPS Mobility and Connection Management State

The Evolved Packet Services (EPS) needs to be able to define and keep track of the availability and reachability of each terminal to offer effective service to the end user. EPS achieves this functionality by maintaining two states of contexts for each UE.The two states are Packet EPS Mobility Management (EMM) and EPS Connection Management (ECM).The EMM is responsible for mobility and session management procedures whereas ECM refers to the existence of signaling connection between the UE and the EPC. Connectivity procedures follow the ECM states [20, 23].

4.1.1. EPS Connection Management (ECM)

ECM describes UE current connectivity status with the EPC. Figure 4.1 shows two ECM states of ECM – ECM-IDLE and ECM-CONNECTED.

- ***ECM-IDLE.*** There is no signaling connection between the UE and the EPC in this state. The UE will also perform Public Land Mobile Network (PLMN) selection, cellselection and cell reselection. The E-UTRAN does not have any knowledge of the UE in this state.

- ***ECM-CONNECTED.***The UE moves to ECM-CONNECTED when a signaling connection is established between the UE and the eNodeB. In this state, the UE has an active signaling connection to the MME. The mobility functionality is handled by the handover procedure. Regardless of the handovers, the UE still performs tracking area updates if necessary. The UE enters the ECM-IDLE state again when the signaling connection is released which happens most often in the case of inactivity.

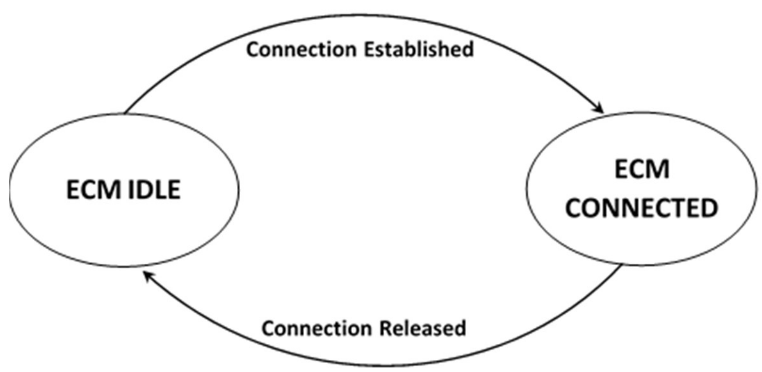


Figure 4.1*ECM Modes and connection states [20]*

4.1.2. EPS Mobility Management (EMM)

EPS connection procedure is necessary for UE to establish connection to EPC. The procedure is carried out by the specific EMM message 'ATTACH REQUEST' that operates in NAS signaling layer. Figure 4.2 shows the two main states of UE-MME.

- ***EMM-DEREGISTERED.*** In this state, EMM is marked as detached but MME is able to answer the attach procedure or TAU procedure initiated by UE. Here the location of the

UE is not known by the network at any level. Thus, the UE is not reachable by the network.

- ***EMM-REGISTERED.***EMM is registered with an 'ATTACH' procedure. It does this by first setting up an RRC connection and then sending an attach request using the NAS protocol. While the UE is registered, the network knows its location at least on the level of a tracking area and is able to page the UE. The registered state also requires that the UE sets up and maintains a security context with the network.

The UE leaves EMM-REGISTERED and enters EMM-DEREGISTERED by performing the detach procedure. The switch to EMM-DEREGISTERED is also performed automatically if all of the bearers have been deactivated or a Tracking Area Update (TAU) is rejected. EMM utilizes the NAS protocol to perform its procedures. This means that the EMM messages sent by the UE are targeted directly to the MME. The eNodeB only forwards them.

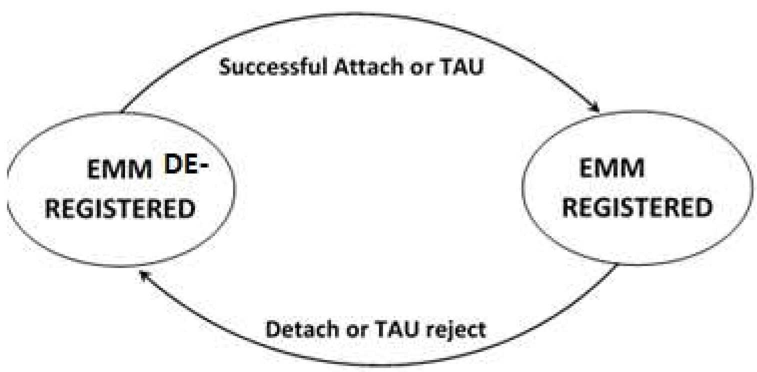


Figure 4.2*EMM modes and connection states [20]*

4.2. IDLE State Mobility Management

The UEs in the mobile environment that are in IDLE state or DEREGISTERED state exhibit the IDLE state mobility. The process is illustrated in Figure 4.3 which begins the moment the UE is in ON state [13, 17].

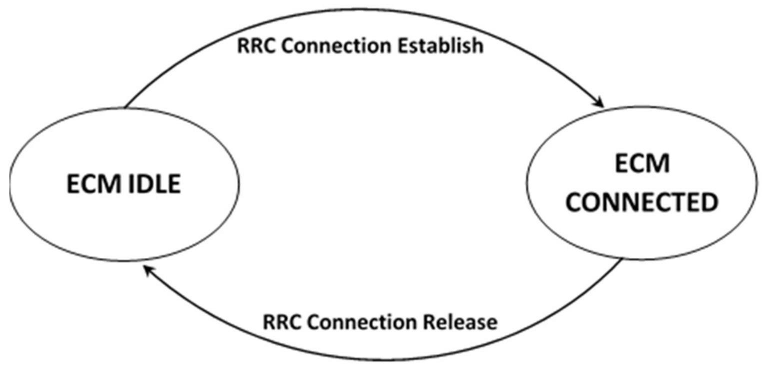


Figure 4.3 *LTE UE Mobility Status [20].*

4.2.1. Public Land Mobile Network (PLMN) Selection

PLMN is a network established by the operator. Each PLMN has its own Mobile Control Code (MCC) and Mobile Network Code (MNC). Each operator has its own code to identify the PLMN. Different PLMN interconnect with each other by transmission links. The UE can select PLMN manually or automatically. UE scans for all Radio Frequency (RF) channels in E-UTRA bands to find available PLMNs. The UE shall search for the strongest cell and read its system information from each carrier. It then reports the strong cells to the NAS as the list of high-quality available PLMNs. Once the PLMN selection is performed by UE, cell selection procedure is initiated.

4.2.2. Cell Selection

Cell selection is a procedure that UE receives cell information from the broadcast channels and then camps on the suitable cell if that cell is not barred and has good radio conditions. Cell selection can be of the following types [20].

- ***Initial Cell Selection.*** This procedure requires no prior knowledge of which RF channels are E-UTRA carriers. The UE shall scan all RF channels in the E-UTRA bands according to its capabilities to find a suitable cell. Then the UE search for the strongest cell from each carrier. Once a suitable cell is found, this cell shall be selected.

- ***Stored Information Cell Selection.*** This procedure requires stored information of carrier frequencies from previously received measurement control information elements or from previously detected cells. Once the UE has found a suitable cell, then the UE shall select it. If no suitable cell is found, the Initial Cell Selection procedure shall be started.

- ***Cell selection when leaving RRC Connected mode.*** This type of selection takes place when there is transition from RRC connected mode to RRC idle mode. UE is directed to a specific RF carrier by eNodeB sending redirected carrier information within RRC Connection Release Message [27].

During cell selection, a UE selects an E-UTRAN cell that meets cell selection criteria. A UE selects an E-UTRAN cell to camp on when the cell meets the following conditions.

1. Received signal level of the UE expressed in decibel (dB) is greater than zero ($S_{rx}> 0$).
2. Cell selection receiving quality expressed in dB is greater than zero ($S_{qual}> 0$).

$$\mathbf{S_{rx} = (Q_{rx\_min} + Q_{rx\_min\_offset}) - P_{cmps}} \quad (4.1)$$

$$\mathbf{S_{qual} = Q_{qual\_meas} - (Q_{qual\_min} + Q_{qual\_min\_offset})} \quad (4.2)$$

Where, P_{cmps} is the resultant power compensation of the function which is expressed as follows.

$$\mathbf{P_{cmps} = max(P_{max} - P_{UE\_max\_out},\quad 0)} \quad (4.3)$$

Where,

- P_{max}: maximum transmit power that the UE can apply to uplink transmission.
- $P_{UE,\ max\_out}$: maximum output power that the UE can physically achieve.
- Q_{rx_meas}: measured Reference Signal Received Power (RSRP) value by UE.
- Q_{rx_min}: minimum required RSRP value required value to camp on a cell.
- $Q_{rx\_min\_offset}$: offset to Q_{rx_min} [2, 20].

Once the suitable cell has been selected and camped upon, the UE starts to measure neighboring cells for the reselection process. UE measures the neighboring cells in the neighbor cell list of the serving cell. To minimize the frequency of neighboring cell measurements or cell reselection measurement, a threshold signal level is defined for the serving cell so that UE does not need to perform the measurement if the serving cell measured value exceeds the threshold. This also helps to reduce the battery power of the mobile device. The threshold is defined for both inter-frequency and intra-frequency cell selections. Intra-frequency measurement criterion is triggered if the received signal level of the serving cell (S_{serv}) is less than or equal to that of neighboring cells ($S_{intrasearch}$): [$S_{serv} \leq S_{intrasearch}$)]. Figure 4.4 is an example of log file for cell selection and reselection process captured in idle mode where cell selection/reselection parameters are marked.

```
001396 02:50:19.397 RRC DL  BCCH-BCH SysInfoType3

Uu_RRC: BCCH_BCH_Message
-   .   .message
-   .   .   .sfn-Prime: 834
-   .   .   .payload:- completeSIB-List
-   .   .   .   .completeSIB-List [ 0 ]
-   .   .   .   .   .sib-Type ( systemInformationBlockType3)
-   .   .   .   .   .sib-Data-variable
-   .   .   .   .   .   .SysInfoType3
-   .   .   .   .   .   .   .sib4indicator: 0
-   .   .   .   .   .   .   .cellIdentity: 6917203
-   .   .   .   .   .   .   .cellSelectReselectInfo
-   .   .   .   .   .   .   .   .cellSelectQualityMeasure:- cpich-Ec-N0
-   .   .   .   .   .   .   .   .   .   .q-HYST-2-S: 1
-   .   .   .   .   .   .   .   .modeSpecificInfo:- fdd
-   .   .   .   .   .   .   .   .   .   .s-Intrasearch: 5
-   .   .   .   .   .   .   .   .   .   .s-Intersearch: 4
-   .   .   .   .   .   .   .   .   .   .rat-List [ 0 ]
-   .   .   .   .   .   .   .   .   .   .   .rat-Identifier: 0 ( gsm)
-   .   .   .   .   .   .   .   .   .   .   .s-SearchRAT: 2
-   .   .   .   .   .   .   .   .   .   .   .s-Limit-SearchRAT: 0
-   .   .   .   .   .   .   .   .   .   .q-QualMin: -18
-   .   .   .   .   .   .   .   .   .   .q-RxlevMin: -58
-   .   .   .   .   .   .   .   .q-Hyst-1-S: 2
-   .   .   .   .   .   .   .   .t-Reselection-S: 1
-   .   .   .   .   .   .   .   .maxAllowedUL-TX-Power: 24 (24)
-   .   .   .   .   .   .   .cellAccessRestriction
-   .   .   .   .   .   .   .   .cellBarred:- notBarred: null
-   .   .   .   .   .   .   .   .cellReservedForOperatorUse: 1 ( notReserved)
-   .   .   .   .   .   .   .   .cellReservationExtension: 1 ( notReserved)
-   .   .   .   .   .   .   .   .accessClassBarredList [ 0 ]: 1 ( notBarred)
```

Figure 4.4 *Example of cell selection and reselection captured in idle conditions.*

4.2.3. Cell Re-Selection

When the UE has successfully selected a cell to camp on, it continues measuring the received signal strength. If the signal strength drops below a threshold value of $S_{intrasearch}$, the UE starts to measure other intra-frequency cells and reports them to the eNodeB. In the case of intra-frequency cell reselection, ranking criteria is used. The serving cell and the neighboring cells are ranked based on measured data and the best ranked cell is re-selected. The serving and neighboring cells are ranked according to Eqs. (4.4) and (4.5), respectively.

$$\mathbf{R_s = Q_{s\_meas} + Q_{hys}} \quad (4.4)$$

$$\mathbf{R_n = Q_{n\_meas} - Q_{offset}} \quad (4.4)$$

Where, R_s is the criterion for the currently serving cell and Rn is the receptive criterion for each of the neighboring cells. Q_{s_meas} and Q_{n_meas} are the measured signal strengths of the serving and neighboring cells, respectively. Q_{hyst} is the hysteresis value used to prevent excessive reselections. Q_{offset} is the offset value and can be used to favor certain cells in the selection process. According to neighbor cell ranking criterion, a neighbor cell is selected $R_s < R_n$ condition is satisfied.

Figure 4.5 shows the cell reselection procedure in idle mode. Threshold is the determining factor. When the serving cell signal strength falls below threshold$S_{intrasearch}$, the UE starts to measure the signal strength of the neighbor cells according to the ranking criteria. Rank of any cell determines the best possible cell for UE to camp on. When the signal strength of the neighbor cell exceeds the serving cell by $Q_{hys}$for a period of $T_{re\text{-}selection}$, the neighboring cell is selected as a new serving cell.

4.2.4. Inter-RAT Cell Reselection Towards 3G

The UE in LTE cell should satisfy the following two criteria to perform Inter-RAT cell reselection towards a 3G cell.

1. The received signal level of the serving LTE cell (S_{serv}) must be less than or equal to the received signal strength of the non-serving 3G cell ($S_{non\_serv\_3G}$): [$Sserv \leq S_{non\_serv\_3G}$].
2. The received signal level of the non-serving 3G cell must be greater than the threshold value used by UE in reselection process ($S_{threshold}$): [$S_{non\_serv\_3G} > S_{threshold}$].

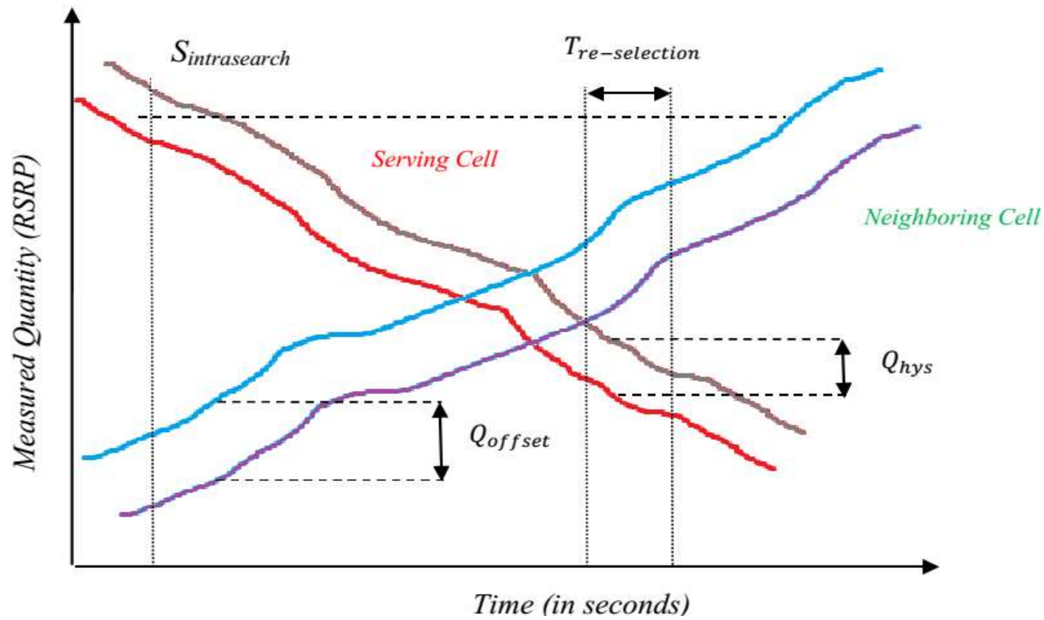


Figure 4.5 *Cell Reselection in idle state [19].*

4.2.5. Inter-RAT Cell Reselection Towards LTE

The UE in 3G cell should satisfy the following criteria for getting back from 3G to LTE network.

1. $S_x \leq S_{searchRATm}$
2. $S_{non\text{-}serv} > S_{threshold}$

Where,

- S_x can be cell selection received level value (S_{rx}) for TDD cells or can be cell selection quality value (S_{qual}) for FDD cells.
- $S_{searchRATm}$ is the measurement threshold for UE to trigger Inter-RAT cell reselection.

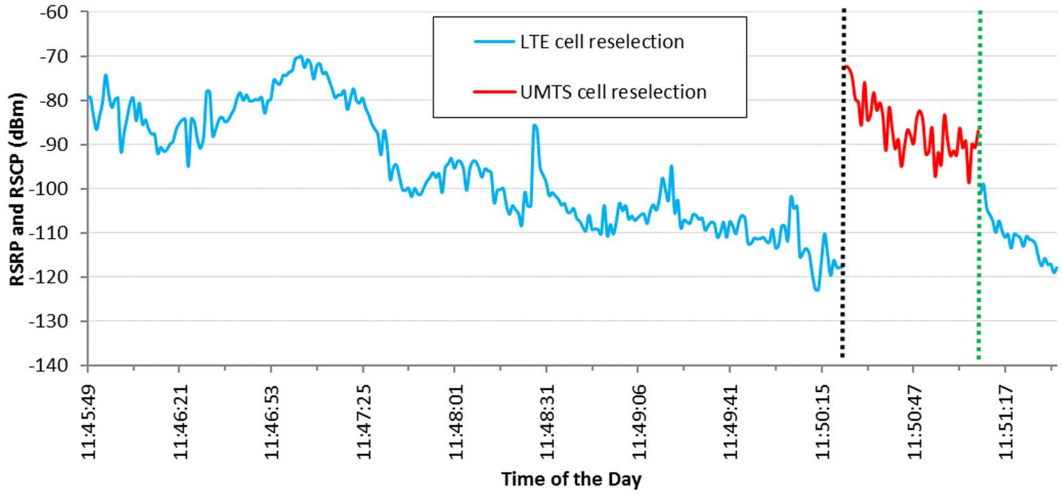


Figure 4.6 *Cell selection and reselection process in idle mobility.*

Figure 4.6 shows cell selection and reselection process in idle mode. The cell reselections are separated by the black and green color vertical lines. Measured quality is RSRP for LTE and RSCP for 3G which are drawn against time on the same graph. The cell selection/reselection steps are marked by dotted lines on the right side of the figure. Two cell reselections are shown in the figure, one from LTE to 3G cell and another from 3G to LTE cells. The first cell reselection occurred when RSRP (LTE) level dropped below -118 dBm. The next one happened when RSCP (3G) value was below -86 dBm. In the latter case, measured RSRP value was -100 dBm. When both LTE's RSRP and 3G's RSCP are satisfactory, the user equipment prefers LTE network because of LTE's higher priority than 3G.

4.2.6. System Information

System information is information which isthe network repeatedly broadcast to be acquired by terminals for them to be able to access the network. It helps in general to operate properly within the network and within a specific cell. UE locates and reads system information before establishing connection with E-UTRAN.

The eNodeB broadcast the System Information in BCCH channel and absolutely needed for a terminal to be able to read the remaining system information provided using DL-SCH. It contains a Master Information Block (MIB) and System Information Blocks (SIB). The MIB is broadcast on the Physical Broadcast Channel (PBCH). UE looks after MIB for downlink synchronization.

SIBs are transferred using PDSCH which indicates the transport format and physical resource blocks used for the system information transmission.SIB1 is carried by 'System-Information-Block-Type-1' message while SIB2 to SIB13 are enclosed within System Information (SI) RRC message which indicates the transport format and physical resource used for the system-information transmission [27].Table 4.1 summarizes the list of the system information available in LTE.

Table 4.1*LTE System information and their functions.*

Type	**Key Functions**
Master Information Block(MIB)	Downlink bandwidth, PHICH configuration, system frame number
System Information Block1(SIB1)	SIB scheduling list, PLMN IDs,TAC, cell baring information, cell selection parameters and frequency band information
System Information Block2(SIB2)	Dedicated cell baring information, UL frequency allocation, UL bandwidth, MBSFN (MBMS over Single Frequency Network) information
System Information Block 3 (SIB3)	Cell reselection information
System Information Block4 (SIB4)	intra-frequency neighbor cells descriptions
System Information Block 5 (SIB5)	inter-frequency EUTRAN inter-frequency descriptions, cell specific selection parameters
System Information Block6 (SIB6)	Inter-RAT UMTS neighbor cells descriptions, frequency specific selection parameters
System Information Block7 (SIB7)	Inter-RAT GSM/GPRS neighbor cells descriptions, frequency specific selection parameters
System Information Block8(SIB8)	Inter-RAT CDMA 2000 neighbor cells descriptions, frequency and cell specific selection parameters
System Information Block9(SIB9)	Home eNodeB identifier
System Information Block 10(SIB10)	ETWS (Earthquake and Tsunami warning system) primary notification
System Information Block 11(SIB11)	ETWS secondary notification
System Information Block 12(SIB12)	CMAS(commercial Mobile Alert Service) notifications
System Information Block 13(SIB13)	MBSFN (MBMS over Single Frequency Network) information

4.2.7. Location Management

The mobile communication network is divided into different traffic areas based on their physical location. Different co-located cells are grouped together to form a tracking area (TA). The basic idea is to allocate a group of adjacent cells the same TA identifier (TIA). As the UE moves through different cells, it reports to the MME about any change in the TAI via TAU message. Updates are also performed periodically to allow the network to discover whether the UE is actually available or not for paging. There are some limitations with the TA. UEs are paged into entire tracking area. A large TA with greater number of cells could cause the paging to UEs fail during the busy hours. This suggests that TA size should be smaller in order to have successful paging. However smaller TA would mean frequent TAU as the UE moves through the TAs. This creates signaling overhead to the network.

To fix these problems 3GPP has introduced a concept of Tracking Area Lists TAL). Each cell can still belong to only one TA but a UE may be registered to many TAs at the same time. TAL is essentially a collection of TAs to which a single UE is registered. Different UEs in the same area may have heterogeneous tracking are lists. If a UE is situated between two TAs, it may simply be registered to both of them to prevent excessive updates. Likewise, the signaling spike related to many UEs crossing a TA border is significantly relieved if most of them have different TALs. It must be noted that this kind of functionality requires intelligence from the network and the algorithms are left for the vendor to design and implement. Update to the list is made when UE detects it has entered a new TA that is not in the list of TAIs that the UE registered with the network. A TAU message is also created when the TA update timer expires [16, 21].

4.3. Connected State Mobility Management

Connected mode refers to a situation where the UE has an active signaling connection with the network. The mobility in the connected mode is handled by a handover process. Just as explained in the earlier section regarding the cell re-selection that takes place in the IDLE mode, handover operates in the RRC CONNECTED mode. It is one of the most important features of any of the cellular radio access technologies.

There are three basic types of handovers in the cellular radio: hard, soft and softer handover. In the soft handover, the UE is connected with multiple cells at a time. As the UE moves through the cells, weaker connections are released and stronger connections are established. In soft handover, a new connection is first made before breaking previous connection. It is also termed make-before-break connection. Softer handover occurs when the UE switches to the different cells of the same site. In LTE, handovers are hard handovers as the connection and ongoing service between the UE and serving cell is temporarily interrupted and the connection is reinstated with the new cell [2, 28].

4.4. Hard Handover in LTE

As the UE moves throughout the cells in the radio environment, the serving cell might become weak or the neighboring cell might be stronger. This gives option for the UE to switch cell to stronger one. The process is known as handover. In LTE, there are three types of handovers: intra-LTE handover, inter-LTE handover and Inter-RAT handover [16]. The latter handover mechanism is the focus of this thesis. Handover procedure in LTE can be divided into three phases: handover preparation, handover execution and handover completion.

- ***Handover preparation.***During the handover preparation, the UE defines measurement parameters and performs continuous measurement on its own cell and neighboring cell and then the measurement report sent accordingly as the triggering criteria is satisfied. Handover decision is then made at the serving eNodeB, which requests a handover to the target cell and performs admission control. Handover request is then acknowledged by the target eNodeB.

- ***Handover execution.*** Handover execution phase is starts when the source eNodeB sends a handover command to the UE. During this phase, data is forwarded from the source to the target eNodeB, which buffers the packets. UE then needs to synchronize to the target cell and perform a random access to the target cell to obtain uplink allocation and timing advance as well as other necessary parameters. Finally, the UE sends a handover confirm message to the target eNodeB after which the target eNodeB can start sending the forwarded data to the UE.

- ***Handover completion.*** In the final phase, the target eNodeB informs the MME at the core network that the user plane path has changed. The S-GW is then notified to update the user plane path. At this point, the data starts flowing on the new path to the target eNodeB. Finally, all radio and control plane resources are released in the source eNodeB.

4.4.1. X2-Based Handover

It is type of Intra-LTE handover which involves only E-UTRAN for the handover process. The eNodeB is the only element deciding on and implementing handovers where direct connectivity between the source eNodeB (S-eNB) and a target eNodeB (T-eNB) using X2 interface. The MME or the S-GW is not aware that a handover has occurred. The S-GW is still sending the downlink data to the source eNodeB even though the UE is already connected to the target eNodeB. The UE still gets the data through the forwarding process. In order to change the user plane path to flow directly to the target eNodeB, the target eNodeB sends a path switch request to the MME. The MME then asks the S-GW to change the endpoint of the GTP-U tunnel to the target eNodeB.

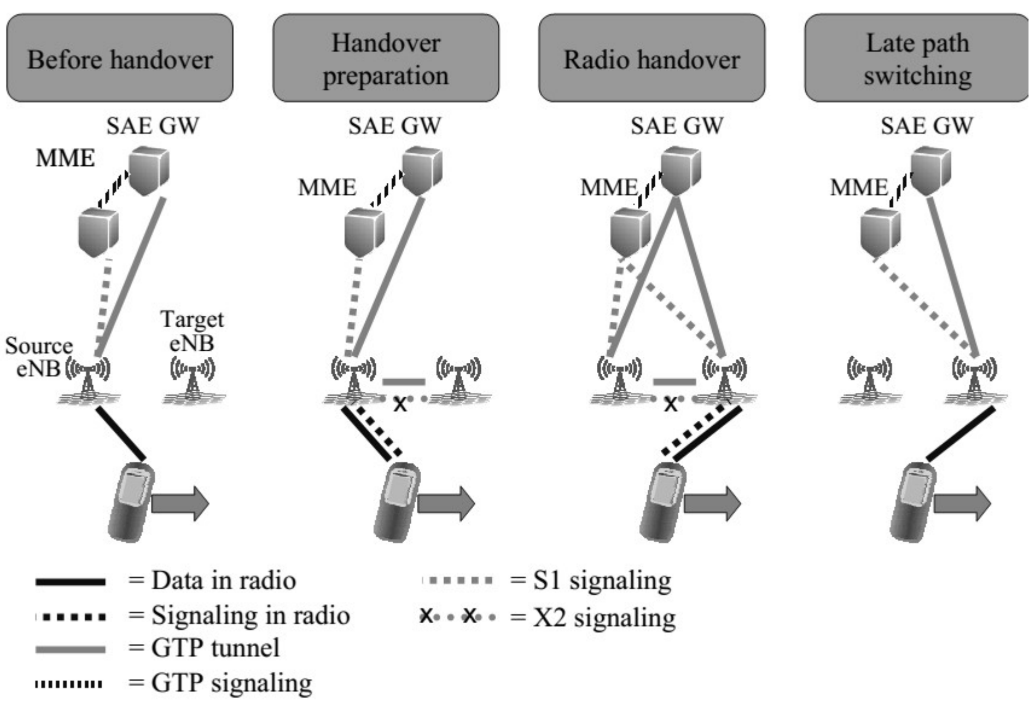


Figure 4.7 *X2 and S1 based handoverprocesses [16]*

4.4.2. S1-Based Handover

An S1 handover is necessary if the MME is to be relocated because of the handover. This happens generally only in MME area limits. The S1 handover may also be initiated if for some reason like an X2 interface is not available. The control signaling will then flow through the S1 interface. The S1 handover possibility is useful, since it allows for a handover to be completed regardless of possible missing X2 definitions. The data packet flow can take place either directly or indirectly from source eNodeB to target eNodeB. The X2 interface between the source eNodeB and the target eNodeB provides the direct path. Figure 4.7 shows the X2 and S1 based handover triggering processes.

4.5. Inter Radio Access Technology (Inter-RAT) Handovers

The Inter-RAT handovers refer to the inter-radio access technology handovers between E-UTRAN and GERAN, UTRAN or cdma2000 both for real time and non-real time services. The handover between LTE/UMTS, LTE/GSM, UMTS/GSM, and LTE/cdma2000 systems are some examples of Inter-RAT handover. The Inter-RAT handover is controlled by the source access system for starting the measurements and deciding the handover execution. It is a backwards handover where the radio resources are reserved in the target system before the handover command is issued to the UE. The GERAN system does not support the Packet Switched Handover so that resources are not reserved before the handover. In this case, the signaling is carried via the core network as there are no direct interfaces between the different radio access systems.

4.5.1. Handover from EUTRAN to UTRAN

Figure 4.8 shows Inter-RAT LTE to 3G radio driven handover when a UE reaches the end of coverage area. It indicates that the UE leaves LTE coverage and thus necessarily driven by radio handover to 3G full coverage. Operators are faced with multiple overlapping radio networks evolving towards more efficient technologies like LTE while keeping legacy 3G deployments [30].

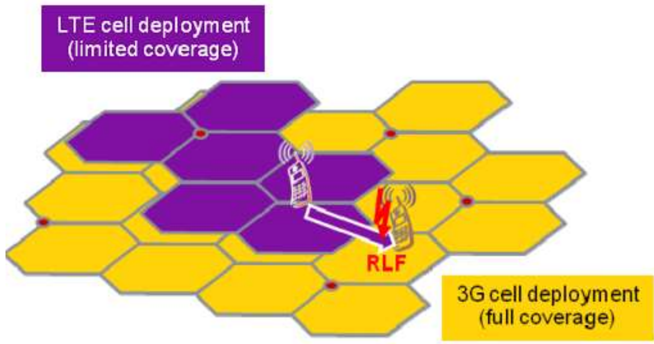


Figure 4.8 *Handover from LTE to UMTS due tocoverage [25].*

Figure 4.9 shows the inter connectivity between the LTE and 3G network elements. In the case of Inter-RAT handover involving the UMTS as the target network, RNC is the target element of the UTRAN. It also involves the SGSN of the target network which is analogous to target MME. The procedure is divided into Preparation and Execution phases.

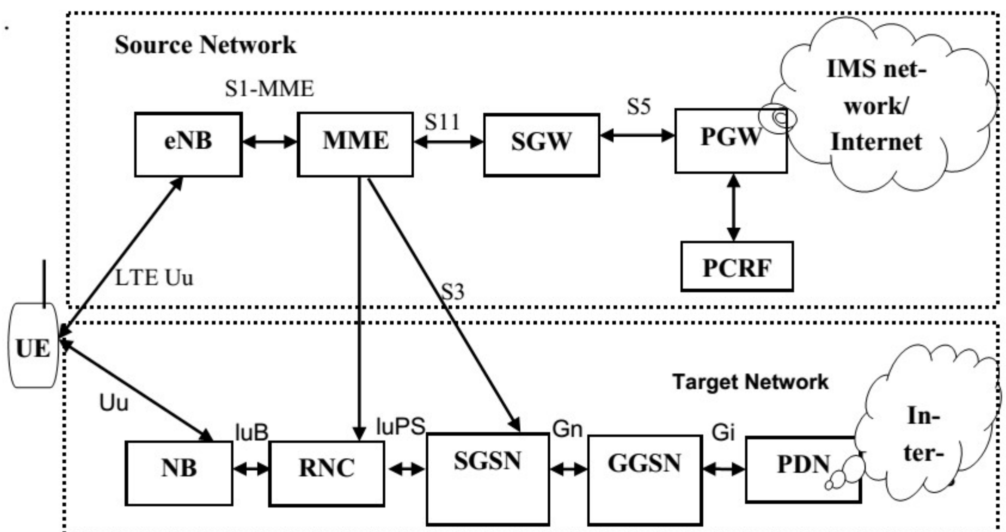


Figure 4.9 *EUTRAN to UTRAN handover process [16]*

4.5.1.1. Preparation Phase

In the preparation phase, the handover request from the serving eNodeB is forwarded to the source MME. It then sends the Forward Relocation Request (FRR) to the target SGSN unlike target MME in the S1 based handover. Target SGSN establishesa session with the target S-GW. Now the target SGSN after creating the session with target S-GW, requests for relocation to target RNC of the UTRAN. After confirmation, the target RNC sends the relocation acknowledge back to the target SGSN. The signaling message flow during preparation phase is illustrated in Figure 4.10.

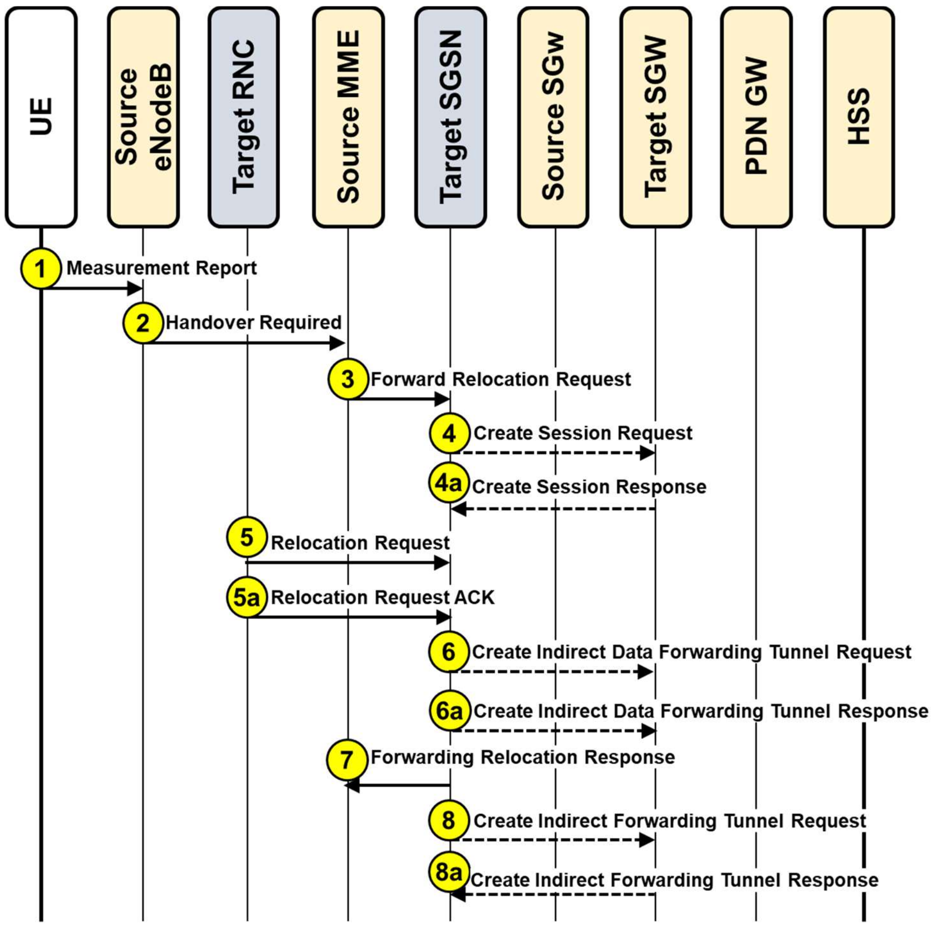


Figure 4.10*Preparation phase: Inter-RAT handover from LTE to UMTS[26]*

The following list describes the major steps involved in the Inter-RAT handover process.

1. The source eNodeB makes the handover decision based on the 'Measurement Report' from the UE. This report contains RSRP and RSRQ information. The data flow takes place

from PGW to UE via source S-GW and source eNodeB. The source eNodeB initiates the Inter-RAT handover to the target access network UTRAN.

2. The source eNodeB sends 'Handover Required' message to the source MME.

3. The source MME detects the Inter-RAT handover message. It allocates the resource in the target RNC, target SGSN and the serving GW. Then it sends 'Forward Relocation Request' to the target SGSN.

4. The target SGSN sends 'Session Creation Request' to the target SGW if serving GW is to be relocated. It creates the radio resources in the target S-GW. The target S-GW reserves resource and sends the 'Create Session Response' message to target SGSN.

5. The target SGSN sends 'Relocation Request' to reserve the resource at the target RNC and then 'Relocation request Acknowledge' is sent back by target RNC after reserving the radio resource.

6. The target SGSN sends 'Create Indirect Data Forwarding Tunnel Request' to the target SGW to transfer the downlink packets from the Source SGW to target SGW. The target SGW sends back 'Create Indirect Data Forwarding Tunnel Response' after creation of the tunnel.

7. The target SGSN sends back 'Forward Relocation Response' to the source MME after indirect data forwarding tunnel creation.

8. The source MME sends 'Create Indirect Data Forwarding Tunnel Request' to the source SGW to transfer the DL user data to the target network. The source SGW sends back 'Create Indirect Data Forwarding Tunnel Response' message after tunnel creation.

4.5.1.2. Execution Phase

The signaling message flow during execution phase is shown in Figure 4.11. The major steps are:

1. The Source MME sends the 'Handover Command' to the source eNodeB to indicate the completion of the preparation phase. It also informs the eNodeB which bearers are subjected to use based on the RRC layer.

2. The source eNodeB sends 'Handover from EUTRAN Command' message to the UE to prepare handover towards target UMTS network.

3. The UE performs 'UMTS Access Procedures' based on the handover command message.

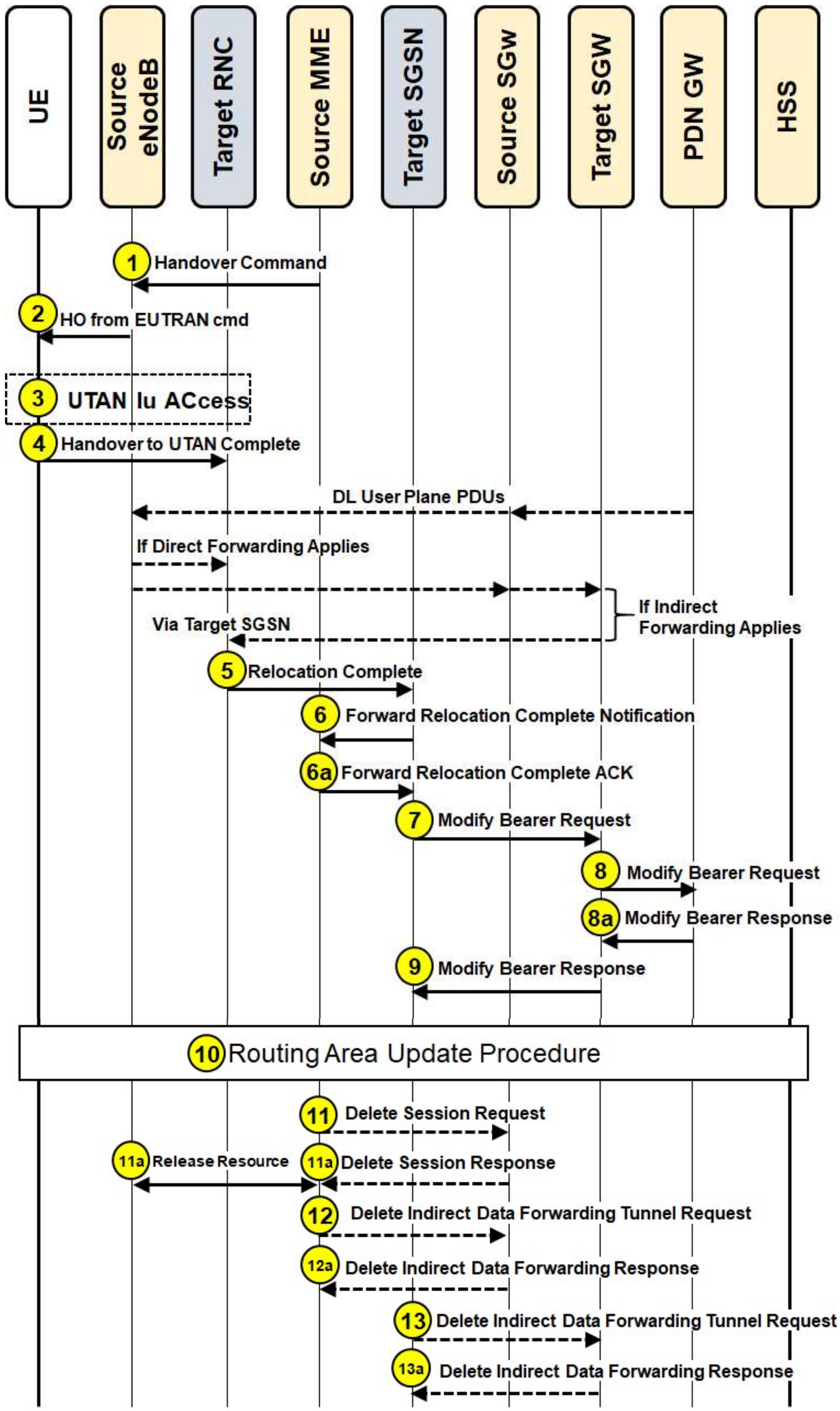


Figure 4.11 Execution phase: Inter-RAT handover from LTE to UMTS[26]

4. The UE sends 'Handover to UTRAN Complete' message to the target RNC after successful handover to the target UMTS cell. The source eNodeB forwards the downlink data packets towards the target RNC via direct path (source eNodeB - target RNC) or indirect path (source eNodeB- source SGW-target RNC).

5. The target RNC sends 'Relocation Complete' message to the target SGSN to indicate successful handover.

6. The target SGSN sends 'Forward Relocation Complete Notification' to the source MME. The message is acknowledged by the source MME. All EPS bearers used at the source SGW and source eNodeB by the UE is released by MME.

7. The target SGSN sends 'Modify Bearer Request' to the target SGW to notify the entire EPS bearer Contexts the UE has established.

8. The target SGW sends 'Modify Bearer Request' to the PDN GW to inform the relocation of the serving GW or the RAT type. The PDN GW updates its context field and sends back 'Modify Bearer Response' to the target SGW.

9. The target SGW acknowledge to the target SGSN by sending 'Modify Bearer Response'. A new user plane path is established between the UE, target RNC, and target SGSN target SGW and PDN GW.

10. A new Routing Area is updated in the network informing the new location of the UE due to Inter-RAT handover.

11. The source MME sends 'Release Resource Message' to the source eNodeB after the timer expires at the source MME. The source eNodeB release all the resources used by the UE.

12. The indirect data forwarding tunnel created in the preparation phase is deleted by the source SGSN as per the source MME request.

13. The UE is now connected to the UMTS network and the handover process is completed.

4.6. Measurement Events and Triggering Reports

For a handover decision to be made at the serving eNodeB, a set of measurements need to be carried out and reported to the eNodeB by the UE. The parameters to be measured are configured via the RRC connection reconfigure message. RRC connection reconfiguration message is used to modify RRC connection between UE and eNodeB.

A set of events and triggers have been defined to provide the real-time information but with the signaling overhead reduced. An event is a typical condition that occurs in the UE end for the measurement parameters like Buffer Status Report (BSR) and Power Headroom Report (PHR) in uplink and MAC layer information like Channel Quality Indicator (CQI) and Hybrid Automatic Repeat Request (HARQ) ACK/NACKs in downlink for SchedulingandRSRP value. These events are strategically defined such that they are enough for the serving eNodeB to know about the channel condition and the radio environment of the serving eNodeB. This events trigger UE to send measurement reports to the eNodeB. The report itself has to be concise enough but delivering all the necessary information required for the handover. In addition to event triggered reports, there are also the periodic reports sent by UE. The measurement configuration includes the following parameters [15, 27].

- ***Measurement objects.*** The objects on which the UE shall perform the measurements. For Inter-RAT EUTRA measurements, a measurement object is a set of cells on a single EUTRA carrier frequency.

- ***Reporting configuration.***A list of reporting configurations where each reporting configuration consists of the following conditions.

  - ***Reporting criteria.*** The criterion that triggers the UE to send a measurement report. This can either be periodical or a single event description.
  - ***Reporting format.***The quantities that the UE includes in the measurement report and associated information like number of cells to report. Table 4.13 shows seven

types of events specified by the 3GPP. From the table, A1, A2, A3, A4 and A5 events are used in the intra-LTE measurements while B1 and B2 events are used for Inter-RAT measurements.

- ***Measurement identity.***Measurement identity which links one measurement object with one reporting configuration and is used as a reference number in the measurement report.
- ***Quantity configurations.*** They define the appropriate filter coefficients for different measurements.
- ***Measurement gaps.***They define the periodic interval upon which the measurement should be carried out.

Table 4.2 *Measurement events and reporting criteria.*

Event	Reporting Criteria
A1	serving becomes better than absolute threshold
A2	serving becomes worse than absolute threshold
A3	neighbor becomes amount of offset better than serving
A4	neighbor becomes better than absolute threshold
A5	Serving becomes worse than absolute threshold 1 and neighbor becomes better than another absolute threshold2
B1	neighbor becomes better than absolute threshold
B2	Serving becomes worse than absolute threshold 1 and neighbor becomes better than another absolute threshold2

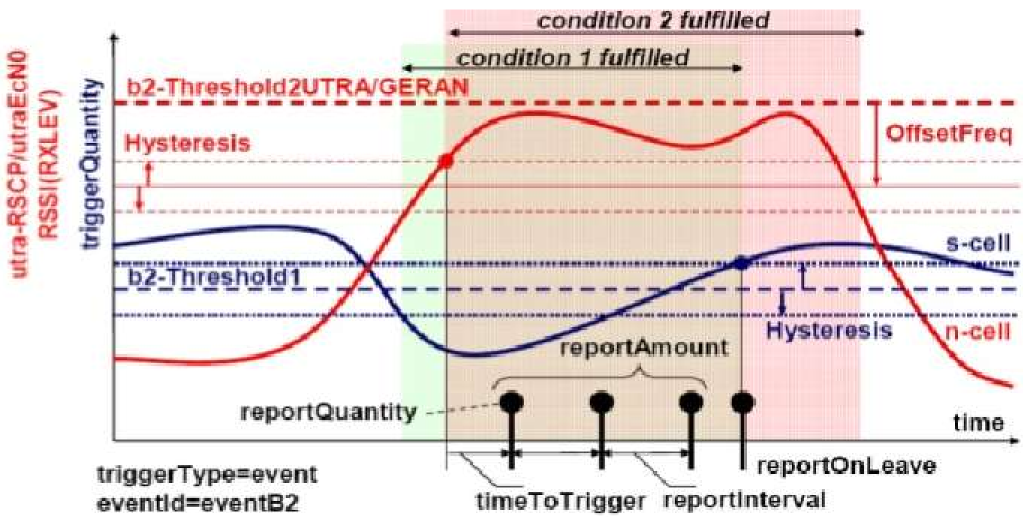


Figure 4.12 *Event B2 type reporting criteria [31]*

Figure 4.12 is an example of Event B2 type reporting criteria. As already mentioned, it is triggered when serving cell become worse than threshold 1 and Inter-RAT neighbor becomes better than threshold2. The blue color graph indicates the signal level for serving cell while red is for neighboring cell. The UE provides a number of periodic reports after triggering an event. Two parameters ‘reportAmount’ and ‘reportInterval’ configure the event triggered period reporting. The ‘reportAmount’ specifies the number of periodic reports while ‘reportInterval’ specifies time period between them.

Figure 4.13 shows the log file for successful Inter-RAT handover signaling message from LTE towards 3G seen by the data card on field test. The first column 'Absolute' represents time interval at which the event takes place. The second column 'LTE RRC’ represents RRC sub channels responsible to carry the RRC message information. They are BCCH, CCCH and DCCH and RRC message name indicates the signaling message exchanged between the UE and the network during Inter-RATmobility. The important signaling messages are labeled with numbers and explanation of each major message follows.

18:01:16.659	UL-DCCH MeasurementReport		
18:01:16.688	DL-DCCH RRCConnectionRelease	1	
18:01:34.051	UL-DCCH InitialDirectTransfer	2	MM Location Updating Request
18:01:34.052	UL-DCCH InitialDirectTransfer	3	GPRS MM Routing Area Update request
18:01:34.284	DL-DCCH MeasurementControl		
18:01:34.324	DL-DCCH DownlinkDirectTransfer	4	MM Authentication Request
18:01:34.425	DL-DCCH SecurityModeCommand	5	
18:01:34.429	UL-DCCH SecurityModeComplete	6	
18:01:34.449	UL-DCCH UplinkDirectTransfer	7	MM Authentication Response
18:01:34.627	UL-DCCH MeasurementReport		
18:01:34.665	DL-DCCH DownlinkDirectTransfer	8	MM Identity Request
18:01:34.667	UL-DCCH UplinkDirectTransfer	9	MM Identity Response
18:01:34.694	DL-DCCH DownlinkDirectTransfer	10	GPRS MM Routing Area Update accept
18:01:34.710	UL-DCCH UplinkDirectTransfer	11	GPRS MM Routing Area Update complete
18:01:35.044	**DL-DCCH DownlinkDirectTransfer**	12	**MM Location Updating Accept**
18:01:35.048	UL-DCCH UplinkDirectTransfer		MM TMSI Reallocation Complete
18:01:35.107	UL-DCCH UplinkDirectTransfer	13	GPRS MM Service request
18:01:35.154	DL-DCCH SignallingConnectionRelease		
18:01:35.214	DL-DCCH DownlinkDirectTransfer	14	GPRS MM Service accept
18:01:35.385	DL-DCCH RadioBearerSetup	15	
18:01:35.709	UL-DCCH RadioBearerSetupComplete	16	

Figure 4.13*Inter-RAT handover signaling message captured by data card.*

1. The *RRCConnectionRelease* message is sent by the E-UTRAN to UE to release the RRC connection in RRC_CONNECTED state.

2. The *'LOCATION_UPDATING_REQUEST'* message is sent by the UE to the UTRAN to update its new location.

3. The *'ROUTING_AREA_UPDATE_REQUEST'* message is sent by the UE to the UTRAN to update its new routing location.

4. The *'AUTHENTICATION REQUEST'* is sent by the UTRAN to UE to initiate the authentication procedure to check the identity of the UE.

5. The *'SECURITY_MODE_COMMAND'* message is sent by UTRAN to UE to start or to modify the integrity protection configuration for all signaling radio bearers.

6. The *'SECURITY_MODE_COMPLETE'* message is sent by the UE to UTRAN to indicate the complete integrity protection procedure for all subsequent messages sent and received.

7. The *'AUTHENTICATION AND RESPONSE'* is sent by the UE to the UTRAN in response to '*AUTHENTICATION AND REQUEST'* message.

8. The *'IDENTITY-REQUEST'* message is sent by the UTRAN to UE to initiate the identification procedure of the UE like IMSI (International Mobile Subscriber Identity) code.

9. The *'IDENTITY_RESPONSE'* is sent by the UE to the UTRAN to identify itself with the IMSI code.

10. The *'ROUTING_AREA_UPDATE_ACCEPT'* message is sent by the UE to UTRAN to indicate the routing area of UE has been updated.

11. The *'ROUTING_AREA_UPDATE_COMPLETE'* message is sent immediately by the UE to indicate that it has stored received routing area identification. This contains the PLMN (Public Land Mobile Network) list information.

12. The *'LOCATION_UPDATING_ACCEPT'* message is sent by the UTRAN to UE to indicate that the location of the UE has been updated in the network.

13. The *'SERVICE_REQUEST'* message is sent by the UE to UTRAN to request the resource reservation for the active PDP (Packet Data Protocol) contexts.

14. The *'SERVICE_ACCEPT'* message is sent by the UTRAN to UE to inform that the resource is reserved.

15. The *'RADIO_BEARER_SETUP'* message is sent by the UTRAN to UE to establish the signaling, data path and reconfigure radio bearer the before the UE data are transmitted.

16. The *'RADIO_BEARER_SETUP_COMPLETE'* is sent by the UE to UTRAN after the signaling path is established and reconfiguring of radio parameters is complete.

4.7. Circuit Switch Fall Back (CSFB)

In the initial phase of LTE deployment, the LTE network may support only data services because the IP multimedia subsystem (IMS) is usually not deployed.IMS architecture framework was introduced by 3GPP to support Voice over LTE (VoLTE) and Single Radio Voice Call Continuity (SR-VCC) schemes. IMS is based on internet standard which uses session initiation protocol (SIP) for (VoLTE). The function of SR-VCC is to support the handover from LTE IMS calls to other legacy 2G and/or 3G legacy voice radio networks. In the case of Ethio telecom's LTE network, when a UE initiates a Circuit Switched (CS) service, the service needs to be transferred to a UMTS or GSM network by CS fallback (CSFB). In other words, when a user inside the LTE network is connected, voice call request is fallback to 3G network with redirection handover and thus the voice call is served by the 3G network. The data service is redirected to LTE once the voice session ended. Figure 4.14shows a block diagram of CSFB Architecture.

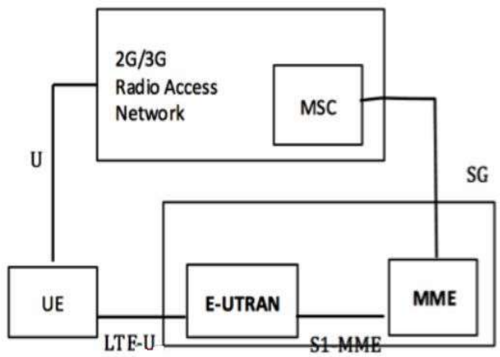


Figure 4.14 *CSFBArchitecture [32].*

CHAPTER 5

MeasurementResults and Analysis

This chapter begins with the discussion of radio performance indicators of LTE and UMTS cellular technologies. Then it continues with description of measurement locations and measurement setup along with tools used during the field test.After that, measurement results are presented with corresponding analysis for two different measurement locations. Finally, concluding remarks that are drawn from findings of this study are outlined together with possible future outlooks.

5.1. Performance Indicators

There are various aspects for the assessment of user Inter-RAT mobility from one system (LTE) to another system (3G) under actual environmental conditions denoted here as performance indicators. These various factors are studied, measured and analyzed to verify theirimpact on the network performance [6].

5.1.1. Received Signal Code Power (RSCP)

UMTS CPICH Received Signal Code Power (RSCP)is the received power on one code after dispreading defined on the pilot symbols by the terminal on Common Pilot Channel (CPICH). RSCP indicates the signal strength in downlink direction in UMTS networks. It also provides a measure of absolute coverage quantifying whetherthe absolute received power at a specific location is sufficient or not. RSCP is a direct measurement from UMTS's CPICH channel so that it provides a ground to compare different UMTS cells according to their signal strengths for two key purposes – cell reselection and triggering handover (Inter-System, Inter-Frequency or Inter-RAT). The signal strength can be affected by various reasons and interference stands out among them. Interference originating from other neighboring cells is the most common source of interference in mobile communication systems. In addition to interference, the received signal strength can be affected by geometric pattern of antennas, multipath propagation and fading due distance between transmitter and receiver or due to environmental obstacles [15, 33].

5.1.2. E_c/N_0

E_c/N_0 is the ratio of received energy per chip (E_c) on the pilot channel of a given cell to the total noise power density (N_0) on the UMTS carrier. It can be calculated from measurable parameters such as the received signal code power (RSCP) and the total received power in the channel bandwidth (RSSI: Received Signal Strength Indicator) as follows.

$$\mathbf{E_c/N_0 = \frac{RSCP}{RSSI}} \tag{5.1}$$

E_c/N_0 is often referred to as a measure of signal quality. As a result, E_c/N_0 measurements are used to rank cells by generating Channel Quality Indicators (CQI) which in turn are used for cell reselection and handover decisions [15, 33].

5.1.3. Reference Signal Received Power (RSRP)

Reference Signal Received Power (RSRP) is a cell specific signal strength related metric which is used as an input for cell resection and handover decisions in LTE systems. For a given cell, RSRP is defined as the average power (in Watts) of the Resource Elements (RE) that carry cell-specific Reference Signals (RS) within the considered bandwidth. RSRP measurement, normally expressed in dBm, is utilized primarily torank different candidate cells according to their signal strength. It is an important LTE physical layer parameter and measured by the end user equipment. Typical measurement reporting of RSRP ranges from -140 dBm to -44 dBm and its value decreases logarithmically as the user moves away from serving base station in accordance with propagation loss models [7].

5.1.4. Reference Signal Received Quality (RSRQ)

Reference Signal Received Quality (RSRQ) is a cell-specific signal quality metric. Its purpose is similar to that of RSRP where it can be used as input to rank cells when RSRP measurements are not sufficient to make reliable cell reselection and/or handover decisions. RSRQ can be calculated from RSRP and RSSI as follows.

$$\mathbf{RSRQ} = \mathbf{N} * \frac{\mathbf{RSRP}}{\mathbf{RSSI}} \tag{5.2}$$

Where, N is the number of Resource Blocks (RB) of the LTE carried RSSI within the measurement bandwidth. RSSI is a linear average of total received power observed only in OFDM symbols carrying reference symbols by UE from all sourceswithin the measurement bandwidth over N RBs. The reporting range of RSRQ is defined from -19.5 dB to -3 dB with 0.5 dB resolution.

5.1.5. Signal to Interference-Noise Ratio (SINR)

Signal to Interference-Noise Ratio (SINR) is expressed in terms of the power of measured usable signals,the power of all interferences and the power of background noiseas shown in Eq. (5.3).

$$\mathbf{SINR} = \frac{\mathbf{S}}{\mathbf{I} + \mathbf{N}} \qquad (\mathbf{dB}) \tag{5.3}$$

Where, S is the average received signal power, I is total interference power and N is the noise power. SINR is one of the most important factors that determine the downlink throughput for the UE because it better quantifies the RF condition of a wireless environment with multiple signals present simultaneously. The maximum channel capacity is determined by the SINR according to Shannon's formula i.e., for a given bandwidth B and $SINR$, the channel capacity C is expressed as follows [29].

$$\mathbf{C = B * \log_2 (1 + SNIR) \quad (bits/s)} \tag{5.4}$$

5.1.6. MAC Layer Downlink Throughput

Medium Access Control (MAC) layer downlink throughput is another parameter which is used to evaluate the performance of anetwork. In thesis, MAC layer throughput is considered as a performance indicator since it reflects actual user experience after the signal is affected by physical layer impairments. Ethio telecom currently implemented LTE network based on Frequency Division Duplex (FDD) at 20 MHz bandwidth supporting different modulation and coding schemes (QPSK, 16 QAM, 64 QAM) and 2x2 Multiple Input Multiple Output (MIMO) technique.Table 5.1 shows theoretical data rates for different modulation techniques at 20 MHz bandwidth.Throughput can be calculated from the size of file downloaded D and the time it takes to download the file T as expressed in Eq. (5.5). Equation (5.4) provides a means to estimate the theoretical capacity of a transmission link. However, the actual radio interface performance is affected by other impairments and thus reducing the system efficiency [3,20]. Therefore, η is always less than C.

$$\eta = \frac{\mathbf{D}}{\mathbf{T}} \qquad \mathbf{(bits/s)} \tag{5.5}$$

Table 5.1 *Theoretical data rates for 20MHz LTE system*

Modulation Scheme	Symbol	Symbol in all PRBs per Time Slot	PDCCHOverheadBits per Time Slot	RS Over-head Bits	Bits per Resource Block	DataRate (Mbps)
QPSK	2	8400	2400	800	13600	27.2
16QAM	4	8400	4800	1600	27200	54.4
64QAM	6	8400	7200	2400	40800	81.6

2x2MIMO, 64 QAM	12	8400	14400	4800	81600	163.2
4x4MIMO, 64 QAM	24	8400	28800	9600	163200	326.4

5.1.7. Link Adaptation

Adaptive link modulation is employed to better utilize the current channel quality. This feature depends on the CQI performance metric. User equipment performs measurement and estimation of the channel condition and reports to the eNodeB in the form of CQI. The UE normally reports the highest CQI index associated with the Modulation Coding Scheme (MCS) for which the DL transport layer Block Error Rate (BLER) does not exceed 10%.The CQI indexing can be wideband (LTE) or sub-band (3G). In the case of wideband, the CQI index is reported between 1 and 15 or a CQI index of 0 if the transport BLER exceeds 1%. In this case, three modulations schemes are available: 64-QAM, 16-QAM and QPSK which are used in the order of decreasing channel quality. In Sub-band 3G, the UE reports the CQI value in the range of 0 to 30 depending on the channel quality. CQI index in the range 1 to 15 corresponds to QPSK modulation scheme with different coding rate while CQI values from 16 to 30 correspond to 16 QAM modulation scheme. CQI indices and associated modulation formats for LTE and 3G (HSDPA) are shown in tables 5.2 and 5.3 below, respectively[18].

Table 5.2 *CQI values and their modulation range in LTE*

CQI index	Modulation	CQI index	Modulation
0	Out of range	8	16 QAM
1	QPSK	9	16 QAM
2	QPSK	10	64 QAM
3	QPSK	11	64 QAM
4	QPSK	12	64 QAM
5	QPSK	13	64 QAM
6	QPSK	14	64 QAM
7	16 QAM	15	64 QAM

Table* 5.3CQI values and their modulation range in HSDPA (3G)*

CQI index	Modulation	CQI index	Modulation
0	Out of range	16	16 QAM
1	QPSK	17	16 QAM
2	QPSK	18	16 QAM
3	QPSK	19	16 QAM
4	QPSK	20	16 QAM
5	QPSK	21	16 QAM
6	QPSK	22	16 QAM
7	QPSK	23	16 QAM
8	QPSK	24	16 QAM
9	QPSK	25	16 QAM
10	QPSK	26	16 QAM
11	QPSK	27	16 QAM
12	QPSK	28	16 QAM
13	QPSK	29	16 QAM
14	QPSK	30	16 QAM
15	QPSK		

5.1.8. Handover Success Rate

Handover success rate is one simple and straightforward indicator of network performance during handover process. Handover mechanisms from LTE to 3G are necessary when a user equipment leaves the LTE coverage area while having an active connection. LTE capable UE connected to 3G network benefits from the better QoS if the handover towards LTE can be carried out. The first form ofInter-RAT handover, from LTE to 3G, is the focus of this thesis. The Inter-RAT handover is triggered by a dual threshold measurement event – B2 forLTE and 3A for 3G mobile system. The first threshold (B2) corresponds to the signal strength of the serving cell and the second (3A) to the signal strength of the target neighboring cell of another RAT. These two Inter-RAT handover thresholds must be configured in the network to have successful handover.

Handover (HO) success rate is calculated as the ratio of total number of successful handovers to the number of handover requests which can be expressed as follows.

$$\textbf{HO Success Rate} = \frac{\textbf{Number of HO Confirms}}{\textbf{Number of HO Requests}} \times \textbf{100} \qquad (\%) \qquad (5.6)$$

The handover is said to be successful if handover signaling command message sent to UE is received as handover complete signaling message. In general, a handover is considered a failure if a handover command message is sent to the UE but a handover complete message is never received. During handover failure, the service is disconnected and a new connection needs to be established. Handover success rate does not differentiate between the handover failure reasons or tell if the service is interrupted or not. Handovers can fail due to one or more of the following reasons: resource allocation problems by the target RAT, protocol errors, radio link layer failures, high speed of a moving user and/or congestion in the network [5, 33].

5.1.9. Handover Delay

Handover Delay is another important metric for analyzing the network performance. It is defined as the time gap between the UE requesting a HO and receiving a HO command confirmation message. HO Delay is also referred to as Control Plane Latency. A UE is handed over from LTE to 3G if its LTE measurement event B2 is triggered. The entering condition of event B2 is fulfilled when:

- The RSRP of the serving cell becomes worse than the threshold value set for LTE cell and

- The RSCP of the Inter-RAT neighboring cell is better than the threshold value set for UMTS cell.

According to 3GPP, handover latency should be less than 300 ms for real-time application services and less than 500ms for non-real-time services. Handover delay can be obtained from Radio Resource Controller (RRC) signaling messages which are visible at the UE. The measurement can be performed simply by looking at timestamps of these messages and manually calculating using the expression given in Eq. (5.7) below [2, 33].

$$\textbf{HO Delay} = \textbf{RRC Procedure Delay} + \textbf{Interrupt Time} \quad (s) \qquad (5.7)$$

Where RRC procedure delay = 50 ms.

5.1.10. Service Interruption Time

Service Interruption Time is a performance metric typically used for real-time and interactive services. It indicates how long a given user service is interrupted within a single connection session.This parameter determines the user plane delay during the handover process and relies on the handover condition. User plane service interruption can be calculated by taking the difference in time of the first packet received from the target RAN and the last packet received from the serving RAN. It is important to analyze the seamless connectivity between the two different networks involved. According to 3GPP, Service Interruption Time (T_{ITR})is defined as the time difference between the data session disconnected and data session resumes which is expressed as follows [2].

$$\mathbf{T_{ITR} = T_{IU} + T_{Synch} + 50 + 10 * F_{max}} \quad (s) \qquad (5.8)$$

Where,

- T_{IU}: interruption uncertainty time when changing from E-UTRAN to UTRAN (~10 ms)
- T_{synch}: time for measuring Downlink Dedicated Physical Control Channel (~10 ms)
- F_{max}: maximum number of radio frames being used [3]

5.2. Tools and Applications for Field Test

Test tools and software applications used during the field measurement of this thesis are presented in Table 5.4 along with their purpose of use.

Table 5.4 *Measurement tools and applications*

Tools	Purpose Use
Laptop (Dell)	Run Nemo outdoor software
Huawei LTE Dongle	Access both LTE and 3G broadband mobile network

Ethio telecom LTESIM	Support both LTE and 3G mobile data access
Nemo outdoor(Anite)	Measuring and recording test results
Actix Analyzer	Analyzing the measured data
GPS (Garmin)	Locating measurementarea coordinates
MS Excel	Processing data
MS Visio	Drawing topology diagram
MATLAB	Plotting measurement and analysis results

5.3. Measurement Locations

Two measurement locations were chosen for the field test – around Bole and Kality sub-cities of Addis Ababa. Bole is selected to represent densely populated urban areas with a wide range of building obstacles while Kality represents sub-urban areas. These two locations are carefully selected keeping the following scenarios under consideration:

- Both locations exist at the edge of the LTE network – less ambiguous.
- Inter-RAT handover can be easily detected by moving away from LTE coverage area.
- Interference from neighboring LTE cells significantly reduced for good radio conditions.

Measurements at both locations are carried out in UMTS FDD 2100 MHz and LTE FDD 1800 MHz frequency bands in Ethio telecom's commercial network. Figures 5.1 and 5.2 illustrate the road maps of our measurements for Bole and Kality, respectively. LTE measurement route (and LTE supporting site) is identified by red color while yellow color indicates UMTS test route. Arrows at junction points of the two routes indicate expected Inter-RAT handover spots.

5.4. Cost Economic Analysis

This subsection presents the cost economic analysis of deploying the 3G and LTE networks in Addis Ababa, Ethiopia. Although the 3G is implemented throughout the country, we only consider Addis Ababa to be consistent with the LTE network coverage. The values shown here are based on agreement data between the operator Ethio telecom and vendor Huawei Technologies Co., Ltd. Tables 5.5 and 5.6 show the capital expenditure (CAPEX) costs for LTE and 3G, respectively.

Table 5.5 *CAPEX for LTE network.*

Item	Unit	Quantity	Unit Price in USD
MIMO enabled eNodeB	Pcs	328	40,000
Core Network elements	-	-	800,000
Backhaul per link	Pcs	328	20,000
Installation cost per co-location per site	Pcs	328	500
startup cost per equipment (License)	-	-	150

LTE Total cost (USD) = 40,000*328 + 800,000 + 20,000*328 + 500*328 + 150*40,000

= **USD 198,724,000**

Table 5.6 *CAPEX for 3G network.*

Item	Unit	Quantity	Unit Price in USD
3G NodeB	Pcs	725	15,000
Core Network elements	-	-	500,000
Backhaul per link	Pcs	725	20,000
Installation cost per co-location per site	Pcs	725	500
startup cost per equipment (License)	-	-	150

3G Total cost (USD) = 15,000*725 + 500,000 + 20,000*725 + 500*725 + 150*15,000

= **USD 251,237,500**

A rough estimate of revenue from both 3G and LTE networks in Addis Ababa reaches 3 Billion Birr (~ 130 million USD) per annum. For the next ten years, estimated net revenue is close to abillion USD. Therefore, the networks can repay the initial CAPEX and generate a revenue three-fold the CAPEX.

Figure 5.1*Measurement location and route in Bole sub-city*

Figure 5.2*: Measurement location and route in Kality sub-city*

At each location, more than eight test attempts are performed to download 100 Mbps file stored at a remote server by using the cellular network. Table 5.7 shows different LTE and UMTS test sites which participated in the handover process as monitored by the UE (Huawei LTE Dongle).

Table 5.7*LTE and UMTS sites that participated in the Inter-RAT Handover process*

Measurement Location	Site ID and Name (Ethio telecom network)	RAT Type	Operating Frequency(MHz)	Bandwidth(MHz)
Bole	111125_Bole Giorgis	LTE	1800 FDD	20
	112171_Bole Selasie Church	UMTS	2100 FDD	5
	112263_Bole Lemi	UMTS	2100 FDD	5
Kality	111034_KalityTextile	LTE	1800 FDD	20
	111248_Tirunesh Beijing Hospital	UMTS	2100 FDD	5

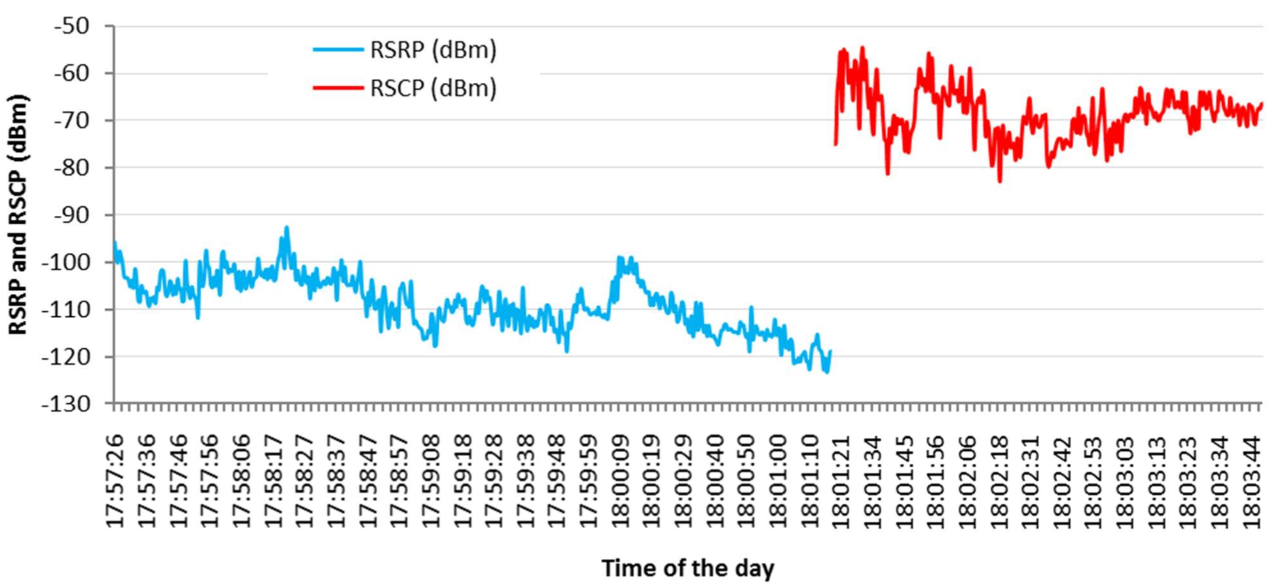
5.5. Measurement Setup

eNodeBs (for LTE) and NodeBs (for UMTS) have been chosen considering the likelihood of LTE to 3G handover with good radio conditions and minimal interferences other neighboring cells. A real time outdoor radio environment measurement was carried out with a laptop running Nemo Outdoor 7.8 and connected to LTE Dongle Data Card (Qualcomm handler). Nemo Outdoor was used to measure, record and save radio related parameters in active condition for further offline analysis. LTE Dongle (hereafter referred as UE) with Ethio telecom LTE SIM card was used as end user device which operates both in LTE and 3G modes depending on the current serving network. A Global Positioning System (GPS) was used along with the modem to gather the coordinates of test location instances. To increase location accuracy, the GPS was placed at the exterior top of the test car. Each time before the test begins, the UE was connected to the LTE network without band locking at places where LTE signal strength dominates (close to the eNodeB). A script was written and defined for Nemo Outdoor LTE and 3G network interoperability and ran continuously throughout the measurement routes until manually disconnected. The measurement unit was placed inside a test car and drive test was done towards the cell edge having poor coverage of the 4G network while the 3G channel condition remains good so that Inter-RAT handover is triggered. Once a route is determined, some tests are repeated up to ten times at both locations to have a reasonable result when averaged out. A 100 Megabyte file located in the remote FTP server was downloaded using the LTE dongle's connection which was attached to the test network for throughput testing and the script was written to run continuously throughout the data transfersessions until UE was manually disconnected. After each test attempt, measurement results were exported from Nemo Outdoor and saved on the computer's hard drive. Those saved measurement results were imported in to Actix Analyzer for analysis. Further analysis, plotting and extrapolations were done by writing MATLAB script codes.

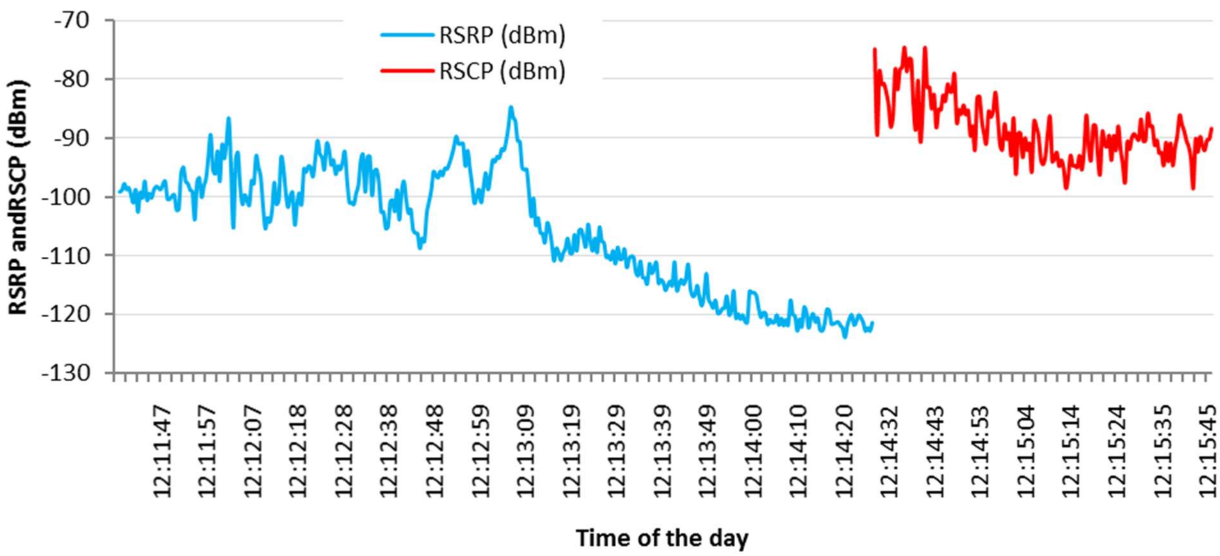
5.6. Results and Discussion

5.6.1. RSRP and RSCP

RSRP and RSCP are cell-specific signal-strength-related metrics in the downlink direction for LTE and 3G, respectively. Both metrics are used in their respective technology domains for cell reselection and handover decisions. Figure 5.3 (a) and (b) illustrates RSRP of LTE (blue) and RSCP of 3G (red) networks against time of the day for the two test locations, Bole and Kality, respectively. In each case, the vertical axis shows the received signal strength in dBm and the x-axis shows time of the day at which measurement took place.



(a)



(b)

Figure 5.3 *RSRP and RSCP comparison vs. time for (a) Bole and (b) Kality*

The graphs show that the received signal strength decreases as the user moves away from the serving eNodeB. The signal quality is further degraded as the user keeps moving finally reaching a point where the signal strength goes below predefined threshold values. At that moment, Inter-RAT handover is triggered (since there are no LTE sites in that direction), Inter-RAT handover is accomplished. Once the handover happens, the user is served with a better signal quality is better as long as the user remains in the coverage area of the 3G network.

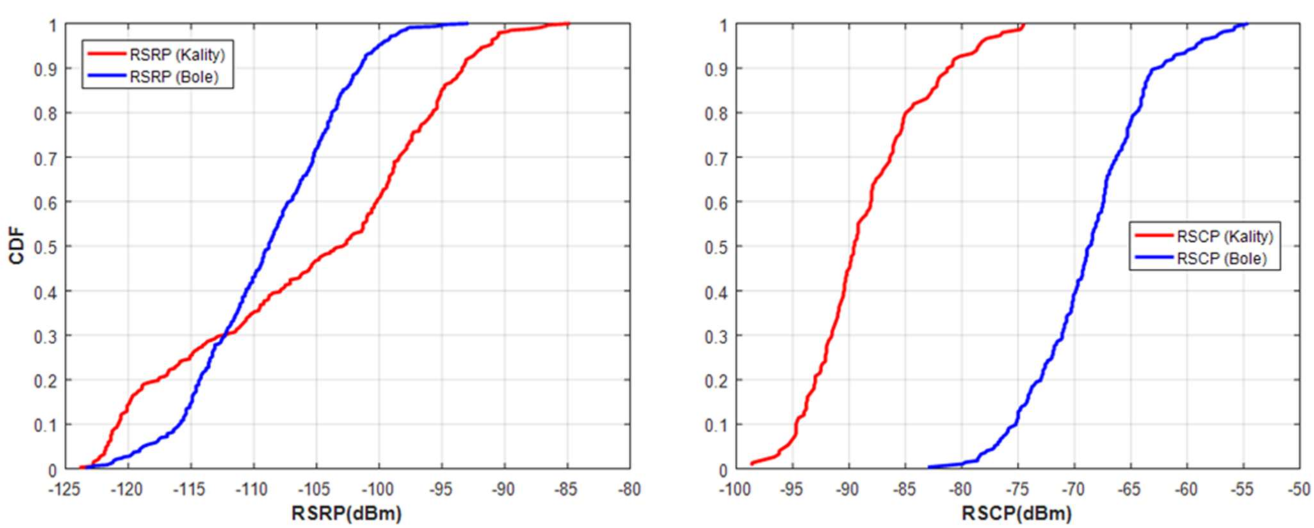
Comparatively, the average LTE RSRP signal level is higher in Kality area than Bole area while the opposite is true for UMTS RSCP. The RSRP at Bole is relatively lower because of the following reasons.

- Serving cells are relatively far away from the UE along the test route.
- There are three potential serving cells – which causes lack of a dominant cell.
- Cells are in cross-coverage because they are exceeding their coverage areas causing signal overshooting which is a planning issue to be addressed.

However, there was only one dominant eNodeB serving at Kality which makes LTE RSRP better. In either case, LTE RSRP levels are not satisfactory. However, it should be noted that these sites are at the edge of the LTE network. On the other hand, the UMTS RSCP level is better at Bole because this area has densely deployed 3G sites which provide better coverage.

At Bole sites, Inter-RAT handover is triggered (at cell edge) when LTE RSRP was ~ -120 dBm while 3G RSCP was ~ -71 dBm. Although these to values differ by 49 dBm, the LTE service continued even if the 3G signal strength was much better than that of LTE’s. This is because LTE has higher priority than 3G which makes LTE a preferred network. As a result, the system keeps LTE to serve until a predefined LTE threshold value is reached to transfer (handover) the service to the 3G network. The handover process at Kality was triggered at almost the same RSRP (-121 dBm) but lower RSCP (-75 dBm) values as Bole. Therefore, eNodeBs use RSRP to make Inter-RAT handover decisions while the UMTS cell satisfies such condition with acceptable RSCP level to maintain service continuity for moving users.

Further visual explanation of the differences in RSRP and RSCP values at the two test locations is shown in Figure 5.4 (a) and (b), respectively, using the Cumulative Distribution Functions (CDF) of the two parameters. As expected, the CDF of RSRP at Bole (blue) is worse than that of Kality (red) as shown in Figure 5.4 (a). Conversely, Figure 5.4 (b) illustrates the CDF of RSCP at Bole (blue) is better than that of Kality (red). The CDF plots for both locations conform to the previous plots of RSRP and RSCP.



(a) (b)

Figure 5.4*CDF plots of (a) RSRP and (b) RSCP at Bole and Kality*

The CDF graphs show that at Bole, the maximum RSRP value recorded is -92 dBm while it is -84.8 dBm for Kality – the latter being a better performance indicator. At both locations, the minimum RSRP level was less than -123 dBm which caused Inter-RAT handover triggering. To better explain the difference in RSRP, the figure on the left shows 50 percent of RSRP samples have above -102.5 dBm at Kality while it is ~ -109 dBm at Bole. On the other hand, the maximum and minimum RSCP values at Bole are -54 dBm and -83 dBm and that of Kality are -74.5 dBm and -98.5 dBm, respectively. Therefore, the distribution clearly shows Bole has UMTS RF conditions than Bole. Conversely, Kality has better LTE RF conditions than Bole.Table 5.8 summarizes the above two paragraphs regarding RSRP and RSCP distributions at the two locations with additional statistical parameters such as average and standard deviations [4].

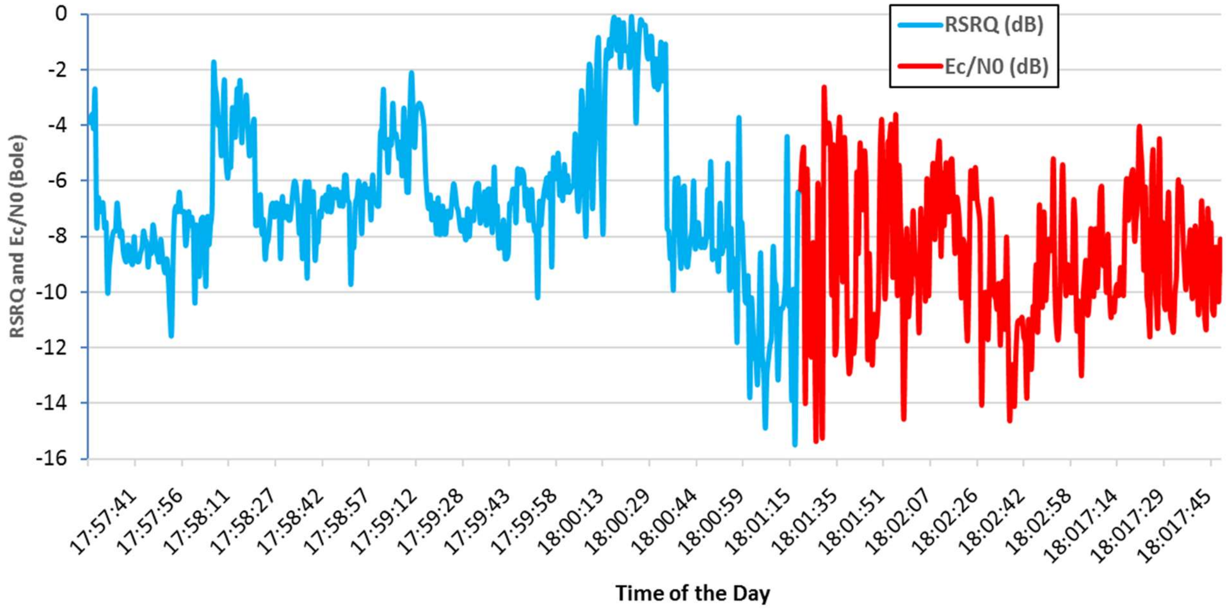
Table 5.8 *Statistical parameters for RSRP and RSCP in Bole and Kality*

Statistics	**RSRP (dBm)**		**RSCP (dBm)**	
	Bole	**Kality**	**Bole**	**Kality**
Maximum	-92.90	-84.80	-54.59	-74.5
Minimum	-123.40	-123.9	-83.00	-98.60
Mean	-108.90	-105.56	-68.68	-88.52
Median	-108.80	-102.90	-68.70	-89.5
Standard Deviation	5.71	10.24	5.17	5.16

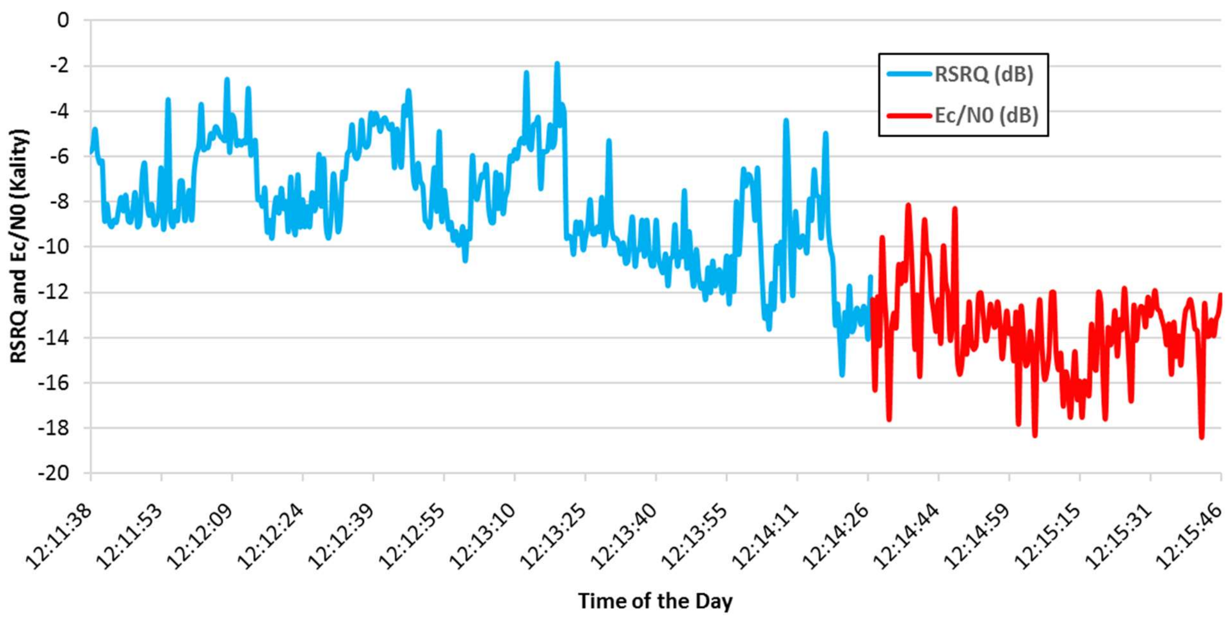
5.6.2. RSRQ and E_c/N_0

The system performance can also be analyzed by considering RSRQ and E_c/N_0 measurements. Figure 5.5 (a) and (b) shows plots of these two metrics for both Bole and Kality.Obviously, RSRQ follows the RSRP pattern as dictated by Eq. (5.2) in section 5.1. For both locations, the respective average RSRQ values are close to one another. Both RSRQ and E_c/N_0 are important but supplementary parameters to evaluate the user experience at a given network rather than comparing the performances of two different locations. For the latter case, RSRP provides a bigger picture than RSRQ. The average RSRQ value for Bole is -6.6 dB and it is -8.15 dB for Kality. From Eq. 5.2 (RSRQ = N*RSRP/RSSI), it is seen that due to the inclusion of RSSI, RSRQ considers the combined effect of signal strength and interference. To find the possible relationship among RSRP, RSSI and RSRQ, a more elaborative study is made in which the difference between

RSRP and RSSI are calculated for each measurement slot but from graph the RSRQ value is good at both location as 50 percent of the data is above -10 dB [30].

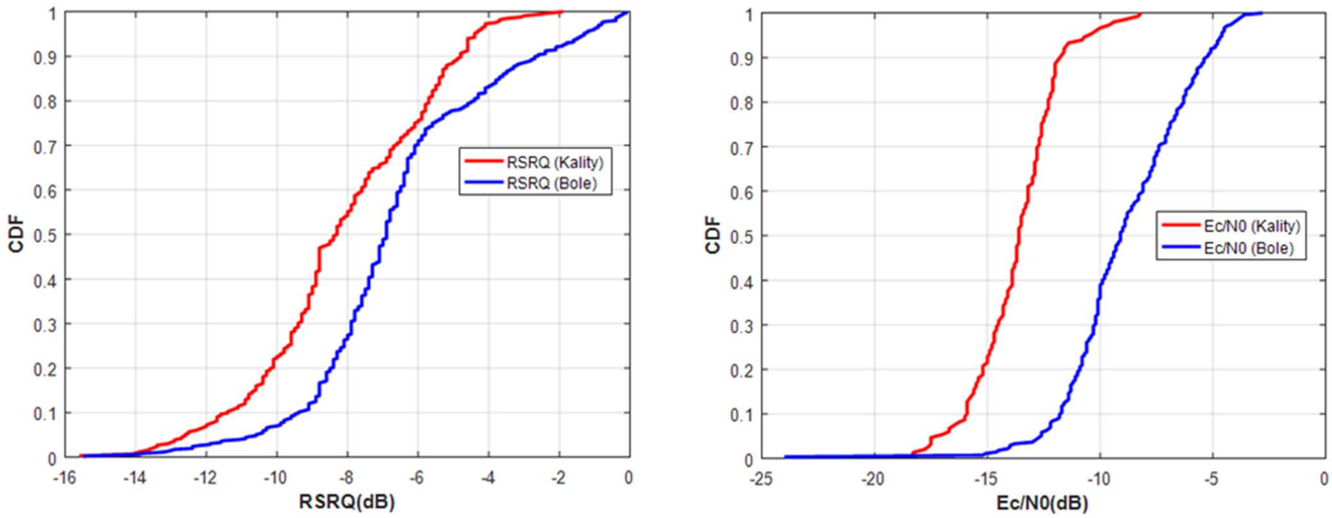


(a)



(b)

Figure 5.5 *RSRQ and E_c/N_0plots for (a) Bole and (b) Kality*



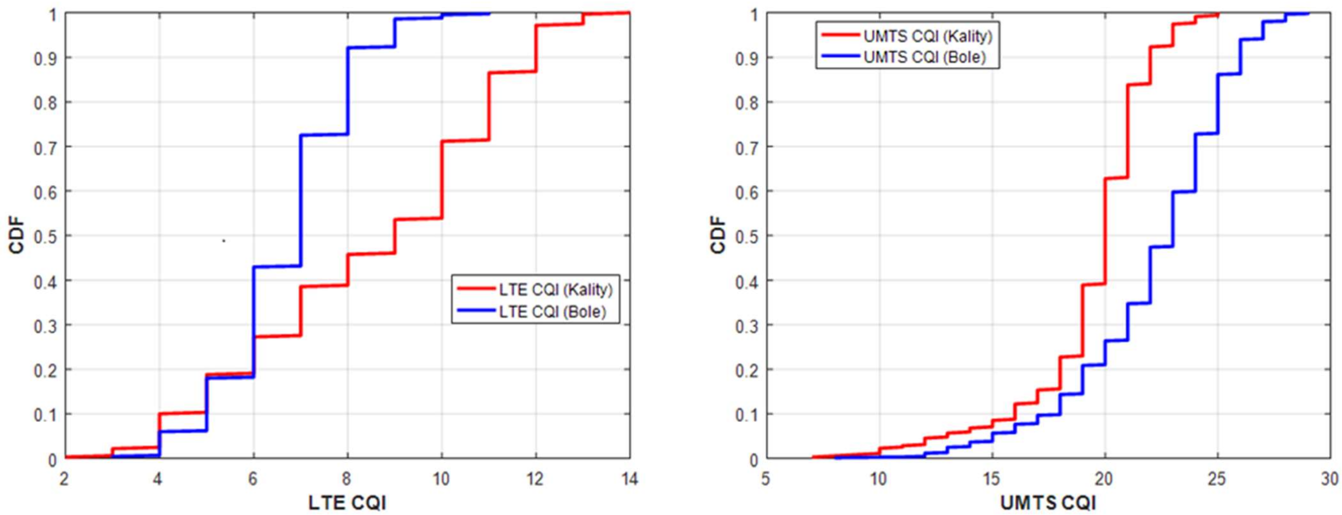
(a) (b)

Figure 5.6 *CDFgraphs of RSRQ and E_c/N_0 for (a) Bole and (b) Kality*

Figure 5.6 illustrates the CDF plots of RSRQ (a) and E_c/N_0 (b) for both measurement locations.Both RSRQ and E_c/N_0 statistics look betterat Bole than Kality. From Eq. (5.2), the lesser the difference between RSSI and RSRP, the better is the RSRQ. However, we cannot say the performance at Bole is better than Kality regarding RSRQ. Since the difference between RSRP and RSSI must be calculated for each measurement slot,such that RSRP is always less than RSSI, a lesser difference between RSRP and RSSI implies lesser interference which in turn leads to a better received signal quality. The same is true for E_c/N_0. On the other hand, we can say the performance at Bole is better that that of Kality directly from the E_c/N_0 CDF graphs. Therefore, we can conclude that the average RSRQ and E_c/N_0 values are acceptable for cell selection and reselection. Nevertheless, Ethio telecomprimarily uses RSRP for cell selection and handover events triggering.

5.6.3. Channel Quality Indicator (CQI)

Channel Quality Indicator (CQI) is a coverage performance indicator as it depicts the coverage condition of the radio environment of the band the UE is attached to. It is reported as a measure of the channel quality to trigger the adaptive modulation.



(a) (b)

Figure 5.7 *CDF plots of (a) LTE and (b) UMTS at Bole and Kality.*

Figure 5.7 shows the CDF graphs of CQI reporting of LTE and UMTS networks for both locations when Inter-RAT handover occurred. The graph on the list shows LTE CQI for Bole (blue) and Kality (red). Similarly, the graph on the right illustrates UMTS CQI with the same color coding. Based on Tables 5.2 and 5.3 in section 5.1 and from Figure 5.7, the following tableshows how each cellular technology's downlink path has been associated with different modulation techniques.

Table 5.9*Percentage of downlink path association with channel modulations*

Modulation	**Bole**		**Kality**	
	Percentage of Association (%)		**Percentage of Association (%)**	
	LTE	**UMTS**	**LTE**	**UMTS**
QPSK	18	5	19	8
16-QAM	74	95	27	92
64-QAM	8	NA*	54	NA*

** NA: not applicable to 3G networks.*

Table 5.9 illustrates how each technology utilized the radio channel at the two locations. Higher modulation techniques are employed when the channel condition is good and vice versa. For example, the LTE network downlink at Kality was associated with 64-QAM for about 54 percent of the total measured samples. Conversely, the same technology at Bole utilized 64-QAM for only 8 percent of the total samples taken. This indicates that channel condition of the LTE network at Kality was reliable for more than half of the connected sessions. In contrast, a fairly poor channel condition was experienced at Bole. This proves the consistency of the previous discussions addressed in this section – LTE connection was better at Kality than that of Bole. On the other hand, the UMTS networks have better and almost stable channel conditions where more than 90 percent of UMTS downlink paths utilized 16-QAM (the maximum modulation technique available to 3G networks) with a relatively better UMTS network performance at Bole.In summary, 16-QAM is the dominant modulation technique in 3G networks whereas LTE networks commonly utilize both 64-QAM (under good channel condition) and 16-QAM (under reasonably poor channel conditions) modulation schemes. Both LTE and UMTS utilize QPSK modulation only when the channel condition is very poor.

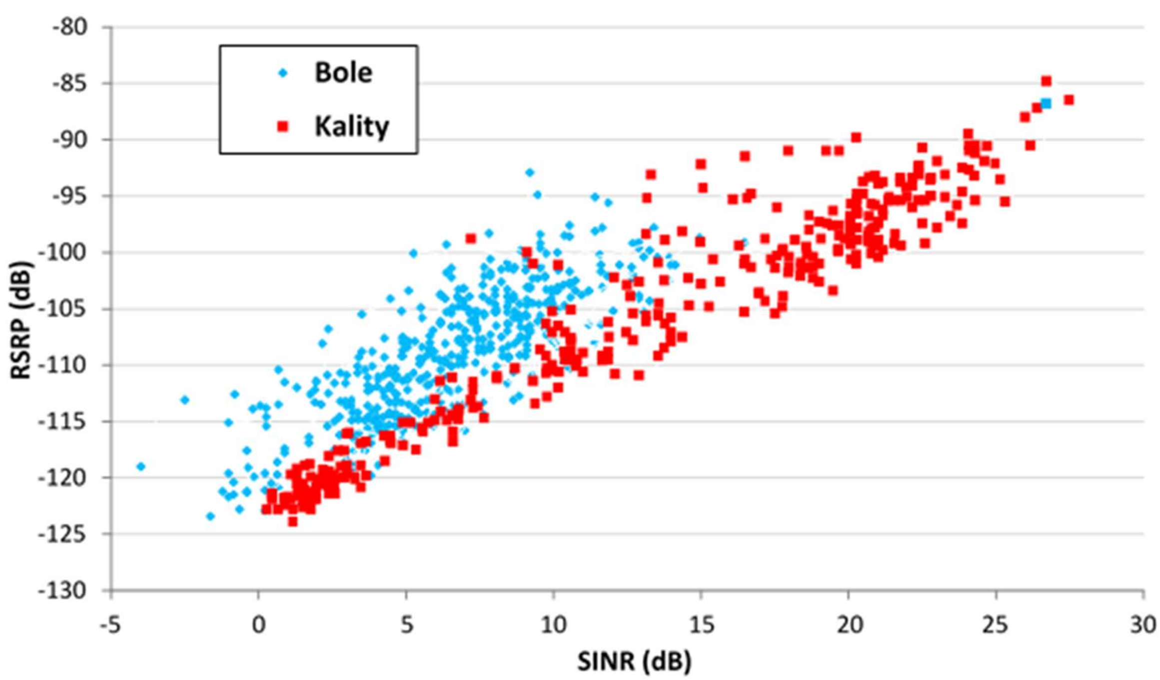


Figure 5.8 *Scatter plot of RSRP vs. SINR for Bole (blue) and Kality (red).*

5.6.4. Signal to Interference Noise Ratio (SINR)

Figure 5.8 shows the scatter plot of LTE's RSRP as a function of SINR for the two test locations. RSRP sample values collected for Bole are indicated with diamond shaped blue markers while those for Kality are shown with red colored square markers. The SINR values range from -4 dB to 16.5 dB and 0.3 dB to 27.5 dB for Bole and Kality, respectively. The figure illustrates above-threshold RSRP samples experience SINR of above 13 dB. That means, the channel condition is good at Kality. Conversely, RSRP samples at Bole are concentrated between SINR of 5 dB and 15 dB which dictates the channel condition can be considered as poor compared to that of Kality. Clearly, lower SINR value for a given signal power means the channel is exposed to more noise and interference as is the case of Bole.

Figure 5.9 also shows the CDF statistics of SINR samples measured at the two locations. Half of the measured SINR samples at Kality have above 15 dB values while that of Bole have values above 5.3 dB but less than 17 dB. Clearly, LET users at Kality area could experience better network performance than those at Bole. Poor SNR might be observed due to interference originating from neighboring eNodeBs, cross coverage due to less optimization, absence of line of sight, line of sight blocked by trees, buildings and other environmental conditions. Although all of them apply to both locations, interference and blocked line of sight due to buildings are the dominant impairments at Bole. Table 5.10 summarizes the statistical SINR of LTE network at both locations.

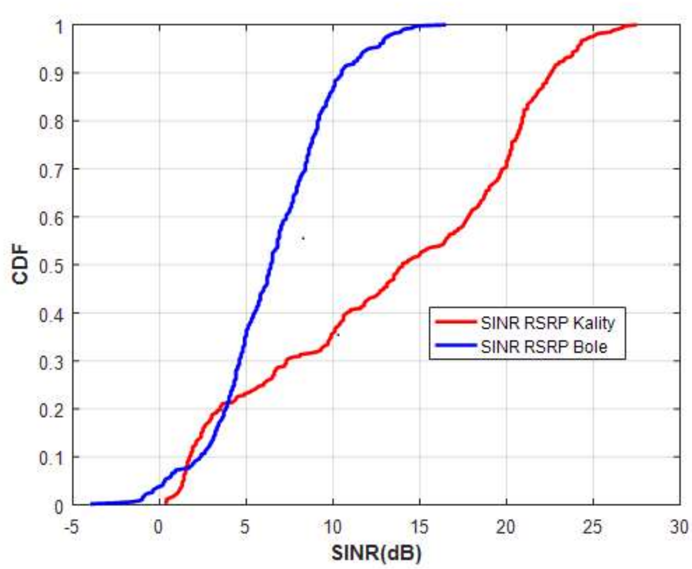


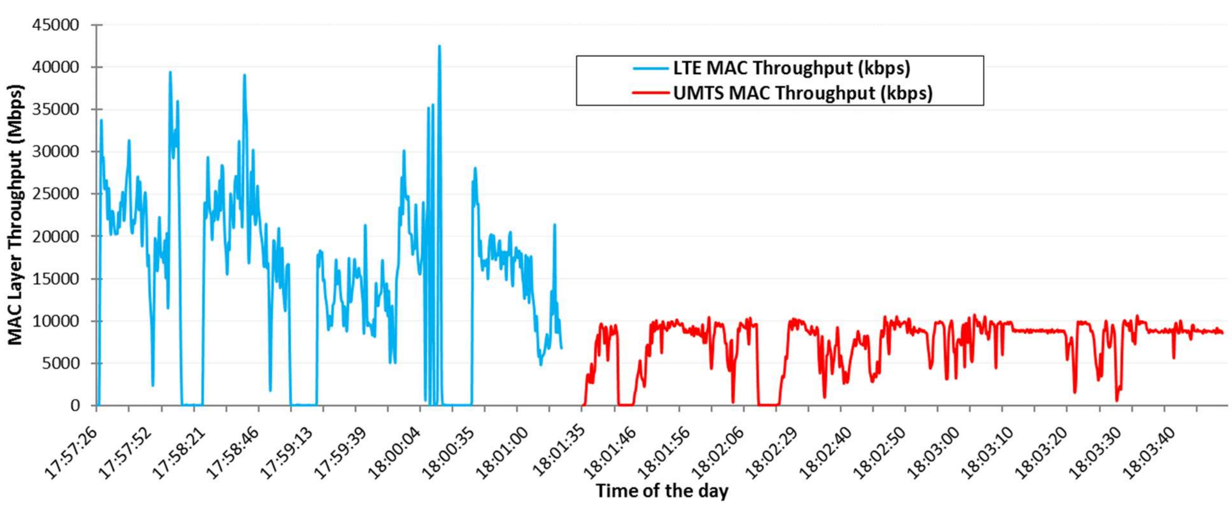
Figure 5.9 CDF plot of LTE SINR for Bole (blue color) and Kality (red line).

Table 5.10 LTE SINR Statistical data for Bole and Kality.

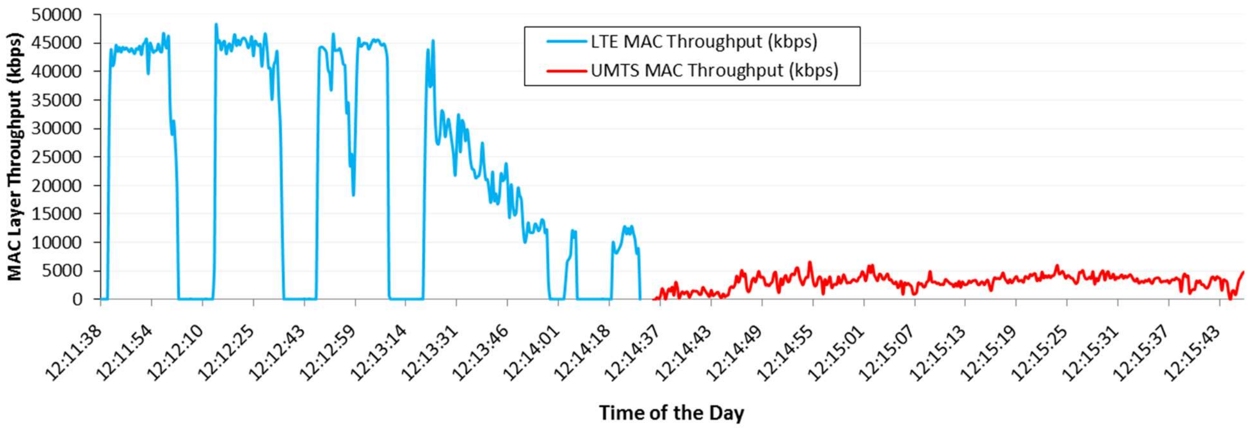
Statistical Parameter	SINR (dB)	
	Bole	Kality
Maximum	16.5	27.5
Minimum	-4	0.30
Mean	6.43	13.33
Median	6.40	14.00
Standard Deviation	3.36	7.88

5.6.5. MAC Downlink Throughput

Downlink throughput is one of the most revealing parameters on characterizing the performance of a radio network when handover is performed. Figures 5.10 (a) and (b) shows LTE (blue line) and UMTS (red line) MAC downlink throughput for Bole and Kality test locations, respectively. The graphs show a zero- value throughput which is due to a gap predefined on the Nemo Outdoor between successive download attempts. On average, the throughput decreases towards the LTE cell edge and it relatively improves (or at least remains stable) as the user moves towards the center of the 3G cell. During the handover process, the file download is interrupted where no actual download takes place. At such moment, the user data is paused for a few seconds – a situation which is further explained in the next sub-section.



(a)



(b)

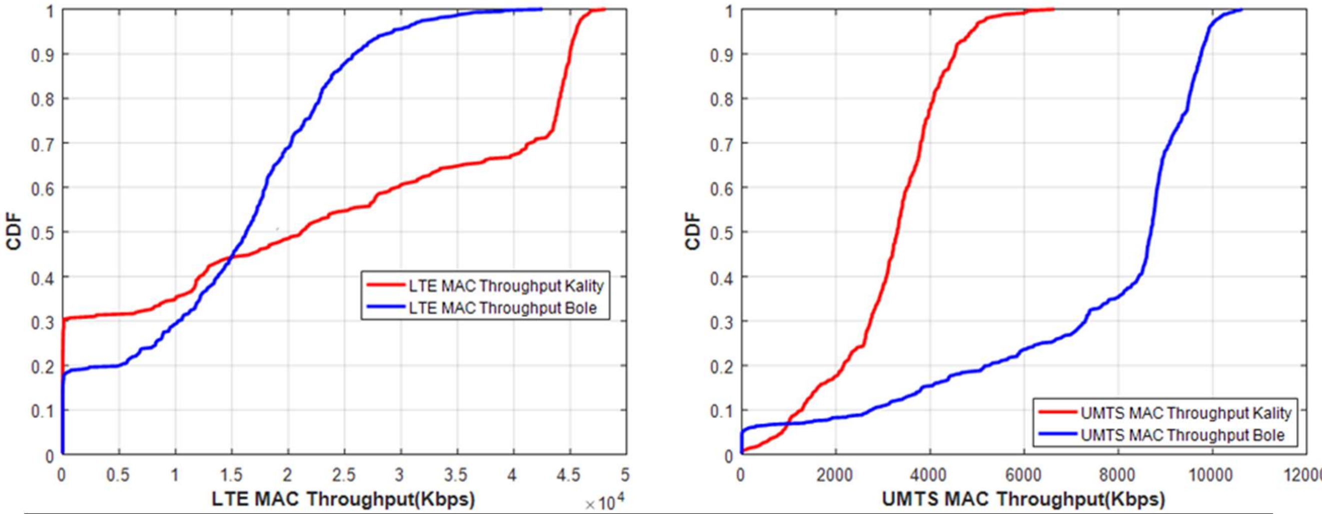
Figure 5.10*Downlink MAC LTE and UMTS throughput for (a) Bole and (b) Kality.*

Figure 5.11 (a) and (b) shows CDF graphs of LTE and UMTS downlink throughputs as measured at the two locations. Considering LTE network, a user experiences more than 1.5 Mbps download speed for more than 50 percent of a download session at both locations. At Kality, the download speed first decreases sharply from ~ 4.8 Mbps to 4.25 Mbps and then more steadily to zero before handover occurs as the user moves away from the LTE cell. Although the pattern is similar for Bole, the CDF graph drops faster than that of Kality towards cell edges. On the other hand, UMTS system performance at the two locations show a significant difference for more than 90 percent of the time. For example, the maximum downlink speed at Bole reaches twice that of Kality when the user is very close to the 3G network cell. Table 5.11 summarizes the statistics of LTE and UMTS downlink Mac throughputs for the two locations. As shown in the table, downlink speeds reaching up to 48 Mbps (LTE) and 10.5 Mbps (UMTS) can be obtained from the current networks.

Table 5.11*Statistical comparison of LTE and 3G downlink MAC throughputs.*

Statistics	LTE Mac DL throughput (Mbps)		3G Mac DL throughput (Mbps)	
	Bole	Kality	Bole	Kality
Maximum	42.53	48.12	10.63	6.63
Minimum	0	0	0	0
Mean	14.79	22.04	7.39	3.13

Median	16.27	21.21	8.68	3.3
Standard Deviation	9.49	18.53	2.88	1.21



(a) (b)

Figure 5.11 *CDF plots of (a) LTE and (b) UMTS downlink MAC throughputs.*

5.6.6. Handover Success Rate

Handover success rate is often calculated by using Eq. (5.6) by counting the number of successful handover signaling flows and then dividing them by the total number of handover attempts. Figure 5.12 shows a snapshot of log files from a successful Inter-RAT handover signaling message captured from mobile during the handover process in Bole (some message lines are removed for brevity). The two key message pairs which typically signify triggering handover end of a successful Inter-RAT Handover are:

- **RRC Connection Release** specifies the release of a connection from source LTE cell.
- **Radio Bearer Setup Complete** specifies successful establishment of 3G radio bearer.

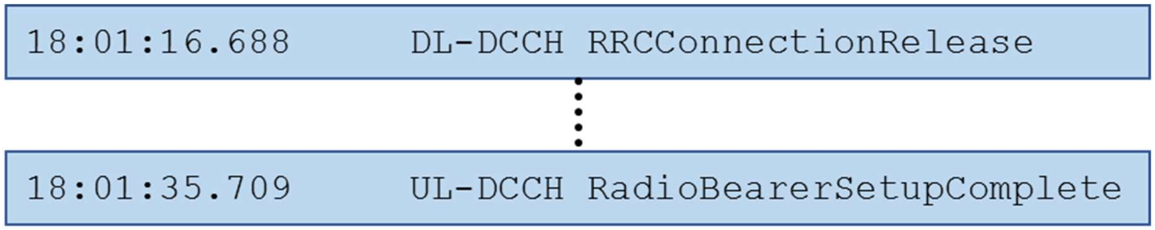


Figure 5.12 *Signaling messages which signify start and end of a successful Inter-RAT Handover.*

The best-case handover success rate is close to 100% at both measurement locations. However, the interruption time is significantly high during the handover process. There are two fundamental reasons for the successful handover to occur in the current Ethio telecom's network.

1. Good signal quality of target UMTS network and
2. Very low handover detection algorithm's threshold values set by the vendor.

The vendor and the operator, Ethio telecom, agreed to implement a minimum RSRP threshold B2 value of -113 dBm (two threshold levels are defined and B2 is the minimum value). However, we observed -122.8 dBm RSRP values at the time the Inter-RAT Handover takes place [6, 35].

5.6.7. Handover Delay

Handover delay is an important metric for analyzing the network performance and for efficient network management. In this thesis, handover delay is calculated from RRC signaling messages time differenceconsidering the first packet received from the target 3G RAN and the last packet received from the serving LTE RAN according to Eq. (5.7). Figure 5.13 shows the CDF of measured handover delays at the two different test locations. From the figure, the handover process takes up to 19 seconds in Bole area while it takes up to 10 seconds at Kality. However, more than 80 percent of handovers took less than 6 seconds at both locations.

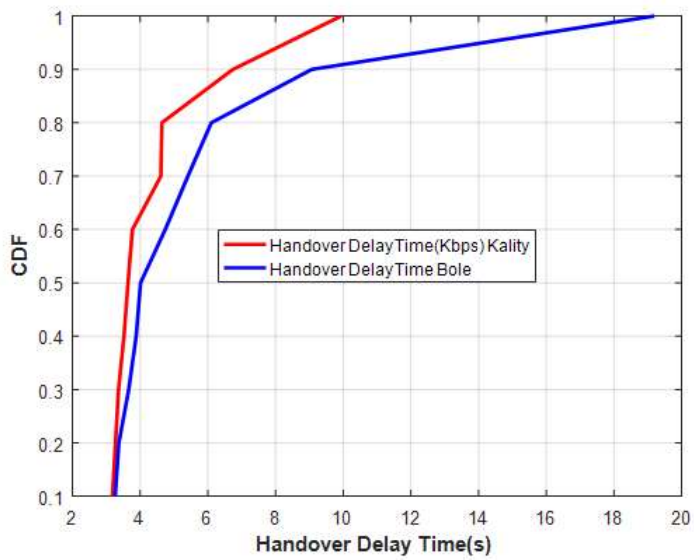


Figure 5.12 *CDF comparison of Handover delaysduring Inter-RATHandover*

Table 5.12 *Statistical data for handover delay.*

Statistics	Handover Delay	
	Bole	**Kality**
Maximum	19.07	9.94
Minimum	3.26	3.18
Mean	6.269	4.667
Median	4.375	3.705
Standard Deviation	4.864	2.138

In general, longer handover delays are experienced at both locations. The ultimate effect of longer handover delay is extended service interruption. Therefore, handover processesmust be performed as fast as possible so that the signal is not deteriorated too much. The recommended handover delay according to 3GPP standard is 300 ms for real-time applications and 500 ms for other services. Longer hand over delay and thus longer service interruption times disturb the ongoing session causing worseQoS and system reliability,and increasing the possibility of handover failures.A failed handover causes radio links to break and service applications disconnected.

5.6.8. Service Interruption Time

Service interruption time is a handover delay without system processing delay dictated by Eq. (5.7). Its CDF plot looks like that of handover delay shown in Figure 5.13 above with visually not so noticeable difference on the graphs due to the small value of RRC process delay.Table 5.13 summarizes the statistics of service interruption time for the two locations.

Table: 5.13 *Statistical data for service interruption times for Bole and Kality.*

Statistics	Service Interruption Time (s)	
	Bole	Kality
Maximum	19.02	9.89
Minimum	3.21	3.13
Mean	6.319	4.616
Median	4.505	3.650
Standard Deviation	4.808	2.138

Conclusion

This thesis focused on handover between LTE and 3G radio access technologies. Key performance indicators (KPI) were measured under realistic environmental conditions with coverage limited LTE network and fully-covered 3G network. The objective of this project was to demonstrate the working principles of Inter-RAT handover, analyze measurement results to illustrate the impact of each KPI on the handover, identify important aspects of the network for further optimization and providing possible suggestions with regard to network design, planning and optimization. Tests are conducted on live commercial network of the operator Ethio telecom deployed by vendor Huawei Technologies.

The KPIs observed in this thesis include RSRP, RSRQ, SINR, CQI in LTE and RSCP, E_c/N_0, CQI in UMTS (3G) systems at two different locations in Addis Ababa, Ethiopia – Bole and Kality sub-cities. Link adaptation mechanisms based on different modulation techniques are also studied. In physical terms, network status, radio signal power, noise and interferences from different sources and their impact on the network are studied. This thesis mainly aimed at studying Inter-RAT handover and analyze network performance in terms of the following physical parameters.

- Handover success rate
- MAC layer throughput
- Handover delay
- Service interruption time

Based on field measurement results, the following are findings of the thesis.

- Inter-RAT handover from LTE to 3G networks works perfectly in both idle and connected user mobility modes.
- Average handover delay ranges from 5 to 7 seconds.
- With this limited number of test attempts, the best-case handover success rate is close to perfection. Increasing the number of attempts could reduce the value further down.
- Up to 48 Mbps MAC layer throughput can be achieved.
- The average service interruption time is above 7 seconds.

Analyzing the measurement results indicate that the average Inter-RAT handover delay is very long compared to 3GPP's recommended value which is half asecond. This implies that an ongoing user session is interrupted for a longer time than recommended values which in turn results in poor user experience. Although perfect handover success rate was recorded, its implementation has a significant flaw. That means, inconsistent parameter configuration was used while defining threshold values which trigger handovers. Even if handover takes place, a longer handover delay indicates that the network cannot maintain ongoing real-time services like Voice over IP (VoIP), video calls, online gaming and online video streaming in an efficient way and as the user expects. However, a reasonably longer delay is not a problem to non-real-time services such as downloading files, email transfers and normal web browsing. In general, longer delay can cause call drop, handover failure, degrading quality of service, packet loss, capacity reduction (shrinking), radio resource wastage and thus reduce the system performance and results in user dissatisfactions.Therefore, the following concluding remarks are made based on observed measurement results and analysis of those results by comparing them with standards defined by the 3GPP.

- The LTE network is poorly optimized in contrast to the 3G network which is relatively better optimized.

- Inter-RAT handover is acceptable in its entirety.
- However, the network cannot effectively support real-time services due to longer delays.
- The MAC layer throughput under good radio conditions is acceptable.
- Configuration parameters are poorly handled and important thresholds are set lower than both agreed values and 3GPP's standards.
- The current LTE network cannot directly support voice traffic due to absence key core network element called IMS.

Future Work and Recommendation

Based on the results and analysis observed in this thesis, the following design, planning, optimization, configuration and deployment suggestions are made in order to rectify the existing performance issues, support limitations and configuration flaws.

– ***Planning and design.*** The number of sites, their locations and coverage areas together with antenna heights and uplink/downlink frequencies must be properly selected in future LTE network expansions as LTE is deployed as co-site with existing 3G sites.

– ***Configuration.*** Signal threshold, margin of time-to-trigger (TTT) setting, handover and cell reselection algorithm settings must be revisited to make sure key values are defined as per agreed engineering, documents and scope.

– ***Optimization.*** Antenna adjustments such as direction, gain, pilot power, electrical and mechanical tilts, and number of neighbor cells per site should be performed to improve system performance while providing good quality of service.

– ***Deployment.*** Future telecom expansion works shall focus on achieving full LTE coverage with possible support to Circuit Switched traffic by installing IP multimedia Subsystem (IMS).

– ***Study Scenarios.***In addition to handover process studied in this thesis, Inter-RAT handover between LTE, 2G, 3G and non-3GPP technologies must be studied to provide complete and accurate results.

Finally, there are some limitations of this study. The field measurements are performed in a single-vendor network environment which signifies the results cannot clearly illustrate performance issues in other networks deployed by different vendors. Furthermore, the internetworking and handover process from 3G to LTE was not studied because of wide coverage of the 3G network including LTE hotspots which in turn could have improved accuracy of the results. However, the test and analysis of such systems could be very challenging and time consuming.

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