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TAMPERE UNIVERSITY OF TECHNOLOGY

BASANTA PANDEY
LTE-3G INTER-OPERABILITY STUDY
Master of Science Thesis

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ABSTRACT

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In this thesis the author has studied and measured how LTE Release 8 interworks with previous legacy 3G networks in real environmental conditions. At present, LTE technology is deployed based on service hotspots that cover small geographical areas. It is expected that full scale deployment of LTE network will take a considerable time, which also means the mobile users have to primarily depend on legacy 3G and 2G networks for years to come. Therefore, it is important to study the interworking mechanisms between LTE and legacy networks in order to provide seamless mobility and uninterrupted user services in primarily available LTE hotspots.

In order to perform this study, field measurements have been carried out in DNA commercial network in outdoor and indoor environments. Initially, cell selection and reselection criteria for inter-RAT mobility in idle condition is mathematically checked and verified. Then, channel conditions are studied and analyzed based on radio parameters like RSRP, RSCP, RSRQ, Ec/No, SNR and CQI when inter-RAT handover is performed. After that, an inter-RAT handover test from LTE towards 3G is studied with the help of signalling message. Next, the impact of inter-RAT handover on KPIs like MAC DL throughput, handover success rate, RTT, handover latency and user plane delay are studied and analyzed. Finally, performance of inter-RAT handover in outdoor and indoor measurement environment is compared based on KPI measurements.

From this study, it is found that inter-RAT mobility from LTE towards 3G network is working in both idle and connected modes with 100 percent handover success rate, however, the user experienced network latency around 4 seconds in average. The user experienced degradation in throughput because of decreasing link quality. The user data service interruption is roughly for 3-4 seconds and the RTT value for 32 bytes of data is observed to be around 300 ms in average during handover. It is also found that the impact of inter-RAT handover in indoor environment is higher than outdoor environment based on KPIs results.

PREFACE

This Master of Science Thesis has been written for the completion of Master of Science Degree in Electrical Engineering from the Tampere University of Technology, Tampere, Finland. The thesis work has been carried out in the Department of Electrical Engineering under Radio Network Planning Group during the year 2012 and 2013.

I would like to thank my examiner Professor, Dr. Tech. Mikko Valkama and supervisor Dr. Tech. Jarno Niemelä for supervising and guiding me throughout my thesis work. I would also like to thank Tero Isotalo and Professor Jukka Lempiäinen for their continuous guidance and support during thesis. I am extremely grateful to my supervisor Jarno Niemelä for helping me in drive test during the measurement. Without this, completion of thesis would not be possible. Thanks to all my colleagues in Radio Network Group for their friendly behaviour and support during this thesis.

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LIST OF ABBREVIATIONS

1G	First Generation
2G	Second Generations
3G	Third Generations
3GPP	Third Generation Partnership Project
4G	Fourth Generations
AM	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
BSS	Base Station Subsystem
CA	Carrier Aggregation
CDF	Cumulative Distribution Function
CN	Core Network
CP	Control Plane
CP	Cyclic Prefix
CPICH	Common Pilot Channel
CQI	Channel Quality Indicator
DCCH	Dedicated Control Channel
DFT	Discrete Fourier Transform
DHCP	Dynamic Host Control Protocol
DL	Downlink
DLSCH	Downlink Shared Channel
DSP	Digital Signal Processing
DTCH	Dedicated
EDGE	Enhanced Data rates for GSM Evolution
EIR	Equipment Identity Register
EMM	EPS Mobility Management
eNodeB	Evolved NodeB
EPC	Evolved packet Core
EPS	Evolved Packet System
EUTRAN	Evolved UTRAN
FACH	Forward Access Channel
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 Tunnelling Protocol
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
IMSI	International Mobile Subscriber Identity
IP	Internet Protocol
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
MAC	Medium Access Control
MCH	Multicast Channel
MCCH	Multicast Control Channel
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MME	Mobility Management Entity
MMS	Multimedia Message Service
MSISDN	Mobile Station Integrated Service Digital Network
MTCH	Multicast Traffic Channel
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

PAPR	Peak to 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
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
RLC	Radio Link Control
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
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
SISO	Single Input Single Output

SIMO	Single Input Multiple Output
SMS	Short Message Service
SMPT	Simple Mail Transfer Protocol
SNR	Signal to Noise Ratio
SR-VCC	Single Radio Voice Call Continuity
TA	Tracking Area
TACS	Total Access Communication System
TAI	Tracking Area Identity
TAL	Tracking Area List
TAU	Tracking Area Update
TDMA	Time Division Multiple Access
TM	Transparent Mode
TTI	Transmission Time Interval
TTY	Tampereen Teknillien Yliopisto
UE	User Equipment
UM	Unacknowledged Mode
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
X2AP	X2 Application Protocol

LIST OF SYMBOLS

S_{rxlev}	Cell selection received signal level
E_c/N_o	Energy per chip divided by power density of the band
$Q_{rxlevmeas}$	Measured RSRP value
$Q_{rxlevmin}$	Required minimum RSRP value
$Q_{rxlevminoffset}$	Offset to signalled $Q_{rxlevmin}$
$P_{compensation}$	Power compensation
$S_{servingcell}$	Serving cell measured value
$S_{intrasearch}$	Intra-frequency cell selection search threshold
$S_{nonintrasearch}$	Inter-frequency cell selection search threshold
$Q_{meas,s}$	Serving cell measured value
$Q_{meas,n}$	Neighbouring cell measured value
Q_{hys}	Hysteresis value
Q_{offset}	Offset value
$T_{reselection}$	Time to trigger
P_{EMAX}	maximum allowed uplink transmit power within a cell
P_{UMAX}	maximum transmit power capability of the UE
R_n	Rank of the neighbour cell
R_s	Rank of the serving cell

1. INTRODUCTION

Technology with low cost and offering high quality of service are always on user's choice. Several efficient technologies are developed and implemented by the mobile operators to satisfy mobile users. In order to meet the expectation of high mobile data rate, quality of service, faster communication and facilitating multimedia service; High Speed Packet Access (HSPA) technology based on the Universal Mobile Telecommunication System (UMTS) called 3G networks is introduced and deployed. This technology has made drastic change in raising the numbers of mobile data service users day by day at exponential rate. As this growth continuous in future, the 3G network might not be enough to hold the network load. Therefore, a new technology providing even more capacity and high data rates than 3G network is developed by 3rd Generation Partnership Project (3GPP) called Long Term Evolution (LTE) to fulfil the requirement.

LTE is a 4th generation (4G) wireless network based on packet switched technique with flat architecture. This architecture is able to provide high data rates, lower latencies, high spectral efficiency and compatible with previous 3GPP networks like UMTS and Global System for Mobile Communication (GSM) as well as non-3GPP networks.

Users always expect uninterrupted, efficient and stable service 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. Mobility of a user is controlled by the handovers algorithms. These algorithms are developed to ensure the consistent performance of the cellular network to offer seamless mobility such that user quality of service is always maintained.

1.1 Objectives and Limit of the Research

The goal of this thesis is to study and perform the test measurements regarding LTE interworking with previous legacy 3G networks. Measurement should be done in realistic radio conditions and test the actual mobility to see the impact on different KPIs for commercial network operators like DNA and Elisa in Finland.

The main outcome of this thesis is the analysis of inter-RAT mobility testing in DNA network from LTE to 3G network in Tampere University of Technology (TUT) campus region in indoor and outdoor measurement environments. The analysed results in this thesis are for the connected mode inter-RAT mobility with a data connection experienced by a single user.

The main limitation is the mobility from 3G towards LTE in this thesis. This is because of wide coverage of 3G networks including LTE hotspot areas. But theoretical explanation of inter-RAT handover from 3G to LTE process is given in detail. One major difficulty during this thesis research is finding the LTE to 3G inter-RAT handover spots during mobility.

1.2 Research Methods

This thesis starts from the literature study from different books, technical papers, conference papers, journal documents and different websites. In the beginning the necessary background theory is provided in simplest manner to help the reader to understand the basic concept, terms and the theories used while analyzing the measured results. The relevant documents used are enlisted under reference headings. Before starting actual measurement, two other measurements were performed: one on intra-cell mobility in LTE within Nokia Test Network in Tampere University of Technology (TUT) premises and other inter-Frequency mobility in LTE between indoor test network of TUT and test network of Nokia in Hermia region. These are done for background information and understand the basic concept of handover signalling message flow between the network elements. After that inter-RAT mobility measurement is conducted in two locations: outdoor and indoor. Both measurements are done in Tampere University of Technology (TUT) campus area. Nemo Outdoor is used to monitor and record the measurement while Nemo Analyzer is used for analyzing the data. The data is extracted and filtered with the help of MS-Excel and the required data is plotted in the Matlab for results. Finally analysis and conclusion is made based on these results.

1.3 Thesis Structure

The entire thesis is divided into seven chapters. Chapter 1 introduces the topic, goals and limitation and the research methodology used in this thesis. Chapter 2 explains the cellular concept, location management schemes used in mobile communication and different types of radio propagation environments. It also deals with the properties of radio channel and different types of channel accessing schemes used in mobile technology. Chapter 3 gives a brief discussion on LTE. It also explains history about the mobile network and evolution path towards LTE. It also gives a detail description on network elements associated with UMTS and LTE network architecture. Chapter 4 focuses on the air interface technology used in LTE. The framing concept, interface and protocols and the different channels used are discussed under same chapter. It explains about the Medium Access Control (MAC) layer and physical layer functions as well. Chapter 5 is the core chapters of literature for this thesis to understand the analysis and results. Chapter 5 begins with a short introduction on system information message and the measurement events in LTE. After that, it gives a detail description on the mobility management within LTE and with previous legacy 3G networks in both idle and connected mode with examples. At last this chapter ends by giving a short introduction on Voice over LTE (VoLTE) and Single Radio Voice Call Continuity (SR-VCC). Chapter 6 begins with the discussion on different key performance indicators used to evaluate the network performance and gives detail information about the measurement and analyzing tools. This chapter ends with measurement results and discussions. Finally Chapter 7 concludes the overall thesis.

2. MOBILE COMMUNICATION SYSTEM

Communication system helps to exchange the information between a sender and a receiver. The communication process becomes effective only when a receiver understand the exact information sent by a sender. A sender and a receiver are always connected with each other by means of communication medium. These communication medium may be guided lines or wireless. In guided lines, the information is guided along a physical path directly connected between a sender and a receiver. Twisted pair cable, coaxial cable and optical fibers are some examples of guided lines. In wireless, the information propagates in the form of electromagnetic waves through air. Microwaves and radio waves are examples of wireless media. Mobile communication, a wireless technology allows a sender or a receiver to communicate with each other anytime, anywhere and anyone.

This chapter starts with the introduction on cellular concept. It contains the detail description about different radio propagation environment and its channel properties. It also explains about the different access technologies used in wireless communication. A short concept behind the spread spectrum technology is explained at the end of this chapter.

2.1 Cellular Concept

The idea of the cellular concept was proposed by Bell Labs (AT&T) in 1947. The main aim behind the development of this concept was to use the available spectrum in efficient manner using low power transmitters and to provide full coverage with high capacity and to ensure full mobility within coverage area with uninterrupted service.

In this concept, a large geometrical area is divided into smaller areas called cells and these cells are grouped together to form a cluster. These sub divided areas utilized frequency reuse mechanism. In this mechanism, the radio frequency or radio channel used by a cell can be utilized by another cell after a certain physical distance called reuse distance. It means the radio channels cannot be used in adjacent neighbouring cells. This is done to avoid co-channel interference. This frequent use of radio resources increases the capacity. The reuse distance, D is calculated by: [1]

$$D = R\sqrt{3N} \tag{2.1}$$

where R is the radius of the cell and N is the number of cells per cluster. The valid cluster size can be constructed if:

$$N = i^2 + i * j + j^2 \tag{2.2}$$

where i and j are non negative integers and is given as: $i \geq 0$ and $j \geq i$.

The shape of the cells can be square, circular, and hexagonal or some other irregular shapes. The shape is chosen in such a way that it should be geometrical, cover the areas without overlap or leave no gaps and has the largest area. The hexagonal shape is the best that satisfies all these conditions. So, it is universally adopted. Figure 2.1 is an example of hexagonal cellular concept with frequency reuse factor 3. Here a geometrical area is subdivided into small cells. Each cell is separated by different colours using three different frequency f1, f2 and f3 after certain reuse distance.

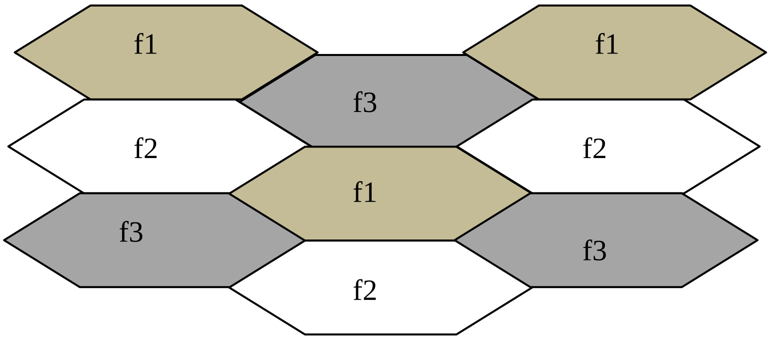


Figure 2.1*: Hexagonal cell with frequency reuse factor 3*

The different types of cell size are deployed depending upon the coverage and capacity.

- ***Macro cells:*** These types of cells are deployed to cover remote and sparsely populated areas. They cover around 10km or even more.
- ***Micro cells:*** They cover around 1km in diameter and mostly deployed in densely populated areas.
- ***Pico cells:*** They are deployed to cover very small areas like buildings and offices or to such types of place where the coverage from the large cell is not possible.

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. More number of base stations can be added to increase radio capacity from fixed radio spectrum to serve more users. The cellular concept has some drawbacks. To increase the capacity, more number of base stations is required. This increases the cost. It should also support seamless handoff between the cells as radio channel condition varies throughout the network. Management of the resource is required and need to track the user location to route incoming call/message.

Those channels assigned to a cell are classified as downlink channels and uplink channels. Downlink channels are used to carry traffic from the base station to mobile stations whereas uplink channels are used to carry traffic from mobile stations to the base station. These channels are further divided into control channels and traffic channels. Control channels carry control information while the traffic channels carry user voice or data information. A mobile station communicates another mobile station via base station. At first, the network needs to know the location of the target mobile station in a cell before starting communication.

2.2 Location Management

In cellular network Location Management (LM) tracks the location of an active mobile station. A mobile is said to be active if it is powered on. The LM involves two operations: location update and paging.

- ***Paging***: Paging is always performed by cellular network. The cellular network will page in all possible cells to find out the cell in which the active mobile station is located.
- ***Location update***: This operation is always performed by the active mobile station. This is done either by globally or locally. A global location update scheme allows all mobile stations to update their locations at the same set of cells whereas local location update allows each mobile user to decide when and where to perform location update.

2.2.1 Location Area (LA)

This is an approach for location management used in first generation and second generation system like Global System for Mobile Communication (GSM). A serving area is subdivided into location areas and each location area consists of several adjacent cells. The base station of each cell broadcast the identification of the location area which is called Location Area Identity (LAI) to which the cell belongs. A mobile station updates its location area and informs the cellular network by sending Location Area Update (LAU) code whenever it enters into a cell which belongs to a new location area.

2.2.2 Routing Area (RA)

This approach is used for location management in second generation and third generation system like Universal Mobile Telecommunication System (UMTS). The routing area is sub-area of a location area with specific means for PS services. Each user informs 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's routing area is changed. This RAI consists of Location Area Code (LAC) and RAC message.

2.2.3 Tracking Area (TA)

This location management approach is used for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) cells. They are used to track the mobile stations which are in standby mode. Adjacent EUTRAN cells are grouped together to form tracking area. These grouped cells have same Tracking Area Identity (TAI). TAI may vary when the mobile station moves from one cell to another cell. The mobile station reports TAI updates by sending Tracking Area Update (TAU) message. The number of cells to be paged to find the location of the cell depends on tracking area. Signalling overhead may rise if frequent TAU happens. Therefore a concept of Tracking Area List (TAL) is introduced. In this concept, each cell belongs to only one TA but a mobile station 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 Handovers

Handover maintains a connection between the network and the Mobile Station (MS) when MS moves from one cell to another. As the mobile station moves towards the cell edge the signal strength starts to deteriorate. Therefore the MS has to find the new cell and camped into it before ongoing services session gets disturbed. Therefore handover process helps to find a suitable cell for UE to maintain quality of service. Generally, handover may be hard, soft and softer. Hard handover is the 'break-before-make' handover. In this type, 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 the radio channels that are connected and released belong to the same site.

The handover process comprises three steps. The first step is the handover initiation. Either MS or network initiates the handover once needed. The second stage is the new connection establishment by finding the available resources for handover process and routing operations. Last stage is the successful data flow from the new established connectivity. Handover may be intra-cell, inter-cell and inter-RAT cell. Intra cell 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. Refer Chapter 5 for detail.

2.4 Radio Propagation Environment

The transmitted radio waves from transmitter and receiver depend upon the environment on which it propagates. The propagation paths between them vary the performance of the communication system. Therefore the coverage and the capacity of any cellular systems rely on the behaviour of different environment. The classification of the environment is done to make the network planning process easier. Figure 2.2 is the classification of the environment in terms of: [2]

- ***Mobile location***: The mobile terminal outside the buildings environment is termed as outdoor whereas mobile located inside is termed as indoor.
- ***Antenna location***: Depending upon the location of antenna, the environment is classified as macro, micro and pico. In macro-cellular, the location of the antenna is above the average height of the buildings whereas in micro-cellular the antenna is below the rooftop level. In pico-cellular the antennas are completely located inside the buildings.

- ***Morphography type:*** The environment is classified into urban, suburban and rural depending upon the population density and natural obstacles present in the surroundings. Urban areas are characterized by the high population densities like cities or towns. Suburban area may be a part of city with low population density compared to urban type. Rural areas are village areas located outside the cities and have least population density.

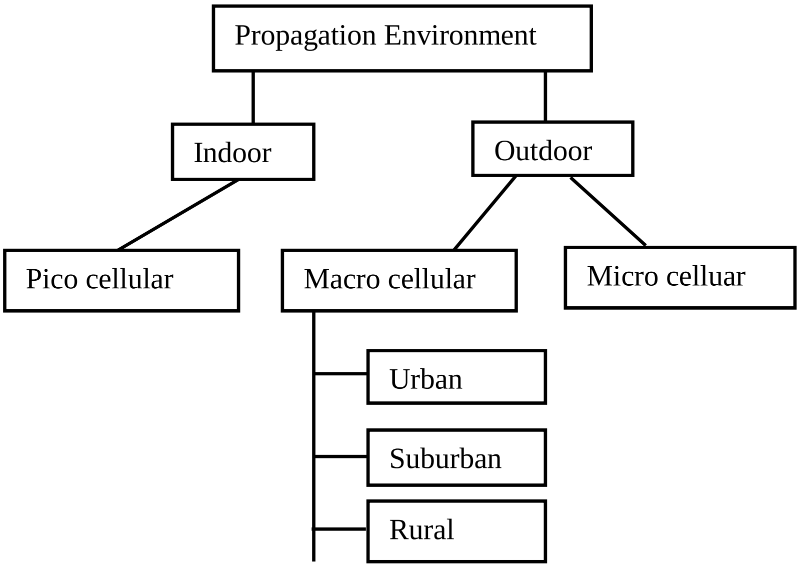


Figure 2.2*: Classification of radio propagation environments*

2.5 Radio Channel Properties

This section describes the parameters that characterized the propagation environment.

2.5.1 Multipath Propagation and Delay Spread

In mobile communication, the signal propagation path between the mobile station and base station is affected by the objects/obstructions present in between them. These obstacles cause the transmitted signal to reflect, diffract and scatter. Reflection is caused by the wall of the buildings and earth surface. Sharp edge of walls, mountains and rooftops cause diffraction of the signal and trees are the source of scattering the signal. Due to these obstacles the received signal consists of several replicas of the originally transmitted signal. These replicas have different amplitudes, phase, polarisation and angle of arrival. This phenomenon of transmitted signal arriving from different path at the receiver is called multipath propagation.

The multipath propagation caused the signal to arrive at different time instants. The variation of this timing instant is measured by delay spread. The delay spread S_τ is calculated from power delay profile (PDP) $P_\tau\left(\tau\right)$. [2]

$$S_\tau = \sqrt{\frac{\int_0^\infty \left(\tau - \overline{\tau}\right)^2 * P_\tau(\tau) * d\tau}{P_{\tau-total}}} \tag{2.3}$$

where power delay profile is power of the received signal received at different time interval through multipath. $\bar{\tau}$ is the average delay and $P_{\tau-total}$ is the total received power. Different propagation environment has different delay spread. The macro cellular environment has high delay spread than in micro cellular and indoor environment due to high arrival time of multipath component.

Frequency separation of the multipath components is given by the coherence bandwidth Δf_c which depends upon the delay spread. Coherence bandwidth is range of frequencies over which a channel is considered flat. The relation between the coherence bandwidth and delay spread is given by,

$$\Delta f_c = \frac{1}{2\pi s_\tau} \tag{2.4}$$

where s_τ is the delay spread. [2]

2.5.2 Angular Spread

The variation of the signal incident angle of the received power due to multipath is given by angular spread (S_ϕ). It can be calculated either in horizontal or vertical planes using formula,

$$S_\phi = \sqrt{\int_{\bar{\phi}-180}^{\bar{\phi}+180} \left(\phi - \overline{\phi}\right)^2 \frac{P(\phi)}{P_{\phi-total}} d\phi} \tag{2.5}$$

where ϕ is the incident angle, $\overline{\phi}$ is the mean angle, $P(\phi)$ is the angular power distribution and $P_{\phi-total}$ is the total power. The angular spread from the horizontal planes is mostly concerned. This is due to large amount of propagation paths between the mobile station and base station. The horizontal angular spread is high in indoor and micro cellular environment than in macro cellular environment. In indoor environment, it has 360 degrees of variation; in micro environment it has 45 degrees deviation value and in macro cellular environment, it has 5-10 degrees variation. [2]

2.5.3 Fast fading and Slow fading

Different replicas of the transmitted signal arrive at the receiver due to reflection and diffraction. These replicated signals vary in amplitude and phase than original one. At the receiver side, the total received signal is achieved by the superposition/combination of these replicated signals. The received signal can be constructive if the phase is same otherwise it is destructive.

As the mobile station moves, the amplitude and phase change of the replicated signals change very quickly as a result the total received signal also change very fast. This phenomenon of rapid fluctuation of amplitude and phase is fast fading. Fast fading is shown in Figure 2.3 with solid lines.

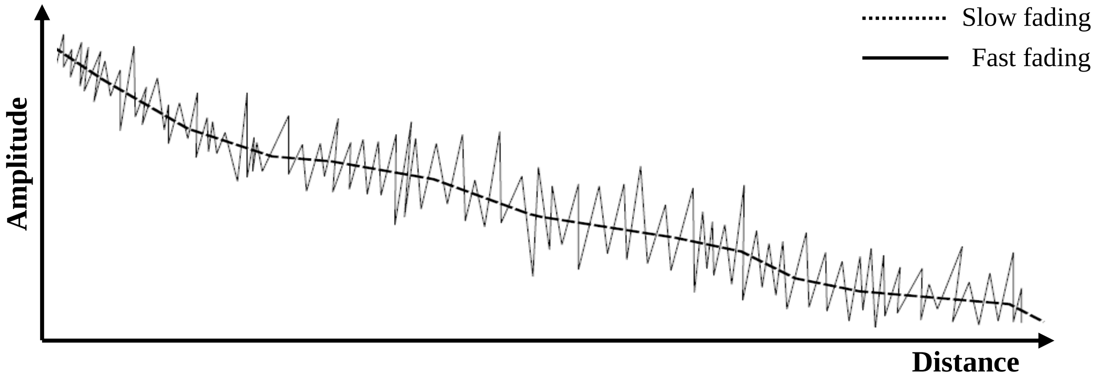


Figure 2.3*: Slow fading and fast fading [2]*

The distribution of *fast fading* varies according to the LOS (Line-of-Sight) and NLOS (Non-Line-of-Sight) environment between transmitter and receiver. In NLOS, there exists no single dominating path. This results in random uniformly distributed phase of all multipath components and the amplitude of received signal is Rayleigh distributed. The fading in NLOS condition is Rayleigh fading. In LOS condition, the amplitude of direct signal always has higher amplitude than the others. When a direct path exists, the total signal amplitude is Rician distributed and the fading caused by LOS is Rician fading.

Slow fading is a slow variation of the received signal level. It is defined as the variation of the local mean value of the fast fading over a wide area. It is due to shadow effect caused large buildings, hills and trees between the transmitter and receiver. These obstacles blocks the main direct path as a result the propagation takes place only from reflection and diffraction. Therefore the change in received signal power can be modelled using log-normal distribution. A dash line in Figure 2.3 shows the slow variation of received signal amplitude over a wide area. [2]

2.5.4 Propagation Slope

Propagation slope is the attenuation of the radio wave with respect to the distance in dB/decade. The propagation slope is defined by the propagation exponent denoted by γ. The propagation exponent differs with the environment. In free space, $\gamma = 2$, which corresponds to 20dB/decade propagation slope. The propagation slope plays an important role in the estimation of path loss denoted by L and can be calculated by the equation,

$$L = L_0 d^{\left(\frac{\gamma}{10}\right)} \tag{2.6}$$

where L_0 is the path loss at the reference point, d is the distance between the transmitter and receiver and γ is the propagation exponent.

The variation of radio condition between the base station and mobile station varies the propagation slope all the time. The distance where the propagation slope change is breakpoint distance, B which is calculated by using the equation [2]

$$B = 4\frac{h_{BTS}h_{MS}}{\lambda} \tag{2.7}$$

where h_{BTS} is the height of the base station antenna, h_{MS} is the height of the mobile station antenna and λ is the wavelength of the received signal.

2.5.5 Characteristics of Radio Propagation Environments

The characteristics of radio propagation environments for Global System for Mobile Communication (GSM) 900 MHz system are summarised in Table 2.1

Table 2.1: *Radio channel characteristics for different environment at 900MHz [2]*

Environment type	*Angular spread(degree)*	*RMS Delay spread (µs)*	*Fast fading*	*Slow fading standard deviation (dB)*	*Propagation slope (dB/dec)*
Macrocellular					
Urban	5-10	0.5	NLOS	7-8	40
Suburban	5-10		NLOS	7-8	30
Rural	5	0.1	(N)LOS	7-8	25
Hilly rural		3	(N)LOS	7-8	25
Microcellular	40-90	<0.01	(N)LOS	6-10	20
Indoor	90-360	<0.1	(N)LOS	3-6	20

These radio channel characteristics parameters for different environment are taken into account in the radio planning. In microcellular and indoor environment, Line of Sight (LOS) and Non Line of Sight (NLOS) are responsible for fast fading. The propagation slope is lower in indoor environment while macrocellular has the highest value of 40 dB/decade. The angular spread is higher whereas delay spread is lower in macrocelluar environment.

2.5.6 Propagation Path Loss Models

Propagation models are used to predict the significant path loss between the base station and mobile station. These models help the mobile network providers to plan and optimize their network. Depending upon the propagation environment, path loss models are classified as empirical models, physical models or semi-empirical models, deterministic models and indoor models.

Empirical models are mainly for macrocellular environment based on extensive measurement campaigns. They are accurate in environments with same characteristics defined by the land use, not by reflections and diffractions. The environment is specified as urban, suburban, rural and open areas. These models are simple and require low computational time but they have accuracy problems. Different environment requires tuning to use empirical model. Okamura-Hata is the most accurate empirical model which is formulated as

$$L = A + B\log_{10}(f) - 13.82\log_{10}(h_{bs}) - a(h_{ms}) + \left[C - 6.55\log_{10}(h_{bs})\right]\log_{10}(d) + C_m \quad (2.8)$$

where

L	Path loss [dB]
A	Constant (see Table 2.2)
B	Constant (see Table 2.2)
f	Frequency [MHz] ($150MHz \le f \le 2000MHz$)
h_{bs}	Height of the base station antenna [m] $\left(30m \le h_{bs} \le 200m\right)$
h_{ms}	Height of the mobile station antenna [m] $\left(1m \le h_{ms} \le 10m\right)$
C	Propagation slope
d	Distance between mobile station and base station [km] $\left(1Km \le d \le 20Km\right)$
C_m	Area type correction factor

The constant parameters A and B differs with respect to frequency and is given as:

***Table 2.2**: Value of A and B [2]*

Parameters	*Frequency*	
	150-1500MHz	1500-2000MHz
A	69.55	46.3
B	26.16	33.9

Depending upon the size of the city, $a(h_{ms})$ can be formulated as

For small and medium city,

$$a(h_{ms}) = (1.1\log_{10} f - 0.7)h_{ms} - \left(1.56\log_{10}(f) - 0.8\right) \quad (2.9)$$

For large city,

$$a(h_{ms}) = 3.2\left(\log_{10}(11.75h_{ms})\right)^2 - 4.97 \quad (2.10)$$

In Equation 2.8 the area correction factor varies typically from -3dB (water) and up to 30dB (buildings).

Physical or semi-empirical models are suitable for macro and micro cells are completely based on geometry of the buildings. They are more accurate than empirical models but require more precise description of the environment and more computation time. COST-231-Walfisch-Ikegami is the famous semi-empirical model.

Deterministic models are based on analytical estimation of the electromagnetic waves equation or using ray optical methods. They are mainly for microcellular and picocellular environment which produces very accurate results in high computation time. These models rely on accurate 3D building information and material information.

Indoor models are based on the layout of the buildings and building materials. This is because of the propagation due to reflection, refraction and diffraction of the radio waves caused by the walls, windows and doors inside the buildings.

2.6 Multiple Access Schemes

Access techniques allow multiple users to share the limited amount of radio spectrum at the same time. *Time Division Multiple Access* (TDMA), *Frequency Division Multiple Access* (FDMA) and *Code Division Multiple Access* (CDMA) are the three major accessing schemes used in a wireless communication system are shown in Figure 2.4.

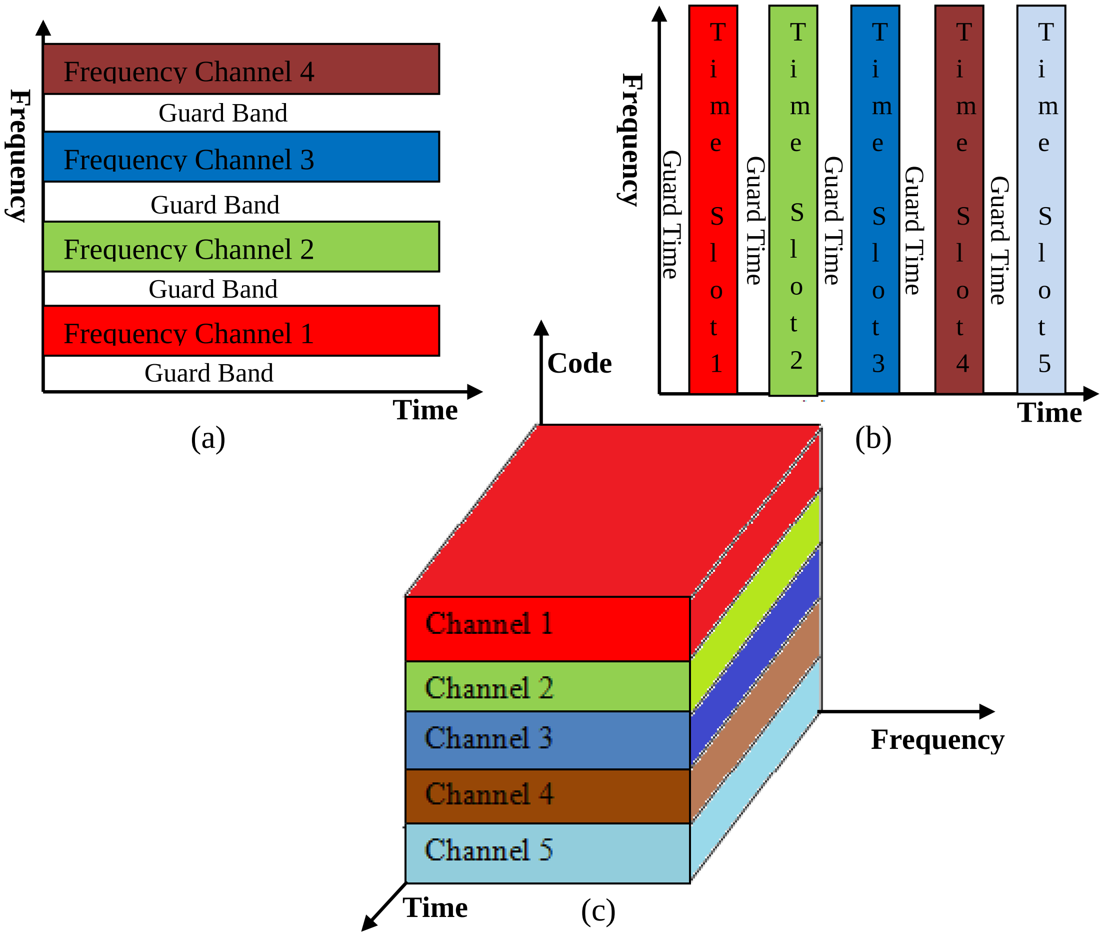


Figure 2.4: *Multiple access techniques: (a) FDMA, (b) TDMA and (c) CDMA [3]*

In TDMA technique, each user is allocated with unique time slot to access a single radio channel. These time slots are separated by the guard slots. Data in this scheme is transmitted in the form of burst and hence synchronization is needed. In FDMA technique the available radio spectrum is divided into large number of narrowband channels. Each user is allocated with fixed channels and is retained until it is released. These narrow band channels are separated by guard bands. In this scheme, an unused channel in idle mode and uneven distribution of the traffic lead towards the wastage of the resources. The combination of TDMA and FDMA schemes are used in GSM system. In CDMA technique, the narrowband message signal is multiplied by the spreading signal to produce a wideband signal. These spreading signals are the sequence of pseudorandom code which has a chip rate higher than the data rate of the message signal. Each user is allocated with unique pseudorandom code and they are orthogonal to each other.

3. HISTORY AND LTE OVERVIEW

This chapter presents a short history on the development of mobile networks and the communication methods used back to ages till present. An introduction on today 3G and 4G networks and their evolution path from the previous legacy networks is also explained in detailed.

3.1 History of Mobile Networks

Going back to the ages, people have their own way to communicate. During those days people used flag as a medium to convey the information. Later on around 150 BC Greek people start to use smoke signals for communication. Then after around 1794 Claude Chappe invented optical telegraph for communication purpose. This is regarded as " The Mother of all Networks". This method was limited by the geography and weather conditions. After that to overcome the limitation, electromagnetic waves were discovered. In 1857 Clark Maxwell derived a theory on electromagnetic fields and introduced wave equations. Later in 1888 Heinrich Hertz demonstrate the first experiment in Germany on wave characteristics in space. Based on the Maxwell equations Guglielmo Marconi demonstrates on wireless telegraphy based on radio waves in 1901. He used huge transmitter's stations with very high antennas. This system requires high power for transmission. In 1920 Marconi discovered the short waves which overcome the requirement of huge transmitters and receivers. During this year the technology was installed in police cars for one way communication. As time passed, radio telephony was used for military purpose during Second World War. In 1940's hand held transmitters were available which were bulky and consumes high power. During 1946 US engineers from Bell lab develop a system which allow user to transmit and receive from automobiles. Soon after, American Telephone and Telegraph (AT&T) launched Mobile Telephone service in urban areas with limited coverage. [4]

3.1.1 Evolution towards 1G

In 1970s the modern cellular network were launched. The system utilizes Analog circuit- switched mainly designed for voice using Frequency Division Multiple Access (FDMA) technology. This was called First Generation (1G) network. These analog systems were developed in different parts of the world using Advanced Mobile Phone System (AMPS) in America, Total Access Communication Systems (TACS) and Nordic Mobile Telephone System (NMT) in Europe and Japanese Total Access Communication Systems (J-TACS) in Japan. In 1979 Nippon Telephone and Telephone Company (NTT) launched commercially so called 1G network in metropolitan areas of Japan. This analog system worked on 800-900 MHz frequency bands and used frequency modulation to transmit the signals. This system was designed to support more number of users and support user mobility. These analog supporting devices were lighter than previous development. The main drawbacks of this system are the lack of security and short battery life. [5]

In 1980s a packet switched technology called X.25 was deployed for data networks whereas voice networks deployed circuit switched technology. During this stage the networks for voice and data were completely separated.

In the 90s a new circuit based telephony Integrated Service Digital Network (ISDN) was introduced to replace the circuit switched analog technology by the digital lines. This standard helps to transmit voice and the limited data simultaneously. Later, a new technology Asynchronous Transfer Mode (ATM) was introduced to support data, voice and video signals to overcome the limitation of X.25. But due to the expensive of the ATM switches, scientists develop the new technology standard called frame relay. This standard was simple and support voice and data. [6]

3.1.2 Evolution towards 2G

A new modern digital technology called Global System for Mobile (GSM) was introduced in Finland in 1991. The other systems were Personal Digital Cellular Technology (PDC), integrated Digital Enhanced Network (iDEN), Interim-standard (IS-95) based on CDMA, IS-136 based on TDMA. They were regarded as the Second Generation (2G) digital cellular network. Among those systems GSM and IS-95 standard were much popular. All the limitations of the 1st generation were overcome by this technology as a result the GSM was spread worldwide. It provides the roaming facilities across the carriers. Later, a new packet switched technology was launched to transfer data as short messaging service with a speed of 9.6 kbps. The use of this technology gave rise to the use of internet and its protocols. It is designed to operate in 900 MHz and 1800 MHz frequency band in Europe. The devices were much lighter and cheaper due to digital technique implementation. The battery life was improved; encryption technique was implemented for security purpose and more immune to noise. In late 1990s, general packet radio service (GPRS) was introduced to support high data packets to the existing GSM networks supporting speed up to 114 kbps. After that Enhanced Data rates for GSM Evolution (EDGE) come on exists. It uses 8 phase shift keying (8-PSK) modulation technique and combines with GPRS to support the data rate of 200kbps. [5] [6]

3.1.3 Evolution towards 3G

During 2000, data services were in high demand. To support this growing, the third generation mobile communication systems were introduced. This 3G technology supports the high speed internet browsing from the mobile devices. This system also supports the additional features like video streaming, TV streaming, navigation and multimedia support. This technology used packet switching for data transmission. Under International Telecommunication Union project IMT-2000; a set of 3G standards were developed such as Universal Mobile Telecommunication System (UMTS), CDMA 2000, Digital Enhanced Cordless Telephone (DECT) and EDGE. The 400MHz to 3GHz frequency band was allocated for 3G communication systems. In 2001 NTT DoCoMo launched 3G in Japan based on WCDMA standard. This technology utilizes frequency reuse concept. In late 2001, UMTS technology was launched commercially in Europe. It was based on CDMA concept which 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. Due to this technique global roaming and internet connection from any location was possible. [5]

In 2002, the SK Telecom from South Korea introduced another 3G technology 1xEV-DO based on CDMA. On the same year the Monet Mobile Network from America launch 1xEV-DO based on CDMA 2000 standards. Later new protocol standards High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA) were introduced in Release 5 and Release 6 termed in WCDMA evolution to improve the data transmission rate in mobile communication for downlink and uplink. It utilizes different modulation and coding techniques. HSDPA offers data rate 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. [7]

3.1.4 Evolution towards 4G

LTE is the next evolution from 3G in wireless mobile networks to 4G introduced in Release 8. It is IP based technology with flat architecture providing data rate of 100Mbps in downlink and 50Mbps in uplink direction. Low latency, seamless mobility and efficient use of radio resources are the characteristics of LTE. This emerging technique can work with previous 2G and 3G networks. LTE-Advanced is another upgrade evolution from LTE. It is defined in Release 10. It mainly focuses on higher capacity. It supports multiple antenna systems and Carrier Aggregation (CA) concept.

3.2 Overview of UMTS System

The Universal Mobile Telecommunication System (UMTS) is the 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.

3.2.1 UMTS Network Architecture

The UMTS network architecture is classified into three major domains: User Equipment (UE), UMTS Terrestrial Access Network (UTRAN) and Core Network (CN). Figure 3.1 shows the complete view of the UMTS network architecture with associated elements.

3.2.1.1 User Equipment (UE)

It is the user end device which contains UMTS Subscriber Identity Module (USIM) and Mobile Equipment (ME). Both are interconnected with each other by Cu interface. The USIM is a smartcard and it contains the subscriber information, authentication and encryption keys. The ME is used to terminate the radio connection with the network.

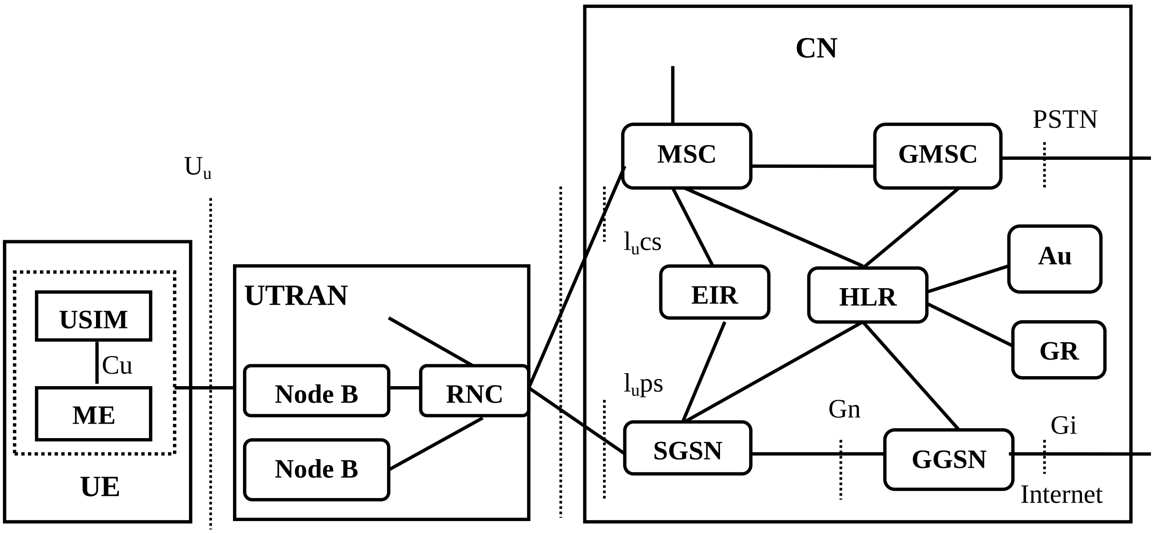


***Figure 3.1**: UMTS network architecture [8]*

3.2.1.2 UMTS Terrestrial Access Network (UTRAN)

The UTRAN is similar like Base Station Subsystem (BSS) in GSM technology. It comprises of two elements: NodeB and the Radio Network Controller (RNC). The UTRAN is connected with the UE via Uu interface for communication.

NodeB: It is a base station responsible for handling the user physical data and signalling between the UE and RNC. It performs the power control and load control mechanism. Channel coding, error handling and modulation and demodulation are other major functions of NodeB.

Radio Network Controller (RNC): It is equivalent to Base Station Controller (BSC) of GSM. It 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 MSC (GMSC). It is interconnect with NodeB via lub interface. Each RNC are interconnected with lur interface.

3.2.1.3 Core Network (CN)

Its performance is similar to the Network Switching Subsystem (NSS) of 2G system. The core network is divided into three different categories according to the data they carried.

- ***Circuit switched elements*****:** It comprise of Mobile Switching Centre (MSC) and Gateway MSC. The primary function of MSC is to route the voice traffic and data traffic as well as other value added services. It is also responsible for end to end connectivity between the users, handling the user mobility and charging. A database known as Visitor Location Register (VLR) is also included in the MSC. This data base stores the information of active users connected to the network. The Gateway MSC forms a gateway to connect UMTS core network with external circuit switch network like PSTN.
- ***Packet switched elements:*** The key elements are Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). The 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 and authentication and billing. The GGSN forms the gateway to connect the GPRS network with external packet switched networks like internet.
- ***Shared elements****:* This section comprises Home Location Register (HLR), Equipment Identity Register (EIR) and Authentication Centre (AuC). The HLR is a data base which contains the information of registered users to the network i.e. 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 data base which stores the cipher text of each user for security purpose. [8]

3.2.2 UMTS Physical, Transport and Logical channels

UMTS channels are classified into three categories: physical, transport and logical channels. [8]

Table 3.1*: UMTS physical channels and their descriptions*

Channels	Descriptions
Common Control Physical Channel (CCPCH)	It broadcast the system information in Broadcast Channel (BCH) and paging information in Paging channel (PCH)
Common Pilot Channel (CPCH)	It is responsible to identify the scrambling code for synchronization between UE and NodeB
Physical Random Access Channel (PRACH)	It is responsible to send random access message for synchronization between UE and NodeB
Physical Downlink Shared Channel (PDSCH)	It is used to share the control information among the UEs within the NodeB coverage

Table 3.1 shows physical channels which are responsible to exchange the information between the user and UMTS Terrestrial Area Network (UTRAN) in UMTS. In UMTS, common control physical channel is classified as Primary CCPCH (P-CCPCH) and Secondary CCPCH (S-CCPCH). Primary common control channel is responsible to carry system information in Broadcast Channel (BCH) and secondary common control channel is responsible to carry paging information in transport Paging Channel (PCH).

Table 3.2*: UMTS transport channels and their descriptions*

Channels	Descriptions
Broadcast Control Channel (BCCH)	This channel is responsible to broadcast the cell information in downlink direction
Paging Control Channel (PCCH)	Its main task is to transmit paging message in downlink direction
Dedicated Control Channel (DCCH)	It is used to carry control information to particular UEs in uplink and downlink direction
Common Control Channel (CCCH)	It transfers control information in both directions
Dedicated Traffic Channel (DTCH)	It a channel used to carry user data in uplink and downlink directions
Common Traffic Channel (CTCH)	It is used to brocast the data to a group of UEs in downlink direction

Table 3.2 shows transport channels that describe the characteristics of the data transferred on the physical layer. The transport layers are interface between physical and MAC layer.

Table 3.3*: UMTS logical channels and their descriptions*

Channels	Descriptions
Synchronization Channel (SCH)	It is responsible for synchronization between the UEs and NodeBs
Dedicated Transport Channel (DCH)	It is responsible to transport the data to the particular UE in both uplink and downlink directions
Broadcast Channel (BCH)	It broadcasts the information necessary to UE to identify the cell and the network
Forward Access Channel (FACH)	It mainly transmits the control data or user data to UE in the downlink direction
Paging Channel (PCH)	It carries paging information to establish the connection with UE in the downlink direction
Random Access Channel (RACH)	It is responsible to carry service request from UEs in uplink direction
Downlink Shared Channel (DCH)	This channel is shared by different UEs to transmit control information or user information in downlink

Table 3.3 presents logical channels which are interface in between Medium Access Control (MAC) layer and Radio Link Control (RLC) layer whereas. Logical channels are mapped into transport channel in the Media Access Control (MAC) layer. They describe what type of data is transferred between the user and the network.

3.3 High Speed Downlink Packet Data Access (HSDPA)

High Speed Packet Access (HSPA) introduced by 3GPP is evolved from WCDMA network to support the high data rate, reduce latency and increased capacity. Initially High Speed Downlink Packet Data Access (HSDPA) was introduced in Release 5 and later on High Speed Uplink Packet Data Access (HSUPA) was introduced in Release 6. HSDPA protocol supports high speed data in the downlink direction.

A new transport channel High Speed Downlink Shared Channel (HS-DSCH) is added to WCDMA for HSDPA for faster downloads in downlink directions. This channel enables to allocate a fraction of radio resources to a specific user for data transmission. HSDPA improves the data rate by a factor of 5 as compare to the WCDMA. Theoretically, it gives the data rate of 8-10 Mbps and even more with Multiple Input Multiple Output (MIMO) technique. This technology can be implemented on 5 MHz channels available for UMTS system. [8] [9]

3.4 LTE Evolution and Upgrade Path

LTE was introduced by 3GPP to overcome the limitations of the previous network technology in terms of system coverage, performance and capacity. This new technology provide high data rates, supports new features like video chatting and multimedia services and serve the existing terminals at the same time in efficient manner. The 3GPP emphasized the key features and performance requirement targets for LTE. [10] [11]

- Higher peak data rate of 100 Mbps for downlink and peak 50 Mbps for uplink in 20 MHz band. It offers downlink data rate of 150 Mbps in downlink using $2*2$ MIMO and 75 Mbps in uplink using $1*2$ antenna configuration for 20MHz channel.
- Significantly improved spectral efficiency, $2 \square 4$ times higher than that of 3GPP Release 6 standards. Peak spectral efficiency is 5 bps/Hz in downlink and 2.5 bps/Hz in uplink is achieved with two receive antennas and one transmit antenna configuration.
- Interoperability with previous 3G or 2G systems and other non-3GPP technologies. It is optimized for low speed $(0 \square 15\, km/h)$ mobile terminals and support high speed $\left(120\, km/h \square 350\, km/h\right)$ mobile terminals or even higher up to $500\, km/h$ depending upon frequency band.
- Provides high quality of service. It has radio access network latency less than 10 ms. 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.
- Bandwidth flexibility allocation with 1.4, 3, 5, 10, 15 and 20 MHz

With growing demand of new technologies to support high data rates and minimum latency with low cost and higher performance, evolution is always needed. These demands are always taken into account during evolution on cellular network for users. LTE is the new emerging technology evolved from 2G and 3G standards like Global System for Mobile Communication (GSM), Universal Mobile Telecommunication System (UMTS) and High Speed Packet Data (HSPA). Figure 3.2 shows the LTE evolution path from its predecessor networks based on release dates.

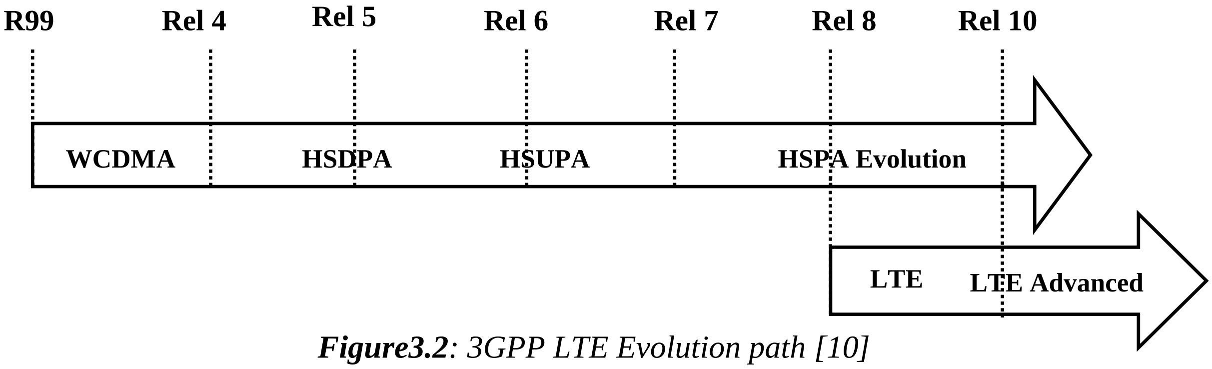


***Figure3.2**: 3GPP LTE Evolution path [10]*

Figure 3.3 shows the LTE upgrade path for 3GPP and Non-3GPP technologies.

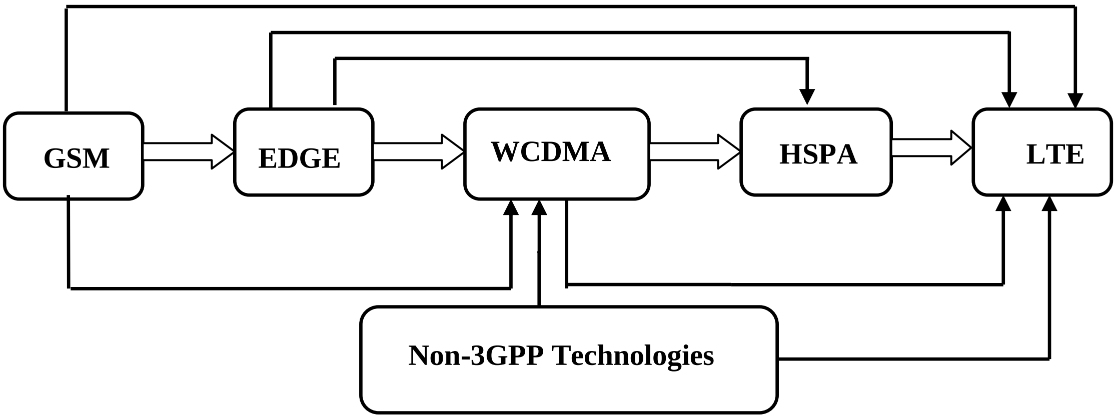


***Figure3.3**: LTE upgrade path for 3GPP and Non-3GPP technologies [8] [10]*

Any 2G and 3G network can be upgraded directly towards LTE by any vendors and operators without following any specific path. This upgrade path helps to reduce cost while adopting new technologies and standards.

3.5 LTE Network Architecture

Figure 3.4 shows the LTE network architecture and the elements associated with it. This architecture is mainly designed to support the IP system. The architecture was made flat to reduce the number of network elements. This helps to increase the system performance. The User Equipment (UE), Evolved Universal Terrestrial Radio Access Network (EUTRAN), Evolved Packet Core (EPC) and Service layer are the major logical elements in LTE which are briefly described below. [11]

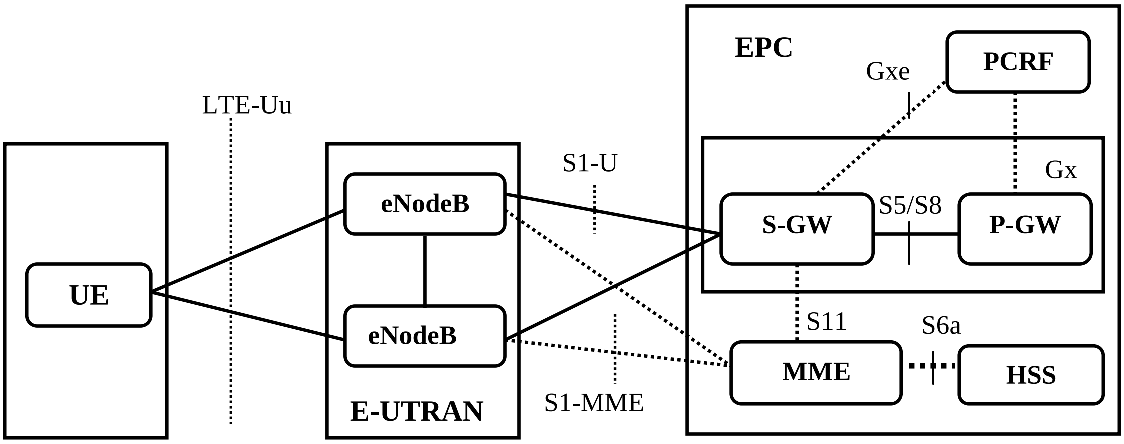


***Figure 3.4**: LTE system architecture [10]*

3.5.1 User Equipment (UE)

User Equipment are hand held devices for user. It may be a smart phone, dongle device or a laptop used to establish, maintain and remove the radio connectivity according to user requirement. Each UE has its own Universal Subscriber Identity Module (USIM) to separate and authenticate from other UEs. They are connected with EUTRAN with LTE-Uu interface. [12]

3.5.2 Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)

The EUTRAN is the evolution from UTRAN network which contains only one node called eNodeB. The NodeB and Radio Network Controller (RNC) are combined to form a single eNodeB to flatten the network architecture in LTE. This reduces the network latency. The eNodeB performs the function of both NodeB and RNC. Each eNodeB are interconnected with each other via X2 interface. The EUTRAN also interconnects MME and SGW with S1-MME interface and S1-U interface respectively. Figure 2.4 also shows the EUTRAN interface with other network elements. These interfaces are standard and defined by 3GPP to facilitate the multi-vendors.

The main functions of EUTRAN are the physical layer processing, Radio Resource Management (RRM) and Mobility Management. It performs power control of the signal, analog-digital-analog conversion of the signal at the air interface, encryption and decryption of user plane data as well as compression of IP header to reduce redundancy. The EUTRAN also manage the radio resources. It indicates the type of modulation used, retransmission of the data, Quality of Service (QoS) management, resource scheduling etc. It receives measurement report of RSRP and RSRQ value from UE for handover decisions.

3.5.3 Evolved Packet Core (EPC)

EPC is the core of the network. The architecture is evolved from the GPRS architecture which is completely based on end to end IP connectivity. The main functions of EPC are to support seamless mobility, QoS and charging functions of IP based networks. The major elements of EPC discussed below.

3.5.3.1 Mobile Management Entity (MME)

MME is a control node in LTE network. It is responsible for mobility management, tracking the location as well as security functions between the UE and the network. It is linked with Home Subscription Server (HSS) via S6a interface for authentication and authorization of the users. It performs activation and deactivation of the radio bearers with Serving Gateway (SGW) connected with S11 interface. The MME also involved in management of Non-access stratum (NAS) signalling security. At the radio interface the NAS forms the apical stratum of the control plane between UE and MME. Its task is to support user mobility and authentication and session management for IP connection between UE and Packet Gateway (PDN- GW). The MME is also responsible for handover performance in between the LTE and previous legacy 3G/2G networks via S3 interface (SGSN to MME). It performs selection of MME and Serving GPRS Support Node (SGSN) for handover change. [10]

3.5.3.2 Serving Gateway (S-GW)

The S-GW is a user plane element for forwarding and receiving the IP packets from UE to P-GW and vice versa. It acts as a local or mobility anchor during handover process. The S-GW switched the user plane path from serving eNodeB to a new eNodeB when MME sends the request depending upon the UE mobility. The IP packets received from the eNodeB are forwarded to the S-GW using GPRS Tunnelling Protocol (GTP). The S-GW receives the IP packets and forward to the Packet Gateway (PDN-GW) using the same GTP. The same thing happens in reverse way. As in case when a UE goes to idle mode all of sudden while receiving the data packets from PGW, the SGW resumes the data flow towards the MME and holds all the incoming packets in its buffer container. Meanwhile it request MME to send a paging message to that idle UE. Once UE in connected mode, the buffer data packets are forwarded towards UE along with the new packets from the PGW. [10]

3.5.3.3 Packet Gateway (P-GW)

The P-GW is the gateway to the external network. The working function is somewhat similar with GPRS Support Node (GGSN) in UMTS system. Internet, IP Multimedia Subsystem (IMS) and other service type networks are the example of external packet data networks. All these packet data networks are identified within the LTE networks by their own Access Point Name (APN). APN is needed when a UE wants the Internet service to be connected. The PDN gateway assigns the temporary address to each connected UE based on IPv4 or IPv6 standard. The PDN-GW can act as an IP anchor as it allows UE to move from eNodeB to eNodeB from serving SGW to another new SGW. It is connected with PCRF via S7 interface. PCRF is responsible to set the quality of service (QoS) for each user whereas PGW enforces the QoS policy. [10]

3.5.3.4 Home Subscription Server (HSS)

The HSS is a database which contains the user information. 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 also stores user subscription state user quality of information. The Authentication Centre (AµC) is integrated with HSS responsible for authentication, ciphering and integration of radio path.

4. LTE RADIO INTERFACE

The 3GPP technologies are designed for smooth inter-working and coexistence. This chapter begins with a brief description about air interface technologies for LTE. It also deals with framing structure and interfaces used in LTE technology. Different physical, logical, control channels and reference signals used in LTE are also explained. A short introduction on different Medium Access Control (MAC) layer and physical layer functions are discussed at the end of this chapter.

4.1 Air Interface Technologies for LTE

LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) channel accessing schemes for downlink and Single Carrier-Frequency Division Multiple Access (SC-FDMA) for uplink purpose. These two schemes provide mutual orthogonality between the users reducing the interference and increasing capacity of the network by utilizing the available spectrum in efficient manner.

4.1.1 OFDMA for Downlink Transmission

In any communication system, different modulation schemes and multiple access techniques are used to increase the system capacity and system performance. Multiple access techniques are used to limit bandwidth and increase number of channels so that it can be shared among users efficiently. In LTE, OFDMA technology is used in downlink direction as it meets all the specification specified in 3GPP.

Orthogonal Frequency Division Multiplex (OFDM) is a type of multicarrier technology which subdivides the available spectral bandwidth into a number of closely spaced narrowband subcarriers. These subcarriers are made mutually orthogonal so they can be overlapped with each other to provide high spectral efficiency and also to mitigate the interference between channels. In order to achieve orthogonality, carrier frequencies are made equal to the reciprocal of the symbol period. For a single carrier sampling instant, the other carriers have zero value at that frequency. Figure 4.2 is a complete block diagram of OFDM transmitter and receiver. [10]

Figure 4.1 shows the orthogonality of subcarriers. OFDM can be used in both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) modes. Quadrature Phase Shifting Keying (QPSK), 16 Quadrature Amplitude modulation (16QAM) and 64 Quadrature Amplitude Modulation (64QAM) are the different modulation types that can be used for OFDM signal. In OFDM each user is allocated with fixed bandwidth for specific time.

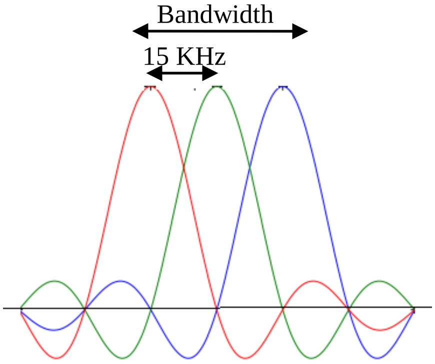


Figure 4.1: Equally spaced OFDM sub-carriers [10]

Orthogonal Frequency Division Multiple Access (OFDMA) use OFDM in which multiple users are allocated to different subcarriers. These subcarriers are created by the Inverse Fast Fourier Transform (IFFT) transformation of the signal at the transmission side. The subcarriers are spaced 15 kHz apart from each other which gives symbol rate 1 / 15 kHz = 66.7 µs. This principle allocates each user by a resource block equivalent to 12 sub-carriers in frequency and 1 Transmission Time Interval (1TTI) corresponds to 1ms in time. A Cyclic Prefix (CP) known as guard interval is added to the transmitted symbols. It is done to remove an ISI caused by multipath components of the transmitted symbols. Figure 4.2 shows the cyclic extension added after the IFFT block. The cyclic extension is nothing but a copied tail part of symbol. It is attached to the beginning of the symbols before transmission to separate the symbols with a time interval to neutralize the delay spread caused by the multipath fading. At the receiver end the cyclic prefix is removed with the FFT operation to extract the correct sent bits. There are two different type of CP: normal with 4.67 µs and extended with 16.67 µs. The extended CP is mainly used for high delay spread environment while normal CP is used for other environment. [10]

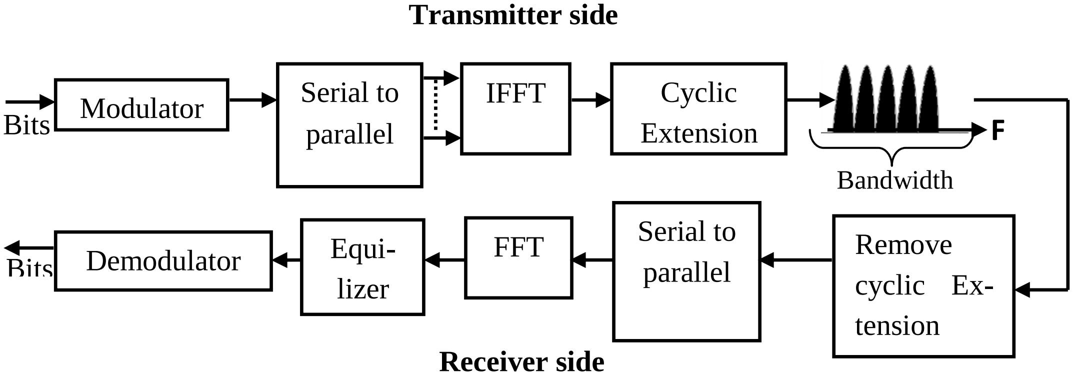


***Figure 4.2**: OFDM transmitter and receiver [10]*

The length of CP is important as it affect on the data rates of any system. Increase in CP increases the timing gap between two frames and this needs extra time to receive the signal form multipath channel. So, higher CP length leads to low data rates. So the duration must be small in comparison with multipath channel duration. Figure 4.3 (a) is an example of subcarrier allocation in OFDMA systems.

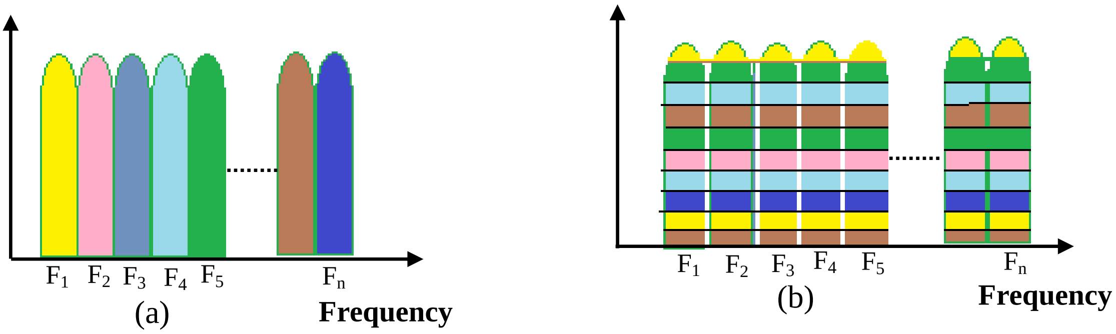


***Figure 4.3**: Sub-carrier allocation: (a) OFDMA and (b) SC-FDMA*

4.1.2 SC-FDMA for Uplink Transmission

Peak-to-Average Power Ratio (PAPR) is a major problem in Orthogonal Frequency Division Multiple Access (OFDMA). It is caused by the interference of the subcarrier signals. Due to interference some of the transmitted signals have peak value larger than the typical one. It leads to the requirement of linear circuits with a large dynamic range otherwise clipping of the signals take place which results in distortion, out of band radiation of the transmitted signal and low efficiency. Therefore, in uplink transmission OFDMA is not used because of high PAPR value. Due to high PAPR, RF power amplifier within a mobile is unable to perform efficiently. So a high linear RF power is required. This decreased the battery life. So, another type of multiple access scheme called Single Carrier- Frequency Division Multiple Access (SC-FDMA) is introduced in uplink transmission which keeps the advantage of Orthogonal Frequency Division Multiplexing (OFDM) as multicarrier transmission and high utilization of bandwidth. It has low PAPR value as well. [10] [11]

SC-FDMA utilizes the single carrier modulation scheme. It is also known as OFDM system with a Discrete Fourier Transform (DFT) mapped because frequency domain symbols are generated using DFT. Thus generated symbols are mapped to available subcarriers by sub-carrier mapping techniques and after that Inverse Fast Fourier transform (IFFT) is performed as like in OFDMA. There are two types of sub carrier mapping: localized and distributed. In localized mapping modulated symbols are assigned to adjacent subcarrier whereas in distributed mapping modulated symbols are equally spaced over the entire bandwidth.

Figure 4.4 shows the block diagram of SC-FDMA transmitter and receiver. In OFDMA each subcarrier carries the information of one specific transmitted symbol whereas in SC-FDMA each sub-carrier carries the information of all transmitted symbols. Symbols in SC-FDMA are transmitted in serial manner. The arrangement of subcarriers in SC-FDMA technology is shown in above Figure 4.3(b).

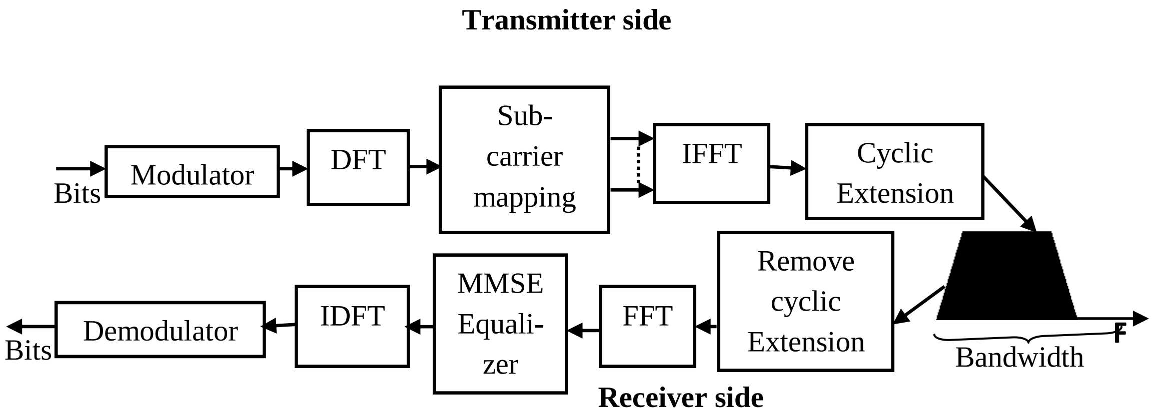


***Figure 4.4**: Block diagram of SC-FDMA transmitter and receiver [10]*

4.1.3 Multiple Antenna Technology

The received signal level from transmitter is always affected by the natural obstacles or manmade obstacles present in the environment. Obstacles like buildings, trees, mountains cause fading due to the multipath or shadow effect from it. Diversity technique can overcome fading problem. Diversity technique produces uncorrelated radio channels between the transmitter and receiver. Figure 4.5 shows different types of diversity techniques like Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO) available in the wireless communication.

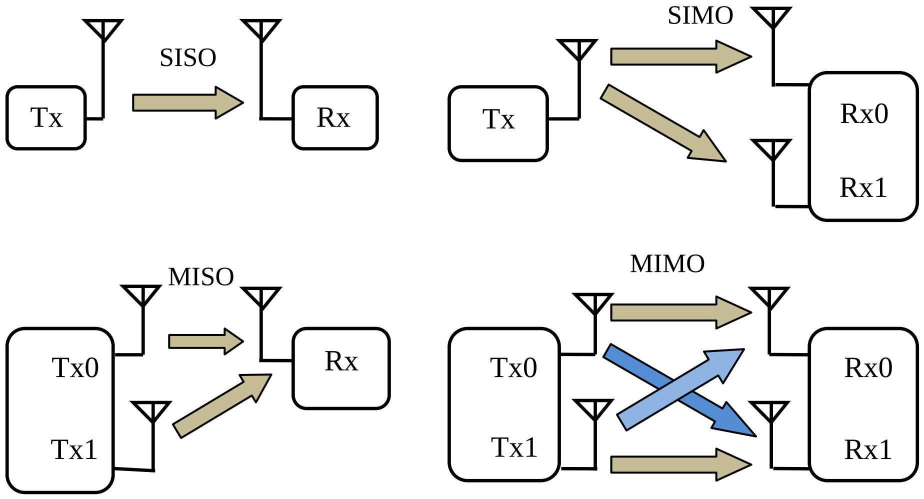


***Figure 4.5**: Diversity techniques [13]*

The LTE network studied during thesis did not use MIMO technology. So this topic is not discussed in detail.

4.2 LTE Framing Structure

LTE supports both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) modes. LTE with different signal bandwidths have different number of resource blocks. There are two different types of frame structure: Type 1 for LTE FDD and Type 2 for LTE TDD. The frame structure for uplink and downlink is same in LTE. In LTE time interval, T_s is calculated by

$$T_s = \frac{1}{(subcarrierBW \times FFTsize)} \tag{4.1}$$

where T_s is also known as basic time unit. With sub-carrier bandwidth 15 kHz and Fast Fourier Transform (FFT) size 2048; the time interval value will be equal to $32.6ns$.

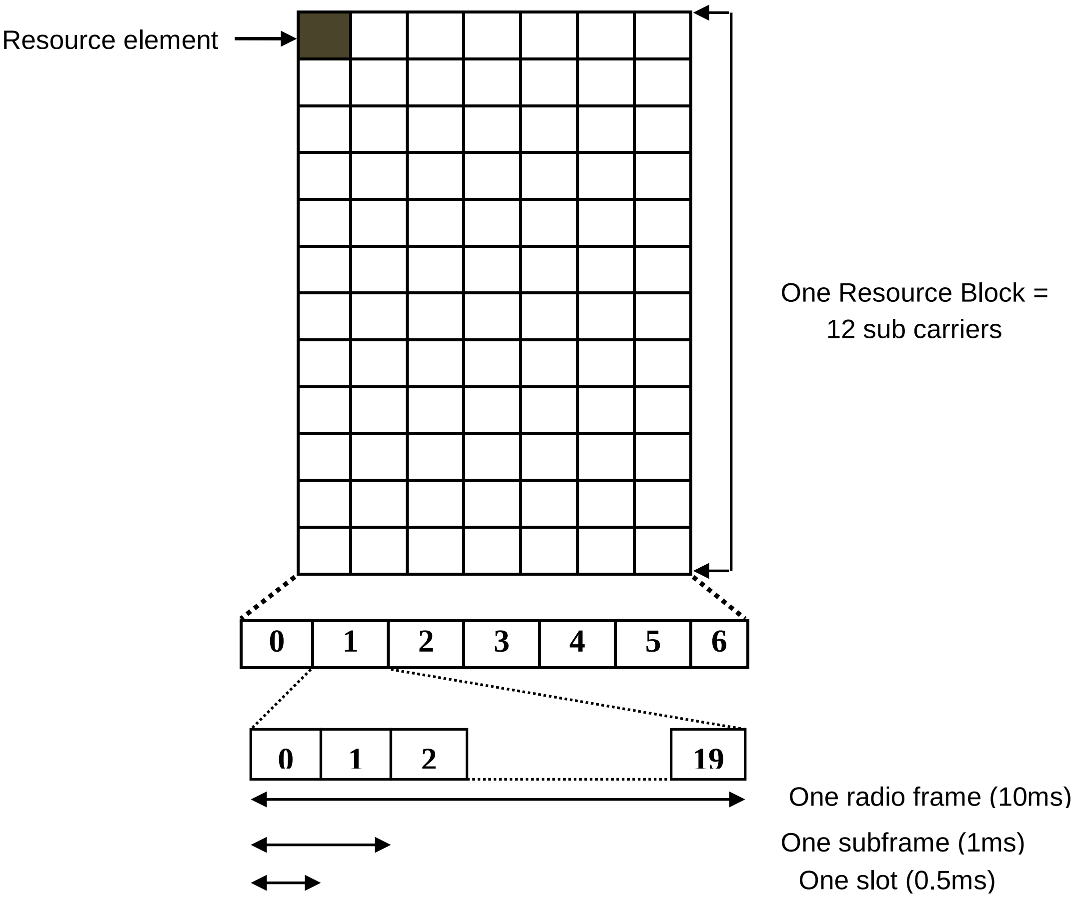


***Figure 4.6**: LTE frame structure Type1*

Length of each radio frame in LTE is given by:

$$T_f = 307200 \times T_s = 10\ ms \tag{4.2}$$

where T_s is the time interval.

Figure 4.6 shows the frame timing structure for Type 1. Each radio frame is divided into 10 equal sub frames with a size of 1ms and each sub frame is divided into 2 equal slots with length 0.5ms. A single frame contains 20 Physical Resource Blocks (PRBs). A PRB consists of 12 sub-carriers. Each carrier is modulated using 6 symbols for extended cyclic prefix and using 7 symbols for normal cyclic prefix. [14]

***Table 4.1**: Bandwidth corresponds with resource blocks [14]*

B.W (MHz)	1.4	3	5	10	15	20
No. Of RBs	6	15	25	50	75	100

Table 4.1 represents the LTE transmission bandwidth and its corresponding number of resource blocks. The LTE has a carrier frequency of 15 kHz and resource block bandwidth of 180 kHz. LTE has bandwidth flexibility from 1.4 to 20 MHz For each channel bandwidth the carrier spacing is fixed. So, number of resource blocks varies according to the channel bandwidth. The maximum number of resources available is 100 for 20 MHz while for 1.4 MHz it is 6 resource blocks.

4.3 LTE Interface and Protocols

Interface defines the physical and logical connection between two different systems in which information is passed through. On the other, protocols are set of rules and requirement to connect and transmit the data between two different systems.

In LTE two types of protocols are classified according their functions: user plane protocol and control plane protocol. The user plane protocol function is to transfer application data and control plane to transfer signalling message. Figure 4.7 shows the EUTRAN layer classification in user plane and control plane.

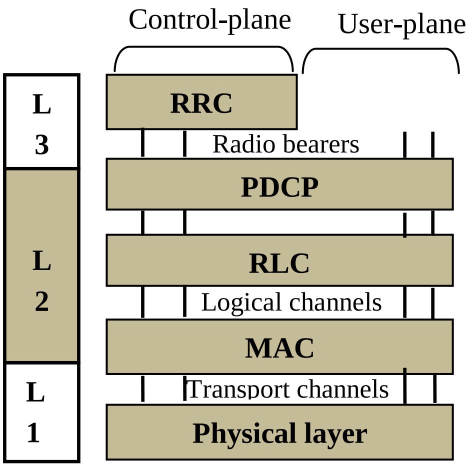


***Figure 4.7**: EUTRAN layer hierarchy and protocols [10]*

Figure 4.8 shows the protocol stack in user plane. The LTE-Uu denotes the interface between the UE and eNodeB. The eNodeB are connected with Serving Gateway (SGW) by S1-U and with Packet Gateway (PGW) by S5/S8 interface. Data packets are tunnelled using GPRS Tunnelling Protocol (GTP) across the S1 and S5/S8 interface. The eNodeB, SGW and PGW are responsible for transferring the application data from application server to users. The function of each protocol in LTE-Uu is explained below.

- ***Layer 1 (L1)***: It is a physical layer defines a transmission medium for high layers. It is the interface between UE and eNodeB. The primary function of this layer is to care of modulation and demodulation of physical information, time and frequency synchronization, power control and cell selection/reselection. The detail description of physical channels and signals is given in Section 4.4.
- ***Medium Access Control (MAC):*** It provides the logical channel to Radio Link Control (RLC) layer. It performs error correction by Hybrid Automatic Repeat Request (HARQ) technique. It also does priority handling between UE by dynamic scheduling and multiplexing/demultiplexing. This layer is present in UE and eNodeB.

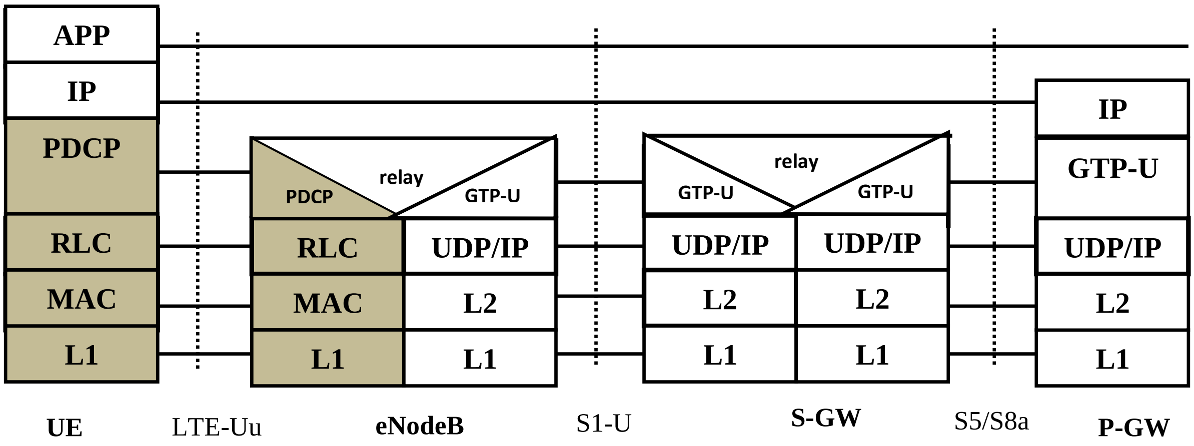


Figure 4.8*: User plane protocol stack [15]*

- ***Radio Link Control (RLC):*** This layer transport Protocol Data Units (PDU) of Packet Data Convergence Protocol (PDCP) layer. The main functions of RLC are segmentation and concatenation of PDUs, error detection and recovery of protocol and duplicate detection of Unacknowledged Mode (UM) and Acknowledge Mode (AM) data. This layer is also present in UE and eNodeB.
- ***Packet Data Convergence Protocol (PDCP):*** This protocol transfers the user plane or control plane data and maintains the sequence number of PDCP. Compression and Decompression of IP header, ciphering and deciphering of user plane and control plane data, retransmission of PDCP SDUs during handover are the major function of PDCP. Both UE and eNodeB contains this protocol.
- ***Internet Protocol (IP):*** It routes the user plane data across packet switched network. IP routers are used to forward the packets in right direction. Each user is assigned with IP address by PDN gateway during data transfer.
- ***Application layer***: These are present on both the UE and the application server. Below this layer there are either Transmission Control Protocol (TCP) layers or Universal Datagram Protocol (UDP) layers. Hypertext Transfer Protocol

(HTTP), File Transfer Protocol (FTP) and Simple Mail Transfer Protocol (SMPT) are examples of application layers that use TCP or UDP to transmit or receive data.

Figure 4.9 shows the control plane protocol stack. The Mobile Management Entity (MME) within Evolved Packet Core (EPC) is responsible to transfer the control message. The function of control plane protocols is explained below.

- ***Radio Resource Control (RRC):*** This protocol handles the Layer 3 (L3) signalling between UE and eNodeB and broadcast system information. It establishes and reconfigures radio bearers and performs paging and mobility procedures functions. This layer resides on both UE and eNodeB.
- ***Stream Control Transmission Protocol (SCTP):*** It is a transport layer protocol defined by IETF which transfer the user data and signalling 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 signalling between eNodeB and MME. It is responsible for location reporting and NAS signalling functions.
- ***Non-Access-Stratum (NAS)***: It is responsible for handling session management procedure for IP connectivity between UE and Packet Data Network Gateway (PDN GW). It also supports UE mobility and Evolved Packet System (EPS) bearer management.

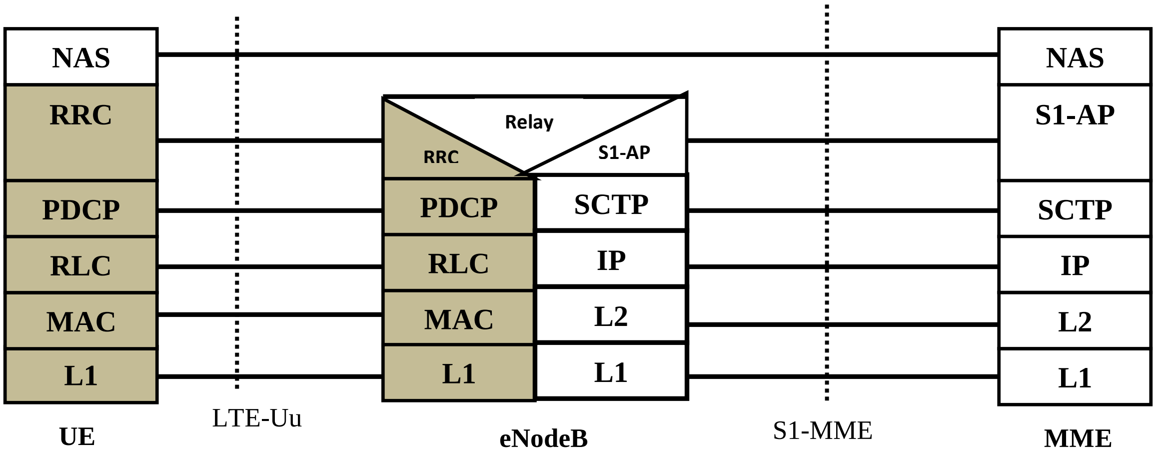


Figure 4.9*: Control plane protocol stack [15]*

4.4 LTE Physical, Transport and Logical Channels

Different channels are needed to transport the data across the radio interface. LTE classified data channels into three different categories based on the information to be sent. They are physical channels, transport channel and logical channels. [15] [16]

4.4.1 Physical channels and signals

Physical channels are responsible to carry physical data and control data from higher layer. They are classified into downlink physical channels and uplink physical channels.

Physical Broadcast channel (PBCH): It is downlink physical channel responsible to broadcast the Master Information Block (MIB) to access the network. MIB contains system bandwidth, Hybrid Automatic Repeat Request (HARQ) indicator and framing number. It is allocated with central 72 subcarriers or 8 central Resource Blocks independent of the channel bandwidth. It uses Quadrature Phase Shift Keying (QPSK) for modulation and Space Frequency Block Code (SFBC) technique for multiple antenna schemes.

Physical Control Indicator Channel (PCFICH): It is also a downlink physical channel responsible to inform the UE about the number of Orthogonal Frequency Division Multiplexing (OFDM) symbols used for Physical Downlink Control Channel (PDCCH) transmission. It uses 16 resource elements of the first OFDM symbol and use QPSK modulation scheme.

Physical Hybrid ARQ Indicator Channel (PHICH): A downlink channel which acknowledge the UE whether eNodeB has been successfully receiving the Transport Block. It uses the HARQ indicator which is 1 bit long '1' for Non acknowledgement (NACK) and '0' for Acknowledgement (ACK). It uses Binary Phase Shift Keying (BPSK) technique for modulation.

Physical Downlink Control Channel (PDCCH): It transfers Downlink Control Information (DCE). The DCE contains UE resource assigning information in it. Large number of PDCCH can be transmitted with Control Channel Element (CCE). Each CCE contains the 9 quadruplets of resource element. Each quadruplet is termed as Resource Element Groups (REG). It uses QPSK modulation technique.

Physical Downlink Shared Channel (PDSCH): It is responsible to carry user data and control data. It carries the user data in Transport Blocks (TB) form which is similar to Medium Access Control Protocol Data Unit (MAC PDU). To transport each block from MAC layer to Physical layer it takes 1 Transmission Time Interval (TTI) which corresponds to 1ms.It uses QPSK, 16 Quadrature Amplitude Modulation (QAM) or 64 QAM for PDSCH modulation.

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. It contains six Resource Blocks or 72 sub-carriers. A random preamble includes a cyclic prefix, a sequence and a guard interval.

Physical Uplink Control Channel (PUCCH): It is used to transfer Uplink Control Information (UCI). Control message like Hybrid ACK/NACK, Channel Quality Indicator (CQI), Rank Indicator (RI), Precoding Matrix Indicator (PMI) are present in PUCCH channel. It reserves 2 Resource Blocks and use BPSK and QPSK to modulate PUCCH information.

Physical Uplink Shared Channel (PUSCH): It is responsible to transfer user data and contains the information of Signalling Radio Bearers (SRB) for RRC signalling. It uses QPSK, 16QAM or 64 QAM for modulation. The eNodeB uses link adaptation algorithm for modulation selection.

4.4.1.1 Downlink Physical Signals

Downlink Reference Signals: These signals consist of reference symbols that are used for channel estimation to perform coherent demodulation at the UE side. Three different types of downlink reference signals are available in LTE. [16]

- *Cell specific downlink reference signals:* The primary function of these signals is to estimate the channel characteristics at a given location within a subframe. They are transmitted in every first and fifth OFDM symbol of a slot. They are transmitted in every antenna port and are unique in nature.
- *Multimedia Broadcast Single Frequency Network (MBSFN) reference signals:* They estimate the channel characteristics that use MBSFN channel. The transmitted signals are received by many UEs. These signals may carry timing information, climate information and calendar information in a cell.
- *User specific reference signals:* These signals are transmitted only on the Physical Downlink Shared Channel (PDSCH) mapped Resource Blocks (RBs). They carry user specific information to one unique direction.

Downlink Synchronization Signals: These signals are responsible to make cell search and identify cell groups for all detected UEs. They always occupy 62 sub carriers of the channels.

4.4.1.2 Uplink Physical Signals

Demodulation Reference Signals (DRS): They are used for channel estimation and correct data modulation. They are transmitted over entire allocated bandwidth that occupies a specific single FDMA symbol.

Sounding Reference Signals (SRS): They are used by the base station to estimate the quality of the uplink channel that can be used to optimize uplink scheduling process. The eNodeB is free to configure bandwidth occupied by SRS and power levels.

4.4.2 Transport Channels

Transport channels forms the interface between the physical layer and Medium Access Control (MAC) layer. They are responsible to transfer information to MAC layer and high layer. These channels act as Service Access Point (SAP) for higher layers. Table 4.2 shows different types of transport channel available in LTE.

***Table 4.2**: Transport channels and their functions*

Channels	*Functions*
Broadcast Channel (BCH)	They broadcast the parameters required to access the system in the cell coverage area
Downlink Shared Channel (DLSCH)	They are responsible for downlink data transfer
Paging Channel (PCH)	To broadcast paging information
Uplink Shared Channel (USCH)	It is responsible for uplink data transfer
Radom Access Channel (RACH)	It is used to send random access procedure to establish the connection with eNodeB in uplink.

The UE acquires the System Information Block (SIB) from BCH. It contains information for cell selection/reselection and to make inter-frequency, intra-frequency and inter-RAT handover decisions. DSCH channel also supports Hybrid Automatic Repeat Request (HARQ), link adaptation algorithm as well as resource allocation procedure.

4.4.3 Logical Channels

Logical channels are the interface between the MAC layer and the Radio Link Control (RLC) layer.

***Table 4.3**: Logical channels and their functions*

Channels	*Function*
Broadcast Control Channel (BCCH)	It is responsible for broadcasting the system information to UEs.
Paging Control channel (PCCH)	It mainly focuses on paging.
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.

Table 4.3 presents the different logical channels along with their functions. These channels are mapped from transport channels to transfer the user plane and control plane information offered by MAC layer. It contains control channel and traffic channel. Control channel are responsible for control plane information whereas traffic channel sent data information.

4.5 Scheduling

Scheduling is the process of assigning the system resources among users at each time instant. This is done to utilize the available radio resource in efficient manner. System resources are defined by frequency and time units. The scheduler present in the eNodeB controls the scheduling process. They determine the user to whom resources should be allocated at each Transmission Time Interval (TTI), 1ms from available resources. Three different types of scheduling algorithm are available. [10] [16]

- ***Round Robin Scheduling***: This algorithm treats all the users equally and assigns the same proportion of radio resources. This algorithm is independent of channel quality conditions so leads towards low system throughput.
- ***Maximum C/I Scheduling***: This algorithm assigns the radio resources to uses with best channel quality. This process is channel dependent and is favourable only to users with good channel conditions. Users with bad channel quality at the cell edge may not get the radio resource with this scheduling process which leads towards low system throughput. Mathematically,

  $$K = \arg\max(i) R_i \tag{4.3}$$

  where K is a scheduling user and R_i is the instantaneous data rate for user i.
- ***Proportional fair Scheduling (PFS):*** This algorithm provides proportional fair as it allocates more resources to users with relatively better channel. This means it schedule the user whose instantaneous channel quality is higher than its average radio channel condition over time. Mathematically,

  $$K = \arg\max(i) \frac{R_i}{R'_i} \tag{4.4}$$

  where K is the selected user at each time instant. R_i is the instantaneous data rate and R'_i is the average data rate for user i.

4.6 Link Adaptation

It is an important feature in LTE that has an ability to adapt the different modulation scheme and coding rate according to the quality of the radio link for each user. It is included in LTE physical shared channels in downlink and uplink. This is based on Adaptive Modulation and Coding (AMC) technique. This technique provides flexibility to match the modulation and coding rate with received channel quality. The user near to the base station is assigned with high order modulation and high coding rate.

4.7 HARQ

Hybrid Automatic Repeat Request (HARQ) process allows reliable data transmission across the channel. It facilitates to retransmit data from the source if erroneous data is collected at the receiver. It is based on stop-and-wait HARQ procedure and is the combination of forward error correction and automatic repeat request. LTE utilize physical channels (physical downlink shared channel (PDSCH) and physical uplink shared channel (PUSCH)) and control channels (physical downlink common control channel (PDCCH), physical uplink common control channel (PUCCH) and physical hybrid indicator channel (PHICH)) for HARQ procedure.

If error is detected in received data packets from PDSCH, a UE can request for retransmission of the same data by sending a Negative Acknowledgement (NACK). After that an Acknowledgement (ACK) is sent by receiver to indicate data packet is successfully received. This ACK/NACK information is sent in PDCCH for downlink or PUCCH for uplink. In LTE 8 HARQ process can be used. HARQ schemes are classified into synchronous and asynchronous. In *synchronous HARQ* scheme, retransmission of data takes place at predefined time relative to the initial transmission and in *asynchronous HARQ* scheme, retransmission can happen at any time. [16]

4.8 Power Control

Power control is required to achieve high system performance. In LTE only uplink power control for Physical Uplink Shared Channel (PUSCH) is defined. Uplink power control is necessary to improve system capacity, network coverage, improved quality of services, minimizes inter/intra cell interference and increased battery life. This mechanism is based on the estimation of path loss, interference, shadowing and fast fading. LTE deploys closed loop and open loop power control mechanism. Open loop power control provides a basic operating point for UE transmit power. In closed loop mechanism the eNodeB adjust the transmission power of the UE by sending Transmit Power Control (TPC) command based on Signal to Interference Noise Ratio (SINR) measurements. The receiver sends increase or decrease the transmission power based on the measurement via TPC command.

4.9 RRM Functions

Radio Resource Management (RRM) checks and manage the radio resource. It uses different available adaptive techniques to serve the users according to their quality of service configurations. Following are the RRM functions. [10][11]

- ***Radio Bearer control (RBC):*** It mainly concerns with the establishment, configuration, maintenance and release of radio bearers. It set up a new radio bearer for a service based on available resource and Quality of Service (QoS). It performs maintenance function during radio resource change in mobility situations and release function during session termination. This is present in eNodeB.
- ***Radio Admission Control (RAC):*** The eNodeB uses admission control to decide the request of Evolved Packet System (EPS) bearers in the cell. The eNodeB makes the decision based on the available resource, QoS requirement and priori-

ty levels. It ensures high utilization of the radio resource available for a new bearer to establish only the estimated QoS is fulfilled.

- ***Connection Mobility Control (CMC):*** The eNodeB manage the radio resource during idle and connected mode mobility using CMC. In idle mode cell selection process are controlled by the threshold and hysteresis value to select the best cell while in connected mode handover decisions are made based on UE and eNodeB measurement parameters.
- ***Dynamic Resource Allocation (DRA) & Packet Scheduling (PS):*** The eNodeB allocate and de-allocate the resource to user plane and control plane packets using DRA or PS. It allocates the available resource to the schedule packets by selecting radio bearers. Generally it takes QoS requirement, channel quality information, buffer status and interference situations to make decisions.
- ***Inter-cell Interference Coordination (ICIC):*** The eNodeB use this mechanism to manage radio resource by controlling inter-cell interference. It takes resource usage status and traffic load information from multiple cells to make decisions.

5. MOBILITY IN LTE

Mobility is important aspect in cellular networks. It enables both end users and nomadic users a seamless connection for voice and data service anywhere within the coverage area. During mobility the network performance has to be reliable and maintain quality without experiencing any interrupt in the service.

In the beginning of this chapter cell selection/reselection criterion in idle conditions is explained. It also contains the description about system information and different handover types in LTE. Inter-RAT handovers are explained briefly with examples and signal flow diagrams. Different events and triggering conditions are also explained in this chapter. A short introduction on Voice over LTE (VoLTE) and Single Radio Voice Call Continuity (SRVCC) is also given at the end of this chapter.

5.1 EPS Mobility and Connection Management

Evolved Packet System (EPS) Mobility Management (EMM) identifies and maintains the connectivity between users and different EPS networks. EPS and EPS Connection Management (ECM) are the two Non-Access-Stratum (NAS) protocols between the UE and Mobility management Entity (MME) responsible for mobility and session management procedures.

5.1.1 EPS Connection Management (ECM)

ECM describes the logical connection between the UE and EPC. An EPS connection procedure is necessary to start the signalling with EPC. Figure 5.1 shows two states of ECM: ECM-IDLE and ECM-CONNECTED.

- ***ECM-IDLE***: It is the state when there is no any signalling connection between the UE and EPC. In this state, a UE performs PLMN search and cell selection/reselection process.
- ***ECM-CONNECTED***: There is a signalling connection between the UE and EPC in this state. The location of the UE connected to serving eNodeB is known. The mobility of UE is controlled by the handover procedure. The tracking area is updated in this state. UE monitors the control channels and provides channel quality feedback.

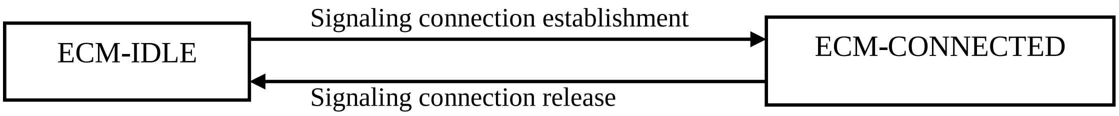


Figure 5.1: *EPS Connection Management States [17]*

5.1.2 EPS Mobility Management (EMM)

EMM is responsible for mobility management. The EPS connection procedure starts with the ATTACH REQUEST EMM message. Figure 5.2 shows two different states of EMM which is termed as EMM-REGISTERED and EMM-DEREGISTERED.

- ***EMM-DEREGISTERED***: In this state MME is unable to reach the UE due to the lack of tracking area.
- ***EMM-REGISTERED***: EMM is registered with an ATTACH procedure. Once registered it holds the location information and routing area information by a successful Tracking Area Update (TAU) procedure for a UE. A default EPS bearer is activated in the Mobility Management Entity (MME).

UE registers to MME successfully with the ATTACH procedure or with the TAU procedure.

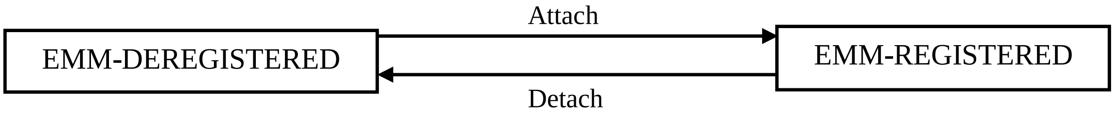


Figure 5.2: *EPS mobility Management States [17]*

Transition from EMM-REGISTERED to EMM-DEREGISTERED occurs when the DETACH procedure form EMM-REGISTERED state is successful. Tracking area update rejection, service request rejection, and EPS bearer's deactivations leads to EMM-DEREGISTERED state.

5.2 Mobility Management in Idle Mode

UE conditional state is determined by mobility in cellular networks. The UE device goes to detach state after it is switch on. After registration to the system network it change to the active state. If the UE has no any activity for some moments it changes its state from active state to idle state and remains in the same state until it has some activity to be performed. When the device is switched off deregistration with the system takes place and get detached. Figure 5.3 shows three mobility states which are detached state, active state, and idle state. [12] [18]

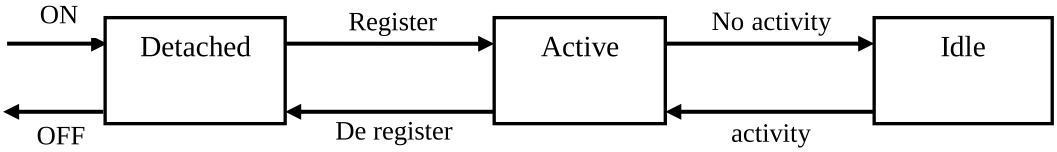


Figure 5.3: *LTE mobility states*

5.2.1 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 are inter connect with each other by transmission links. UE can select PLMN manually or automatically. UE scans all RF channels in EUTRAN bands to find available PLMNs. Once PLMN is selected by NAS it searches for strongest cell based on the radio measurements and read its system information. After PLMN selection, the UE starts the cell selection procedure.

5.2.2 Cell Selection

The UE receives cell information from the broadcast channels. UE camps on the suitable cell if that cell is not barred and has good radio conditions. This is cell selection process.

Cell selection can be:

- *Initial cell selection*: Without using the previous stored information, UE scans all the EUTRAN frequency bands to determine the best cell to camp on it.
- *Stored information cell selection*: UE uses the previous stored data to select a best suitable cell. Stored data contains cell parameters and carrier information of the previous measurement of that cell.
- *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.

Each cell should satisfy the S-criteria (Selection-criteria) for UE to camp on it.

S-criteria states that:

$$S_{rxlev} > 0 \tag{5.1}$$

where S_{rxlev} is received signal level of the UE is expressed in decibel (dB) and is calculated from

$$S_{rxlev} = Q_{rxlevmeas} - (Q_{rxlev\min} - Q_{rxlev\min offset}) - P_{compensation} \tag{5.2}$$

In Equation 4.2, $Q_{rxlevmeas}$ is the measured Reference Signal Received Power (RSRP) value by UE in dBm. $Q_{rxlev\min}$ is the minimum required RSRP value required value to camp on a cell. This is expresses in dBm. This parameter is signalled in System Information Block 1(SIB1) message. $Q_{rxlev\min offset}$ is the offset value for Public Land Mobile Network (PLMN) search. It is also included in SIB1 message. If not present, a value of 0dB is applied. $P_{compensation}$ is the power compensation expressed in dB and is given by:

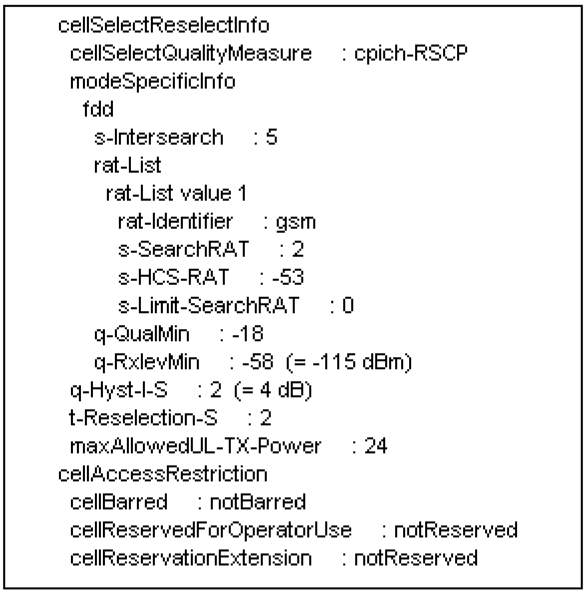
$$P_{compensation} = \max(P_{EMAX} - P_{UMAX}, 0) \tag{5.3}$$

where P_{EMAX} is the maximum allowed uplinks transmit power level within the cell and P_{UMAX} *is the* maximum transmit power capability of the UE. Both are expressed in dBm.

When the UE moves from one place to another, cell with the strongest signal per carrier is selected. It always performs the periodic updates of the neighbouring detected cells in accordance to the signal strength. If it finds the neighbouring cell stronger it tries to camp on it which will become a new serving cell to it. This process is called cell reselection. To have reduced number of 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 signal level value exceeds the threshold. This helps to reduce the battery power of the mobile device. The threshold is defined for inter-frequency and intra-frequency. The intra-frequency measurement criterion is satisfied if: [19] [20]

$$S_{servingcell} \le S_{intrasearch} \tag{5.4}$$

where $S_{servingcell}$ is S_{rxlev} of the serving cell and is expressed in dB. $S_{intrasearch}$ controls the UE to make measurement of intra-frequency cells for camping or not. If the quality of the serving cell is better than $S_{intrasearch}$, the UE does not need to measure other neighbour cell during camping. It is present in SIB3 and is expressed in dB. Figure 5.4 is an example of cell selection and reselection captured in idle conditions.



```
cellSelectReselectInfo
  cellSelectQualityMeasure    : cpich-RSCP
  modeSpecificInfo
    fdd
      s-Intersearch    : 5
      rat-List
        rat-List value 1
          rat-Identifier    : gsm
          s-SearchRAT    : 2
          s-HCS-RAT    : -53
          s-Limit-SearchRAT    : 0
      q-QualMin    : -18
      q-RxlevMin    : -58  (= -115 dBm)
  q-Hyst-l-S    : 2  (= 4 dB)
  t-Reselection-S    : 2
  maxAllowedUL-TX-Power    : 24
cellAccessRestriction
  cellBarred    : notBarred
  cellReservedForOperatorUse    : notReserved
  cellReservationExtension    : notReserved
```

Figure 5.4*: Cell selection and reselection log seen by the mobile*

5.2.3 Cell Re-selection

Cell re-selection process selects a suitable new serving cell for UE. UE camps to a new cell once it satisfies the reselection criteria.

5.2.3.1 Intra-Frequency Cell Reselection Criteria

Rank criteria (R-criteria) must be fulfilled as well in case of intra-frequency cell reselection. According to this criterion, a neighbour cell which is ranked higher than the current serving cell during the time period defined by the $T_{reselection}$, then the neighbour cell will now be the serving cell. The ranking is done according to the radio measurement data. According to the R-criteria neighbour cell is selected when $R_n > R_s$ is satisfied.

R_s And R_n are the rank of the serving cell and neighbouring cell respectively. The rank of the serving cell, R_s is evaluated from:

$$R_s = Q_{meas,s} + Q_{Hyst} \tag{5.5}$$

where $Q_{meas,s}$ is the measured RSRP value of the serving cell and Q_{Hyst} is the power domain hysteresis. Similarly, the rank of the neighbouring cell, R_n is calculated by

$$R_n = Q_{meas,n} + Q_{offset} \tag{5.6}$$

where $Q_{meas,n}$ is the measured RSRP of the neighbouring cell and Q_{offset} is an offset value to control different frequency specific characteristics or cell specific characteristics.

Figure 5.5 shows the cell reselection procedure in idle mode. Threshold is the deciding factor. When the serving cell signal strength falls below threshold $S_{\text{int}rasearch}$, the UE starts to measure the signal strength of the neighbour cells according to the ranking criteria. Rank of any cell determines the best possible cell for UE to camp on it. When the signal strength of the neighbour cell exceeds the serving cell by Q_{Hyst}, for $T_{reselection}$ time period, neighbour cell is selected as a new serving cell. [8]

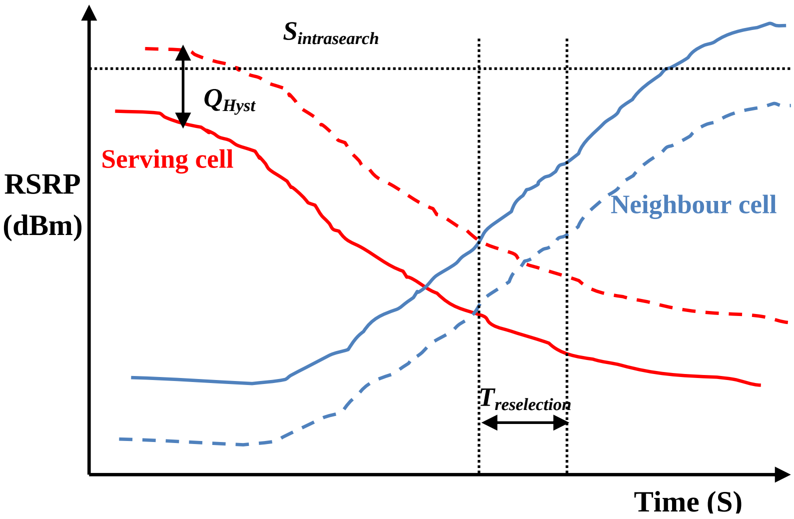


***Figure 5.5**: Cell reselection in idle state*

5.2.3.2 Inter-RAT Cell Reselection Criteria towards 3G

The UE in LTE cell should satisfy the measurement criteria and reselection criteria to perform inter-RAT cell reselection towards 3G cell.

Measurement criteria:

$$S_{servingcell} \leq S_{non\,\text{int}rasearch} \tag{5.7}$$

where $S_{servingcell}$ is S_{rxlev} of the serving LTE cell. $S_{non\,\text{int}rasearch}$ is the controlling parameter for inter-frequency measurement for cell reselection process. It is expressed in dB.

Reselection criteria:

$$S_{nonservingcell} > ThresXLow \tag{5.8}$$

where $S_{nonservingcell}$ is S_{rxlev} of the non serving 3G cell. $ThresXLow$ is the threshold used by UE in reselection process.

5.2.3.3 Inter-RAT Cell Reselection Criteria towards LTE

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

Measurement criteria:

$$S_x \leq S_{searchRATm} \tag{5.9}$$

where S_x can be cell selection received level value, S_{rxlev} for TDD cells or can be cell selection quality value denoted by S_{qual} for FDD cells. $S_{searchRATm}$ is the measurement threshold for UE to trigger inter-RAT cell reselection.

Reselection criteria:

$$S_{nonservingcell} > ThresXLow \tag{5.10}$$

where $S_{nonservingcell}$ is S_{rxlev} of the non serving cell. $ThresXLow$ is the threshold used by UE in reselection process. [12]

5.2.4 Example of inter-RAT cell selection and reselection

Figure 5.6 shows cell selection and reselection process in idle mode. The cell reselections are separated by the red color vertical lines. The left side of the y-axis is for RSRP level and it is denoted by blue color while right side of the y-axis is for RSCP level represented by red color. The figure indicates two cell reselection processes, one from LTE cell to the 3G cell and another is from 3G cells towards the LTE cell. First cell reselection happens when RSRP level dropped to -112 dBm. The next cell reselection towards the LTE cell happens when RSCP level dropped to -128 dBm. The RSRP level measured at this point is -110 dBm.

The RSRP value becomes worse as the UE moves towards the LTE cell edge. The cell reselection from LTE to 3G is triggered because RSCP value from the neighbouring 3G cell is satisfactory enough and satisfies the cell selection and reselection criteria. After reselection, the UE is camped to the 3G cell. This is the first reselection point. Similarly, the second reselection is triggered because the RSCP level is dissatisfactory as compared to the RSRP. After that the UE is camped in the LTE cell.

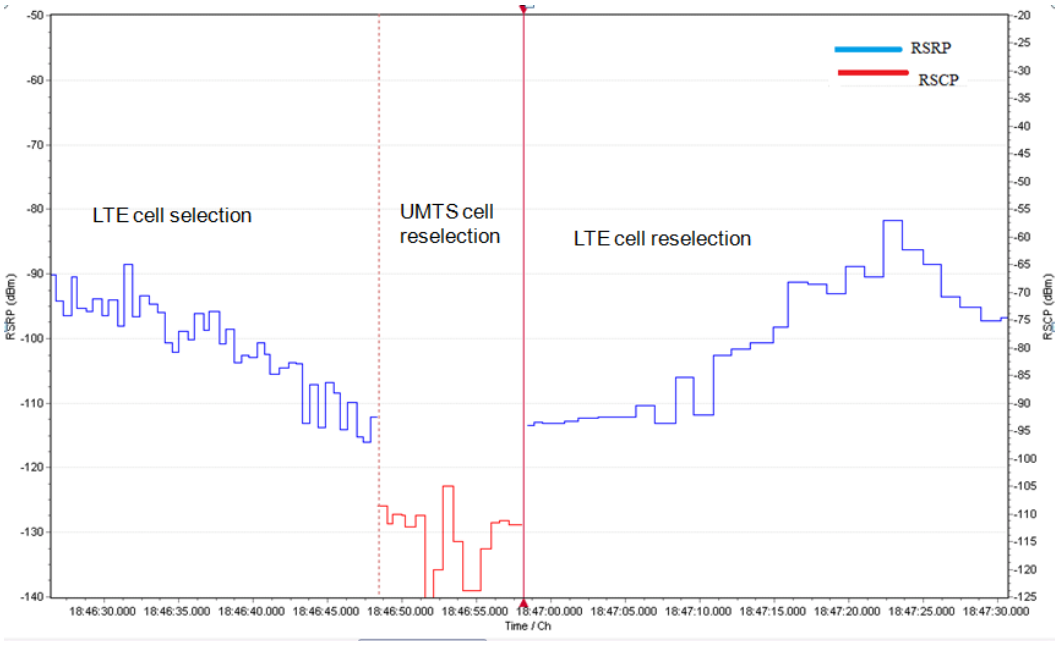


***Figure 5.6**: Cell selection and reselection process in idle mobility*

A cell selection criterion (S-criteria) decides if the cell is suitable or not. Therefore this criterion is fulfilled when cell selection level is $S_{rxlev} > 0$.

$$S_{rxlev} = Q_{rxlevmeas} - \left(Q_{rxlev\min} + Q_{rxlev\min offset}\right) - P_{compensation} \tag{5.11}$$

The observed values from the system information for equation are: $Q_{rxlevmeas}$=-105.6dBm, $Q_{rxlev\min}$=-132 dBm, $Q_{rxlev\min offset}$=0 and $P_{compensation}$=0. Therefore, putting the value in Equation 5.11 we have,

$$S_{rxlev} = -105.6 - (-132 + 0) - 0 = 26\ dB > 0$$

The result shows the LTE cell satisfies the cell selection criteria.

To detect and reselect 3G cell while in LTE, the UE has to satisfy the measurement criteria and reselection criteria. The measurement criterion is fulfilled if

$$S_{servingcell} \le S_{non\,int\,rasearch}\,. \tag{5.12}$$

From SIB3 message log captured by mobile, it is observed that, $S_{non\,int\,rasearch}$ is (14*2=28 dB) and from Equation 5.11 $S_{servingcell}$=26 dB. It shows that the measurement criterion is fulfilled. To satisfy the reselection criteria,

$$S_{nonservingcell} > ThresXLow \tag{5.13}$$

where $S_{nonservingcell}$ is the received signal level of neighbouring 3G cell and is evaluated by,

$$S_{nonservingcell} = Q_{rxlevmeas} - Q_{rxlev\min} \tag{5.14}$$

where $Q_{rxlevmeas}$ is the measured RSCP level and $Q_{rxlev\min}$ is the minimum RSCP level for camping. From the system information, we have, $Q_{rxlev\min}$=-66 (-66*2=-132 dBm), $Q_{rxlevmeas}$=-51(-51*2=-102) and $ThresXLow$=6 (6*2=12 dB). Finally the calculated value for $S_{nonservingcell}$ is 30 dB which is greater than $ThresXLow$. This shows the cell reselection criterion is fulfilled. The mathematical result verifies the graphical result that the UE has camped on the neighbouring cell only after inter-RAT cell reselection criteria is satisfied.

In this thesis, we are mainly concern regarding cell reselection towards 3G from LTE. Therefore, the measurement criteria and reselection criteria for getting back from 3G network to LTE network is not in the scope of this thesis.

5.3 System Information

System information contains the necessary parameters to access the network and to find neighbouring cells. Table 5.1 represents the list of the system information available in LTE.

***Table 5.1**: System information and their functions [21]*

System information	Content
Master Information Block	Physical layer information, cell bandwidth, Physical Hybrid ARQ Indicator Channel (PHICH) configuration, SFN (System Frame Number)
System Information Block 1	SIB scheduling information, PLMN id, tracking area code, cell selection parameters, frequency band, cell barring
System Information Block 2	Common and shared channel information, UE timers and constants, uplink carrier frequency.
System Information Block 3	Cell reselection information
System Information Block 4	Information for neighbour cells for intra-frequency reselection.
System Information Block 5	Information for neighbour cells for inter-frequency reselection.
System Information Block 6	Information for UMTS neighbouring cells for cell reselection
System Information Block 7	Information for GERAN neighbouring cells for cell reselection
System Information Block 8	Information for CDMA 2000 for cell reselection
System Information Block 9	Home eNodeB identifier (HNBID)
System Information Block 10	ETWS (Earthquake and Tsunami warning system) primary notification
System Information Block 11	ETWS secondary notification

UE locates and reads system information before establishing connection with E-UTRA. The eNodeB broadcast the System Information in BCCH channel. It contains a Master

Information Block (MIB) and System Information Blocks (SIBs). The MIB is broadcast on the Physical Broadcast Channel (PBCH). UE looks after MIB for downlink synchronization. SIBs are transferred using Physical Downlink Shared Channel (PDSCH). SIB1 is carried by “SystemInformationBlockType1” message while SIB2 to SIB11 are enclosed within “SystemInformation (SI)” RRC message.

5.3.1 System Information Block 1 (SIB1)

SIB1 contains cell access information. UE decode the SIB1 once in every 10ms radio frame from the Physical Downlink shared Channel (PDSCH) channel. The first SIB1 transmission takes place whenever SFN mod 8=0 in the subframe #5. The SIB1 includes Public Land Mobile Network (PLMN) identity list which contains up to six PLMN identities. PLMN is nothing but a network provided by the operator. The first PLMN is known as primary PLMN. It also contains Tracking Area Code (TAC) and Cell ID. All PLMN shared a common TAC code. It ranges from 0 to 65536. The Cell ID contains the eNodeB identity and can have a length of 20 or 28 bits. It also includes cell selection information. The cell barred flag indicates whether a cell is allowed to camp on it or not. The cell reselection flag indicates whether UE is allowed to reselect the other cells on same carrier frequency or not. SIB1 also includes scheduling information for other SIBs in terms of SI-periodicity and a SI-window. Each specific groups of SIB have a different periodicity whereas all SIB has a common window. System Information value Tag is used to acquire change information on SIB2 to SIB9. It is indicated in the SIB1. [21]

5.3.2 System Information Block 3 (SIB3)

SIB3 contains cell selection and reselection information for intra-frequency, inter-frequency and/or inter-RAT. Figure 5.3 is the captured SIB message by the mobile during the measurement process. $Q_{Hyst}, S_{non\text{int}rasearch}, threshServingLow, Q_{rxlev\min}$ and $S_{\text{int}rasearch}$ are the important information elements available in SIB3. Q_{Hyst} is the hysteresis value that defines the cell reselection ranking criteria. The common configured value is 4dB. $S_{non\text{int}rasearch}$ is the triggering value for inter-frequency and inter-RAT measurements during cell reselection measurements than the target cell. The actual value is signalled value *2. $threshServingLow$ is the threshold value for cell reselection towards the low priority cell. The actual value is signalled value *2. $Q_{rxlev\min}$ is the minimum Reference Signal Received Power (RSRP) value for cell reselection. The actual value is signalled value * 2. Finally $S_{\text{int}rasearch}$ represents the intra frequency measurement value for a cell. The actual value is signalled value*2. [21]

5.4 Mobility Management in Connected Mode

In this mode, UE always maintains an active signalling connection with the EUTRAN. Mobility of the UE is handled by the handover process. The handover process operates in RRC_CONNECTED mode. UE can transmit and receive the data from the network during this mode.

5.5 Hard Handover in LTE

UE measures and compares the radio signal strength/quality of the neighbour cells and finds the best cell for camping. Once found, eNodeB allows moving towards best cell along with an ongoing application. This is handover. In LTE handovers are hard handovers as there is short interruption in ongoing service when handover is performed. In LTE there are three types of handovers; intra-LTE handover, inter-LTE handover and inter-RAT handover. In this thesis the first two handover types are explained shortly while the last one inter-RAT is discussed more detail. The handover procedure completes in three phase. [10]

- ***Handover Preparation:*** In this phase, the UE performs continuous measurement on its own cell and neighbouring cell and sent measurement report according to the triggering criteria. The serving eNodeB makes handover decision and request for handover towards the target cell. The target eNodeB performs admission control and sends acknowledgement for handover request.
- ***Handover Execution:*** This phase begins once the source eNodeB receives the handover command. The forwarded data packets from source eNodeB are buffered at the target eNodeB. The UE synchronize the target cell and performs random access procedure to get UL allocation. After that UE sends handover confirm message to the target eNodeB and it starts to send the data packets to UE.
- ***Handover Completion:*** The target eNodeB sends the user plane change notification to Mobile management Entity (MME) to update new user plane in Serving Gateway (SGW). All the data packets are forwarded to the target eNodeB to send towards UE.

5.5.1 X2 based Handover

X2 handover is a type of intra-LTE handover which involves a direct connectivity between the source eNodeB (S-eNB) and a target eNodeB (T-eNB) using X2 interface. Figure 5.7 show the scenario of X2 based handover when only one SGW is involved. The Mobility Management Entity (MME) and Serving Gateway (SGW) remain unchanged during this handover process. This handover is performed involving only EUTRAN.

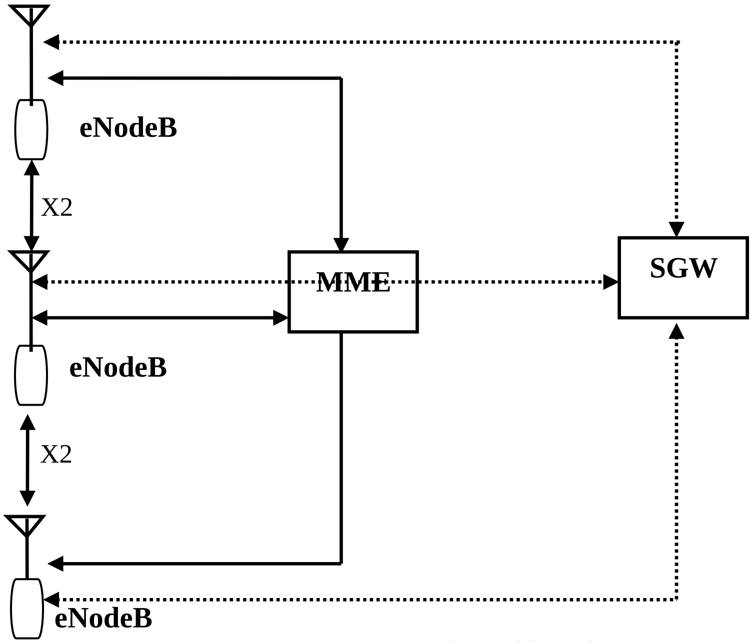


Figure 5.7*: X2 based handover*

5.5.2 S1 based Handover

Figure 5.8 shows S1 based handover process. This is also a type of intra-LTE handover which is favoured when the X2 based handover cannot be implemented.

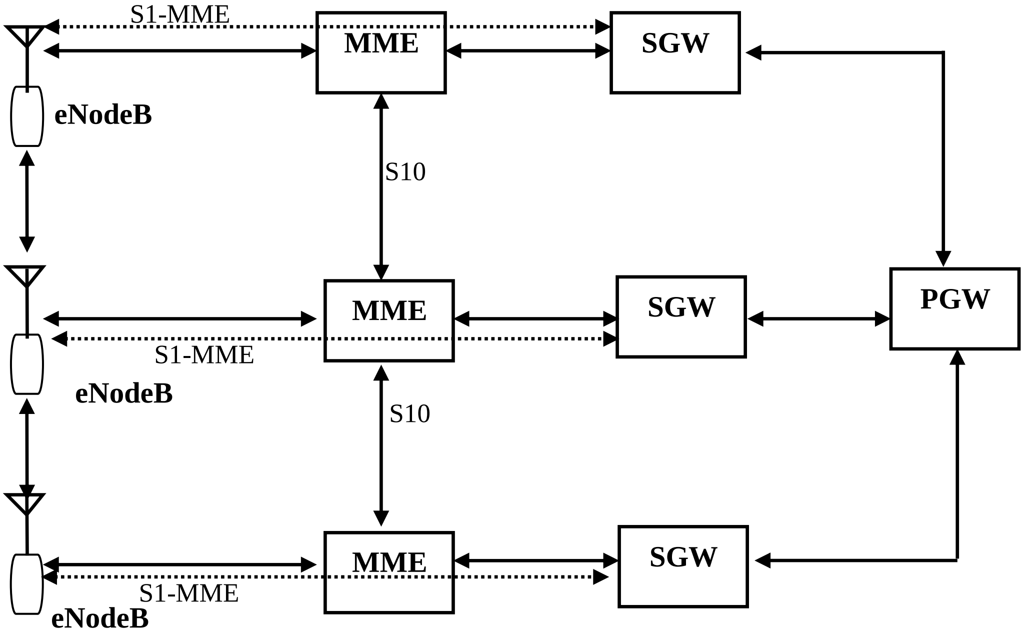


Figure 5.8*: S1 based Intra-LTE Handover*

The initiation of S1 based handover may be due to X2 based handover failure, relocation of the MME due to MME area limitation, lack of X2 interface connection between two eNodeB while UE moves, the target eNodeB does not acknowledge to the X2 Application Protocol (X2AP) message. The data packet flow can takes place either direct or indirect from source eNodeB to target eNodeB. The X2 interface between the source eNodeB and the target eNodeB provides the direct path. [22]

5.6 Inter Radio Access Technology Handovers

The inter-RAT handover is handover between two different systems. LTE, UMTS, GSM and CDMA 2000 are the different types of radio access technology which are actively used. The handover between LTE/UMTS, LTE/GSM, UMTS/GSM, and LTE/cdma2000 systems are some examples of inter-RAT handover. The radio resource in the target system is reserved by the source access system to the UE before the preparation of the handover. The source system provides all the necessary information to the target system before execution. The UE gets radio resource configuration and cell information to access the target system during the handover process. The GERAN system does not support the Packet Switched Handover (PS HO). So, the resource reservation before handover is not available.

5.6.1 Handover from EUTRAN to UTRAN

Figure 5.9 shows the inter connection between the LTE and 3G network elements. The source eNodeB connects to the source MME and source SGW while the target RNC connects to the target SGSN. Both networks are inter connect with each other with the help of MME.

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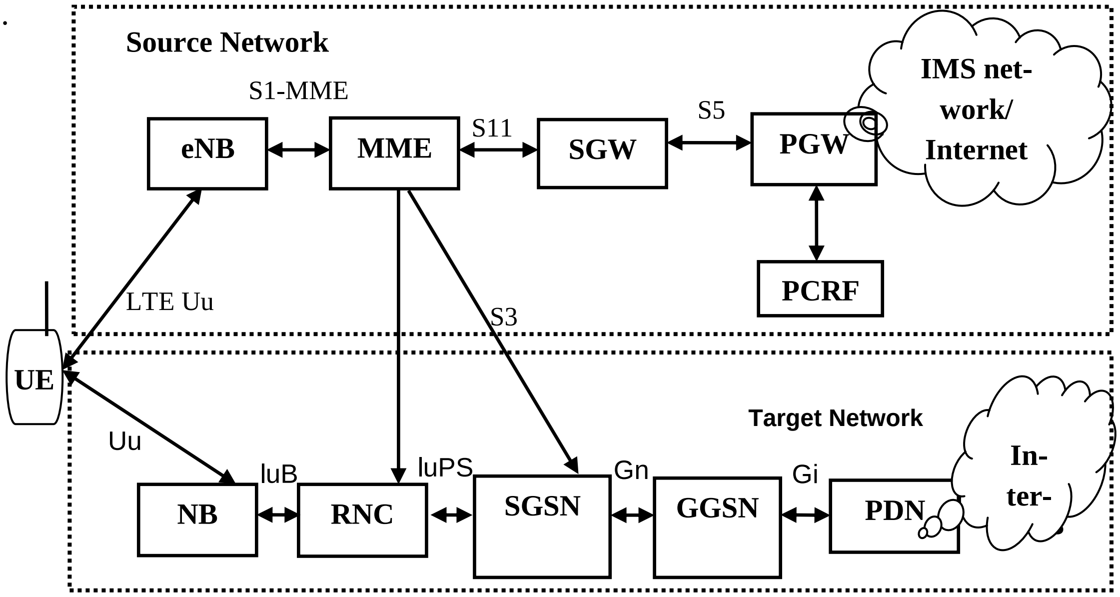


***Figure 5.9**: EUTRAN to UTRAN handover process*

The handover message flow is described in two phase, preparation phase and execution phase. The preparation phase describes how the resource is reserved to the UE in the target system by the source system whereas the execution phase describes how the UE is handled over to the target access system. This message flow is shown in Figure 5.10 and 5.11.

5.6.1.1 Preparation phase

The preparation phase is explained below with signalling flow diagram presented in Figure 5.10.

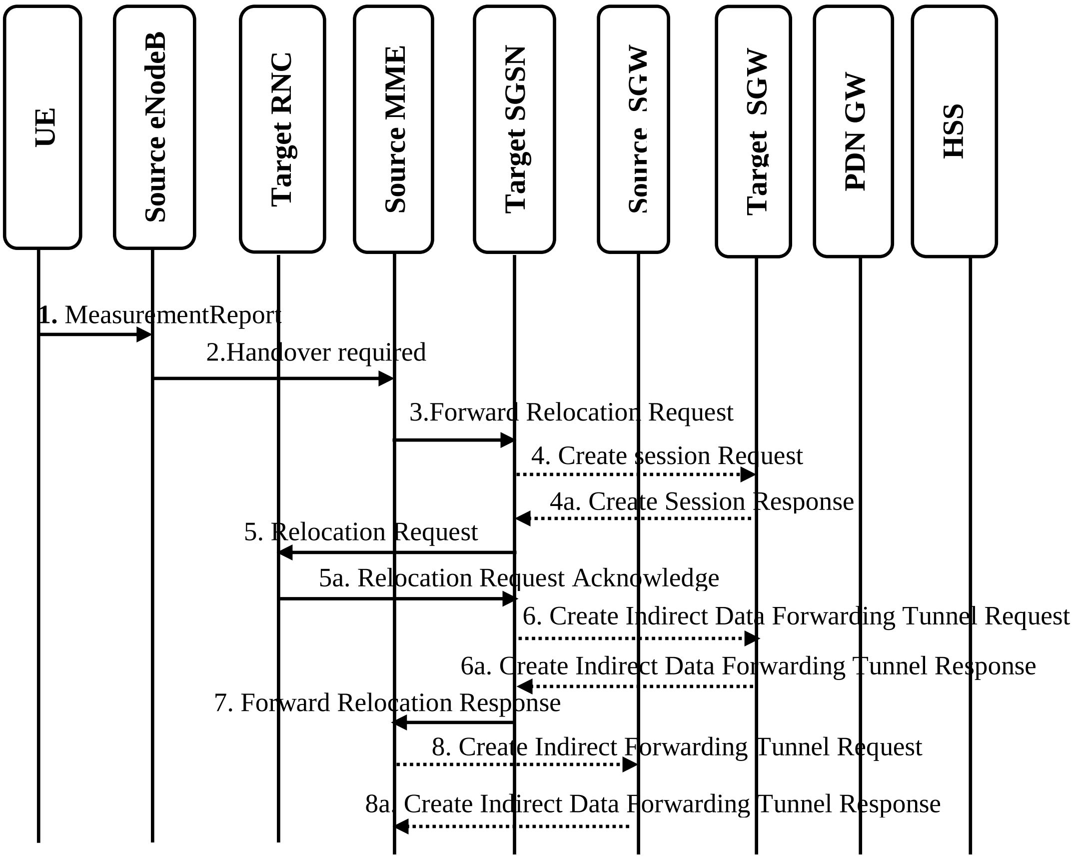


***Figure 5.10**: Preparation phase: inter-RAT handover, LTE to UMTS [22]*

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 SGW and source eNodeB. The source eNodeB initiates the Inter RAT handover to the target access network UTRAN.
2. The source eNodeB sends the '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 SGW. The target SGW 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.

5.6.1.2 Execution phase

The signalling message flow during execution phase is explained briefly with the help of Figure 5.11.

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.
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 acknowledge 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.

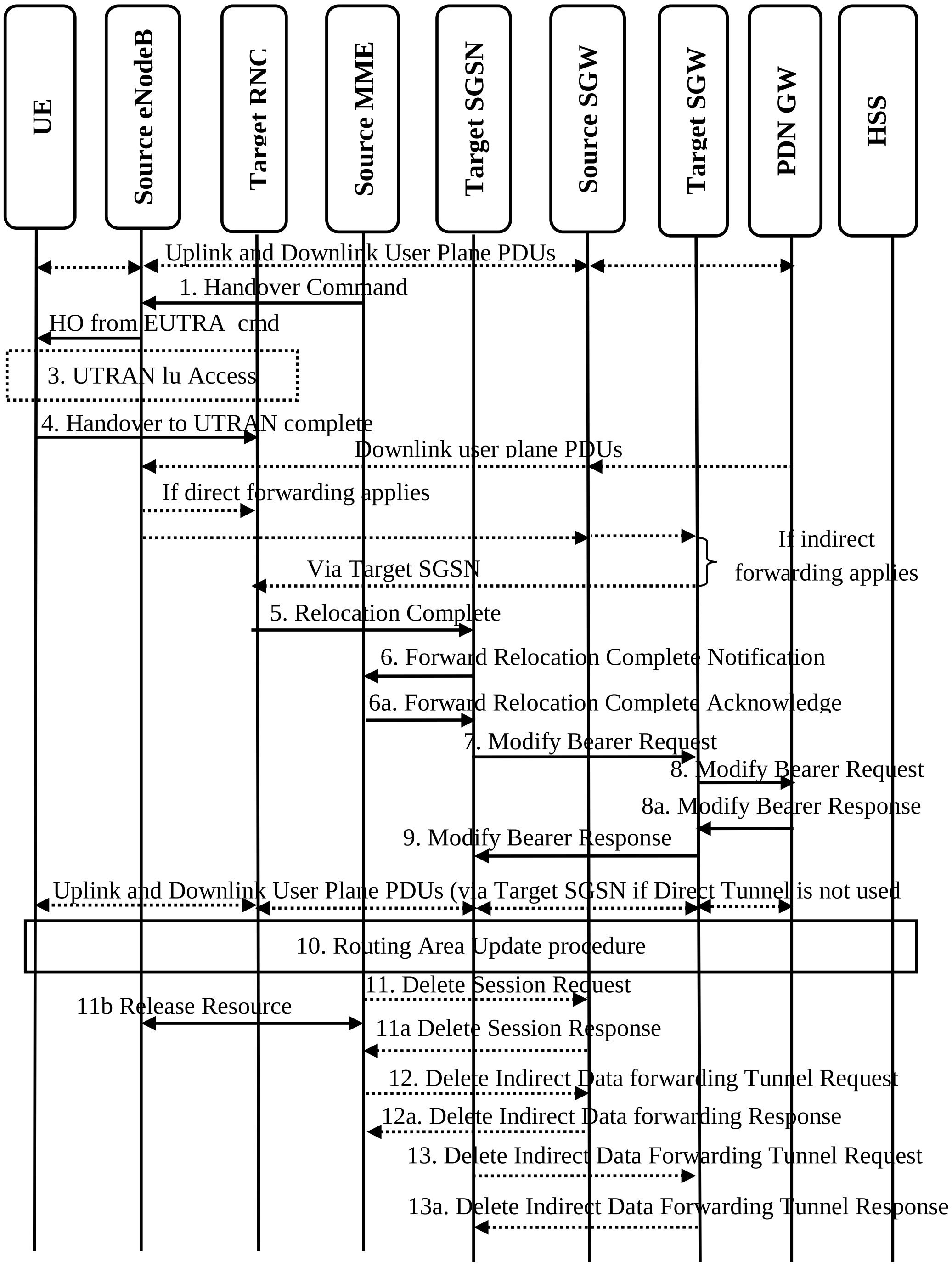


Figure 5.11*: Execution phase: Inter-RAT handover, LTE to UMTS [22]*

5.6.2 Handover from UTRAN to EUTRAN

The source RNC is connected to the source SGSN and source SGW whereas the target eNodeB is connected to target MME. The whole procedure is also explained in two phases: preparation and execution along with the signalling diagram shown in figure below.

5.6.2.1 Preparation phase

The signalling message flow during preparation phase is explained below with the help of Figure 5.12.

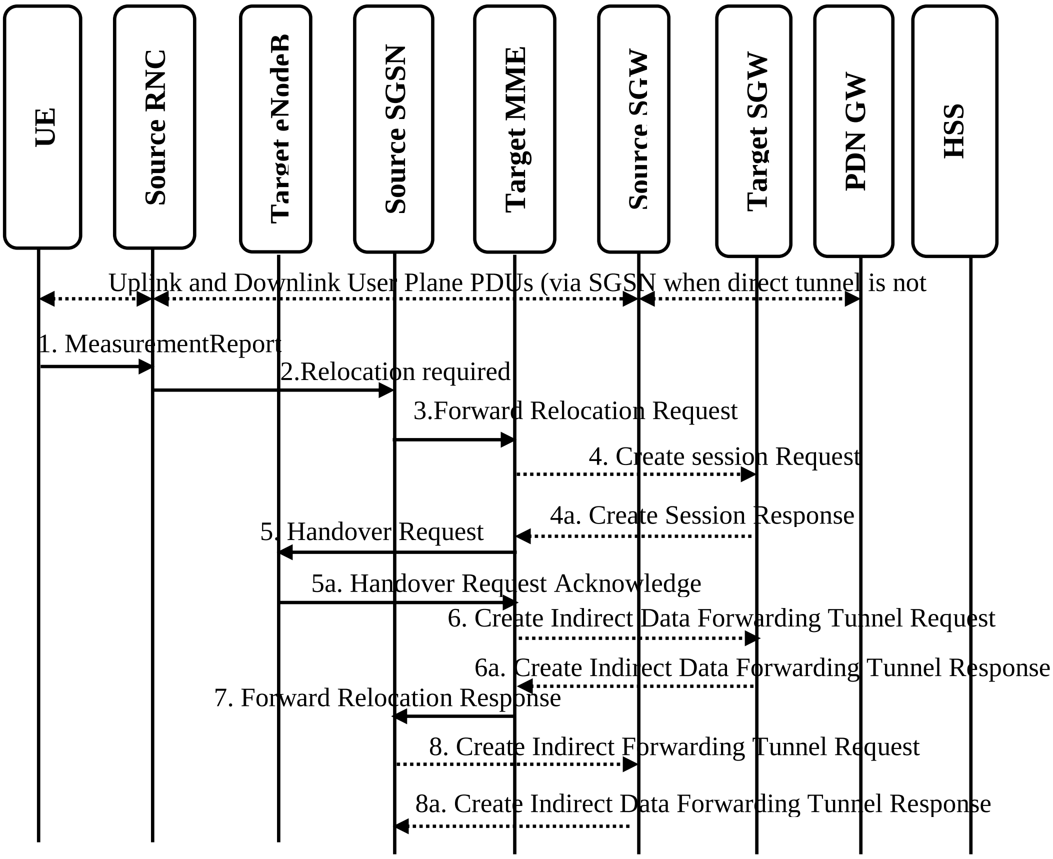


Figure 5.12*: Preparation phase: Inter-RAT handover, UMTS to LTE [22]*

1. The handover is initiated and decided by the source RNC to the EUTRAN based on 'MeasurementReport'.
2. The source RNC sends 'Relocation required' message to the source SGSN to create a radio resource to the target eNodeB.
3. The source SGSN identifies that this is inter-RAT handover to EUTRAN and access the target MME details. It then sends 'Forward Relocation Request' message to the target MME for handover resource allocation.
4. The target MME detects and relocates if necessary the target SGW. It sends 'Create Session Request' message the target SGW to create the bearer resource. The target SGW responds by sending 'Create Session Response' message after resource reservation is done.

5. The target MME sends 'Handover Request' command to the target eNodeB to establish the radio bearer. Once the radio bearer is established and resource is reserved, it sends 'Handover Request Acknowledge message' back to the target MME.
6. The target MME creates indirect data forwarding tunnel in the target SGW to transfer the DL data packets from source SGW to target SGW during handover process. The target SGW responds the target MME after indirect data forward tunnel creation with 'Indirect Tunnel creation Response' message.
7. The target MME responds by sending 'Forward Relocation Response' message to the source SGSN.
8. The source SGSN now creates the indirect data forwarding tunnel in the source SGW to forward the DL data packets to the target network. The source SGW responds the source SGSN after successful creation.

5.6.2.2 Execution phase

The signalling message flow between different network elements during handover execution phase is explained with the help of Figure 5.13

1. The source SGSN sends 'Relocation Command' to the source RNC after completion of the preparation phase.
2. The source RNC sends 'Handover from UTRAN' command to UE for handover preparation towards the target network.
3. The UE enters the EUTRAN network and performs EUTRAN accessing procedures.
4. The UE sends' Handover to EUTRAN complete' message once it is handover to target eNodeB.
5. The target eNodeB informs the completion of handover procedure to the target MME by sending ' Handoff notify message'.
6. The target MME sends 'Forward Relocation Complete Notification' message to the source SGSN to indicate UE has successfully access to the target MME. The source SGSN acknowledge back by sending 'Forward Relocation Complete Notification Acknowledge' message. Now all the resources occupied by UE at the source SGW and source RNC side is released.
7. The target MME sends 'Modify Bearer Request' to the target SGW to indicate the complete modification of all radio bearers associated to the UE.
8. The target SGW sends 'Modify Bearer Request' message to PDN GW to indicate the change in the serving GW due to relocation procedure. The PDN GW updates its context field' and sends 'Modify Bearer Response' message back to target MME.
9. The target serving GW sends 'Modify Bearer Response' to the target MME when a user path is established between UE, target eNodeB, target serving GW and PDN GW for all radio bearers.

10. A new Tracking Area is updated in the network informing the new location of the UE due to inter-RAT handover.
11. The source RNC sends' lu Release Message' to the source SGSN after the timer expires all the resources are released.
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.

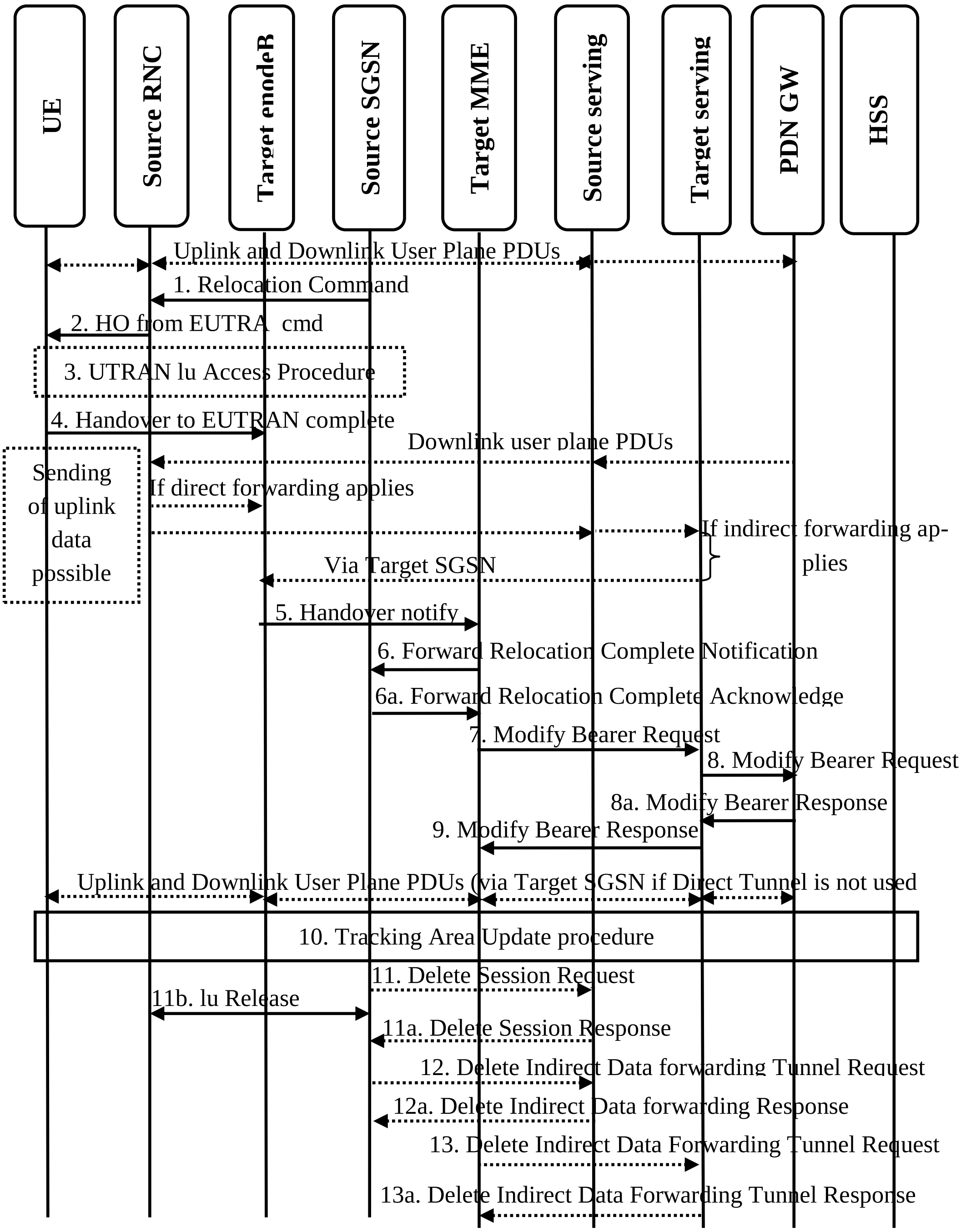


***Figure 5.13**: Execution phase: Inter-RAT handover, UMTS to LTE [22]*

5.7 Measurement Events and Triggering

Measurements are done by the UE for cell selection/reselection, scheduling and handovers. These measurements are sent to the eNodeB for decision making. UE decides the cell selection/reselection process based on $Q_{rxlevmin}$ and $Q_{qualmin}$ value of the serving and neighbouring cells in the idle mode. Each UE is allocated with the radio resources to transfer the data in uplink and downlink direction. The UE sent physical layer information 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 Scheduling**.**

Handover decisions are made based on the RRC measurements in the connection state. RRC connection reconfiguration message is used to modify RRC connection between UE and eNodeB. The UE reports a set of measurements called events to the network. These events trigger the UE to inform about the channel condition and the radio environment of the serving eNodeB. A measurement configuration parameter is used to configure the UE in LTE or other RATs. These parameters are present in the RRC connection reconfiguration message. The measurement configuration parameters are: [10]

- ***Measurement objects*****:** The EUTRAN configures one measurement object at a time for a given frequency. These measurement objects can be a set of cells or a set of carrier frequencies.
- ***Reporting configuration*****:** UE can trigger a measurement report periodically. This triggering condition is decided by the reporting criteria and is reported according to the reporting format. Reporting format includes parameters present in the measurement report whereas the measurement reports are sent according to the reporting criteria. [5] [23]

Table 5.2: *Measurement events and their Triggering conditions*

Events	Triggering conditions
A1	serving becomes better than absolute threshold
A2	serving becomes worse than absolute threshold
A3	neighbour becomes amount of offset better than serving
A4	neighbour becomes better than absolute threshold
A5	serving becomes worse than threshold 1 and neighbour becomes better than another threshold 2
B1	neighbour becomes better than absolute threshold
B2	serving becomes worse than absolute threshold 1 and neighbour becomes better than another absolute threshold2

Table 5.2 shows seven types of events specified by the 3GPP. The first five events A1, A2, A3, A4 and A5 are triggered for intra-EUTRA measurements and the remaining B1 and B2 are triggered for inter-RAT measurements. The threshold values for each event

are independent to each other. All this triggering conditions has to satisfy at least for Time to Trigger (TTT) value. TTT value is the time interval defined by the network and is operator specific.

- ***Measurement identities*****:** These entities are reference numbers that links one measurement object and one reporting configuration together.
- ***Quantity configurations:*** They are configured per RAT with the help of filter coefficient.
- ***Measurement gaps*****:** It is an interval used by the UE to perform measurement. No transmission and reception occurs during this period.

Figure 5.14 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 neighbour becomes better than threshold2. The red color graph indicates the signal level for serving cell while black is for neighbouring cell. The UE provides a number of periodic reports after triggering an event. Two parameters reportAmount and reportInterval configures the event triggered period reporting. The reportAmount specify the number of periodic reports while reportInterval specify time period between them.

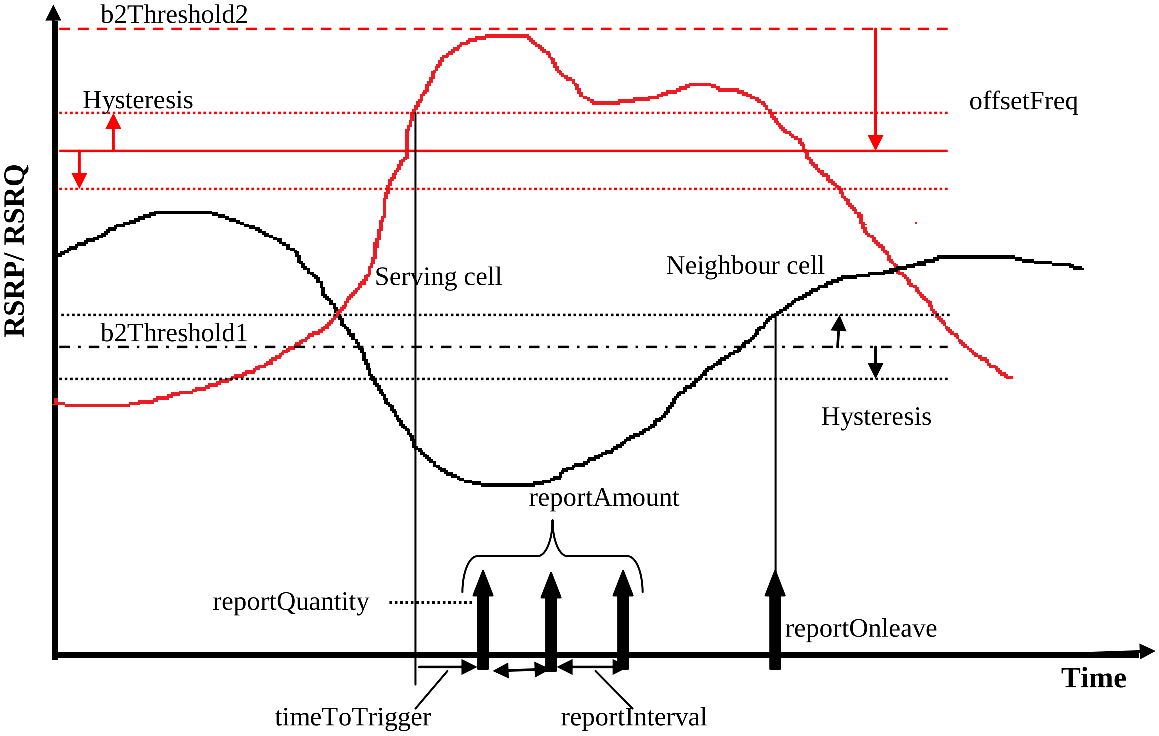
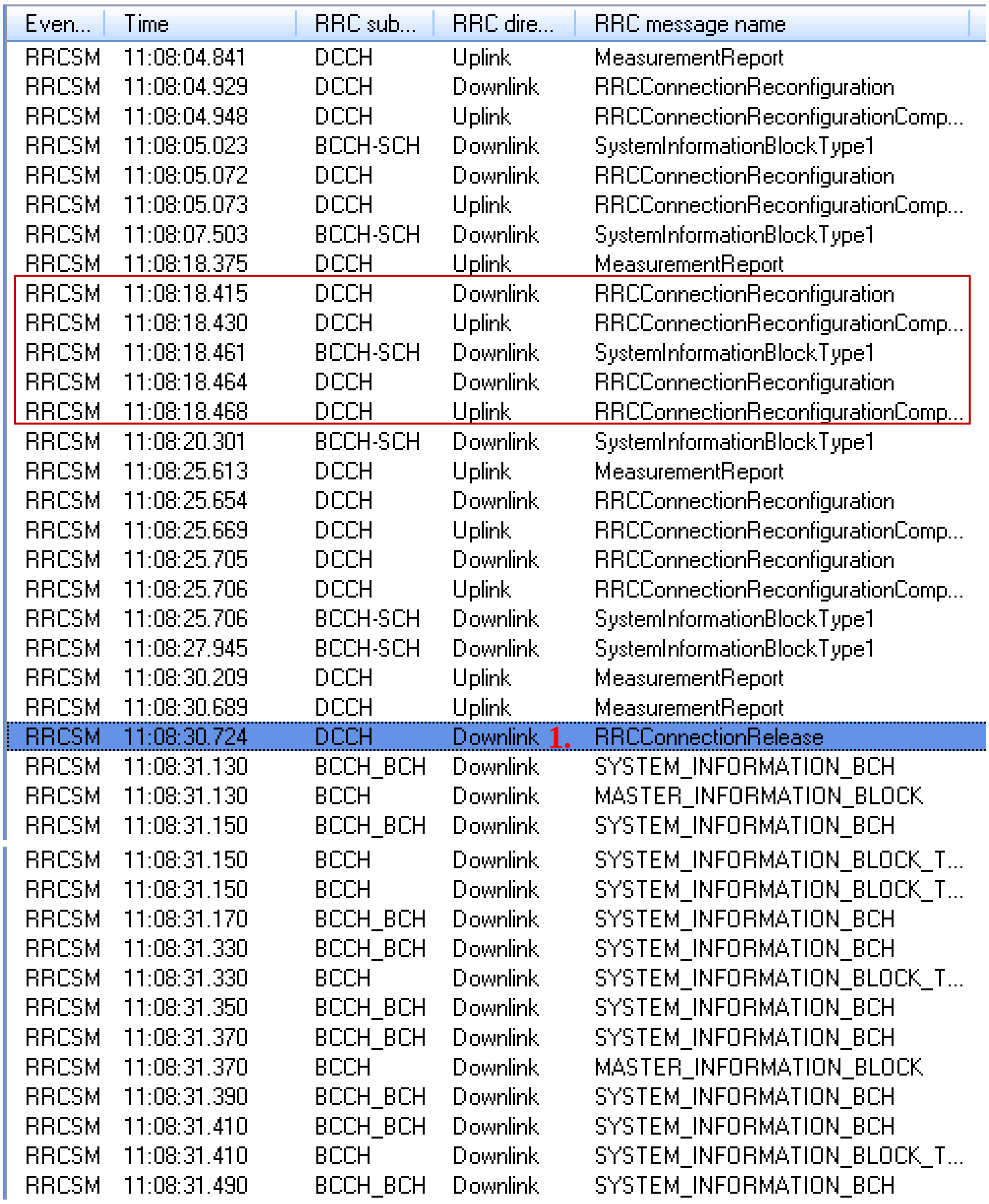


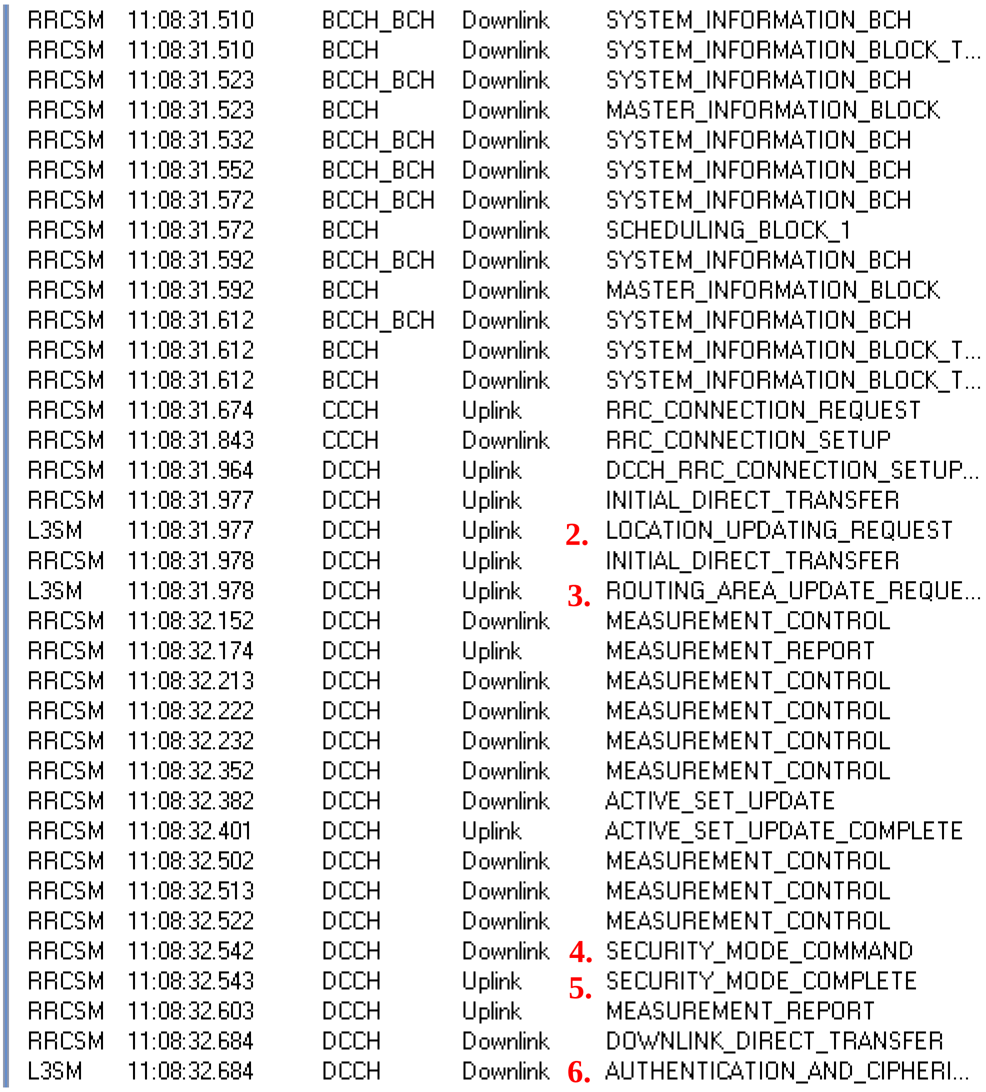
Figure 5.14*: Event B2 type reporting criteria*

Figure 5.15 is an example of the successful inter-RAT handover signalling message from LTE towards 3G seen by the mobile. The first column of the figure contains 'Event ID (Event Identity)' that represents the signalling events type being used. RRCSM (Radio Resource Control Signalling Message) or L3SM (Layer 3 Signalling Message) is the signalling event of control plane. The second column 'Time' represents time interval at which the event takes place. The third column 'RRC sub channels' represent the channels responsible to carry the RRC message information. They are BCCH (Broadcast Control Channel), CCCH (Common Control Channel) and DCCH (Dedicated Control Channel). The last column 'RRC message name' indicates the signalling message exchanged between the UE and the network during inter-RAT mobility. The important signalling messages are labelled with the red numbers.

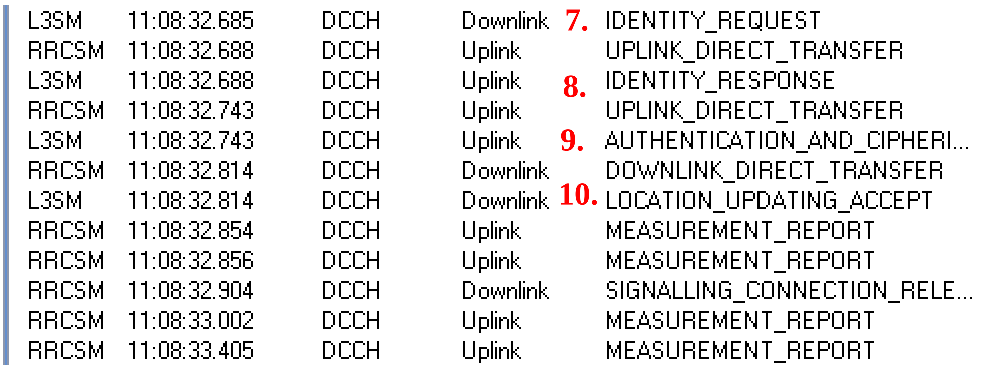


Even...	Time	RRC sub...	RRC dire...	RRC message name
RRCSM	11:08:04.841	DCCH	Uplink	MeasurementReport
RRCSM	11:08:04.929	DCCH	Downlink	RRCConnectionReconfiguration
RRCSM	11:08:04.948	DCCH	Uplink	RRCConnectionReconfigurationComp...
RRCSM	11:08:05.023	BCCH-SCH	Downlink	SystemInformationBlockType1
RRCSM	11:08:05.072	DCCH	Downlink	RRCConnectionReconfiguration
RRCSM	11:08:05.073	DCCH	Uplink	RRCConnectionReconfigurationComp...
RRCSM	11:08:07.503	BCCH-SCH	Downlink	SystemInformationBlockType1
RRCSM	11:08:18.375	DCCH	Uplink	MeasurementReport
RRCSM	11:08:18.415	DCCH	Downlink	RRCConnectionReconfiguration
RRCSM	11:08:18.430	DCCH	Uplink	RRCConnectionReconfigurationComp...
RRCSM	11:08:18.461	BCCH-SCH	Downlink	SystemInformationBlockType1
RRCSM	11:08:18.464	DCCH	Downlink	RRCConnectionReconfiguration
RRCSM	11:08:18.468	DCCH	Uplink	RRCConnectionReconfigurationComp...
RRCSM	11:08:20.301	BCCH-SCH	Downlink	SystemInformationBlockType1
RRCSM	11:08:25.613	DCCH	Uplink	MeasurementReport
RRCSM	11:08:25.654	DCCH	Downlink	RRCConnectionReconfiguration
RRCSM	11:08:25.669	DCCH	Uplink	RRCConnectionReconfigurationComp...
RRCSM	11:08:25.705	DCCH	Downlink	RRCConnectionReconfiguration
RRCSM	11:08:25.706	DCCH	Uplink	RRCConnectionReconfigurationComp...
RRCSM	11:08:25.706	BCCH-SCH	Downlink	SystemInformationBlockType1
RRCSM	11:08:27.945	BCCH-SCH	Downlink	SystemInformationBlockType1
RRCSM	11:08:30.209	DCCH	Uplink	MeasurementReport
RRCSM	11:08:30.689	DCCH	Uplink	MeasurementReport
RRCSM	11:08:30.724	DCCH	Downlink 1.	RRCConnectionRelease
RRCSM	11:08:31.130	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.130	BCCH	Downlink	MASTER_INFORMATION_BLOCK
RRCSM	11:08:31.150	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.150	BCCH	Downlink	SYSTEM_INFORMATION_BLOCK_T...
RRCSM	11:08:31.150	BCCH	Downlink	SYSTEM_INFORMATION_BLOCK_T...
RRCSM	11:08:31.170	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.330	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.330	BCCH	Downlink	SYSTEM_INFORMATION_BLOCK_T...
RRCSM	11:08:31.350	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.370	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.370	BCCH	Downlink	MASTER_INFORMATION_BLOCK
RRCSM	11:08:31.390	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.410	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH
RRCSM	11:08:31.410	BCCH	Downlink	SYSTEM_INFORMATION_BLOCK_T...
RRCSM	11:08:31.490	BCCH_BCH	Downlink	SYSTEM_INFORMATION_BCH

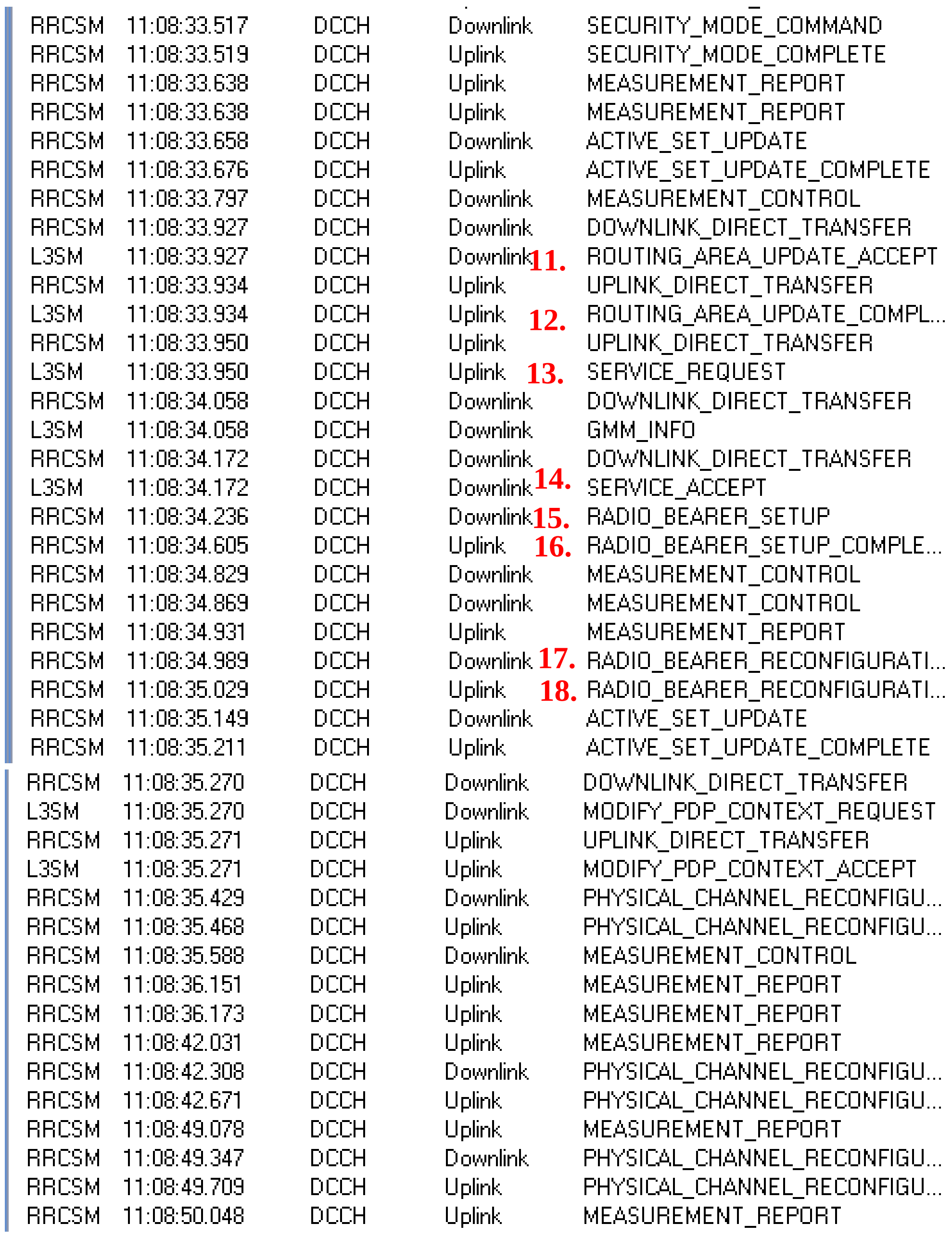
Intra-cell H/O in LTE



```
RRCSM   11:08:31.510   BCCH_BCH   Downlink      SYSTEM_INFORMATION_BCH
RRCSM   11:08:31.510   BCCH       Downlink      SYSTEM_INFORMATION_BLOCK_T...
RRCSM   11:08:31.523   BCCH_BCH   Downlink      SYSTEM_INFORMATION_BCH
RRCSM   11:08:31.523   BCCH       Downlink      MASTER_INFORMATION_BLOCK
RRCSM   11:08:31.532   BCCH_BCH   Downlink      SYSTEM_INFORMATION_BCH
RRCSM   11:08:31.552   BCCH_BCH   Downlink      SYSTEM_INFORMATION_BCH
RRCSM   11:08:31.572   BCCH_BCH   Downlink      SYSTEM_INFORMATION_BCH
RRCSM   11:08:31.572   BCCH       Downlink      SCHEDULING_BLOCK_1
RRCSM   11:08:31.592   BCCH_BCH   Downlink      SYSTEM_INFORMATION_BCH
RRCSM   11:08:31.592   BCCH       Downlink      MASTER_INFORMATION_BLOCK
RRCSM   11:08:31.612   BCCH_BCH   Downlink      SYSTEM_INFORMATION_BCH
RRCSM   11:08:31.612   BCCH       Downlink      SYSTEM_INFORMATION_BLOCK_T...
RRCSM   11:08:31.612   BCCH       Downlink      SYSTEM_INFORMATION_BLOCK_T...
RRCSM   11:08:31.674   CCCH       Uplink        RRC_CONNECTION_REQUEST
RRCSM   11:08:31.843   CCCH       Downlink      RRC_CONNECTION_SETUP
RRCSM   11:08:31.964   DCCH       Uplink        DCCH_RRC_CONNECTION_SETUP...
RRCSM   11:08:31.977   DCCH       Uplink        INITIAL_DIRECT_TRANSFER
L3SM    11:08:31.977   DCCH       Uplink    2.  LOCATION_UPDATING_REQUEST
RRCSM   11:08:31.978   DCCH       Uplink        INITIAL_DIRECT_TRANSFER
L3SM    11:08:31.978   DCCH       Uplink    3.  ROUTING_AREA_UPDATE_REQUE...
RRCSM   11:08:32.152   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.174   DCCH       Uplink        MEASUREMENT_REPORT
RRCSM   11:08:32.213   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.222   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.232   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.352   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.382   DCCH       Downlink      ACTIVE_SET_UPDATE
RRCSM   11:08:32.401   DCCH       Uplink        ACTIVE_SET_UPDATE_COMPLETE
RRCSM   11:08:32.502   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.513   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.522   DCCH       Downlink      MEASUREMENT_CONTROL
RRCSM   11:08:32.542   DCCH       Downlink  4.  SECURITY_MODE_COMMAND
RRCSM   11:08:32.543   DCCH       Uplink    5.  SECURITY_MODE_COMPLETE
RRCSM   11:08:32.603   DCCH       Uplink        MEASUREMENT_REPORT
RRCSM   11:08:32.684   DCCH       Downlink      DOWNLINK_DIRECT_TRANSFER
L3SM    11:08:32.684   DCCH       Downlink  6.  AUTHENTICATION_AND_CIPHERI...
```



```
L3SM    11:08:32.685   DCCH       Downlink  7.  IDENTITY_REQUEST
RRCSM   11:08:32.688   DCCH       Uplink        UPLINK_DIRECT_TRANSFER
L3SM    11:08:32.688   DCCH       Uplink    8.  IDENTITY_RESPONSE
RRCSM   11:08:32.743   DCCH       Uplink        UPLINK_DIRECT_TRANSFER
L3SM    11:08:32.743   DCCH       Uplink    9.  AUTHENTICATION_AND_CIPHERI...
RRCSM   11:08:32.814   DCCH       Downlink      DOWNLINK_DIRECT_TRANSFER
L3SM    11:08:32.814   DCCH       Downlink 10.  LOCATION_UPDATING_ACCEPT
RRCSM   11:08:32.854   DCCH       Uplink        MEASUREMENT_REPORT
RRCSM   11:08:32.856   DCCH       Uplink        MEASUREMENT_REPORT
RRCSM   11:08:32.904   DCCH       Downlink      SIGNALLING_CONNECTION_RELE...
RRCSM   11:08:33.002   DCCH       Uplink        MEASUREMENT_REPORT
RRCSM   11:08:33.405   DCCH       Uplink        MEASUREMENT_REPORT
```



```
RRCSM   11:08:33.517    DCCH    Downlink        SECURITY_MODE_COMMAND
RRCSM   11:08:33.519    DCCH    Uplink          SECURITY_MODE_COMPLETE
RRCSM   11:08:33.638    DCCH    Uplink          MEASUREMENT_REPORT
RRCSM   11:08:33.638    DCCH    Uplink          MEASUREMENT_REPORT
RRCSM   11:08:33.658    DCCH    Downlink        ACTIVE_SET_UPDATE
RRCSM   11:08:33.676    DCCH    Uplink          ACTIVE_SET_UPDATE_COMPLETE
RRCSM   11:08:33.797    DCCH    Downlink        MEASUREMENT_CONTROL
RRCSM   11:08:33.927    DCCH    Downlink        DOWNLINK_DIRECT_TRANSFER
L3SM    11:08:33.927    DCCH    Downlink 11.    ROUTING_AREA_UPDATE_ACCEPT
RRCSM   11:08:33.934    DCCH    Uplink          UPLINK_DIRECT_TRANSFER
L3SM    11:08:33.934    DCCH    Uplink   12.    ROUTING_AREA_UPDATE_COMPL...
RRCSM   11:08:33.950    DCCH    Uplink          UPLINK_DIRECT_TRANSFER
L3SM    11:08:33.950    DCCH    Uplink   13.    SERVICE_REQUEST
RRCSM   11:08:34.058    DCCH    Downlink        DOWNLINK_DIRECT_TRANSFER
L3SM    11:08:34.058    DCCH    Downlink        GMM_INFO
RRCSM   11:08:34.172    DCCH    Downlink        DOWNLINK_DIRECT_TRANSFER
L3SM    11:08:34.172    DCCH    Downlink 14.    SERVICE_ACCEPT
RRCSM   11:08:34.236    DCCH    Downlink 15.    RADIO_BEARER_SETUP
RRCSM   11:08:34.605    DCCH    Uplink   16.    RADIO_BEARER_SETUP_COMPLE...
RRCSM   11:08:34.829    DCCH    Downlink        MEASUREMENT_CONTROL
RRCSM   11:08:34.869    DCCH    Downlink        MEASUREMENT_CONTROL
RRCSM   11:08:34.931    DCCH    Uplink          MEASUREMENT_REPORT
RRCSM   11:08:34.989    DCCH    Downlink 17.    RADIO_BEARER_RECONFIGURATI...
RRCSM   11:08:35.029    DCCH    Uplink   18.    RADIO_BEARER_RECONFIGURATI...
RRCSM   11:08:35.149    DCCH    Downlink        ACTIVE_SET_UPDATE
RRCSM   11:08:35.211    DCCH    Uplink          ACTIVE_SET_UPDATE_COMPLETE
RRCSM   11:08:35.270    DCCH    Downlink        DOWNLINK_DIRECT_TRANSFER
L3SM    11:08:35.270    DCCH    Downlink        MODIFY_PDP_CONTEXT_REQUEST
RRCSM   11:08:35.271    DCCH    Uplink          UPLINK_DIRECT_TRANSFER
L3SM    11:08:35.271    DCCH    Uplink          MODIFY_PDP_CONTEXT_ACCEPT
RRCSM   11:08:35.429    DCCH    Downlink        PHYSICAL_CHANNEL_RECONFIGU...
RRCSM   11:08:35.468    DCCH    Uplink          PHYSICAL_CHANNEL_RECONFIGU...
RRCSM   11:08:35.588    DCCH    Downlink        MEASUREMENT_CONTROL
RRCSM   11:08:36.151    DCCH    Uplink          MEASUREMENT_REPORT
RRCSM   11:08:36.173    DCCH    Uplink          MEASUREMENT_REPORT
RRCSM   11:08:42.031    DCCH    Uplink          MEASUREMENT_REPORT
RRCSM   11:08:42.308    DCCH    Downlink        PHYSICAL_CHANNEL_RECONFIGU...
RRCSM   11:08:42.671    DCCH    Uplink          PHYSICAL_CHANNEL_RECONFIGU...
RRCSM   11:08:49.078    DCCH    Uplink          MEASUREMENT_REPORT
RRCSM   11:08:49.347    DCCH    Downlink        PHYSICAL_CHANNEL_RECONFIGU...
RRCSM   11:08:49.709    DCCH    Uplink          PHYSICAL_CHANNEL_RECONFIGU...
RRCSM   11:08:50.048    DCCH    Uplink          MEASUREMENT_REPORT
```

Figure 5.15*: Inter-RAT handover signalling message*

Figure 5.16 is the somewhat like a summary of the previous logs of Figure 5.15. This figure shows how the signalling message is exchanged between the UE and the network during the mobility. A short description of the important message is also provided. The numbers labelled here corresponds to the same numbering plan as of Figure 5.15. [23] [24] [25] [26]

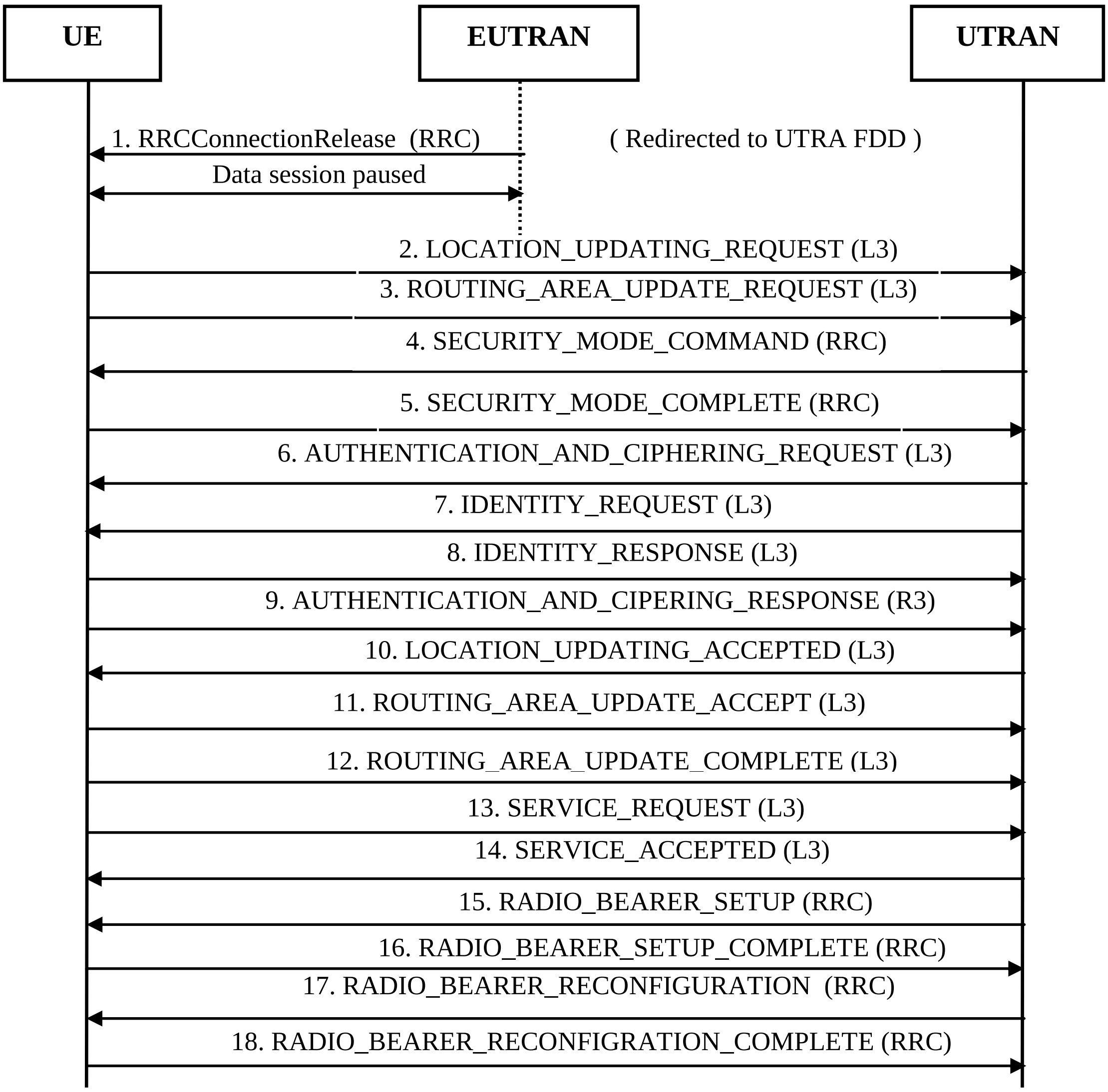
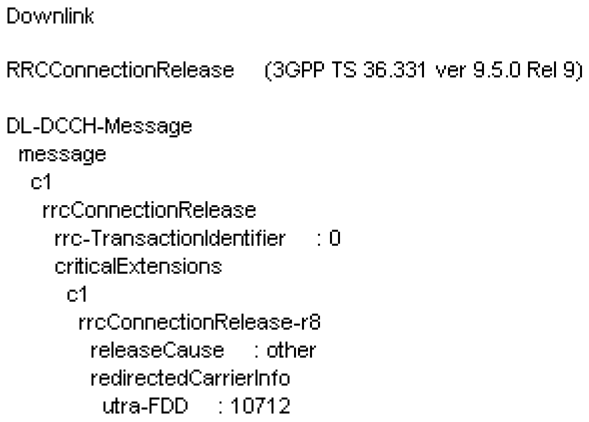


Figure 5.16*: EUTRAN to UTRAN message flow during successful I-RAT handover*

1. The *RRCConnectionRelease* message is sent by the E-UTRAN to UE to release the RRC connection in RRC_CONNECTED state. It releases the established radio bearers and used radio resource with a proper cause. A DCCH (Dedicated Control Channel) logical channel carries this message.



```
Downlink

RRCConnectionRelease    (3GPP TS 36.331 ver 9.5.0 Rel 9)

DL-DCCH-Message
  message
    c1
      rrcConnectionRelease
        rrc-TransactionIdentifier    : 0
        criticalExtensions
          c1
            rrcConnectionRelease-r8
              releaseCause    : other
              redirectedCarrierInfo
                utra-FDD    : 10712
```

Figure: 5.17*: RRCConnectionRelease message log*

Figure 5.17 is an example of an RRCConnectionRelease message log from Nemo Analyzer during inter-RAT mobility. The *'redirectedCarrierinfo'* with cause 'utra-FDD' indicates the handover towards the 3G network.

2. The *'LOCATION_UPDATING_REQUEST'* message is sent by the UE to the UTRAN to update its new location. A DCCH channel carries this information.
3. The *'ROUTING_AREA_UPDATE_REQUEST'* message is sent by the UE to the UTRAN to update its new routing location. A DCCH channel is responsible to carry this message.
4. The *'SECURITY_MODE_COMMAND'* message is sent by UTRAN to UE to start or to modify the integrity protection configuration for all signalling radio bearers.
5. 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.
6. The *'AUTHENTICATION_AND_CIPHERING_REQUEST'* is sent by the UTRAN to UE to initiate the authentication procedure to check the identity of the UE. This authentication procedure enables UE to calculate a new UMTS ciphering key and a new integrity key. These keys are like passwords provided in order to use the system.
7. The *'IDENTITY-REQUEST'* message is sent by the UTRAN to UE to initiate the identification procedure of the UE. The network request for the IMSI (International Mobile Subscriber Identity) code.
8. The *'IDENTITY_RESPONSE'* is sent by the UE to the UTRAN to identify itself with the IMSI code.
9. The *'AUTHENTICATION_AND_CIPHERING_RESPONSE'* is sent by the UE to the UTRAN in response to *'AUTHENTICATION_AND_CIPHERING _REQUEST'* message.
10. 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.
11. The *'ROUTING_AREA_UPDATE_ACCEPT'* message is sent by the UE to UTRAN to indicate the routing area of UE has been updated.
12. 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.
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 signalling/data path before the UE data are transmitted.
16. The *'RADIO_BEARER_SETUP_COMPLETE'* is sent by the UE to UTRAN after the signalling path is established.

17. The *'RADIO_BEARER_RECONFIGURATION'* is sent by the UE to UTRAN to reconfigure the parameters for a radio bearer or the signalling link.
18. The ' *RADIO_BEARER_RECONFIGURATION_COMPLETE'* is sent by the UTRAN to UE after reconfiguring of radio parameters is complete. Any old configuration may be deleted by the UTRAN.

5.8 VoLTE and SR-VCC

3GPP introduced LTE technology to support both data and voice service with high efficiency by increasing the capacity and speed. LTE is an IP based system which use IP to provide end to end connectivity between the users and the core network. Voice over LTE (VoLTE) and Single Radio Voice Call Continuity (SR-VCC) schemes are introduced to transfer the voice traffic in LTE network. IP Multimedia Subsystem (IMS) architecture framework was introduced by 3GPP to support these schemes. IMS is based on internet standard which use SIP protocol for call establishing, managing and terminating the session. VoLTE is somewhat like VoIP. VoLTE uses the LTE spectrum for connectivity whereas VoIP uses IP protocol. VoLTE offers voice, video chat and other multimedia communication service for LTE users. The function of SR-VCC is to support the handover from LTE VoIP/IMS calls to other pervious 2G and 3G legacy voice radio networks when LTE coverage and capacity are limited. Simply it allows the mobility of a voice call from packet domain to voice domain without any call drop using single radio channel at a time. SR-VCC offers the advantage to those operators who have not fully deployed the LTE network all over as compare to the other legacy network.

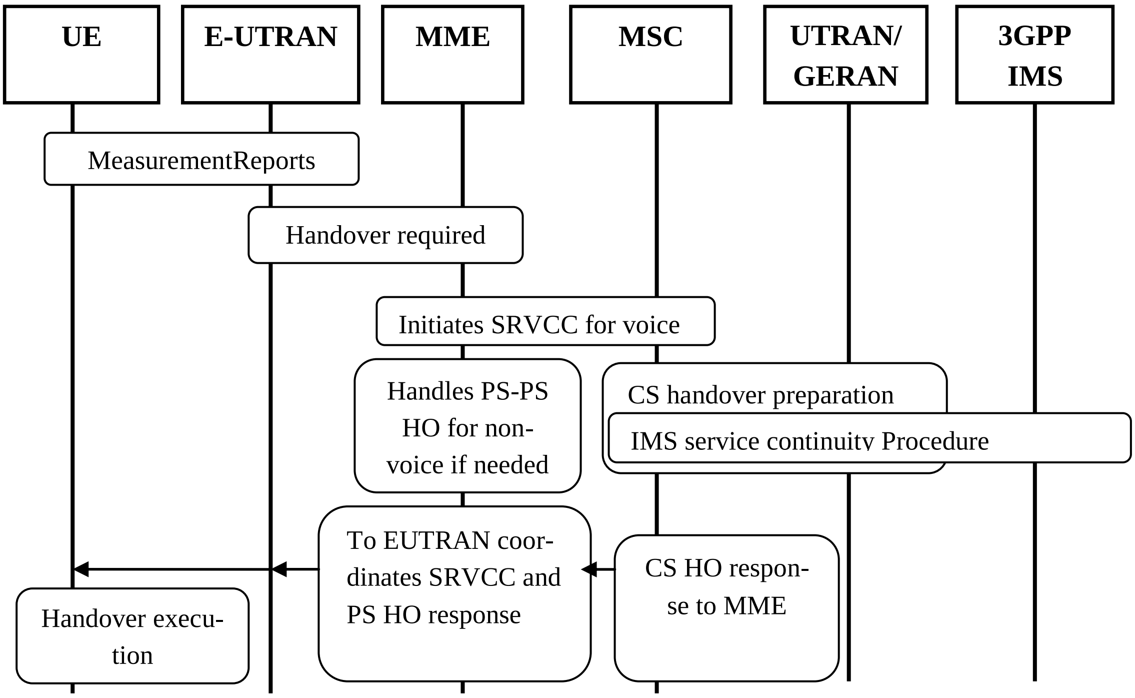


***Figure 5.18**: SR-VCC procedure form EUTRAN to UTRAN/GERAN [27]*

Figure 5.18 shows the SR-VCC procedure from LTE to UMTS network. [9] [27]. Based on the measurement report sent by UE, EUTRAN trigger the SRVCC handover to UTRAN. Then the UTRAN sends the handover required message to MME. After that the MME triggers SRVCC procedure towards the MSC server and initiates the session transfer procedure to IMS and coordinates with it for CS handover preparation to the target cell. The IMS service continuity procedure is implemented to execute the session transfer procedure. The MSC server sends PS-CS handover response to MME, which includes the CS handover information for UE to access the UTRAN. The MME sends handover command to EUTRAN containing the information of voice bearer. The MME encapsulates the handover command and sent it to UE. At last, the UE camps on UTRAN and voice call is resumed.

6. MEASUREMENT AND RESULTS

This chapter begins with the discussion on performance parameters. It explains different radio measurement parameters of LTE and UMTS network. After that measurement and post processing tools used during measurements are explained along with their functions. It also presents the measurement scenario and campaigns. Finally the measurement results are presented in different measurement environment with graphical results.

6.1 Performance Parameters

Different performance parameters are studied and measured to see the effect on network performance, troubleshoot and optimize it during the user inter-RAT mobility from one system to another system in real environment conditions. It helps to maintain the quality and performance for operators. The measurement results were analyzed based on the following performance indicators.

6.1.1 UMTS User Equipment Measurements

Received Signal Code Power (RSCP) and Energy per bit to Noise Power Density (Ec/No) are two important radio parameters that indicate the strength and quality of a UMTS cell.

6.1.1.1 UMTS CPICH Received Signal Code Power (RSCP)

RSCP indicates the signal strength in downlink direction in UMTS. It is equivalent to LTE RSRP. This measurement helps to compared different UMTS cells according to their signal strength using the same carrier to make handover and cell reselection decisions. The factors that affect the signal strength in the outdoor environment are geometric field pattern of antenna in the measurement location, slow fading due to trees and buildings, fast fading due to multipath propagation and diffraction by obstacles. Similarly, in the indoor environment penetration loss due to number of the walls, doors and basements, reflection caused by people walking and door opening and closing, building material and attenuation due to thick walls and ceilings affects the signal strength. [28]

6.1.1.2 UMTS CPICH Ec/No

The signal quality of a UMTS cell is indicated by *Ec/No*. It is defined as the received energy per chip (E_c) on the P-CPICH of a given cell divided by the total noise power density (N_o) on the UMTS carrier. This parameter compares the signal quality and ranks each cell to make cell reselection and handover decisions easy. [28]

6.1.2 LTE User Equipment Measurements

Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) indicate the strength and quality of a LTE cell.

6.1.2.1 Reference Signal Received Power (RSRP)

RSRP indicates the strength of the received reference signal. It is the average linear received power over the power contributions of the resource elements carrying cell specific reference signals within certain frequency bandwidth. The value decreases logarithmically with respect to the distance from the base station based on propagation loss model. The measured RSRP value is sent by the UE in RRC measurement reports once a predefined event is triggered. RSRP is important in cell selection/ reselection and handover decision making when the UE moves from one cell to another. It is expressed in dBm. RSRP measurement reporting range is defined from -140 dBm to -44 dBm. [29]

6.1.2.2 Reference Signal Received Quality (RSRQ)

RSRQ indicates the quality of the received reference signal for which RSRP is measured. It plays an important role when RSRP value is not sufficient in making cell reselection and handover decisions. It is expressed in dB. Mathematically it is defined as:

$$RSRQ = N\frac{RSRP}{RSSI} \tag{6.1}$$

where N is the number of resource blocks, $RSSI$ is the received strength signal indicator which measures total average power in OFDM symbols and $RSRP$ is the received signal received power of the signal. The reporting range of RSRQ is defined from -19.5 dB to -3 dB with 0.5 dB resolution. [28] [29]

6.1.3 Downlink Throughput

Downlink throughput is another indicator for network performance.

***Table 6.1**: Theoretical data rate for 20MHz*

Modulation scheme	***bit/ symbol***	***Symbols in all PRB/ time slot***	***PDCCH overhead bits/time slot***	***RS overhead bits***	***Bits/ resource blocks***	***Data rate (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
2*2MIMO 64 QAM	12	8400	14400	4800	81600	163.2
4*4MIMO 64 QAM	24	8400	28800	9600	163200	326.4

Table 6.1 presents theoretical data rate for 20 MHz. In this thesis Medium Access Control (MAC) layer downlink throughput is taken into account because it does not include

any overheads from the physical layer. The downlink throughput depends upon bandwidth, modulation and coding scheme, Multiple Input Multiple Output (MIMO) utilization and interference level.. The data rate for 64 QAM is calculated as for the example For 64 QAM, total number of bits per symbol (bps) is 6. For short cyclic prefix, number of symbols per sub-carrier is 7. There are 100 PRBs in 20 MHz and each PRB contains 12 sub-carriers. Therefore, total number of symbols in 20 MHz is $7 \times 100 \times 12 = 8400\ symbols / timeslot$. Each time slot is of 0.5 ms. In 1 time slot there are 12 Physical Downlink Control Channel available. Altogether, there are $6 \times 12 \times 100 = 7200\ bits$ per time slot. There are 4 symbols in a single PRB for reference signals. Hence total number of bits in 100 PRBs for 64 QAM is $6 \times 4 \times 100 = 2400\, bits$. Hence, total overhead bits per time slot is $7200 + 2400 = 9600\ bits / timeslot$. Now the total available number of bits per time slot is $8400 \times 6 = 50400\ bits$. Overall available data bit per slot is $50400 - 9600 = 40800\ bits / slot$ which gives the data rate of 81.6 M bps. [10]

6.1.4 Link Adaptation

In LTE, link adaptation depends upon Channel Quality Indicator (CQI). The UE measures the channel quality and sent to the eNodeB in the form of CQI. These values are used by the link adaptation algorithm at eNodeB.

***Table 6.2**: CQI values and their modulation in LTE [19]*

CQI Index	*Modulation Scheme*	*Coding rate* 1024*	*Bits / Resource Element*
0	Out of range		
1	QPSK	78	0.15
2	QPSK	120	0.23
3	QPSK	193	0.38
4	QPSK	308	0.60
5	QPSK	449	0.88
6	QPSK	602	1.18
7	16 QAM	378	1.48
8	16 QAM	490	1.91
9	16 QAM	616	2.41
10	64 QAM	446	2.73
11	64 QAM	567	3.32
12	64 QAM	666	3.90
13	64 QAM	772	4.52
14	64 QAM	873	5.12
15	64 QAM	943	5.55

Table 6.2 presents the CQI reported value for LTE. Every CQI corresponds to MCS (Modulation and Coding Scheme) that helps to determine the number of bits transferred

in each Transport Block Size (TBS). CQI may be wideband or sub band. In wideband, a single CQI is used to indicate the whole channel quality whereas sub band CQI indicates the particular sub bands. [19] [30]. The UE report the highest CQI for BLER does not exceed to 10% but if it exceeds then CQI value range from 1 to 15 are reported depending upon channel quality. CQI from 1 to 6 has corresponds QPSK modulation scheme with variable coding rate. CQI from 7 to 9 has the 16 QAM modulation scheme while 10-15 corresponds to 64 QAM modulation scheme with different coding rate.

***Table 6.3**: CQI values and their modulation in HSDPA [30]*

CQI index (HSDPA)	Modulation Scheme		CQI index (HSDPA)	Modulation Scheme
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			

Table 6.3 shows the CQI reported table with modulation and coding scheme for 3G network. The UE report the CQI value from 0 to 30 depending upon the channel quality. CQI with 1 to 15 corresponds with QPSK modulation scheme with different coding rate while CQI value from 16 to 30 corresponds with 16 QAM modulation scheme.

6.1.5 Handover Success Rate

Handover success rate is one of the key performance parameter to test the network performance during handover process. In this thesis inter-RAT handover from LTE to UMTS is mainly concerned. It is triggered by dual measurement event B2 for LTE and A3 for 3G toward the LTE network. In order to have error free handovers between different RATs, thresholds for inter-RAT systems must be configured. [31] [32]

Handover success rate is defined as total number of handover confirms to number of handover request. Mathematically,

$$Handover\ Success\ Rate = \left(\frac{number\ handover\ confirms}{number\ handover\ attempts}\right) \times 100 \tag{6.2}$$

It is calculated from the received signalling message sent to UE.

A handover is said to be successful if a handover command is sent to the UE and a handover complete command is received. If it doesn't receive then the handover is said to be failure. Simply,

$$Handover\ Failure\ Rate = 1 - Handover\ Success\ Rate \tag{6.3}$$

During the handover process, there are two possibilities: the data session stops and after some interval data session resumes or the data session get disconnect and a new connection is re-established. During the measurement in this thesis, handover failure is considered only if data session fails and starts from the beginning from the new connection link. Some common examples like failure of target resource allocation by Radio Network Controller (RNC), high speed of the mobile, poor radio link condition, congestion in the network, handover facility not supported by the network and target unreachable are the common reasons that may leads towards handover failure.

6.1.6 Control Plane Latency

The important parameter for analyzing the network performance is control plane latency also called handover latency. The measurement report sent by the user to eNodeB triggers the handover from LTE to 3G network if the triggering condition B2 is satisfied. The triggering condition B2 is fulfilled when the Reference Signal Received Power (RSRP) value of the serving LTE cell becomes worse than that of the threshold value set for LTE cell and the Received Signal Code Power (RSCP) of the 3G neighbour cells becomes better than the threshold value set for UMTS cell. Handover delay is the timing gap between the UE sends the measurement report indicating handover and the time the UE sent handover confirm message. According to 3GPP, handover latency should be less than 300ms for real time applications service and less than 500ms for non real time services. [33] [34]

In this thesis delay is calculated manually from RRC signalling message from UE side using mathematical expression: [19]

$$D_{handover} = RRC\ procedure\ delay + \text{int}\,errupt\ time \tag{6.4}$$

where, $RRC\ procedure\ delay$ = 50ms.

Some possible reasons like authentication and authorization interval to connect new network, moving speed of the user, limited resources available, imperfection in the synchronization between the base stations, mismatch of the mobility parameters and evolvement of more network elements may leads to the longer delay.

6.1.7 User Plane Latency

User plane delay is another important factor that directly affects on the subscriber quality of service.. This section discusses two methods of studying the user plane delay.

6.1.7.1 Round Trip Time (RTT)

RTT test is done using the ping method. Ping technique is a simplest technique to measure the RTT from the end user (client) to the remote server in the internet. RTT is a delay type between the end user and the operator's internet gateway. Such kind of delay can be optimized by the network operators. It is also used to check and troubleshoot the internet connections between two IP hosts and delay measurement. It uses the Internet Control Message Protocol (ICMP) protocol to transfer packets. The network layer is responsible for delivering the data packets from source to destination. ICMP is a network layer control protocol used to check the network connectivity by utilizing the RTT values. The packets sent to the host are called echo-Request and packet sent back is called echo-Response. The time requirement for a packet to travel from a source to a destination and back again is RTT. For any Internet Protocol (IP), RTT can be determined by ping to that particular address. This parameter helps in diagnosing reliable quality for real time applications like VOIP and online game application. Any network capacity can be estimated by Bandwidth-delay product (BDP) with expression: [33]

$$Bandwidth - delay\ product = Estimated\ \ RTT \times Bandwidth \tag{6.5}$$

Longer BDP leads to high risk of packet loss, packet reordering, and TCP retransmission issues. The acceptable RTT differs from one service type to another. Some of the factors like different radio technology used, different types of transmission media, physical distance between the source and remote server, number of nodes between the transmitter and receiver, amount of traffic in the network and speed of the intermediate nodes affect the RTT values. [28]

Figure 6.1 shows the RTT values for different packet size in LTE and 3G networks taken in static position. The bar diagram shows the difference in RTT value for different packet size. For 16 bytes of data LTE has round trip time of 31 ms while for 3G network is 50 ms which is 1.6 times high. On further comparing, for 32 bytes, 64 bytes, 1024 bytes and 2048 bytes LTE has 1.65, 1.76, 2.36 and 2.65 times lower in RTT value than in 3G network.

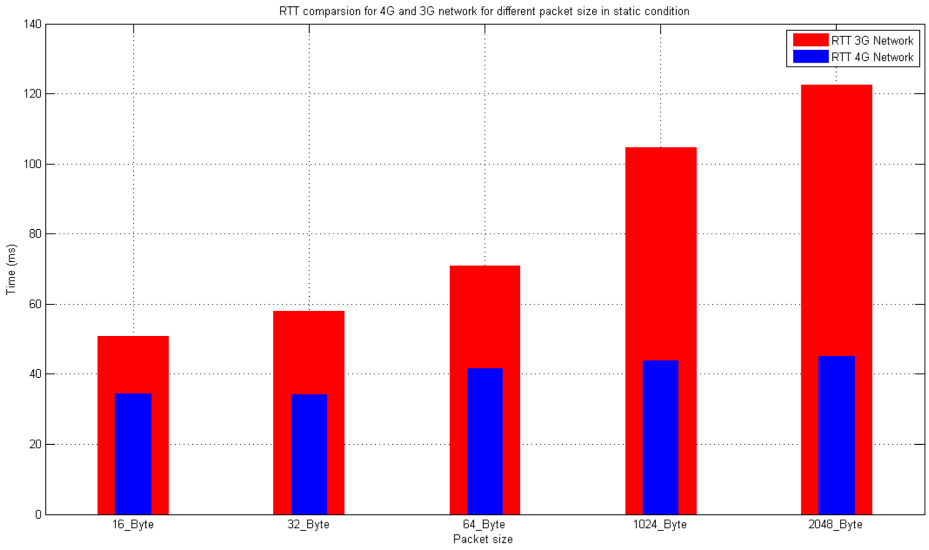


Figure 6.1: *RTT comparison between 3G and 4G network for different packet size*

6.1.7.2 Service Interrupt Time

This is another metric to determine the user plane delay during the handover process. It gives how long a UE data service is interrupted during the handover process. This parameter relies on the handover condition. This parameter helps to analyze the seamless connectivity between two different networks. According to 3GPP, interruption time is defined as the time difference between the data session disconnected and data session resumes. Depending upon the target cell it may be: [19]

$$T_{interrupt1} = T_{IU} + T_{sysc} + 50 + 10 \times F_{\max} ms \qquad (6.6)$$

$$T_{interrupt2} = T_{IU} + T_{sys} + 150 + 10 \times F_{\max} ms \qquad (6.7)$$

where T_{IU} is the interruption uncertainty when changing from E-UTRAN to UTRAN. It can be up to 10 ms. T_{sysc} is the time for measuring Downlink Dedicated Physical Control Channel (DPCCH). If high layers use post-verification method, T_{sysc} =0 otherwise 40 ms and $F_{\max}$ is the maximum number of radio frames being used. Equation 6.6 is used if the target cell is known and Equation 6.7 is used if the target cell is unknown. In this thesis service interruption is calculated manually from the signalling message as well as from the MAC layer throughput graph.

6.2 Measurement and Post-processing Tools

The required test tools and software used during measurement campaign are presented in Table 6.4 along with their motive of use.

***Table 6.4**: Measurement Tools*

Tools	*Manufacturer*	*Purpose of use*
Laptop	IBM	Run Nemo Outdoor and Nemo Analyzer
LTE Dongle	Huawei	Access broadband networks anytime and anywhere
LTE SIM	DNA	Data storage mobile device
Nemo Outdoor	Anite	Monitoring and recording the measurement
Nemo Analyzer	Anite	Analyzing the measured data
MS Excel	Microsoft	Post processing the data
MS paint	Microsoft	Edit pictures
MS Visio	Microsoft	Draw pictures
MathType	Microsoft	Mathematical equations
Matlab	MathWorks	Data plot
GPS	Garmin	Location coordinates

6.3 Measurement Campaigns

The whole measurements are done for DNA commercial network in Tampere University of Technology (TUT) campus area in Hervanta. The environment is classified as a macrocellular suburban type based on the location of the antenna, amount of the tall buildings and natural obstacles. Two different measurement campaigns conducted in two different locations such that radio conditions are different for both scenarios are presented in Table 6.5. Both measurements are conducted in LTE FDD 1800 MHz and UMTS FDD 2100 MHz frequency bands in DNA network.

***Table 6.5**: Measurement campaigns*

Measurement location	*measurement environment*	*Operating frequency*		*Bandwidth (MHz)*
		LTE (MHz)	UMTS (MHz)	
TUT	Outdoor	1800	2100	20
TUT	Indoor	1800	2100	20

Figure 6.2 and 6.3 are the maps of measurement location. The red color indicates the measurement route and the blue oval circle in the map indicates expected inter-RAT handover spot.

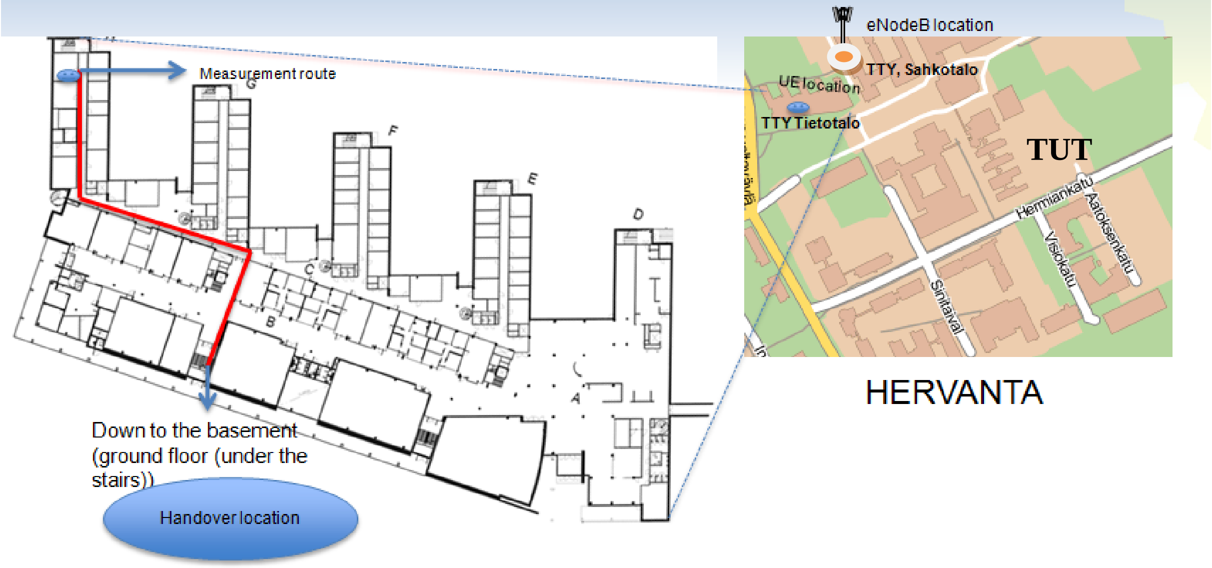


Figure 6.2: Measurement location and route in Tietotalo TUT

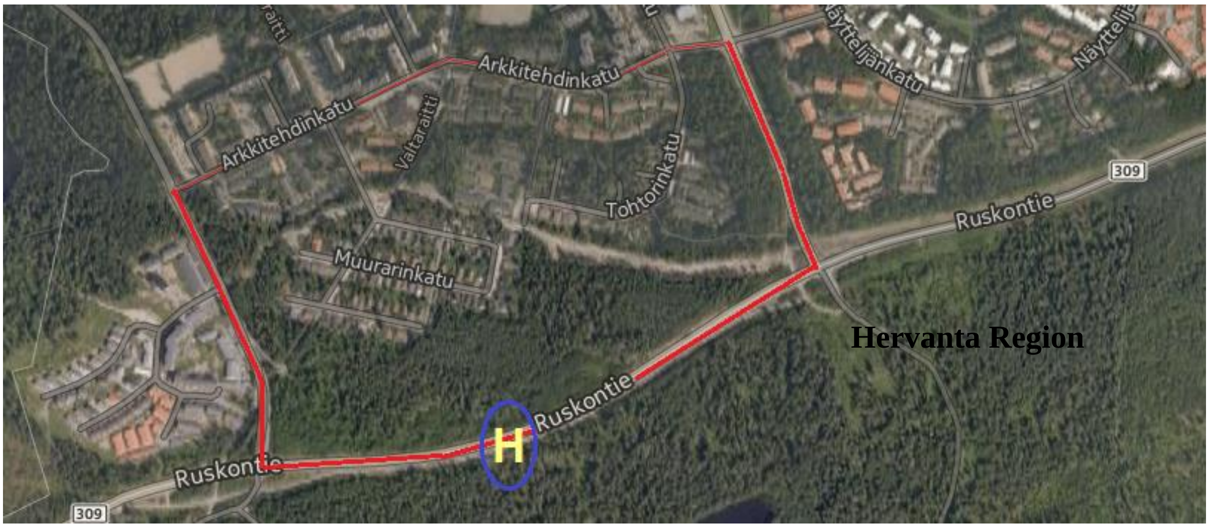


Figure 6.3: Measurement location and route outside TUT area

6.4 Measurement Setup

This section describes the setup done before the measurement for two different locations.

6.4.1 Outdoor Scenario

A measurement laptop running the Nemo Outdoor with LTE dongle connected to it was made ready. A LTE dongle was used as end user device which operates in both LTE and 3G modes of operation. Nemo Outdoor was used to record and save radio related parameters for further analysis. A Global Positioning System (GPS) was connected to the measurement laptop to determine the location coordinates and placed on the top of a test car. Initial position to start the measurement was chosen such that UE lie on 4G

LTE dominance area in connected mode. This was done to camp the UE in the LTE network without band locking. A 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. A script was defined in such a way that it runs continuously until it manually disconnected. Once the location and route was determined, same process was repeated for multiple runs to have more precise results. Altogether 14 measurements were made for outdoor location during day time. The measured files were analyzed from Nemo Analyzer. Final data analysis was done by extracting the data into Matlab.

For *throughput* testing in the downlink direction, a 272 MB file was downloaded using Hypertext Transfer Protocol (HTTP) protocol during the whole measurement. A script was written in such a way that data is continuously transferred until the UE gets disconnected.

For *RTT latency*, a measurement unit, Nemo Outdoor and an application server were used for packet switched data testing. 32 bytes of packet size was used to test the Round Trip Time (RTT). The response time from the server was set to 1second. The waiting time to send a new packet was also set to 1 second. The script was modified in such a way that it continuously PING the application server after UE gets connected to the network till UE gets disconnected using loop command.

6.4.2 Indoor Scenario

The measurement setup was almost similar as in the outdoor location measurements. The only difference was the speed of the UE. Measurement was done in walking speed by carrying in the hand. At this location independent 10-15 min data samples were collected for 30 measurements during mobility conditions. The measurements were taken in both day and evening time on different days.

6.5 Measurement Results

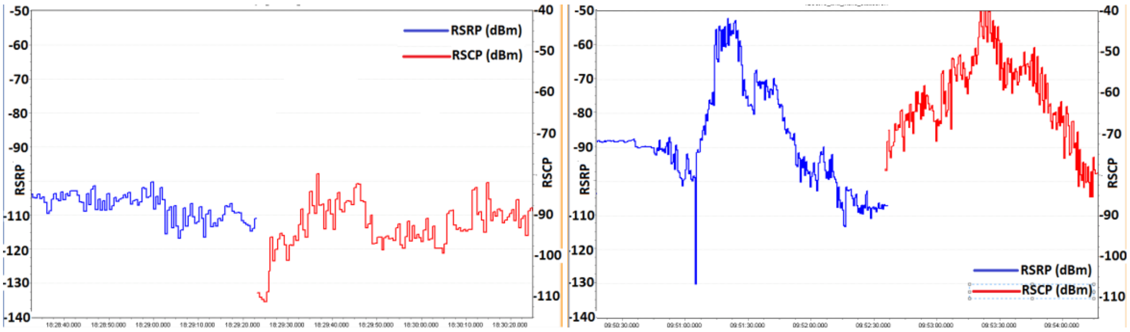
In this section the measurement results are presented in the following pattern. At first, measurement parameters like Reference Signal Received Power (RSRP), Reference Signal Code Power (RSCP), Reference Signal Received Quality (RSRQ), Energy per bit to Noise Power Density (E_c / N_0), Channel Quality Indicator (CQI) and Signal to Noise Ratio (SNR) are presented with graphs to see the radio propagation variation when UE moves from LTE network towards 3G. In the middle section, channel conditions are compared in two different scenarios. Additionally, the impact of inter-RAT handover system performance is evaluated based on different KPI's like handover success rate, MAC DL throughput, user plane latency, control plane latency and Round Trip Time (RTT). Finally the performance of inter-RAT handover in indoor and outdoor environment is compared based on the KPI's measurement results.

6.5.1 Connected Mode Mobility

All the measurement results are compared using Cumulative Distribution Function (CDF) plots.

6.5.1.1 RSRP and RSCP

RSRP and RSCP are the measurement parameters to determine the signal strength of the LTE cell and 3G cell respectively. They are necessary parameter for making cell selection/reselection and handover decisions as well. Figure 6.4 shows the RSRP and RSCP level during mobility from LTE to 3G networks for two scenarios. The signal level graph is plotted against time. The y-axis indicates the signal level while x-axis shows the time interval. The left side of the y-axis represents the RSRP level indicated by blue color while right side of y-axis indicates the RSCP level and is represented by red color.



(a) (b)

***Figure 6.4**: RSRP and RSCP level: (a) Indoor scenario and (b) Outdoor scenario*

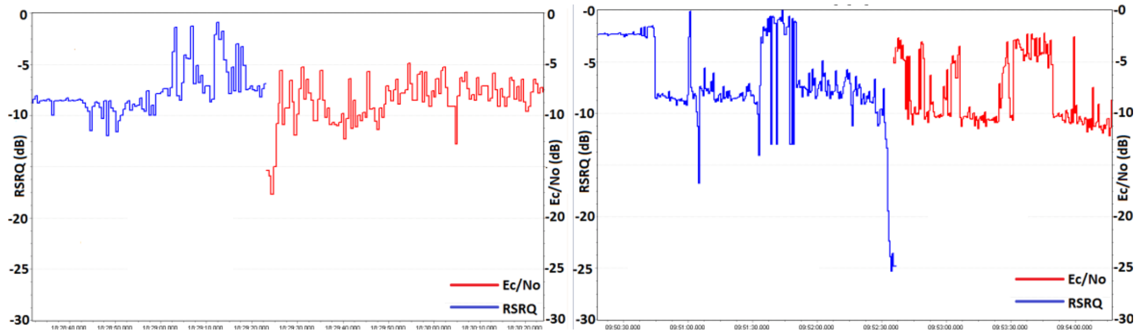
The graph shows signal level is degraded as the user moves away from the LTE coverage area. After the inter-RAT handover, the signal level starts to increase towards the 3G coverage. The graph shows the signal level is high in the outdoor scenario than indoor scenario. The reason may be due to the involvement of more number of base stations in the outdoor locations. But the signal level varies faster in outdoor than indoor. This is due to fading caused by the tall buildings, forest areas and terrain effect.

In outdoor scenario, the inter-RAT handover is triggered at the RSRP value of -105 dBm which is less than RSCP for the UMTS neighbour cell is -91 dBm. The main reason for inter-RAT triggering is that RSCP level is higher enough by 14 dB than RSRP at the cell edge. The decision is made by the eNodeB based on the RSRP measurement in the LTE cell because the 3G cell satisfies the inter-RAT handover triggering conditions and can provide the running service with better quality of service.

In indoor scenario, handover is triggered even though the RSRP value is good enough than the RSCP value. The primary reason is due to the high effect of shadowing and fast fading. Another reason may be due to small value of handover margin (Q_{hyst}) which also lead to the unnecessary handover decisions. [35]

6.5.1.2 RSRQ and E_c/N_0

Figure 6.5 shows the RSRQ and Ec/No level for two measurement locations. The RSRQ is important in making cell reselection decision when RSRP value is not sufficient. LTE RSRQ is equivalent to 3G UMTS Ec/No value. The figure clearly shows that RSRQ and the Ec/No level is good in both measurement routes. The RSRQ and Ec/No value are above -10 dB for most of the time in both routes. The RSRQ follows the pattern of RSRP. The value goes on decreasing as the UE moves away from the coverage area and same pattern applies to the Ec/No level.



(a) (b)

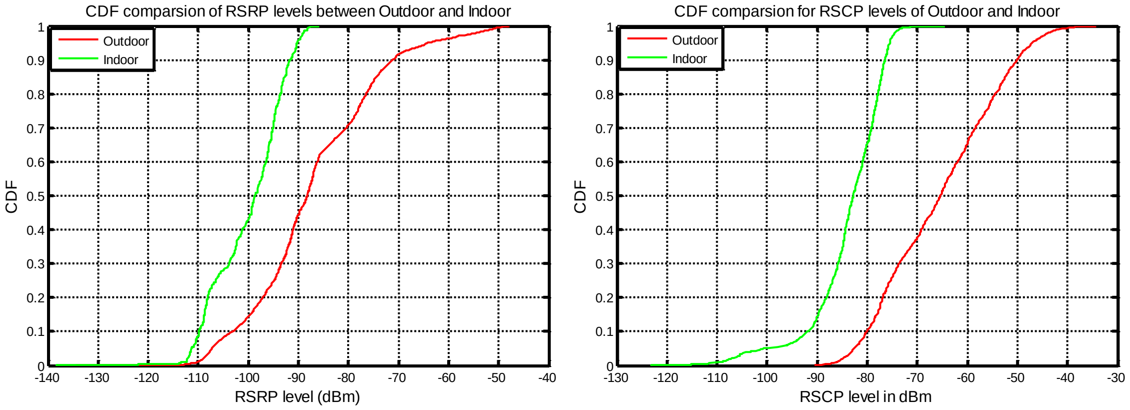
Figure 6.5: RSRQ and Ec/No level: (a) indoor scenario and (b) outdoor scenario

6.5.2 Channel Condition Comparison

Now, the channel conditions are compared and analysed for outdoor and indoor environments with the help of cdf plots of radio measurements parameter and mobile reports.

6.5.2.1 RSRP and RSCP Comparison

Figure 6.6 shows the comparison of cumulative distribution function of RSRP and RSCP levels for two different scenarios when inter-RAT handover is performed.



(a) (b)

***Figure 6.6**: CDF comparison in outdoor and indoor scenarios: (a) RSRP and (b) RSCP*

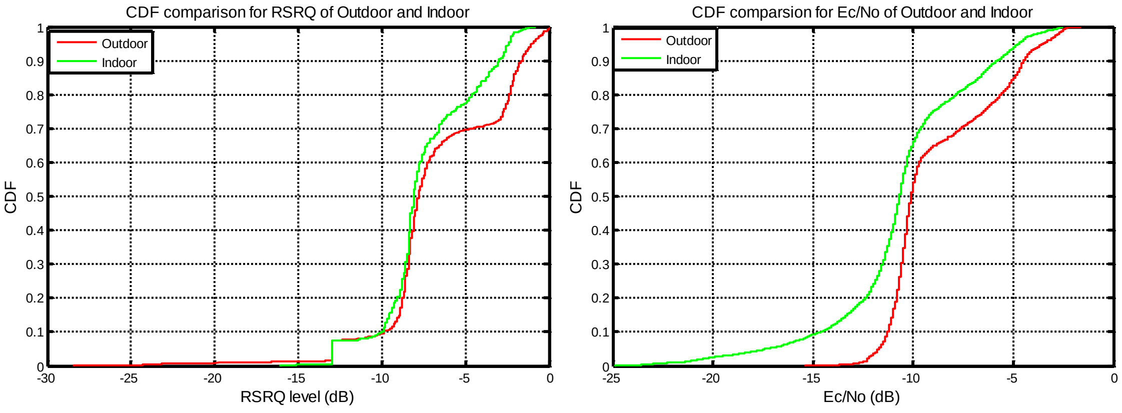
The red color line indicates the RSRP and RSCP level in outdoor scenario whereas the green color indicates the RSRP and RSCP for indoor scenarios. Maximum RSRP level reached for outdoor is -47.8 dBm and for indoor is -85.9 dBm while minimum RSRP for outdoor is -134.3 dBm and for indoor is -138.3dBm. 50th percentile of RSRP samples has above -88.3 dBm whereas for indoor is -98.65 dBm. The highest and lowest RSCP level measured in the outdoor is -34 dBm and -90 dBm whereas in indoor is -64 dBm and -123 dBm respectively. The distribution clearly shows that outdoor scenarios have better RF condition as compare to indoor. The statement is confirmed by signal level shown in Figure 6.4.

***Table 6.6**: Statistical parameters for RSRP and RSCP*

Statistics	RSRP (dBm)		RSCP (dBm)	
	Indoor	Outdoor	Indoor	Outdoor
Maximum	-85.90	-47.80	-64.40	-34.30
Minimum	-138.30	-134.30	-123.10	-90.80
Mean	-99.90	-86.99	-83.82	-65.51
Median	-98.65	-88.30	-82.80	--65.4
St. Deviation	7.02	12.64	7.280	11.42

Table 6.6 shows the statistical comparisons between the signal level in outdoor and indoor. The overall measurement result shows that the signal strength and mobility are closely related. This is because handover algorithms are triggered based on signal strength measurements. The number of handovers, service delay and the Quality of Service (QoS) are decided based on these parameters. So, during network optimization these parameters are taken into account carefully. Handover process reduces radio resources being wastage; degrade quality level and system performance.

6.5.2.2 RSRQ and E_c/N_0 Comparison



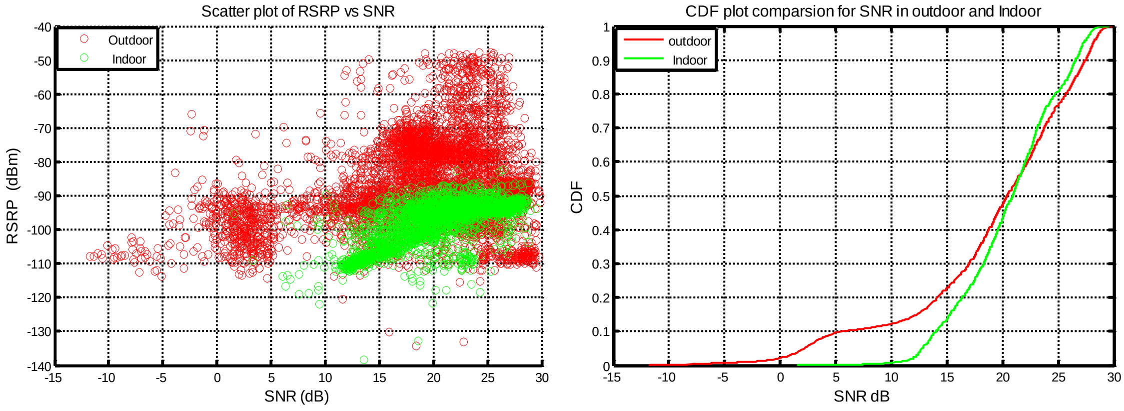
(a) (b)

***Figure 6.7**: CDF comparison for outdoor and indoor: (a) RSRQ and (b) Ec/No*

Figure 6.7 gives a clear picture of the cdf comparison of the RSRQ level and Ec/No level for both measurement scenarios. The graph clearly shows that the RSRQ and Ec/No level for the outdoor are better than indoor scenarios. The maximum value for RSRQ is 0 dB and for Ec/No is -1.6 dB for outdoor whereas the maximum value observed for RSRQ and Ec/No is -0.8 dB and -2.5 dB for indoor. 90 percentile of the samples have RSRQ value above than -12 dB for both locations while for Ec/No value slightly differs in two different locations. The graphical trend of RSRP and RSRQ is almost similar. The value declines at the same time and at the same location. This shows that the measurement locations have problem of coverage not of interference. The same theory applies for Ec/No value. RSRQ compares the signal quality and helps in ranking each cell to make cell reselection and handover decisions easy. [8]

6.5.2.3 SNR Comparison

Figure 6.8 (a) shows the scatter plot between RSRP and SNR for two different scenarios. RSRP level is plotted in y-axis while SNR is plotted in x-axis. The red color circle represents the RSRP samples collected from outdoor scenarios while green circle indicates the RSRP samples collected for indoor. The SNR value for the outdoor ranges from -11.7 dB to 29.9 dB whereas for indoor it ranges from 1.6 dB to 29.6 dB. It shows the SNR level for both locations are good as maximum measurement samples are concentrated on 15 dB to 30 dB. This is due to the high signal level near the measurement location which fairly dominates the interference and noise. It indicates that link quality is in good condition.



(a) (b)

***Figure 6.8**: a) scatter plot RSRP vs. SNR and (b) CDF comparison of SNR*

Figure 6.8 (b) is the cdf plot comparison of SNR for two measurement scenarios. The cumulative plot shows that the indoor location has better SNR than outdoor location. The maximum SNR observed for outdoor was 29.9 dB while for indoor was 29.6 dB. The mean SNR value for indoor is higher than outdoor by around 1.5 dB. Half of the measurement data for outdoor has SNR above 20.4 dB while half of the measurement data for indoor has SNR above 20.9 dB. The minimum SNR observed for indoor was 1.6 dB while for outdoor was -11.7 dB. This information is summarized in Table 6.7

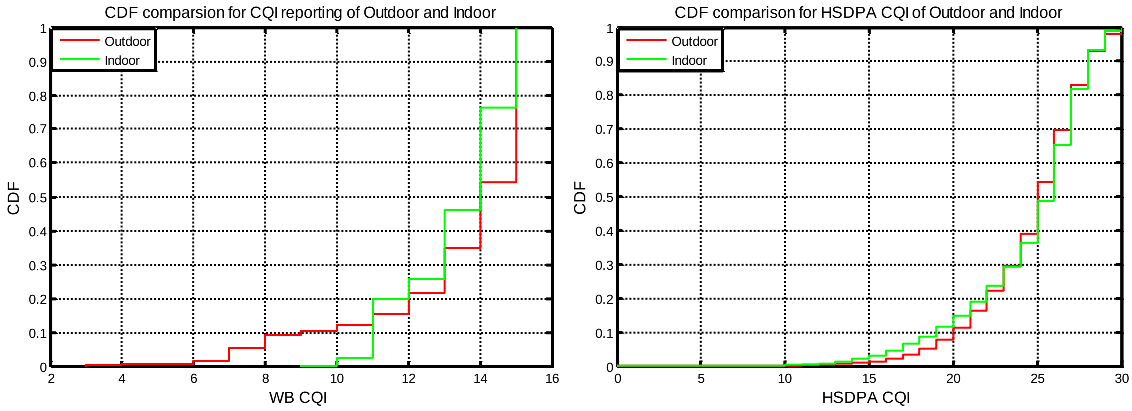
***Table 6.7**: Statistical parameters for SNR*

Statistics	SNR (dB)	
	Indoor	Outdoor
Maximum	29.6	29.9
Minimum	1.6	-11.7
Mean	20.5	19
Median	20.9	20.4
St. Deviation	4.5	7.7

Poor SNR was observed due to obstruction of line of sight components by trees and buildings. Outdoor has a mean SNR of 19 dB while indoor has 20.5 dB which shows that indoor offers a better radio condition.

6.5.2.4 CQI Comparison

Channel Quality Indicator (CQI) is an important parameter to indicate the channel quality of the radio environment in the coverage area and to see the impact in system performance of the band.



(a) (b)

***Figure 6.9**: CDF comparison: (a) WB CQI and (b) HSDPA CQI*

Figure 6.9 shows the cdf comparison of CQI reporting for both scenarios when handover is performed. The green color indicates CQI reported in indoor while red color denote for outdoor scenarios. The maximum wideband CQI reported for outdoor and indoor is 15 in LTE whereas the maximum HSDPA CQI reported in 3G network is 30.

***Table 6.8**: Statistical data of reported CQIs during I-RAT handover*

Statistics	Wide band CQI		HSDPA CQI	
	Indoor	Outdoor	Indoor	Outdoor
Maximum	15	15	30	30
Minimum	9	3	0	0
Mean	13	13	24	25
Median	14	14	26	25
St. Deviation	2	2	4	3

Table 6.8 shows the minimum wideband CQI 0 for outdoor and indoor is 3 and 9 respectively. The average CQI reported is 13 for both locations. The results shows 64 QAM is the most dominant modulation in LTE whereas 16 QAM for 3G network. In indoor the proportion of 64 QAM used is pretty high as compared to the outdoor. Nearly 99% of the total measured samples used 64 QAM for indoor whereas for outdoor it used 90% which is also a high value. The highest modulation is due to the good channel condition and less number of users. Obviously it can be verified from RSRP and SNR plot in previous sections.

6.5.3 MAC DL Throughput

Throughput is an important factor to analyse the network performance when handover is performed. This section compares the MAC layer throughput for two measurement scenarios during mobility from LTE to UMTS network with HSDPA technology.

Figure 6.10 is an example of MAC layer throughput trend in downlink direction for outdoor and indoor scenarios captured by the mobile. The graph is plotted between MAC layer throughput and time interval. In both graph the left corner of y-axis shows the throughput value for LTE and is represented by blue color while in right side of the y-axis shows throughput for 3G network denoted by red color. In the graph there is zero download as well. This is due to gap between file downloads caused by small file size.

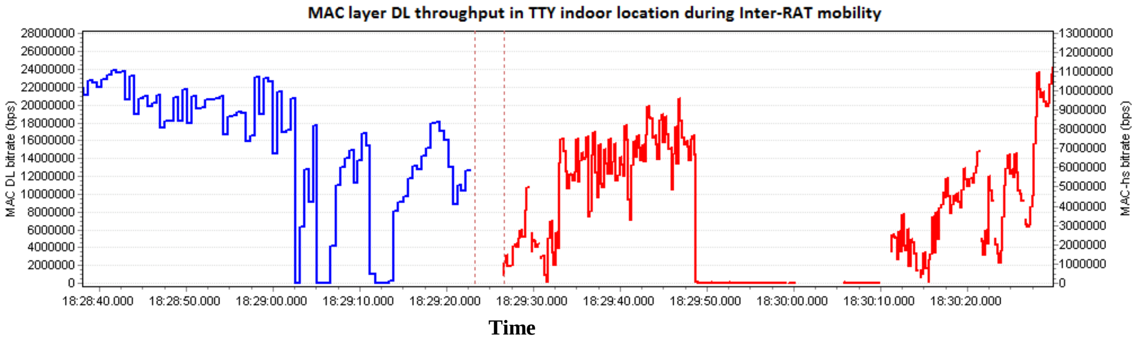


***Figure 6.10**: (a) MAC DL bit rate comparison during inter-RAT handover in outdoor*

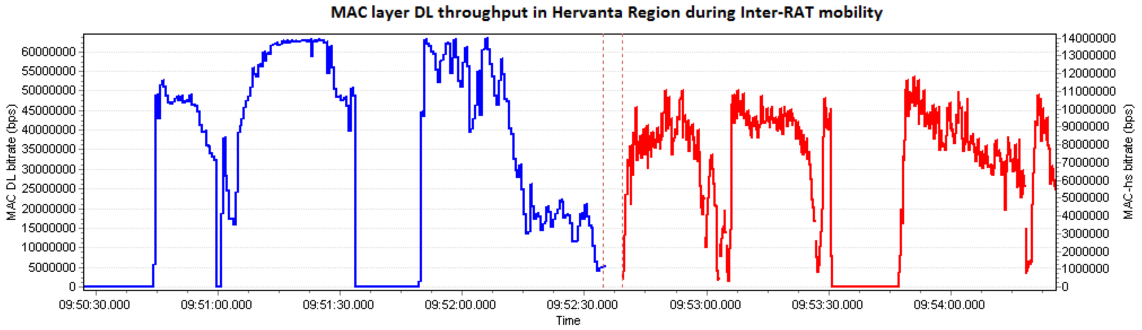


***Figure 6.10**: (b) MAC DL bit rate comparison during inter-RAT handover in outdoor*

The throughput is decreasing towards the LTE cell edge and after successful handover the throughput starts improving as the UE moves towards the centre of the 3G cell. During the handover time, download is interrupted and there is no any download of the data. The user data is paused for few seconds. This download interruption is shown by the two red dotted vertical lines in the graph.

Figure 6.11 depicts the cdf comparison of MAC layer throughput rate for both measurement scenarios. Nearly 25th percentile of data for outdoor and around 22nd percentile of data shows zero downlink rate. This is because of the gap caused between file downloads. 50th percentile of measurement data for outdoor has throughput about 40 Mbps while for indoor has 25 Mbps.

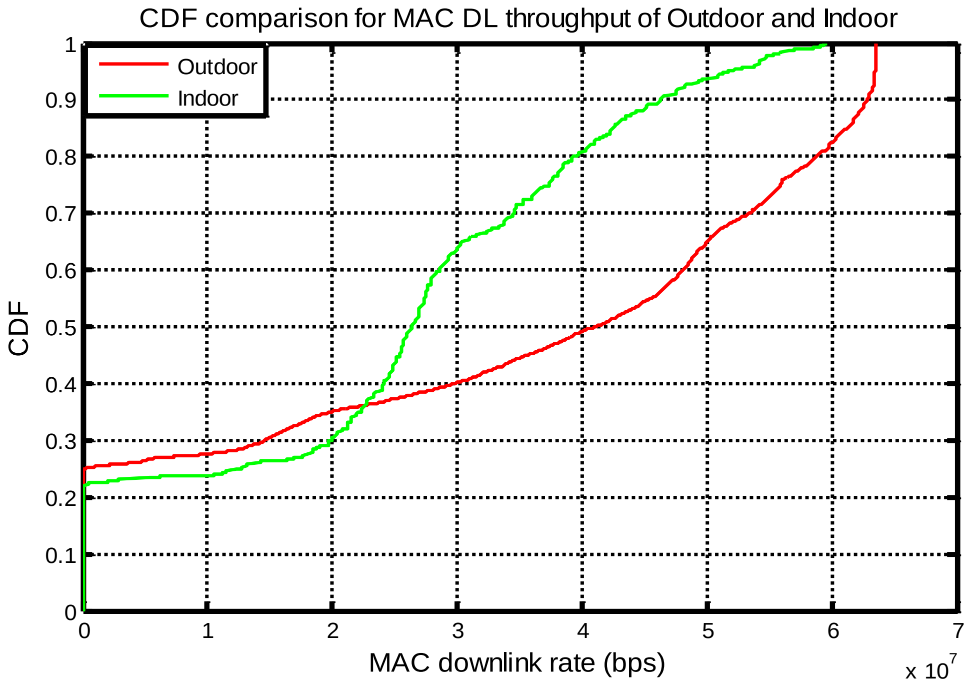


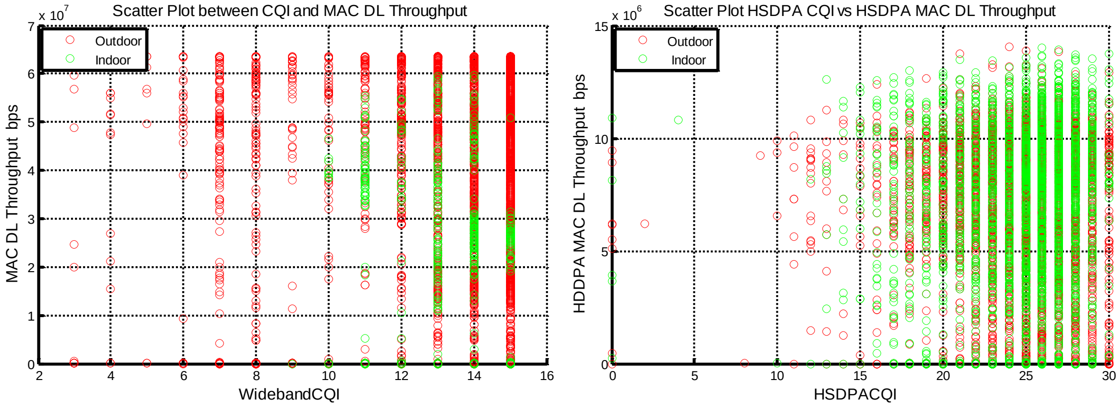
***Figure 6.11**: CDF comparison for MAC DL throughput*

The average throughput for outdoor is 33.7 Mbps whereas for indoor is 24.8 Mbps. The standard deviation for both measurement locations is very high. This is due to the abrupt change in the radio channel condition. The statistical comparisons of the collected samples for MAC layer DL rate in two different scenarios are summarized in Table 6.9.

Table 6.9: *CDF statistics comparison for MAC DL throughput*

Statistics	Mac DL throughput (Mbps)	
	Indoor	Outdoor
Maximum	59.63	63.60
Minimum	0	0
Mean	24.80	33.70
Median	26.30	41.09
St. Deviation	16.71	24.30

The result shows that mobility has caused abrupt change in the throughput value. The data service interruption is due to time taken to switch the path of the packet from the source eNodeB of LTE cell to the target NodeB of 3G cell. This interval starts once UE gets disconnected to the serving eNodeB after receiving the handover control message. The downlink packets are forwarded to the NodeB and are queued by the NodeB in the UE buffer. These buffered packets are transmitted only after successful radio link setup to the NodeB. Laterally with the increase in SNR, throughput rate rises. This shows throughput decreases towards the cell edge due to poor radio conditions and starts to improve towards cell centre.



(a) (b)

Figure 6.12: *CQI vs. DL rate: (a) MAC DL vs. CQI and (b) HSDPA DL vs. CQI*

Figure 6.12 shows the scatter plot of CQI vs. MAC layer throughput and for two measurements. These samples are collected when successful inter-RAT handover is performed. The red circle represents the outdoor MAC DL samples while the green indicates the samples from indoor. The figure clearly shows that the downlink rate depends upon the CQI reported values. The maximum wideband CQI samples reported to UE in the LTE network ranges from 7 to 15 for outdoor while it ranges from 9 to 15 for indoor scenario. It indicates that the radio channel condition is good. During that reporting range the maximum observed throughput is 63.6 Mbps for outdoor whereas 59.63 Mbps for indoor at LTE network. In 3G network side, the CQI reporting range for outdoor and indoor from 16 to 30. This indicates that the 16 QAM is the most dominant modulation in the measurement route. The maximum observed throughput in 3G network is 14 Mbps for both locations.

It is seen from result that as UE moves away from the LTE coverage area, low CQI values are reported by eNodeB. This is due to the drop in signal level (RSRP). Lower CQI has reduced the order of modulation and coding rate. This has reduced the spectral efficiency and finally decreased the MAC layer throughput. After successful handover, when UE moves towards the 3G cell centre, signal level (RSCP) starts increasing. This leads to increase the CQI value which yields the high order of modulation of 16 QAM.

6.5.4 Handover Success Rate

Inter-RAT handover success rate is another performance parameter to test the network performance during mobility from one network to other. Literally, a handover is successful when the UE's context and enough resource are available at the target cell when UE tries to access it. Based on the number of measurements performed on the different location in their respective measurement route handover success rate is calculated.

Figure 5.15 presented in previous Section 5.7 is an example of successful inter-RAT handover message captured during the measurement for outdoor. In the figure the red color box indicates the successful intracellular handover within the LTE network. In this series of measurement, a successful inter-RAT handover is determined by verifying the message sequences starting from when UE receives " RRC connection Release" (labelled by number 1) from the source LTE cell till "Radio Bearer Reconfiguration Complete" message (labelled by number 18) from the target 3G cell. After successful handover the new radio bearer from the 3G network is established and traffic starts to schedule from the new 3G cell. In both locations, there is short interruption in service when handover is performed but the result shows impressive result with a 100% handover success rate and is presented in Table 6.10.

***Table 6.10**: Handover success rate during I-RAT mobility*

Measurement Location	*No. Of H/O attempts*	*No. Of H/O Conformed*	*Success rate (%)*
TUT outdoor	14	14	100
TUT indoor	31	31	100

The result presented here is valid only for the respective locations and specific number of measurement performed in particular date for this thesis. The success rate is calculated only for the 14 measurements in outdoor and 31 measurements in indoor measurement routes. The successful handover location is shown in Figure 6.2 and 6.3 by the blue circle area. The handover is randomly distributed in those areas due to signal level fluctuations in propagation environment.

The primary reason for 100 percent success rate is due to the signal level of the target 3G network (RSCP value) is good enough to decode the measurement report from the UE. The next reason may be due to low traffic congestion. This can be verified from the Figure 6.12. Other possible reasons are low system load in the target cell and good propagation condition. Higher success rate minimizes the packet loss and deliver packets in the order manner between the source and the target base station.

This rate should be high enough to maintain radio link connectivity otherwise online applications like Voice over Internet protocol (VoIP), online games and IP-TV which are delay sensitive can cause effect on user perceived performance resulting in user dissatisfaction. This directly affects the business of the operator. [36]

6.5.5 Control Plane Latency

Handover latency is another important factor for maintaining the network performance. Network controls the handover in LTE and usually triggered based on the measurement report sent by the user. In this thesis handover latency is calculated by time interval between the successful inter-RAT processes from LTE to 3G networks and the interval of UE receiving the first packet after moving to the new attachment to 3G network.

The handover delay is calculated manually by using the formula presented in Section 6.1.6. The exchange of signalling message between the network elements observed by the mobile during handover process is shown in Figure 5.15 and 5.16 labelled with numbers from 1 to 18. The delay and impact of handover latency on downlink throughput can be seen in Figure 6.10 as well.

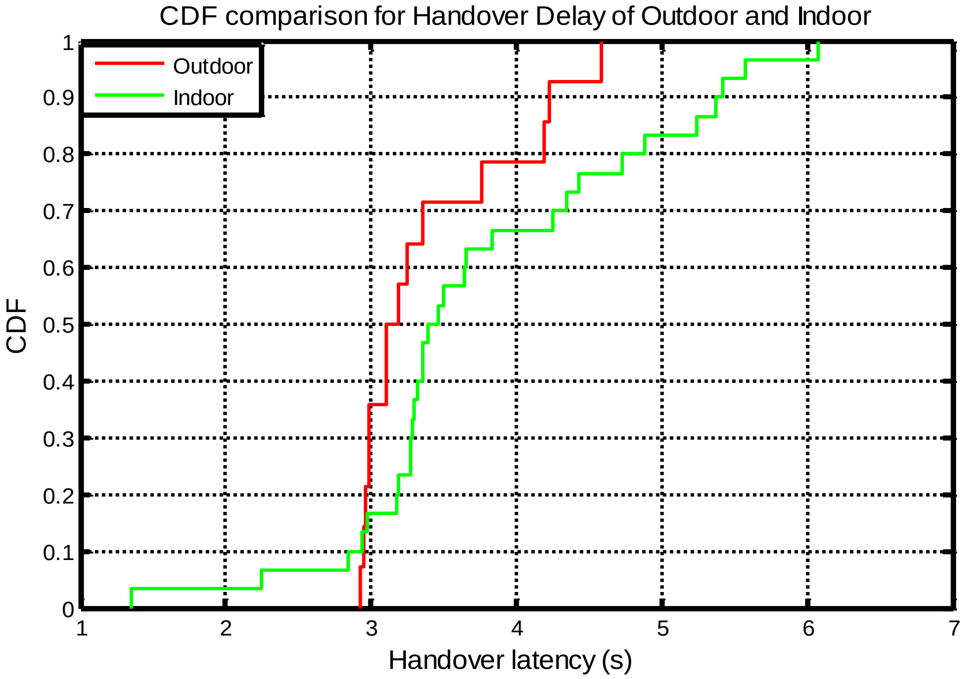


***Figure 6.13**: CDF comparison of Handover delay during inter-RAT mobility*

Figure 6.13 shows the cdf comparison of the handover delay when handover is performed in two different locations. The maximum delay for the outdoor scenario is 4.59 sec while for indoor is 6.07sec. But the indoor scenario experience lowest latency of 1.35 sec compared to that of outdoor with 2.92 sec. The half of the sample data for outdoor are below 3.15 sec while for indoor are below 3.42 sec. Outdoor has an average delay of 3.39 sec and the indoor has 3.78 sec which is very high. The calculated data are presented in Appendix A and B. Table 6.11 shows the statistical data of the cdf plots.

***Table 6.11**: Statistical data for handover delay*

Statistics	Handover delay (s)	
	Indoor	Outdoor
Maximum	6.07	4.59
Minimum	1.35	2.92
Mean	3.78	3.39
Median	3.42	3.15
St. Deviation	1.05	0.55

The main reason for longer delay in both scenarios is due to longer processing time for handover after getting measurement report. Due to bad channel condition UE may be unable to receive or respond the network message. Longer handover delay has results into longer data interruption therefore; handover should be as fast enough to prevent the radio condition from deteriorating too much. Longer delay has high chance of handover failure. Once the handover is failed radio links breaks and service applications get disconnected. This interrupts the ongoing session and the ongoing real time application reducing the Quality of Service and traffic reliability. [37]

6.5.6 User Plane Latency

6.5.6.1 Round Trip Time (RTT)

RTT is a network measurement parameter to enhance the quality of service and efficient network management. The consistent network performance is needed to provide good QoS. This parameter also determines the user plane latency. Ping command test whether the target host is reachable or not by sending ICMP packets and waits for ICMP response.

Figure 6.14 compares the cumulative distribution functions of RTT for two scenarios in their respective measurement routes. The red color indicates round trip time for outdoor while green indicates for indoor environment. The trend of the RTT is similar for both locations.

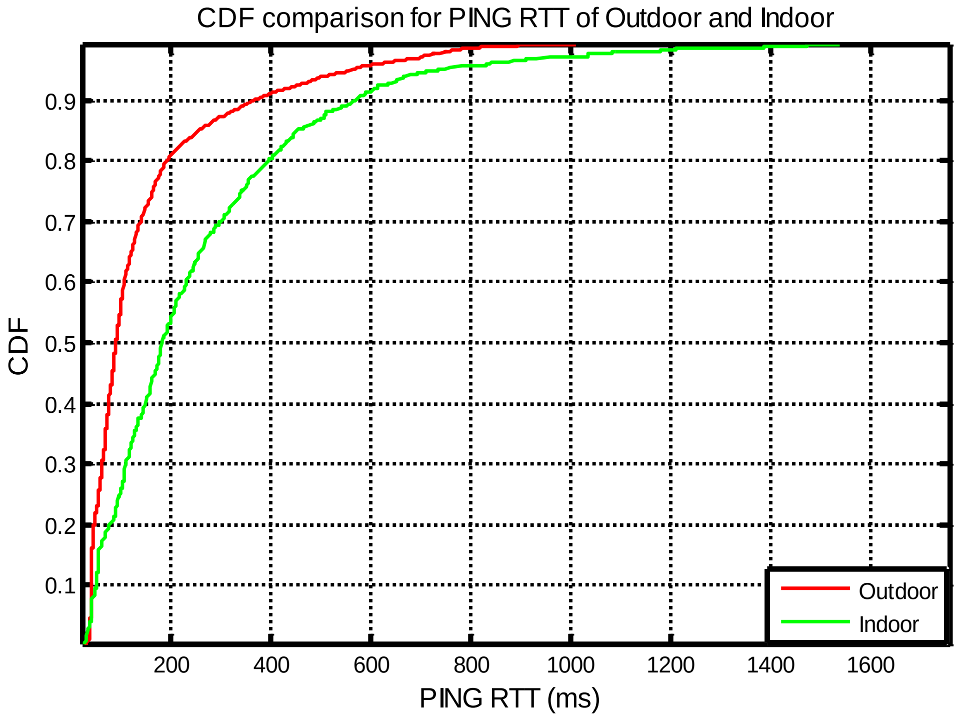


Figure 6.14*: CDF comparison of RTT for outdoor and indoor during inter-RAT*

The graph shows 15% of the samples for both locations align with each other. The complete statistics of the collected samples is outlined in Table 6.12.

Table 6.12*: Statistical comparison of Ping RTT for both locations*

Statistics	Ping RTT (s)	
	Indoor	Outdoor
Maximum	7.33	4.76
Minimum	0.02	0.03
Mean	0.28	0.16
Median	0.18	0.09
St. Deviation	0.40	0.23

The maximum round trip delay observed for outdoor is 4.7 sec while for indoor is 7.3sec. Mean value for outdoor is 162 ms while that for indoor is 280 ms. The round trip time in outdoor is small 92 ms compared to indoor 184 ms by considering median.

The main reason of drastic change in the RTT value is the handover process. During this interval the RTT value has reached to 4.3 sec. The UE receives the response from the server from the 3G network only after successful radio link setup. Therefore during the handover; RTT experienced long interval to complete one request loop. The other possible reasons may be the working speed and location of the router, interface clocking rates and the traffic queue in the router. After successful handover RTT value decreases and data rate starts to increase. [38]

6.5.6.1 Service Interruption Time Comparison

Service interruption signifies interrupt time of the user service. Figure 6.10 shown above is an example of the MAC layer throughput graph illustrating the service interruption estimation during inter-RAT handover. The graph indicates that throughput starts to decrease when the UE is moving towards the LTE cell edge. The throughput goes to the lowest level towards the cell edge. There is interruption of data download for few seconds. The two vertical red colored lines in the graph shows the data interruption interval due to handover delay process. After successful handover towards 3G cell, the throughput increase gradually as radio conditions improves. The service interruption interval is calculated manually by seeing the throughput graph for each measurement for both locations and is presented in Appendix A and B.

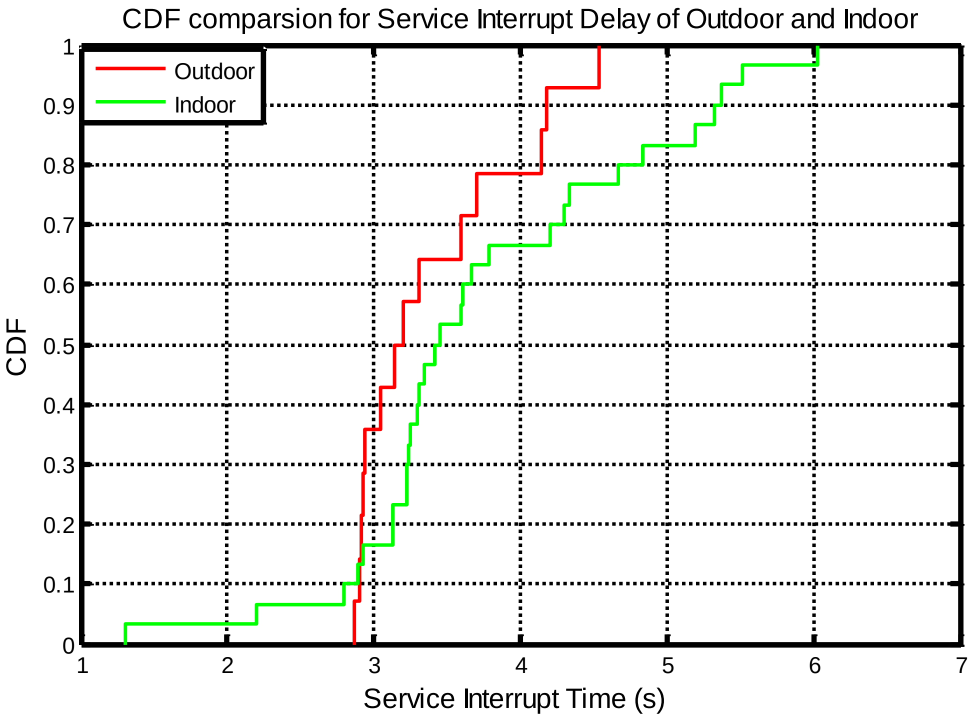


Figure 6.15*: Service interruption time during inter-RAT handover from LTE to 3G*

Figure 6.15 is a cdf comparison of service interruption delay for two different locations. The red graph indicates the cdf for outdoor whereas the green is for indoor environment. The plot shows that the outdoor region has lower service interruption delay throughout the measurement as compared to indoor scenarios.

***Table 6.13**: Statistical data for the service delay*

Statistics	Service delay (s)	
	Indoor	Outdoor
Maximum	6.02	4.45
Minimum	1.30	2.87
Mean	3.75	3.38
Median	3.42	3.17
St. Deviation	1.04	0.56

Table 6.13 shows the statistical data for measurement taken for both locations. The maximum delay for outdoor observed is 4.45 sec while for indoor is 6.02 sec. The median of the measurement data for outdoor has 3.17 sec while for indoor has 3.42 sec. The standard deviation for both locations has lower value indicating each data point is close to the mean value. It shows minimum fluctuation.

The service interruption experienced by UE is due to measurement gaps. This measurement gaps is from the handover process. During handover UE has to complete three important phases: preparation, execution and completion as explained in Section 5.5. The radio link with the source base station is released before establishing the new connection to the target network. At this time the downlink packets are forwarded and queued by the target base station in the UE buffer. These packets are transferred only after successful handover towards the RNC. Once connected to the target 3G cell, the service resumes.

The impact of delay depends upon the type of application that is being used. Non real time applications like http downloading have data forwarding mechanism. So during the handover data might not get lost. But real time applications which do not have any forwarding mechanism results in packet loss and awful result in quality of service.

7. CONCLUSIONS AND DISCUSSION

The purpose of the current study is to understand the interworking principle between LTE Release 8 and previous legacy 3G networks in real environment scenario. The study is also focused on the impact of inter-RAT handover process to performance parameters like MAC DL throughput, handover success rate, round trip time, handover latency and user plane latencies. It is also intended to study the performance of inter-RAT handover in outdoor and indoor measurement environment.

The following conclusions are drawn from the current study. One of the most significant finding from this study is that mobility from LTE towards 3G network work perfectly in both idle and connected mode. Although, the handover success rate is 100 percent, user experiences the handover delay roughly around 3-4 seconds. This study also found that user experiences degradation in downlink throughput due to decreasing radio link quality. The data interruption experienced by the user is around 4 sec in average when handover is performed. This delay can be tolerable for non real time applications like downloading the data but online applications like VoIP, online games and IP-TV which are delay sensitive requires delay as low possible to maintain radio link connectivity. Otherwise, longer delay may lead handover failure that cause effect on user perceived performance resulting in user dissatisfaction. This research also shows that the average round trip time is 280 ms for 32 bytes of data during handover conditions. It also shows that the impact of inter-RAT handover on performance parameters is high. The inter-RAT handover performance is better in outdoor environmental conditions compared to indoor. This is concluded based on the impact results seen on performance parameters.

Networks and equipments employed are vendor specific; therefore, the results found during this study may vary for different vendors. The result shows that there is a large impact on network performance due to handover process and vary depending on the environmental conditions. So, it is suggested that the number of handover should be as low as possible and right decision should be made on the measurement. Any unnecessary handovers reduced the radio resources and increases the network load. Further, it is suggested to implement efficient handover detection algorithm and deployment of LTE coverage everywhere as a possible solution. The additional measurements in various environmental conditions in different networks can be a next step to generalize the results more precisely.

There are some limitations of this study. It is conducted for only one vendor network which means the results cannot clearly depict the situations in other vendor networks. Furthermore, the interworking mechanism from 3G network towards LTE was not studied because of wide coverage of 3G including LTE hotspots, which could have improved the accuracy of the results.

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APPENDIX

***Appendix A**: Service interruption and handover delay in indoor environment*

Measurement number	Service interrupt time (sec)	Handover delay (sec)
1	3.45	3.50
2	4.38	4.43
3	2.80	2.85
4	3.25	3.30
5	4.30	4.35
6	1.31	1.36
7	5.32	5.37
8	5.37	5.42
9	3.23	3.28
10	3.61	3.66
11	4.67	4.72
12	3.67	3.72
13	2.20	2.25
14	3.35	3.40
15	5.19	5.24
16	3.23	3.28
17	5.52	5.57
18	2.89	2.94
19	2.92	2.97
20	3.31	3.36
21	6.02	6.07
22	3.13	3.18
23	3.78	3.83
24	3.13	3.18
25	3.23	3.28
26	4.83	4.88
27	3.41	3.46
28	4.20	4.25
29	3.30	3.35
30	3.59	3.64

***Appendix B**: Service interruption and handover delay for outdoor region*

Measurement number	Interruption time (sec)	Handover delay (sec)
1	4.14	4.19
2	4.18	4.23
3	2.90	2.95
4	2.93	2.98
5	3.20	3.25
6	2.91	2.96
7	3.6	3.65
8	3.31	3.36
9	2.93	2.98
10	3.14	3.19
11	2.87	2.92
12	3.71	3.76
13	3.05	3.1
14	4.54	4.59