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LTE Handover Performance Evaluation Based on Power Budget Handover Algorithm

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Abstract

LTE (Long Term Evolution) is a fourth generation cellular network technology that provides improved performance related to data rate, coverage and capacity compared to legacy cellular systems. In this context, one of the main goals of LTE is to provide fast and seamless handover from one cell to another to meet a strict delay requirement while simultaneously keeping network management simple. Hence, the decision to trigger a handover is a crucial component in the design process of handover, since the success and the efficiency, to a large extent, depends on the accuracy and timeliness of the decision.

The design of an efficient and successful handover requires a careful selection of HO parameters and the optimal setting of these. The LTE standard supports two parameters to trigger the handover and select the target cell: hysteresis margin and Time-to-Trigger (TTT)

The research topic of this thesis which is "LTE Handover Performance Evaluation Based on Power Budget Handover Algorithm", focuses on different combinations or settings of HOM and TTT values to evaluate the handover performance based on Reference Signal Received Power (RSRP) measurement within certain deployment scenarios, such as different UE speeds, system loads and cell sizes.

The Power Budget Handover Algorithm (PBHA) picks the best hysteresis and time-to-trigger combinations to evaluate the system performance in terms of number of handovers, signal-to-interference plus noise ratio (SINR), throughput, delay and packet lost for UE's which are about to perform the handover.

Key words: LTE, Handover, Power Budget Handover Algorithm*,* Hysteresis margin, Time-To-Trigger.

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List of Acronyms

3G	3^{rd} Generation (Cellular Systems)
3GPP	Third Generation Partnership Project
4G	4^{th} Generation (Cellular Systems)
4QAM)	4 Quadrature Amplitude Modulation
16QAM	16 Quadrature Amplitude Modulation
64QAM	64 Quadrature Amplitude Modulation
AC	Admission Control
ACK	Acknowledgement (in ARQ protocols)
AM	Acknowledged mode
AGW	Access Gateway
AS	Access Stratum
BS	Base Station
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CQI	Channel Quality Indicator
CS	Circuit-Switched
dB	Decibel
DFT	Discrete Fourier Transform
DL	Downlink
DRB	Data Radio Bearer
eNB	Enhanced Node B (3GPP Base Station)
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access
FDD	Frequency Division Duplex
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
HO	Handover
HOM	HO margin
HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber Server
IMS	IP Multimedia Sub-system
IP	Internet Protocol
L1	Layer 1 (physical layer)
L3	Layer 3 (network layer)
LTE	Long Term Evolution
MAC	Medium Access Control
MME	Mobility Management Entity
NACK	Negative Acknowledgement
NAS	Non-Access Stratum
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-to-Average Power Ratio
PBHA	Power Budget Handover Algorithm
PCRF	Policy and Charging Rules Function
PDCP	Packet-Data Convergence Protocol

PDN	Packet Data Network
PDU	Protocol Data Unit
PGW	PDN Gateway
QoS	Quality of Service
RAN	Radio Access Network
RB	Resource Block
RF	Radio Frequency
RLC	Radio Link Protocol
RNC	Radio Network Controller
ROHC	RObust Header Compression
RRC	Radio Resource Control
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SAE	System Architecture Evolution
S1	The interface between eNB and Access Gateway
S1AP	S1 Application Part
SC-FDMA	Single Carrier – Frequency Division Multiple Access
SGW	Serving Gateway
SINR	Signal-to-Interference-plus-Noise Ratio
SIR	Signal-to-Interference Ratio
SN	Sequence Number
SRB	Signaling Radio Bearers
TE	Terminal Equipment
TM	Transparent Mode
TTI	Transmission Time Interval
TTT	Time-to-Trigger
UE	User Equipment, the 3GPP name for the mobile terminal
UL	Uplink
UM	Unacknowledged Mode
UMTS	Universal Mobile Telecommunication System
USIM	Universal Subscriber Identity Module
VoIP	Voice over IP
X2	Interface between eNB’s

1. Introduction

In recent years, there has been enormous growth in mobile telecommunications traffic in line with the rapid spread of smart phone devices. The cellular networks are evolving to meet the future requirements of data rate, coverage and capacity. The Third Generation Partnership Program (3GPP) has defined Long Term Evolution (LTE) as a new radio access technology to meet these goals enabling high-speed data communications of up to 150 Mbps, and is anticipated to support the ever-increasing demand for mobile broadband services.

Mobility enhancement is an important aspect for the Long Term Evolution technology since it should support mobility for various mobile speeds up to 350km/h or even up to 500km/h. With the moving speed even higher, the handover procedure will be more frequent and fast; therefore, the handover performance becomes more crucial especially for real time services [11].

One of the main goals of LTE or any wireless system for that matter is to provide fast and seamless handover from one cell (a source cell) to another (a target cell). The service should be maintained during the handover procedure, data transfer should not be delayed or should not be lost; otherwise performance will be dramatically degraded. This is especially applicable for LTE systems because of the distributed nature of the LTE radio access network architecture which consists of just one type of node, the base station, known in LTE as the eNodeB (eNB) [7].

In LTE there are also some predefined handover conditions for triggering the handover procedure as well as some goals regarding handover design and optimization such as decreasing the total number of handovers in the whole system by predicting the handover, decreasing the number of ping pong handovers, and having fast and seamless handover. Hence, optimizing the handover procedure to get the required performance is considered as one important issue in LTE networks [11].

Actually, many studies are carried out to achieve improvements in LTE handover, with different HO algorithms and which take several stages for different cases, but certainly all of them are done in order to get optimum handover mechanisms that can handle the smooth handover on cell boundaries of the LTE network.

In this context, the main goal of this thesis is to evaluate the performance of LTE handover based on Power Budget Algorithm (PBHA), with measurements for different handover parameters settings in certain deployment scenarios; a simulation procedure is carried out and an evaluation methodology is applied to analyze the simulation results.

1.1 Background

Long Term Evolution (LTE) is the 4th generation cellular mobile system that is being developed and specified in 3GPP as a successor of UMTS; compared with 2G/3G, LTE shows many differences in architecture, key technologies, network design and planning, and so on.

The standardization of LTE system has been completed in March 2009 by the 3GPP within its release 8. Compared to the previous releases, the LTE Radio Access Network architecture, (called E-UTRAN) is considerably different as the radio control functionality has been distributed to the base stations (eNB's); all the traffic and signaling is sent over shared channels for both directions of transmission-downlink and uplink [16]. Therefore, Radio Resource Control (RRC) has to be implemented in a distributed way without the assistance of a central control entity.

Another major difference of LTE in comparison to its 3GPP ancestors is the radio interface; Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Domain Multiple Access (SC-FDMA) are used for the downlink and uplink respectively, as radio access schemes due to their good spectral properties and bandwidth scalability [5].

LTE-4G standardization is developing very fast and it is assumed to support different technologies, different terminals and to serve them in a seamless way. Seamless services introduce the challenge of handovers either intra-network handovers or inter-network handovers that should be well studied and standardized.

1.2 Goals and objectives of the thesis

Handover procedure is one of the most important functions of a mobile system which tries to keep a user connected to the best base station such that QoS of the ongoing session is met. In LTE, handover is user assisted and network controlled, and it is usually based on the downlink and/or uplink channel measurements which are processed in the user-equipment (UE) [12].

The main goal of this thesis is to evaluate the LTE handover performance. For this purpose some specific objectives are achieved: first the handover procedure within 3GPP LTE and the designing and optimization principles are studied, and the different parameters affecting handover are identified.

Then, the LTE Power Budget Handover Algorithm (PBHA) is selected and an evaluation methodology is defined. At the same time the deployment scenarios according to 3GPP specifications are chosen for simulation.

Finally, using a dynamic system level simulator, the handover parameters are tuned according to the evaluation methodology for certain scenarios with the main objective to carry out the HO performance evaluation in terms of number of handovers, Signal to Interference plus Noise Ratio (SINR), Throughput, Delay and Packet Lost.

1.3 Thesis Structure

This thesis is organized as follows:

Chapter 2: This chapter presents an overview of Long Term Evolution technology; the main characteristics and functionalities of the system are described as well as the enabling technologies, network architecture, protocols etc.

Chapter3: Presents the general concepts of handover and the whole HO procedure is described. Optimization and design principles as well as the variables used as inputs and the different HO parameters are introduced.

Chapter 4: This chapter refers the handover performance evaluation process: the LTE power budget handover algorithm used in this thesis is specified; the evaluation is based on RSRP measurement for different handover parameters, e.g. HOM and TTT basically for different UE speeds. Modeling and simulation parameters are proposed and simulation using a dynamic system level simulator in C++ is performed. Then simulation results are analyzed and finally the HO performance evaluation is carried out.

Chapter 5: This chapter provides a conclusion of the overall study and considerations for future work.

2. LTE Overview

LTE (Long Term Evolution) is the project name of a new high performance air interface for cellular mobile communication systems. It is the last step toward the 4th generation (4G) of radio technologies designed to increase the capacity and speed of mobile telephone networks. Where the current generation of mobile telecommunication networks are collectively known as 3G, LTE is marketed as 4G [5].

Table 1: Evolution from 3G to 4G [6]

	WCDMA (UMTS)	HSPA HSDPA/HSUPA	HSPA+	LTE
Max downlink speed bps	384k	14M	28M	100M
Max uplink speed bps	128k	5.7M	11M	50M
Latency round trip time approx.	150ms	100ms	50ms (max)	~10ms
3GPP releases	Rel 99/4	Rel 5/6	Rel 7	Rel 8
Approx. years of initial roll out	2003/4	2005/6 HSDPA 2007/8 HSUPA	2008/9	2009/10
Access methodology	CDMA	CDMA	CDMA	OFDMA/SC-FDMA

2.1 Requirements and Targets for LTE

3GPP completed the process of defining the Long Term Evolution (LTE) for radio access, so that the technology systems remain competitive in the future. The 3GPP has identified a set of high level requirements that have already been exceeded so far.

Some of key LTE requirements related to data rate, throughput, latency, and mobility are provided below [3]:

Peak data rate:

- Instantaneous DL peak data rate of 100 Mb/s within a 20 MHz DL spectrum allocation (5 bps/Hz).
- Instantaneous UL peak data rate of 50 Mb/s (2.5 bps/Hz) within a 20 MHz UL spectrum allocation.

Control-plane latency

- Transition time of less than 100 ms. from a camped state.

- Transition time of less than 50 ms. between a dormant state and an active state.

Control-plane capacity

- At least 200 users per cell in the active state for spectrum allocations up to 5 MHz.

User-plane latency

- Less than 5 ms in unload condition (i.e. single user with single data stream) for small IP packet.

User throughput

- DL: average user throughput per MHz, 3 to 4 times Release 6 HSDPA.
- UL: average user throughput per MHz, 2 to 3 times Release 6 Enhanced Uplink.

Spectrum efficiency

- DL: In a loaded network, target for spectrum efficiency (bits/sec/Hz/site), 3 to 4 times Release 6 HSDPA.
- UL: In a loaded network, target for spectrum efficiency (bits/sec/Hz/site), 2 to 3 times Release 6 Enhanced Uplink.

Mobility

- E-UTRAN should be optimized for low mobile speed from 0 to 15Km/h.
- Higher mobile speed between 15 and 120 km/h should be supported with high performance.
- Mobility across the cellular network shall be maintained at speeds from 120 km/h to 350 km/h (or even up to 500 km/h depending on the frequency band).

Coverage

- Throughput, spectrum efficiency and mobility targets above should be met for 5 km cells, and with a slight degradation for 30 km cells. Cells range up to 100 km should not be precluded.

2.2 LTE Enabling Technologies

LTE has introduced a number of new technologies when compared to the previous cellular systems. They enable LTE to be able operate more efficiently with respect to the use of spectrum, and also to provide much higher data rates that are being required.

A major difference of LTE in comparison to its 3GPP ancestors is the radio interface; Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) are used for the downlink and uplink respectively, as radio access schemes [6].

2.2.1 Downlink OFDMA (Orthogonal Frequency Division Multiple Access)

OFDMA is a variant of OFDM (Orthogonal Frequency Division Multiplexing) and it is the downlink access technology. One of the most important advantages is the intrinsic orthogonality provided by OFDMA to the users within a cell, which translates into an almost null level of intra-cell interference. Therefore, inter-cell interference is the limiting factor when high reuse levels are intended. In this case, cell-edge users are especially susceptible to the effects of inter-cell interference.
OFDMA divides the wide available bandwidth into many narrow and mutually orthogonal subcarriers and transmits the data in parallel streams. The smallest transmission unit in the downlink LTE system is known as a Resource Block (RB).

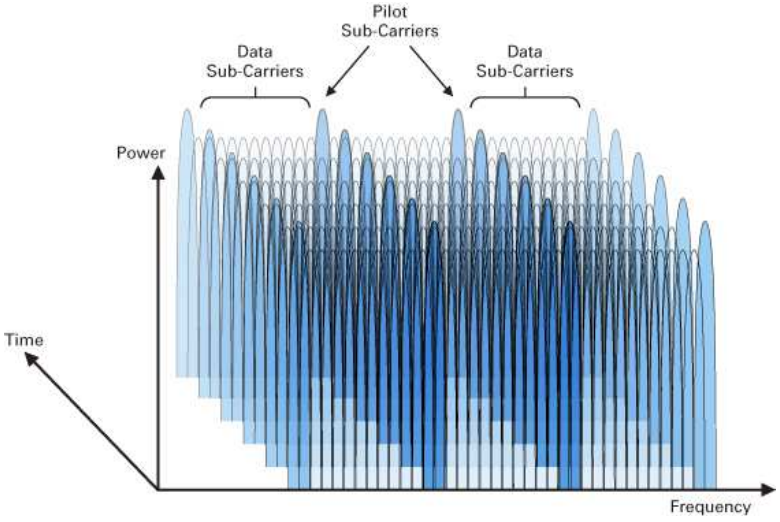


Figure 1. Orthogonal Frequency Division Multiple Access [5].

A resource block contains 12 subcarriers, regardless of the overall LTE signal bandwidth. They also cover one slot in the time frame; this means that different LTE signal bandwidths will have different numbers of resource blocks.

Table 2: Resource Block per Bandwidth

Channel Bandwidth (MHz)	1.4	3	5	10	15	20
Number of Resource Blocks	6	15	25	50	75	100

The OFDM signal used in LTE comprises a maximum of 2048 different sub-carriers having a spacing of 15 kHz. Although it is mandatory for the mobiles to have capability to be able to receive all 2048 sub-carriers, not all need to be transmitted by the base station (eNodeB) which only needs to be able to support the transmission of 72 sub-carriers. In this way all mobiles will be able to talk to any base station. Within the OFDM signal it is possible to choose between three types of modulation:

1. **QPSK (= 4 QAM)** 2 bits per symbol
2. **16 QAM** 4 bits per symbol
3. **64 QAM** 6 bits per symbol

2.2.2 Uplink SC-FDMA (Single Carrier Frequency Division Multiple Access)

For the LTE uplink, a different concept is used for the access technique. Although still using a form of OFDMA technology, the implementation is called Single Carrier Frequency Division Multiple Access (SC-FDMA). The main task of this scheme is to assign communication resources to multiple users. The major difference to other schemes is that it performs DFT (Discrete Fourier Transform) operation on time domain modulated data before going into OFDM modulation.

One of the key parameters that affect all mobiles is that of battery life. Even though battery performance is improving all the time, it is still necessary to ensure that the mobiles use as little battery power as possible. With the RF power amplifier that transmits the radio frequency signal via the antenna to the base station being the highest power item within the mobile, it is necessary that it operates in as efficient mode as possible. This can be significantly affected by the form of radio frequency modulation and signal format. Signals that have a high peak to average ratio and require linear amplification do not lend themselves to the use of efficient RF power amplifiers [5].

As a result it is necessary to employ a mode of transmission that has as near a constant power level when operating.

2.2.3 LTE Channel Bandwidths

One of the key parameters associated with the use of OFDM within LTE is the choice of bandwidth. The available bandwidth influences a variety of decisions including the number of carriers that can be accommodated in the OFDM signal and in turn this influences elements including the symbol length and so forth [6].

LTE can support 6 kinds of bandwidth and obviously, to higher bandwidth we will obtain greater channel capacity.

1. 1.4 MHz
2. 3 MHz
3. 5 MHz
4. 10 MHz
5. 15 MHz
6. 20 MHz

In addition to this, the subcarriers are spaced 15 kHz apart from each other. To maintain orthogonality, this gives a symbol rate of 1 / 15 kHz = of 66.7 µs. Each subcarrier is able to carry data at a maximum rate of 15 ksps (kilo symbols per second). This gives a 20 MHz bandwidth system a raw symbol rate of 18 Msps. In turn this is able to provide a raw data rate of 108 Mbps as each symbol using 64QAM is able to represent six bits.

2.3 LTE Network Architecture

LTE has been designed to support only packet switched services, in contrast to the circuit-switched model of previous cellular systems. It aims to provide seamless Internet Protocol (IP) connectivity between User Equipment (UE) and the Packet Data Network (PDN), without any disruption to the end users' applications during mobility [2].
While the term "LTE" encompasses the evolution of the Universal Mobile Telecommunications System (UMTS) radio access through the Evolved UTRAN (E-UTRAN), it is accompanied by an evolution of the non-radio aspects under the term "System Architecture Evolution" (SAE).

Together LTE and SAE comprise the Evolved Packet System (EPS). This EPS in turn includes the EPC (Evolved Packet Core) on the core side and E-UTRAN (Evolved UMTS Terrestrial Radio Access Network) on the access side [2].

In addition to these two components, User Equipment (UE) and Services Domain are also very important subsystems of LTE architecture.

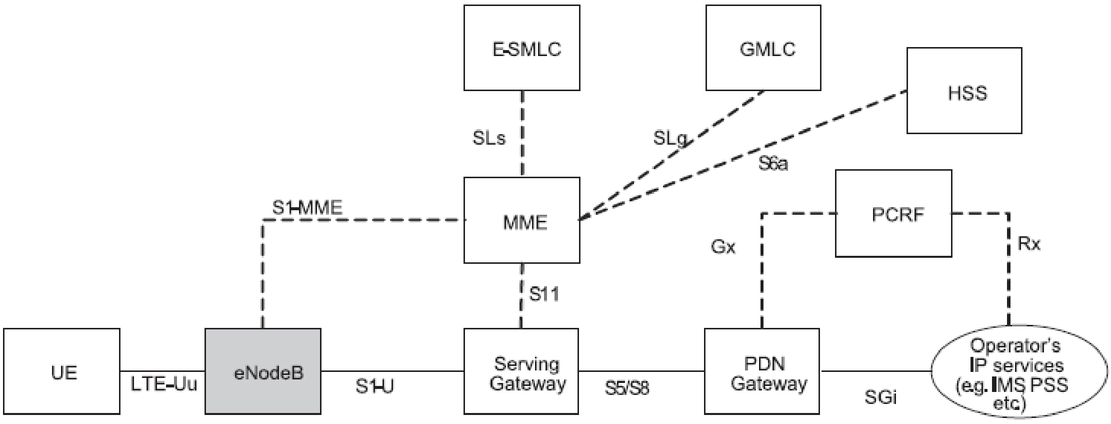


Figure 2. System Architecture Evolution (SAE) and LTE Network [5].

2.3.1 The Core Network: Evolved Packet Core (EPC)

The core network is responsible for the overall control of the UE and establishment of the bearers. The Evolved Packet Core is the main element of the

LTE SAE network. This consists of four main elements and connects to the eNodeB's as shown in the diagram below.

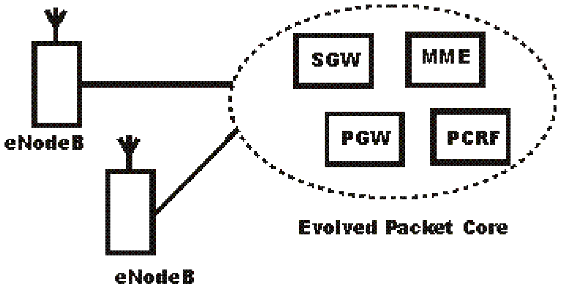


Figure 3. LTE SAE Evolved Packet Core [6]

- **Mobility Management Entity (MME)**

  The MME is the main control node for the LTE SAE access network, handling a number of features, it can therefore be seen that the SAE MME provides a considerable level of overall control functionality. The protocols running between the UE and the CN are known as the Non Access Stratum (NAS) protocols. The main functions supported by the MME can be classified as:

  Functions related to bearer management – This includes the establishment, maintenance and release of the bearers and is handled by the session management layer in the NAS protocol.

  Functions related to connection management – This includes the establishment of the connection and security between the network and UE and is handled by the connection or mobility management layer in the NAS protocol layer.

- **Serving Gateway (SGW)**

  The Serving Gateway, SGW, is a data plane element within the LTE SAE. Its main purpose is to manage the user plane mobility and it also acts as the main border between the Radio Access Network, RAN and the core network. The SGW also maintains the data paths between the eNodeB's and the PDN Gateways. In this way the SGW forms an interface for the data packet network at the E-UTRAN.

- **PDN Gateway (PGW)**

  The LTE SAE PDN (Packet Data Network) gateway provides connectivity for the UE to external packet data networks, fulfilling the function of entry and exit point for UE data. The UE may have connectivity with more than one PGW for accessing multiple PDNs.

- **Policy and Charging Rules Function (PCRF*)***

  This is the generic name for the entity within the LTE SAE EPC which detects the service flow, enforces charging policy. For applications that require dynamic policy or charging control, a network element entitled the Applications Function, is used.

  In addition to these nodes, EPC also includes another logical node and function which is:

- **Home Subscription Server (HSS)**

  The HSS is a database server which is located in the operator's premises. All the user subscription information is stored in the HSS. The HSS also contains the records of the user location and has the original copy of the user subscription profile. The HSS is interacting with the MME, and it needs to be connected to all the MMEs in the network that controls the UE.

- **Evolved Serving Mobile Location Centre** (**E-SMLC)**

  The E-SMLC manages the overall coordination and scheduling of resources required to find the location of a UE that is attached to E-UTRAN. It also calculates the final location based on the estimates it receives, and it estimates the UE speed and the achieved accuracy.

- **Gateway Mobile Location Centre** (**GMLC)**

  The GMLC contains functionalities required to support Location Services (LCS). After performing authorization, it sends positioning requests to the MME and receives the final location estimates.

2.3.2 The Access Network: Evolved Universal Terrestrial Radio Access Network (E-UTRAN)

The E-UTRAN is the Access Network of LTE and simply consists of a network of eNodeB's that are connected to each other via X2 interface as illustrated in Figure 4. The eNodeB's are also connected to the EPC via S1 interface, more specifically to the MME by means of the S1-MME interface and to the S-GW by means of the S1-U interface.

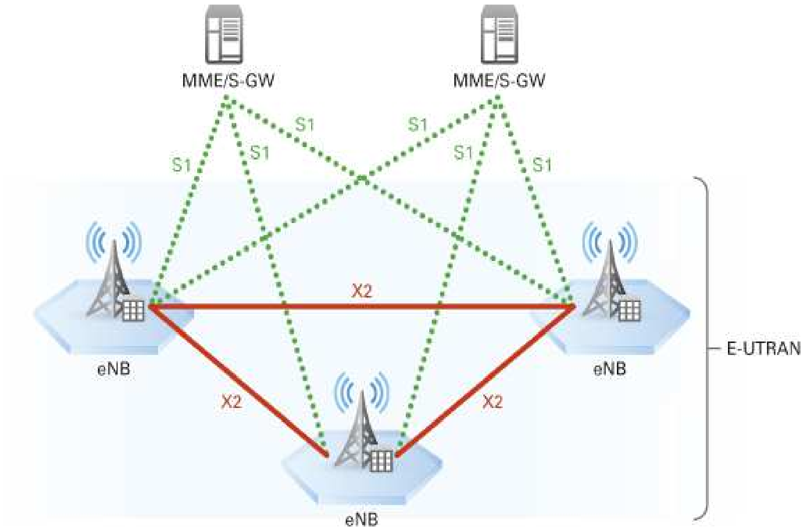


Figure 4. E-UTRAN Architecture [9]

2.3.2.1 eNodeB

The eNodeB is a radio base station of a LTE network that controls all radio-related functions in the fixed part of the system. These radio base stations are distributed throughout the coverage region and each of them is placed near a radio antenna. One of the biggest differences between LTE network and legacy mobile communication system 3G is a base station.
Practically, an eNodeB provides bridging between the UE and EPC. All the radio protocols that are used in the access link are terminated in the eNodeB. The eNodeB does ciphering/deciphering in the user plane as well as IP header compression/decompression. The eNodeB also has some responsibilities in the control plane such as radio resource management and performing control over the usage of radio resources.

The E-UTRAN has many responsibilities regarding to all related radio functions. The main features that supports are the following:

- **Radio Resource Management**

  The RRM objective is to make the mobility feasible in cellular wireless networks so that the network with the help of the UE takes care of the mobility without user intervention. RRM covers all functions related to the radio bearers, such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources to UEs in both uplink and downlink.

- **IP Header Compression**

  This helps to ensure efficient use of the radio interface by compressing the IP packet headers which could otherwise represent a significant overhead, especially for small packets such as VoIP.

One of the main functions of PDCP (Packet Data Convergence Protocol) is header compression using the Robust Header Compression (ROHC) protocol defined by the IETF. In LTE, header compression is very important because there is no support for the transport of voice services via the Circuit-Switched (CS) domain.

- **Security**

Security is a very important feature of all 3GPP radio access technologies. LTE provides security in a similar way to its predecessors UMTS and GSM. Because of the sensitivity of signaling messages exchanged between the eNodeB itself and the terminal, or between the MME and the terminal, all this set of information is protected against eavesdropping and alteration.

The implementation of security architecture of LTE is carried out by two functions: Ciphering of both control plane (RRC) data and user plane data, and Integrity Protection which is used for control plane (RRC) data only. Ciphering is used in order to protect the data streams from being received by a third party, while Integrity Protection allows the receiver to detect packet insertion or replacement. RRC always activates both functions together, either following connection establishment or as part of the handover to LTE.

- **Connectivity to the EPC**

This function consists of the signaling towards the MME and the bearer path towards the S-GW. All of the above-mentioned functions are concentrated in the eNodeB as in LTE all the radio controller functions are gathered in the eNodeB. This concentration helps different protocol layers interact with each other better and will end up in decreased latency and increase in efficiency.

On the network side, all of these functions reside in the eNodeB's, each of which can be responsible for managing multiple cells. Unlike some of the previous second and third generation technologies, LTE integrates the radio controller function into the eNodeB. This allows tight interaction between the different protocol layers of the radio access network (RAN), thus reducing latency and improving efficiency. Such distributed control eliminates the need for a high-availability, processing-intensive controller, which in turn has the potential to reduce costs and avoid "single points of failure".

Furthermore, as LTE does not support soft handover there is no need for a centralized data-combining function in the network. One consequence of the lack of a centralized controller node is that, as the UE moves, the network must transfer all information related to a UE, that is, the UE context, together with any buffered data, from one eNodeB to another. Mechanisms are therefore needed to avoid data loss during handover.

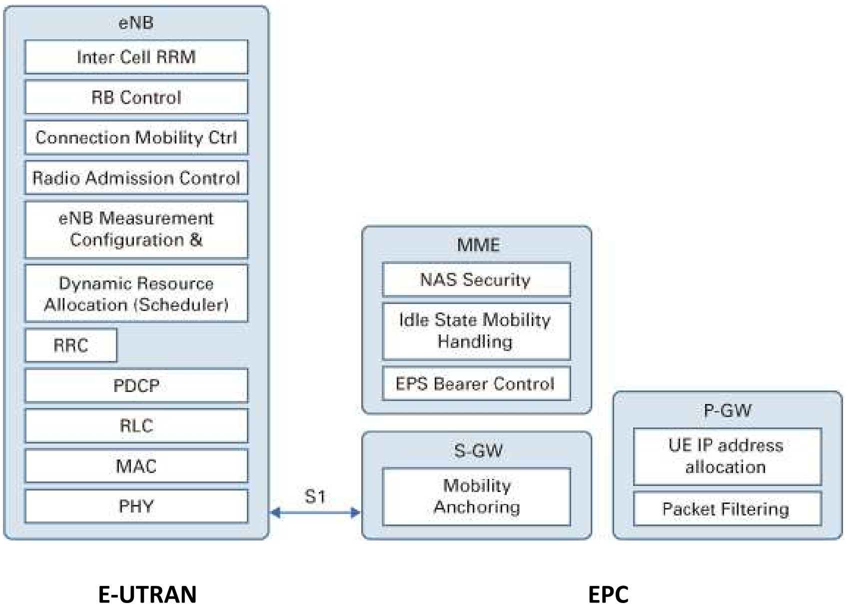


Figure 5. Functional Split between E-UTRAN and EPC [5]

2.3.3 The User Equipment (UE)

The end user communicates using a UE. The UE can be a handheld device like a smart phone or it can be a device which is embedded in a laptop. The UE is divided into two parts: the Universal Subscriber Identity Module (USIM) and the rest of the UE, which is called Terminal Equipment (TE).

The USIM is an application with the purpose of identification and authentication of the user for obtaining security keys. This application is placed into a removable smart card called a universal integrated circuit card (UICC).

The UE in general is the end-user platform that by the use of signaling with the network, sets up, maintains, and removes the necessary communication links. The UE is also assisting in the handover procedure and sends reports about terminal location to the network.

2.3.4. Services Domain

The Services domain is not a fixed entity in the EPC like the other entities. It may include various sub-systems, which in turn may contain several logical nodes. The following is a possibility of various services provided to LTE EPC.

- IMS based operator services: The IP Multimedia Sub-system (IMS) is service machinery that the operator may use to provide services using the Session Initiation Protocol (SIP). IMS has 3GPP defined architecture of its own.

- Non-IMS based operator services: The architecture for non-IMS based operator services is not defined in the standards. The operator may simply place a server into their network, and the UE's connect to that via some agreed protocol that is supported by an application in the UE. A video streaming service provided from a streaming server is one such example.

- Other services not provided by the mobile network operator, e.g. services provided through the internet: This architecture is not addressed by the 3GPP standards, and the architecture depends on the service in question. The typical configuration would be that the UE connects to a server in the internet, e.g. to a web-server for web browsing services, or to a SIP server for internet telephony service (i.e. VoIP).

2.4 E-UTRAN Network Interfaces

There are two interfaces concerned in handover procedure in LTE for UEs in active mode, which are X2 and S1 interfaces. Both interfaces can be used in handover procedures, but with different purposes.

2.4.1 X2 Interface

The X2 interface has a key role in the intra-LTE handover operation. The source eNodeB will use the X2 interface to send the Handover Request message to the target eNodeB. If the X2 interface does not exist between the two eNodeB's in question, then procedures need to be initiated to set one up before handover can be achieved [3].

The Handover Request message initiates the target eNodeB to reserve resources and it will send the Handover Request Acknowledgement message assuming resources are found.

There are different information elements provided (some optional) on the handover Request message, such as:

- Requested SAE bearers to be handed over.

- Handover restrictions list, which may restrict following handovers for the UE.

- Last visited cells the UE has been connected to, if the UE historical information collection functionality is enabled. This has been considered to be useful in avoiding the Ping-Pong effects between different cells when the target eNodeB is given information on how the serving eNodeB has been changing in the past. Thus actions can be taken to limit frequent X2 User Plane.

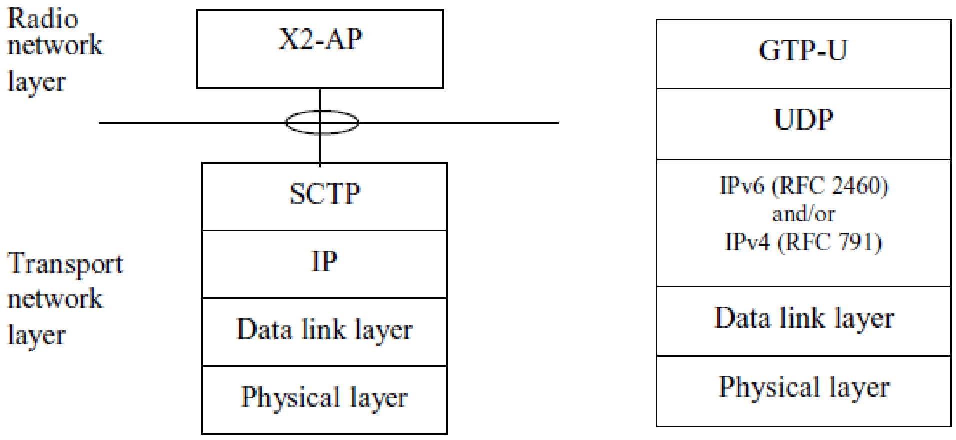


Figure 6. Protocol stack for the user-plane and control-plane at X2 interface [3].

2.4.2 S1 Interface

The radio network signaling over S1 consists of the S1 Application Part (S1AP).The S1AP protocol handles all procedures between the EPC and E-UTRAN. It is also capable of carrying messages transparently between the EPC and the UE. Over the S1 interface the S1AP protocol primarily supports general E-UTRAN procedures from the EPC, transfers transparent non-access signaling and performs the mobility function.

The figure below shows the protocol stack for the user-plane and control-plane at S1 interface [3].

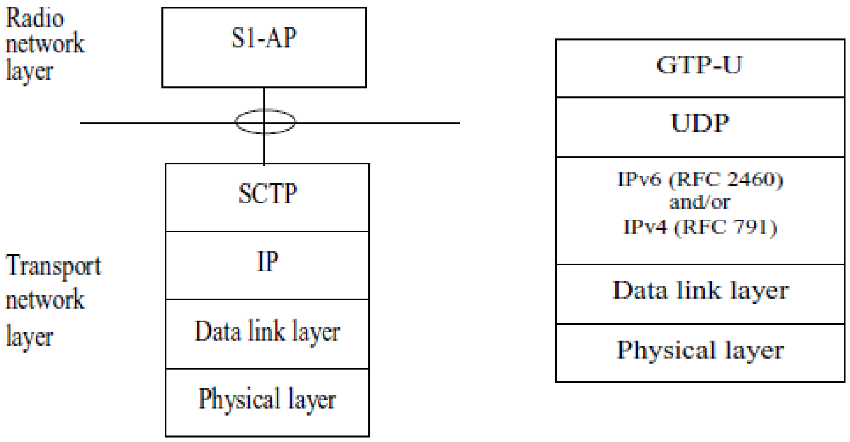


Figure 7. Protocol stack for the user-plane and control-plane at S1 interface [3].

2.5 LTE Protocol Architecture

The overall radio interface protocol architecture for LTE can be divided into User Plane Protocols and Control Plane Protocols. The U-UTRAN protocol stack is depicted in the figure 8.

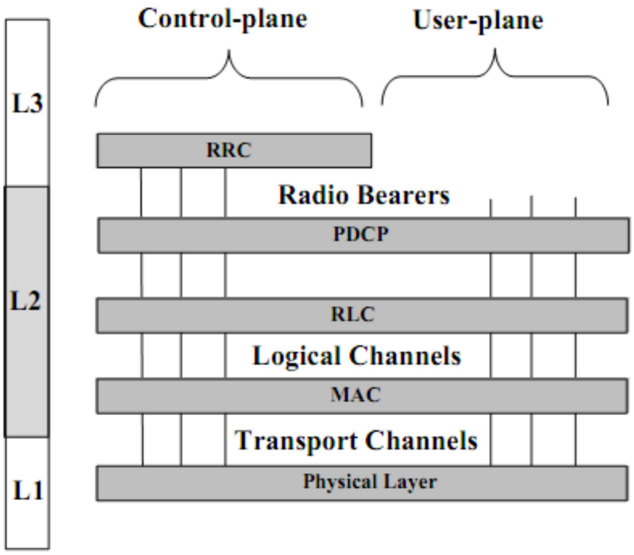


Figure 7. U-UTRAN Protocol Stack [8]

2.5.1 User Plane

An IP packet is tunneled between the P-GW and the eNodeB to be transmitted towards the UE. Different tunneling protocols can be used. The tunneling protocol used by 3GPP is called the GPRS tunneling protocol (GTP) [8].

The LTE Layer 2 user-plane protocol stack is composed of three sub layers: Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC). These sub layers are terminated in the eNodeB on the network side. The respective roles of each one are explained in detail below:

2.5.1.1 Packet Data Convergence Protocol (PDCP)

Packet Data Convergence Protocol (PDCP) is one of the sub layers in the Data Link layer. The PDCP protocol terminates in the eNB from one side and in the UE from the other side, and it also acts both in the user plane and control plane. This layer processes Radio Resource Control (RRC) messages in the control plane and Internet Protocol (IP) packets in the user plane [8].

PDCP Services:

The PDCP provides services both to the upper layer and to the lower layer. The following services are provided by PDCP to upper layers:

- Transfer of user plane data
- Transfer of control plane data
- Header compression
- Ciphering
- Integrity protection

PDCP services to the lower layers:

- Acknowledged data service, including indication of successful delivery of PDCP PDUs
- Unacknowledged data transfer service
- In-sequence delivery, except at re-establishment of lower layers
- Duplicate discarding, except at re-establishment of lower layers

PDCP Functions:

The Packet Data Convergence Protocol supports the following functions:

- Header compression and decompression of IP data flows using the ROHC protocol, at the transmitting and receiving entity, respectively.
- Transfer of data (user plane or control plane). This function is used for conveyance of data between users of PDCP services.
- Maintenance of PDCP sequence numbers for radio bearers mapped on RLC AM.
- In-sequence delivery of upper layer PDUs (Protocol Data Unit) at handover.
- Duplicate elimination of lower layer SDUs (Service Data Unit) at handover for radio bearers mapped on RLC AM.
- Ciphering and deciphering of user plane data and control plane data.
- Integrity protection and integrity verification of control plane data.
- Timer based discard.
- Duplicate discarding.

2.5.1.2 Radio Link Control (RLC)

Radio Link Control (RLC) is another sub layer of the data link layer. It is located between the PDCP and MAC. The main purpose of this E-UTRAN protocol layer is to receive/deliver a data packet from/to its peer RLC entity.

The communication between the RLC layer and the PDCP layer is done through the Service Access Point (SAP) and the communication of the RLC layer with the MAC layer is done through logical channels. Because RLC is located between the PDCP and MAC, it receives some PDCP PDUs from the PDCP layer in transmission time, reformats them and delivers them to the MAC layer. In reception time RLC receives RLC PDUs from MAC, reassembles them and sends them to the PDCP layer. The other functionality of RLC is reordering.

The RLC proposes three transmission modes; Transparent Mode(TM), Unacknowledged Mode (UM), and Acknowledged Mode (AM).

- **Transparent Mode (TM):** The TM mode is the simplest one, as it does not change or alter the upper layer data. This mode is typically used for BCCH or PCCH logical channel transmissions which require no specific treatment from the RLC layer. The RLC Transparent Mode Entity receives data from the upper layers and simply passes it to the underlying MAC layer. There is no RLC header addition, data segmentation or concatenation.

- **Unacknowledged Mode (UM):** Unacknowledged mode as its name indicates does not have any retransmission. Therefore using the UM entity provides less delay and more error probability. The added value of the UM mode is to allow the detection of packet loss (the receiving entity can detect that a RLC packet has not been received correctly) and provides packet re-ordering and re-assembly. These operations can be performed thanks to the presence of a Sequence Number (SN) in the RLC packet header.

- **Acknowledged Mode (AM):** Finally, the AM mode is the most complex one. AM RLC is the only mode that provides bidirectional data transfer. The prominent difference of AM RLC with UM RLC is retransmission; therefore all the functions performed by UM RLC are applicable for AM RLC as well. This mechanism, specific to the AM mode, which can support error-free transmission, is known as ARQ (Automatic Repeat Request). For that reason, the AM mode only applies to DCCH or DTCH logical channels.

2.5.1.3 Medium Access Control (MAC)

The MAC layer is the lowest sub layer of Layer 2 architecture of the LTE radio protocol stack and it is located between the RLC layer and the physical layer. Logical channels connect MAC to the RLC and Transport channels connect MAC to the physical layer; therefore the main responsibility of the MAC layer is mapping the logical channels to the transport channels.

This layer also performs multiplexing of data from different radio bearers. Therefore there is only one MAC entity per UE. By deciding the amount of data that can be transmitted from each radio bearer and instructing the RLC layer as to the size of packets to provide, the MAC layer aims to achieve the negotiated Quality of Service (QoS) for each radio bearer. For the uplink, this process includes reporting to the eNodeB the amount of buffered data for transmission.

The MAC layer supports the main following functions:

- **Mapping between logical channels and transport channel**: when the standard offers different options for the transport of data for a given logical channel, it is up to the MAC layer to choose the transport channel according to the configuration defined by the operator.

- **Transport format selection:** this refers to, for example, the choice of Transport Block size and modulation scheme made by the MAC layer and provided as input parameters to the physical layer.

- **Priority handling:** between logical channels of one terminal as well as between terminals. Priority handling is one of the main functions supported by the MAC layer and it refers to the process which selects the packets from the different waiting queues to be submitted to the underlying physical layer for transmission on the radio interface.

  This process is complex, as it takes into account the different flows of information to be transmitted, including pure user data (the DTCH logical channel) as well as signaling initiated by the UTRAN or the EPC (the DCCH logical channel) with their relative priority, as well packet repetition in case an already transmitted packet has not been correctly received by the other end. For that reason, the priority handling part of the MAC layer is tightly coupled with the Hybrid ARQ part.

- **HARQ**

  Hybrid Automatic Repeat Request (HARQ) is based on the use of traditional stop-and-wait ARQ protocol. Each received packet is performed a CRC check to ensure correct reception. An Acknowledgement (ACK) or a Negative Acknowledgement (NACK) is sent back depending on whether the packet is successfully decoded or not, and in case of NACK, a retransmission will take place. HARQ operation then supports multiple simultaneous ARQ processes to improve channel throughput. Retransmission can use soft combining which means the same data is sent in retransmission, or incremental redundancy which means that additional redundancy is used in retransmissions to increase the probability of correct reception. The received packets are combined for additional coding and decoding decisions are done for the combined packets.

  In E-UTRAN, HARQ is composed of several parallel parts, so that transmission can continue on other processes while one of them is stuck with retransmissions. In the downlink, HARQ is based on asynchronous retransmissions with adaptive transmission parameters. In the uplink, HARQ is based on synchronous retransmissions.

2.5.2 Control Plane

Control plane and User plane have common protocols which perform the same functions except that for the control plane protocols there is no header compression. In the access stratum protocol stack and above the PDCP, there is the Radio Resource Control (RRC) protocol which is considered as a "Layer 3" protocol. RRC sends signaling messages between the eNodeB and UE for establishing and configuring the radio bearers of all lower layers in the access stratum.

The Access Stratum (AS) interacts with the Non-Access Stratum (NAS), which is also referred to as the "upper layers". Among other functions, the NAS control protocols handle Public Land Mobile Network (PLMN) selection, tracking area update, paging, authentication and Evolved Packet System (EPS) bearer establishment, modification and release.

A UE has two different Radio Resource Control (RRC) states that are RRC-IDLE and RRC-CONNECTED. When a UE is in RRC-IDLE mode, it decides about the cell that it is camping on. The first decision is called cell selection and all the following decisions are called cell reselection. From the paging channel the UE in RRC-IDLE mode can receive the notification of incoming calls. System information parameters are necessary for cell reselection.

2.5.2.1 Radio Resource Control (RRC)

The RRC (Radio Resource Control) layer is a key signaling protocol which supports many functions between the terminal and the eNodeB. The RRC protocol enables the transfer of common NAS information which is applicable to all UEs as well as dedicated NAS information which is applicable only to a specific UE. In addition, for UEs in RRC_IDLE, RRC supports notification of incoming calls.

The key features of RRC are the following:

- **Broadcast of System Information:** Handles the broadcasting of system information, which includes NAS common information. Some of the system information is applicable only for UE's in RRC-IDLE while other system information is also applicable for UEs in RRC-CONNECTED.

- **RRC Connection Management:** Covers all procedures related to the establishment, modification and release of an RRC connection, including paging, initial security activation, establishment of Signaling Radio Bearers (SRB's) and of radio bearers carrying user data (Data Radio Bearers, DRB's), handover within LTE (including transfer of UE RRC context information), configuration of the lower protocol layers, access class barring and radio link failure.

- **Establishment and release of radio resources:** This relates to the allocation of resources for the transport of signaling messages or user data between the terminal and eNodeB.

- **Paging:** this is performed through the PCCH logical control channel. The prominent usage of paging is to page the UE's that are in RRC-IDLE. Paging can also be used to notify UE's both in RRC-IDLE and RRC-CONNECTED modes about system information changes or SIB10 and SIB11 transfers.

- **Transmission of signaling messages to and from the EPC:** these messages (known as NAS for Non Access Stratum) are transferred to and from the terminal via the RRC; they are, however, treated by RRC as transparent messages.

- **Handover**: the handover is triggered by the eNodeB, based on the received measurement reports from the UE. Handover is classified in different types based on the origination and destination of the handover. The handover can start and end in the E-UTRAN, it can start in the E-UTRAN and end in another Radio Access Technology (RAT), or it can start from another RAT and end in E-UTRAN.

The RRC also supports a set of functions related to end-user mobility for terminals in RRC Connected state. This includes:

- **Measurement control:** This refers to the configuration of measurements to be performed by the terminal as well as the method to report them to the eNodeB.

- **Support of inter-cell mobility procedures**: which are also known as handover

- **User context transfer:** between eNodeB at handover.

2.5.2.2 Radio Resource Control States

The main function of the RRC protocol is to manage the connection between the terminal and the EUTRAN access network. To achieve this, RRC protocol states have been defined and they are depicted in the figure below. Each of them actually corresponds to the states of the connection, and describes how the network and the terminal shall handle special functions like terminal mobility, paging message processing and network system information broadcasting [18].

In E-UTRAN, the RRC state machine is very simple and limited to two states only: RRC-IDLE, and RRC-CONNECTED.

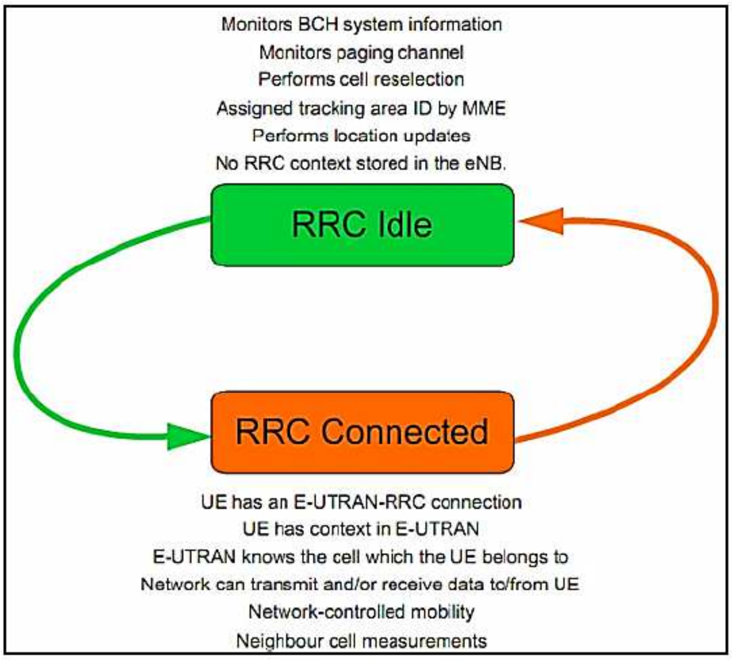


Figure 8. The RRC States [18]

In the RRC-IDLE state, there is no connection between the terminal and the eNodeB, meaning that the terminal is actually not known by the E-UTRAN Access Network. The terminal user is inactive from an application level perspective, which does not mean at all that nothing happens at the radio interface level. Nevertheless, the terminal behavior is specified in order to save as much battery power as possible and is actually limited to three main items:

- **Periodic decoding of System Information Broadcast by E-UTRAN:** this process is required in case the information is dynamically updated by the network.
- **Decoding of paging messages:** so that the terminal can further connect to the network in case of an incoming session.
- **Cell reselection:** the terminal periodically evaluates the best cell it should camp on through its own radio measurements and based on network System Information parameters. When the condition is reached, the terminal autonomously performs a selection of a new serving cell.

In the RRC-CONNECTED state, there is an active connection between the terminal and the eNodeB, which implies a communication context being stored within the eNodeB for this terminal. Both sides can exchange user data and or signaling messages over logical channels. Unlike the RRC-IDLE state, the terminal location is known at the cell level. Terminal mobility is under the control of the network using the handover procedure, which decision is based on many possible criteria including measurement reported by the terminal of by the physical layer of the eNodeB itself.

3. Handover in LTE

3.1 Introduction

Mobility is an essential component of mobile cellular communication systems because it offers clear benefits to the end users: low delay services such as voice or real time video connections can be maintained while moving even in high speed trains. Mobility at high speed is a challenge, and LTE as long term evolution has promised more than former technologies to overcome this challenge.

One of the main goals of the LTE radio network is to provide fast and seamless handover from one cell to another while simultaneously keeping network management simple. LTE technology is designed to support mobility for various mobile speeds up to 350km/h or even up to 500km/h. With the moving speed even higher, the handover will be more frequent and fast.
Handover is one of the key procedures for ensuring that the users move freely through the network while still being connected and being offered quality services. Since its success rate is a key indicator of user satisfaction, it is vital that this procedure happens as fast and as seamlessly as possible. But the problem of providing seamless access becomes even more important in LTE since it uses hard handover (break-before-make).

Hence, optimizing the handover procedure to get the required performance is considered an important issue in LTE networks.

3.2 Handover Characteristics

Depending on the required QoS, a seamless handover or a lossless handover is performed as appropriate for each radio bearer. The descriptions of each of them are presented below.

3.2.1 Seamless Handover

The objective of seamless handover is to provide a given QoS when the UE moves from the coverage of one cell to the coverage of another cell. In LTE seamless handover is applied to all radio bearers carrying control plane data and for user plane radio bearers mapped on RLC-UM. These types of data are typically reasonably tolerant of losses but less tolerant of delay, (e.g. voice services). Therefore seamless handover should minimize the complexity and delay although some SDUs might be lost [4].

In the seamless handover, PDCP entities including the header compression contexts are reset, and the COUNT values are set to zero. As a new key is anyway generated at handover, there is no security reason to keep the COUNT values. On the UE side, all the PDCP SDUs that have not been transmitted yet will be sent to the target cell after handover. PDCP SDUs for which the transmission has not been started can be forwarded via X2 interface towards the target eNB. Unacknowledged PDCP SDUs will be lost. This minimizes the handover complexity because no context (i.e. configuration information) has to be transferred between the source and the target eNodeB.

3.2.2 Lossless Handover

Lossless handover means that no data should be lost during handover. This is achieved by performing retransmission of PDCP PDUs for which reception has not been acknowledged by the UE before the UE detaches from the source cell to make a handover. In lossless handover, in-sequence delivery during handover can be ensured by using PDCP Data PDUs sequence numbers. Lossless handover can be very suitable for delay-tolerant services like file downloads that the loss of PDCP SDUs can enormously decrease the data rate because of TCP reaction.

Lossless handover is applied for user plane and for some control plane radio bearers that are mapped on RLC-AM. In lossless handover, on the UE side the header compression protocol is reset because its context is not forwarded from the source eNB to the target eNB, but the PDCP SDUs' sequence numbers and the COUNT values are not reset [4]. To ensure lossless handover in the uplink, the PDCP PDUs stored in the PDCP retransmission buffer are retransmitted by the RLC protocol based on the PDCP SNs which are maintained during the handover and deliver them to the gateway in the correct sequence.

In order to ensure lossless handover in the downlink, the source eNodeB forwards the uncompressed PDCP SDUs for which reception has not yet been acknowledged by the UE to the target eNodeB for retransmission in the downlink.

3.3 Types of Handover

The handover is triggered by the eNodeB, based on the received measurement reports from the UE. Handover is classified in different types based on the origination and destination of the handover. The handover can start and end in the E-UTRAN, it can start in the E-UTRAN and end in another Radio Access Technology (RAT), or it can start from another RAT and end in E-UTRAN [24].

Handover is classified as:

- Intra-frequency intra-LTE handover
- Inter-frequency intra-LTE handover
- Inter-RAT towards LTE handover
- Inter-RAT towards UTRAN handover
- Inter-RAT towards GERAN handover

- Inter-RAT towards cdma2000 system handover

3.3.1 Intra LTE Handover

In intra LTE handover, which is focused by this study, both the origination and destination eNB's are within the LTE system. In this type of handover, the RRC connection reconfiguration message acts as a handover command. The interface between eNodeB's is an X2 interface. Upon handover, the source eNodeB sends an X2 handover request message to the target eNodeB in order to make it ready for the coming handover.

3.4 Handover Techniques

Handover can be categorized as: Soft handover and hard handover also known as Connect-Before-Break (CBB) and Break-Before-Connect (BBC) respectively.

3.4.1 Soft handover, Connect-Before-Break

Soft handover is a category of handover procedures where the radio links are added and abandoned in such manner that the UE always keeps at least one radio link to the UTRAN. Soft and softer handover were introduced in WCDMA architecture. There is a centralized controller called Radio Network Controller (RNC) to perform handover control for each UE in the architecture of WCDMA. It is possible for a UE to simultaneously connect to two or more cells (or cell sectors) during a call. If the cells the UE connected are from the same physical site, it is referred as softer handover [10].

In handover aspect, soft handover is suitable for maintaining an active session, preventing voice call dropping, and resetting a packet session. However, the soft handover requires much more complicated signaling, procedures and system architecture such as in the WCDMA network.

3.4.2 Hard handover, Break-Before-Connect

Hard handover is a category of handover procedures where all the old radio links in the UE are abandoned before the new radio links are established. The hard handover is commonly used when dealing with handovers in the legacy wireless systems. The hard handover requires a user to break the existing connection with the current cell (source cell) and make a new connection to the target cell [10].

In LTE only hard handover is supported, meaning that there is a short interruption in service when the handover is performed.

3.5 Handover Procedure

Handover procedure in LTE can be divided into three phases: handover preparation, handover execution and handover completion [4]. The procedure starts with the measurement reporting of a handover event by the User Equipment (UE) to the serving evolved Node B (eNB**).** The Evolved Packet Core (EPC) is not involved in handover procedure for the control plane handling, i.e. preparation messages are directly exchanged between the eNB's [1]. That is the case when X2 interface is deployed, otherwise MME will be used for HO signaling.

The handover procedure with the basic handover scenario is depicted in Figure 10.

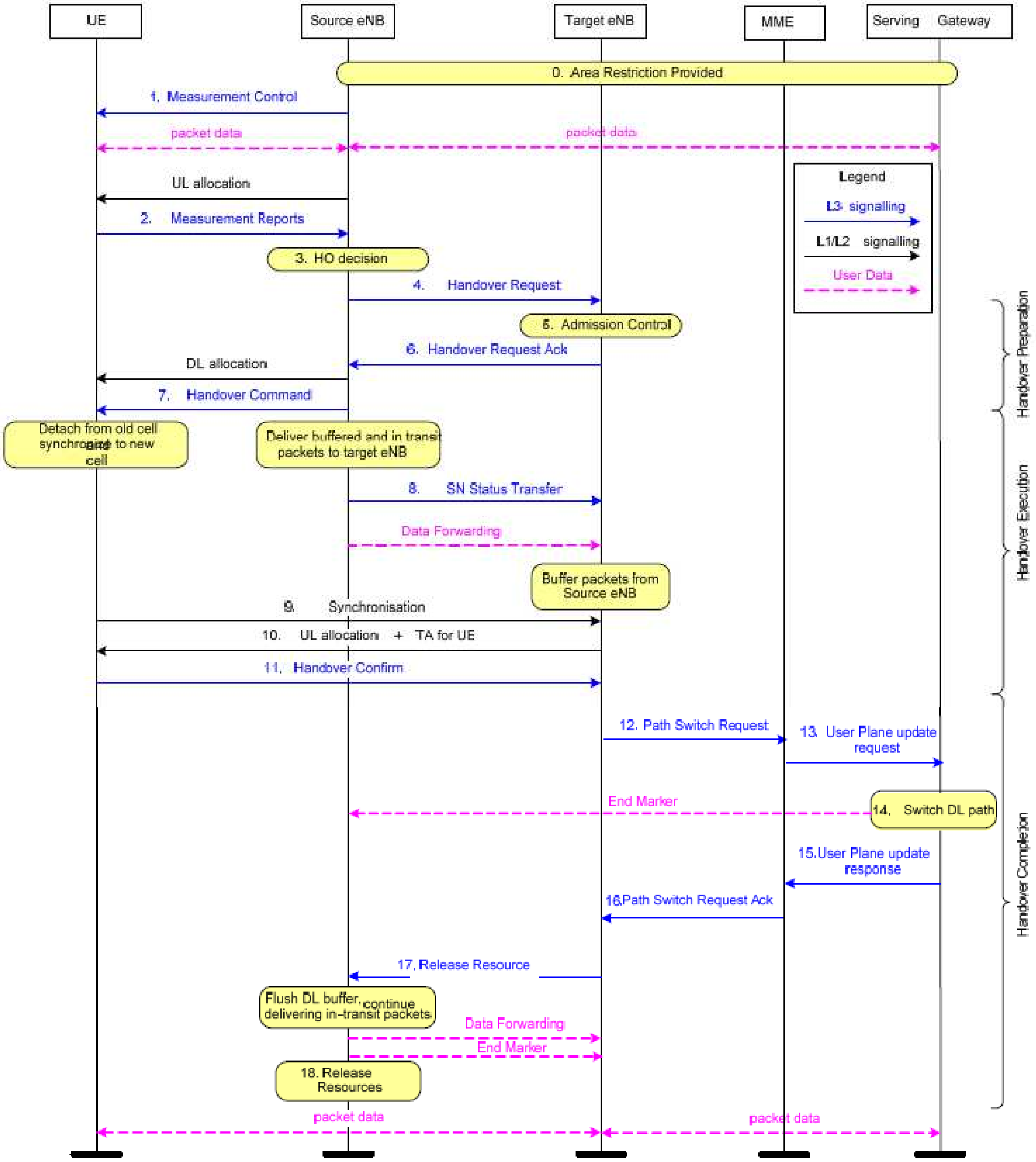


Figure 9. Intra-MME/Serving Gateway handover [9]

- **Handover preparation**

During the handover preparation, data flows between UE and the core network as usual. This phase includes messaging such as measurement control, which defines the UE measurement parameters and then the measurement report sent accordingly as the triggering criteria is satisfied. Handover decision is then made at the serving eNodeB, which requests a handover to the target cell and performs admission control. Handover request is then acknowledged by the target eNodeB.

- **Handover execution**

Handover execution phase is started when the source eNodeB sends a handover command to UE. During this phase, data is forwarded from the source to the target eNodeB, which buffers the packets. UE then needs to synchronize to the target cell and perform a random access to the target cell to obtain UL allocation and timing advance as well as other necessary parameters. Finally, the UE sends a handover confirm message to the target eNodeB after which the target eNodeB can start sending the forwarded data to the UE [1].

- **Handover completion**

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

A more detailed description of the intra-MME/Serving Gateway HO procedure is given below:

1. Based on the area restriction information, the source eNB configures the UE measurement procedure.

2. MEASUREMENT REPORT is sent by the UE after it is triggered based on some rules.

3. The decision for handover is taken by the source eNB based on MEASUREMENTREPORT and RRM information.

4. HANDOVER REQUEST message is sent to the target eNB by the source eNB containing all the necessary information to prepare the HO at the target side.

5. RAB QoS information. Performing admission control is to increase the likelihood of a successful HO, in that the target eNB decides if the resources can be granted or not. In case the resources can be granted, the target eNB configures the required resources according to the received E-RAB QoS information then reserves a Cell Radio Network Temporary Identifier (C-RNTI) and a RACH preamble for the UE.

6. The target eNB prepares HO and then sends the HANDOVER REQUEST ACKNOWLEDGE to the source eNB. There is a transparent container in the HANDOVER REQUEST ACKNOWLEDGE message which is aimed to be sent to the UE as an RRC message for performing the handover. The container includes a new C-RNTI, target eNB security algorithm identifiers for the selected security algorithms, may include a dedicated RACH preamble, and possibly some other parameters like RNL/TNL information for the forwarding tunnels. If there is a need for data forwarding, the source eNB can start forwarding the data to the target eNB as soon as it sends the handover command towards the UE.

Steps 7 to 16 are designed to avoid data loss during HO:

7. To perform the handover the target eNB generates the RRC message, i.e. RRC Connection Reconfiguration message including the mobility Control Information. This message is sent towards the UE by the source eNB.

8. The SN STATUS TRANSFER message is sent by the source eNB to the target eNB. In that message, the information about uplink PDCP SN receiver status and the downlink PDCP SN transmitter status of E-RABs are provided. The PDCP SN of the first missing UL SDU is included in the uplink PDCP SN receiver status. The next PDCP SN that the target eNB shall assign to the new SDUs is indicated by the downlink PDCP SN transmitter status.

At this point, data forwarding of user plane downlink packets can use either a “seamless mode” minimizing the interruption time during the move of the UE, or a “lossless mode” not tolerating packet loss at all. The source eNodeB may decide to operate one of these two modes on a per EPS bearer basis, based on the QoS received over X2 for this bearer.

9. After reception of the RRC Connection Reconfiguration message including the mobility Control Information by the UE, the UE tries to perform synchronization to the target eNB and to access the target cell via RACH. If a dedicated RACH preamble was assigned for the UE, it can use a contention free procedure; otherwise it shall use a contention based procedure. In the sense of security, the target eNB specific keys are derived by the UE and the selected security algorithms are configured to be used in the target cell.

10. The target eNB responds based on timing advance and uplink allocation.

11. After the UE is successfully accessed to the target cell, it sends the RRC Connection Reconfiguration Complete message for handover confirmation, The C-RNTI sent in the RRC Connection Reconfiguration Complete message is verified by the target eNB and afterwards the target eNB can now begin sending data to the UE.

12. A PATH SWITCH message is sent to MME by the target eNB to inform that the UE has changed cell.

13. UPDATE USER PLANE REQUEST message is sent by the MME to the Serving Gateway.

14. The Serving Gateway switches the downlink data path to the target eNB and sends one or more \end marker" packets on the old path to the source eNB to indicate no more packets will be transmitted on this path. Then U-plane/TNL resources towards the source eNB can be released.

15. An UPDATE USER PLANE RESPONSE message is sent to the MME by the Serving Gateway.

16. The MME sends the PATH SWITCH ACKNOWLEDGE message to confirm the PATH SWITCH message.

17. The target eNB sends UE CONTEXT RELEASE to the source eNB to inform the success of handover to it. The target eNB sends this message to the source eNB after the PATH SWITCH ACKNOWLEDGE is received by the target eNB from the MME.

18. After the source eNB receives the UE CONTEXT RELEASE message, it can release the radio and C-plane related resources. If there is ongoing data forwarding it can continue.

3.6 Optimization and Design Principles

In LTE there are some predefined handover conditions or threshold definitions in the network for triggering the handover procedure as well as some goals regarding handover design and optimization such as decreasing the total number of handovers in the whole system by predicting the handover, decreasing the number of ping pong handovers, and having fast and seamless handover.

Thus, the decision to trigger a handover is a crucial component in the design process of handover, since the success and the efficiency of the handover, to a large extent, depends on the accuracy and timeliness of the decision [16].

In the following the main criteria for designing handovers are discussed [20][24]:

- *Minimize the number of handover failures*

  The call termination due to handover should be avoided, and the conversation should be preserved when the mobiles move from one serving cell to another by doing handover. This is a crucial goal for handover design and optimization.

- *Minimize the number of unnecessary handovers*

  It is always desirable to minimize the number of handovers because excessive handovers increase the switching load and decrease the communication quality, and traffic capacity of a system. Mitigating Ping-Pong effects (in which the user repeatedly switches between adjacent cells) and identifying the correct target cell can help avoiding unnecessary handovers.

- *Minimize the absolute number of initiated handovers*

  The handover procedure is risky because the call may be dropped due to the handover. The number of handover initiations will be significantly increased if there are many Ping-Pong handovers or incorrect target cell selection. Hence, it is very important for the operator to minimize the number of handovers to provide a good service to their customers.

- *Minimize handover delay*

  Handover should be fast so that the user does not experience service degradation or interruption. This goal is more important for hard handover where there is an interruption in the user plane.

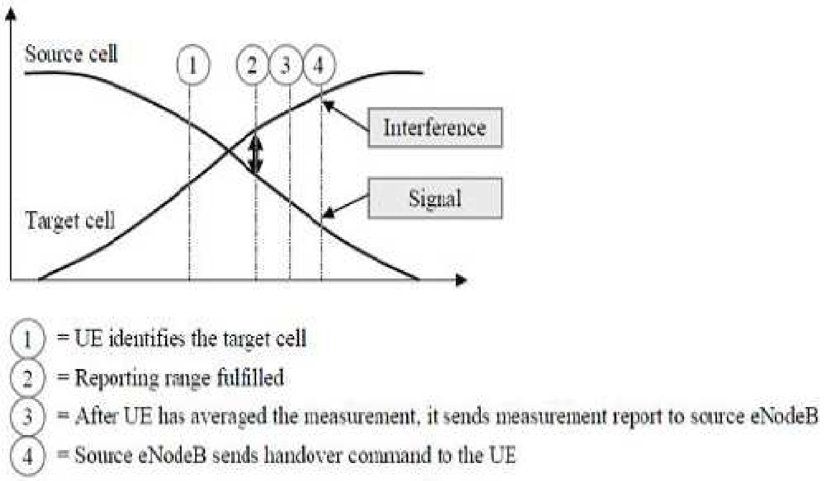


Figure 10. Handover Timing [8]

- *Maximize the total time the user being connected to the best cell*

  Handover is performed to have the UE connected to the best cell. Achieving this goal will be easier if the handover is designed in a way that prolongs the amount of time that the UE is connected to the best cell. Hence, maximizing the total time that user is connected to the best cell is an important design goal.

- *Minimize the impact of handover on system and service performance*

  Minimizing the impact of handover on system and service performance can be obtained by optimizing the handover procedure. With an efficient handover algorithm, there should be good system performance for the user. For example, the SIR and signal strength of current link should be good. This requires the efficient handover algorithm to minimize the effect of handover on the system performance. In addition, to minimize the impact of handover procedure on service performance, with a specific consideration of delay critical services such as real time services, is also important for handover design.

  Some of the goals mentioned above are in contradiction to each other. For example, minimizing the number of unnecessary handovers can increase the handover delay to some extent, and to maximize the time user is connected to the best cell can increase the numbers of handovers. Different combinations of the parameters in handover algorithm can make this trade-offs and affect the performance of the handover.

  Therefore when designing a well-performed handover, it is very important to find an optimal setting of these parameters by considering the importance of different goals in order to obtain generally good performance.

3.7 Handover Measurements

The handover procedure in LTE, which is a part of the RRM, is based on the UE's measurements. Handover decisions are usually based on the downlink channel measurements which consist of Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) made in the UE and sent to the eNB regularly [12]. The descriptions of each of them are presented following:

- **Reference Signal Received Power (RSRP)**

  The RSRP measurement provides cell-specific *signal strength metric*. This measurement is used mainly to rank different LTE candidate cells according to their signal strength and is used as an input for handover and cell reselection decisions. RSRP is defined for a specific cell as the linear average received power (in Watts) of the signals that carry cell-specific Reference Signals (RS) within the considered measurement frequency bandwidth [4].

- **Reference Signal Received Quality (RSRQ)**

  This measurement is intended to provide a cell-specific *signal quality metric*. Similarly to RSRP, this metric is used mainly to rank different LTE candidate cells according to their signal quality. This measurement is used as an input for handover and cell reselection decisions, for example in scenarios for which

RSRP measurements do not provide sufficient information to perform reliable mobility decisions.

The RSRQ is defined as:

$$\text{RSRQ} = \frac{\text{N . RSRP}}{\text{RSSI}}$$

Where N is the number of Resource Blocks (RBs) of the LTE carrier RSSI measurement bandwidth. The measurements in the numerator and denominator are made over the same set of resource blocks. While RSRP is an indicator of the wanted signal strength, RSRQ additionally takes the interference level into account due to the inclusion of RSSI. RSRQ therefore enables the combined effect of signal strength and interference to be reported in an efficient way [4].

Besides RSRP/RSRQ, handover technology has other decision criterions, such as:

- **Signal Noise Ratio (SNR)**

  The SNR is a measurement that compares the level of a desired signal to the level of background noise (unwanted signal). It is defined as the ratio of signal power and the noise power. A ratio higher than 1:1 indicates more signal than noise.

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}},$$

  Where *P* is average power. Both signal and noise power must be measured at the same or equivalent points in a system, and within the same system bandwidth [27].

- **Carrier-to-Interference Ratio (CIR)**

  CIR expressed in decibels (dB) is a measurement of signaling effectiveness and it is defined as the ratio of the power in the carrier to the power of the interference signal.

- **Signal Interference plus Noise Ratio (SINR)**

  This metric is used to optimize the transmit power level for a target quality of service assisting with handover decisions. Accurate SINR estimation provides a more efficient system and a higher user-perceived quality of service.

SINR is defined as the ratio of signal power to the combined noise and interference power:

$$\mathrm{SNIR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}} + P_{\mathrm{interference}}}$$

Where P is the averaged power, values are commonly quoted in dB [27].

- **Received Signal Strength Indicator (RSSI)**

  The LTE carrier RSSI is defined as the total received wideband power observed by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference and thermal noise within the measurement bandwidth specified by the 3GPP. LTE carrier RSSI is not reported as a measurement in its own right, but is used as an input to the LTE RSRQ measurement [4].

As mentioned earlier, handover measurements in LTE are done at the downlink reference symbols in the frame structure as shown in Figure 11. However, handover decision can also be based on the uplink measurements. This study focuses on downlink handover measurements.

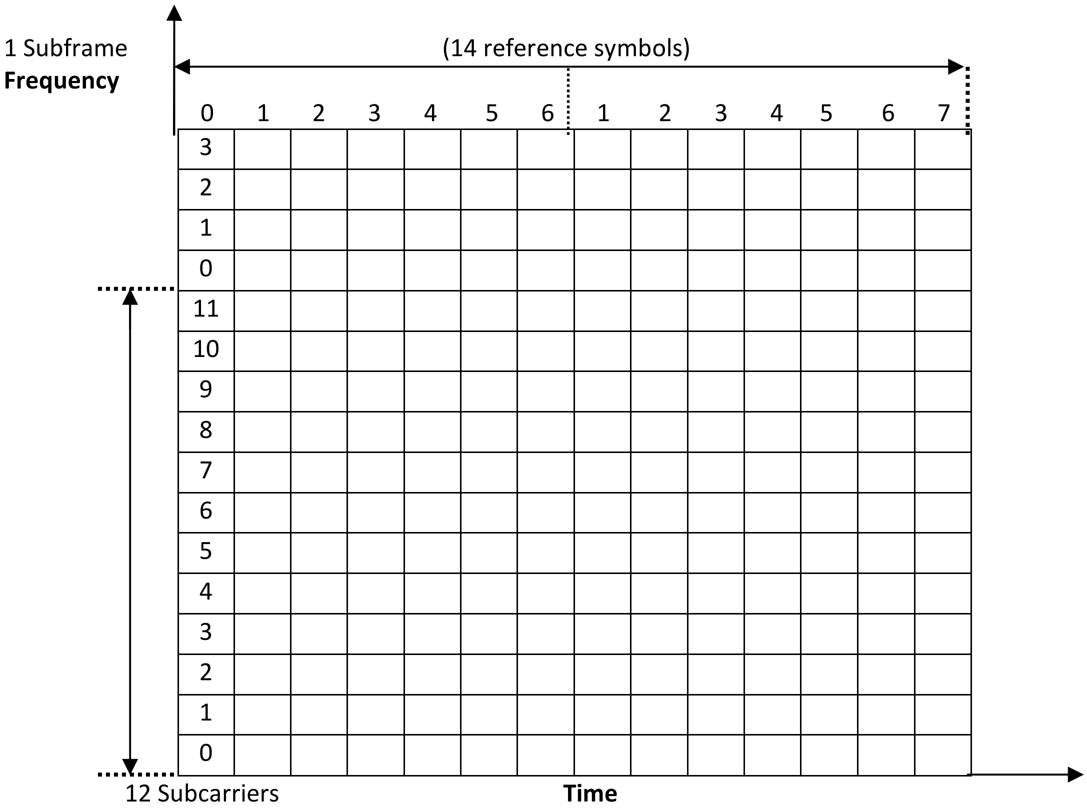


Figure 11. Downlink reference signal structure for LTE.

The averaging of fast fading over all the reference symbols is done at L1 and hence is called L1 filtering (Figure 12). The use of scalable bandwidth in LTE allows doing the handover measurement on different bandwidth.

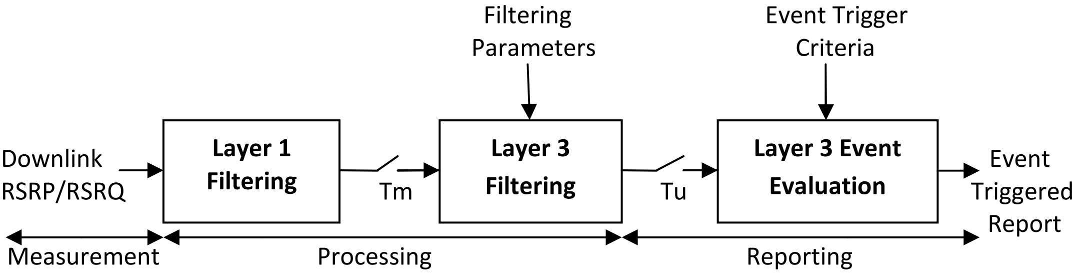


Figure 12. Handover measurement filtering and reporting [10].

3.8 Handover Parameters

The handover procedure has different parameters which are used to enhance its performance and setting these parameters to the optimal values is a very important task. In LTE the triggering of handover is usually based on measurement of link quality and some other parameters in order to improve the performance. The most important ones include [16]:

- Handover initiation threshold level RSRP and RSRQ

  This level is used for handover initiation. When the handover threshold decreases, the probability of a late handover decreases and the ping-pong effect increases. It can be varied according to different scenarios and propagation conditions to make theses trade-offs and obtain a better performance.

- Hysteresis margin

  The Hysteresis margin also called HO margin is the main parameter that governs the HO algorithm between two eNB's. The handover is initiated if the link quality of another cell is better than current link quality by a hysteresis value. It is used to avoid ping-pong effects. However, it can increase handover failure since it can also prevent necessary handovers.

- Time-to-Trigger (TTT)

  When applying Time-to-Trigger, the handover is initiated only if the triggering requirement is fulfilled for a time interval. This parameter can decrease the number of unnecessary handovers and effectively avoid ping-pong effects. But it can also delay the handover which then increase the probability of handover failures.

- The length and shape of averaging window

  The effect of the channel variation due to fading should be minimized in handover decision. Averaging window can be used to filter it out. Both the length and the shape of the window can affect the handover initiation. Long windows reduce the number of handovers but increase the delay. The shape of the windows, e.g. rectangular or exponential shape, can also affect the number of handovers and probability of unnecessary handovers.

The listed parameters will affect directly the handover initiations and hence they can be tuned according to certain design goals. However there are other parameters like the measurement report period which can also have an impact on the handover initiations.

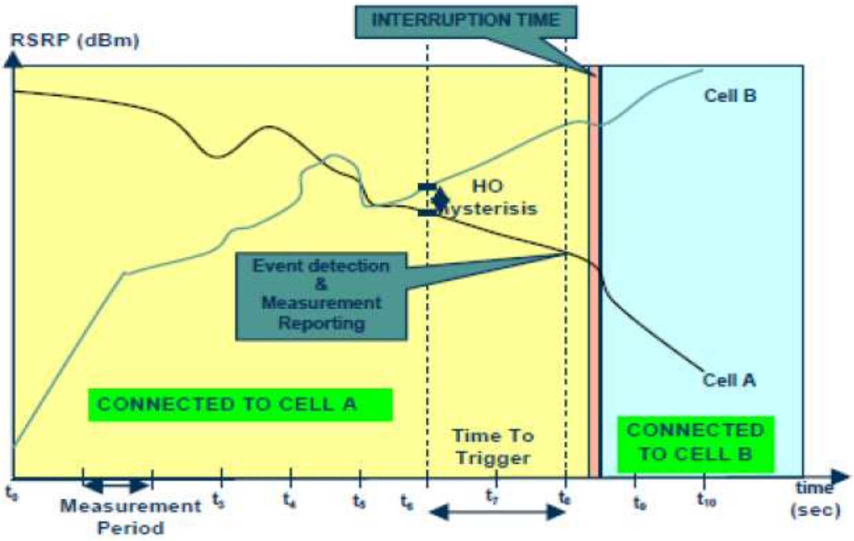


Figure 13. Handover triggering procedure [11].

In summary, the starting point of the handover triggering procedure is the measurements performed by the UE. These are done periodically as defined by the measurement period parameter configured at the eNodeB. When a condition is reached in which the serving cell RSRP drops an amount of the configured HO offset, usually 2-3dB, below the measured neighbor cell, a timer is started.

In case this condition lasts the amount of the Time to Trigger (TTT) value, a measurement report is sent to the eNodeB, which initiates the handover by sending a handover command to the UE. In case the reporting conditions change and no longer satisfy the triggering conditions before the timer reaches the TTT value, a measurement report will not be sent and new measurement calculations and timers are started [11].

The handover parameters need to be optimized for good performance. Too low handover offset and TTT values in fading conditions result in back and forth ping-pong handovers between the cells. Too high values then can be the cause of call drops during handovers as the radio conditions get too bad for transmission in the serving cell.

It should be noted however that the user data interruption time is not affected by these parameters since the handover, and thus the interruption time, is initiated only after the UE receives a handover command. Prior to receiving the command, the UE sends and receives data as usual. For example handover command may have to be retransmitted several times by the HARQ process but if the call is eventually successfully handed over, the user service delay remains unaffected.

4. Handover Performance Evaluation Process

4.1 Problem Statement

One of the main characteristics of Long Term Evolution (LTE) is to provide seamless access to voice and multimedia services with strict delay requirements which is achieved by supporting handover. Within 3GPP LTE only hard handover is supported meaning that there is a short interruption in service when the handover is performed. In this context it is very important to implement an efficient handover according to the design and optimization principles such as minimizing the number of unnecessary handovers, decreasing handover delay and increasing system throughput. [10].

As stated earlier, handover triggering is a primary component in handover design since the success and the efficiency of the handover, to a large extent, depends on the accuracy and timeliness of the decision. Moreover, a careful selection of HO parameters and the optimal setting of these are required as well. The LTE standard supports two main parameters to trigger the handover and select the target cell: hysteresis margin (HOM) and Time-to-Trigger (TTT) [11]. These two parameters are considered the most important control parameters because they play an important role in reducing the unnecessary HO triggers due to the short term and sudden variations in signal strength due to shadowing and fast fading.

The optimal setting of HOM and TTT depends on UE speed, radio network deployment, propagation conditions and the system load. The instant when the HO is triggered defines the radio propagation conditions to be met upon transmission of the HO-involved signaling; both for the messages transmitted in the serving and in the target cell [11].

4.2 Previous Work

So far, many studies have been done concerning problems related to handover algorithms for HO performance optimization and evaluation. In [10] a new handover algorithm known as LTE Hard Handover Algorithm with Average Received Signal Reference Power (RSRP) Constraint (LHHAARC) is proposed in order to minimize number of handovers and the system delay as well as maximize the system throughput. The system performance is evaluated and compared with other three HO algorithms: LTE Hard Handover Algorithm, Received Signal Strength based TTT Window Algorithm and the Integrator Handover Algorithm. The results showed that the LHHAARC algorithm can efficiently reduce the number of handovers, minimizing the total system delay and maximizing the total system throughput. The study in [11] considers the setting of HO triggers of primary importance for the design of a good performing HO procedure. It is inferred that adaptation of the HO triggers on the basis of speed, propagation conditions and cell sizes is needed. Considering the difficulties in adapting properly the HO triggers, another solution using a series of HO triggers is proposed. LTE specific HO issues are considered by [12] and [13]. The study in [12] recommends us a range of HOM in dB considering the average number of HO for different user speeds. Research in [13] provides us linear and dB domain L3-filter performance improvements in terms of global number of handovers.

In [14] they have investigated the improvements of LTE handover performance through ICIC. It has been shown that optimum HO performance can be achieved through optimum parameters selection by finding a compromise between HO rates and Residual BLER for HO Command message. Paper in [15] has shown that the user perceived performance at handovers will not degrade due to the relocation based handover scheme of LTE. There is no radio efficiency drawback associated with the restart of user plane protocols (i.e., RLC/MAC) at the target cell. However, they recommend to employ packet forwarding from the source to the target cell and to ensure the correct delivery order of packets in order to achieve high TCP throughput performance.

The impacts of triggering setting {hysteresis/TTT} on handover performance have been investigated in [16] for different scenarios with low, medium and high system loads. System level simulations have been done and it has been shown that the setting can affect the handover loss rate, system and service performance. The optimal setting for each case has been proposed. The research in [17] proposed a new handover optimization algorithm which changes the values of the hysteresis and time-to-trigger parameters in an automated manner in response to changes in the network performance. It picks the best hysteresis and time-to-trigger combination for the current network status and the results show an improvement from the static value settings.

4.3 LTE Power Budget Handover Algorithm (PBHA)

The LTE Power Budget Handover Algorithm (PBHA) is a basic but effective handover algorithm used for performance evaluation consisting of two variables: handover margin (HOM) and Time to Trigger (TTT) value. HOM is usually measured in decibels and TTT is measured in seconds [10].

As it has been explained in previous section, HOM or hysteresis is a constant variable that represents the threshold of the difference in Received Signal Strength (RSS) between the serving and the target cells. HOM ensures the target cell is the most appropriate cell the mobile camps on during handover. A TTT value is the time interval that is required for satisfying HOM condition. Both HOM and TTT are used for reducing unnecessary handovers which is called “Ping-Pong effect”.

When a mobile is experiencing this effect, it is handed over from a serving cell to a target cell and handed back to original serving cell again in a small period of time. This effect increases the required signaling resources, decreases system throughput, and increases data traffic delay caused by buffering the incoming traffic at the target cell when each handover occurs. Therefore effectively preventing unnecessary handovers is essential.

TTT restricts the handover action from being triggered within certain time duration. A handover action can only be performed after the TTT condition has been satisfied. When a mobile is moving away from the serving cell, the RSRP which the mobile receives from the serving cell will degrade as time increases. Meanwhile, the mobile will move towards the target cell, therefore the RSRP the mobile receives from the target cell will increase as time increases [10].

A handover is triggered when the triggering condition (1) and (2) are both satisfied, followed by the handover command.

$$RSRP_T > RSRP_S + HOM \quad (1)$$

$$HO\ Trigger > TTT \quad (2)$$

Where $RSRP_T$ and $RSRP_S$ are the RSRP received from the target cell and the serving cell, respectively, and HO Trigger is the handover trigger timer which starts counting when condition (1) gets satisfied. Figure 14 shows the basic concept of LTE hard handover algorithm.

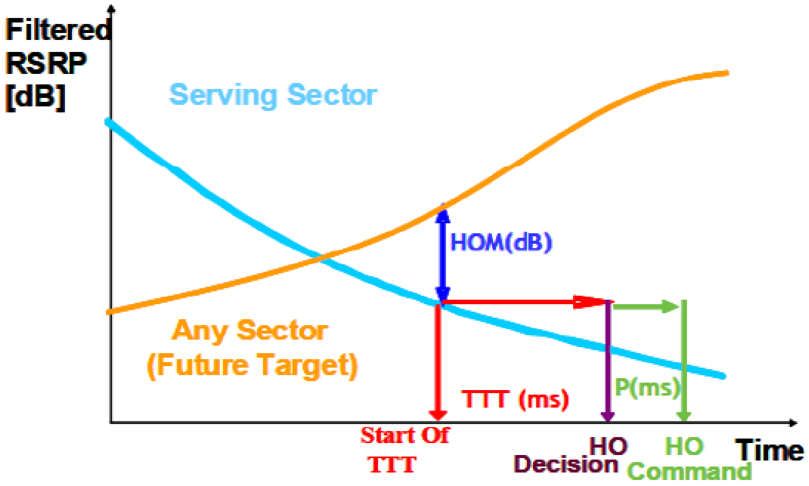


Figure 14. PBHA [10].

4.4 Evaluation Methodology

The design of an efficient and successful handover requires the careful selection of HO performance based on RSRP measurements within certain deployment scenarios. The evaluation methodology of this thesis is based on the method developed in [16].

This study measures the absolute number of handovers, which is a very important variable for the network operators, in relation with the Average Signal to Interference plus Noise Ratio (SINR) measured to select the connected cell and possible handover candidate. This is done through different combinations of HOM and TTT with the main objective to minimize the number of handovers. Thus, minimizing the expected number of handovers minimizes the signaling overhead.

In order to compute the SINR, the following procedure is done:

The physical layer computes for each sub channel the SINR for the received signal considering the received power, the noise, and the interference, as it follows:

$$SINRi, j = \frac{P_{RX,i,j}}{(FN_0B) + I}.$$

Where F, No, B, and I are the noise figure (default value 2.5), the noise spectral density (default value -174dBm), the bandwidth of a resource block (i.e., 180 kHz) and the interference, respectively. The interference is the total power received from the eNB's sharing the same frequency resources. SINR value is obtained as a weighted average among SINRs of a set of sub channels per UE and evaluated in the moment where handover occurs.

4.4.1 Performance Metrics

The PBHA picks the best hysteresis and time-to-trigger combinations to evaluate the system performance in terms of number of handovers, throughput, delay, packet lost and SINR.

4.4.2 System Level Simulator description

The study is done using a dynamic system level simulator called LTE-Sim, an open source framework to simulate LTE networks. In order to ensure modularity, polymorphism, flexibility, and high performance, LTE-Sim has been written in C++, using the object-oriented paradigm, as an event-driven simulator.

LTE-Sim encompasses several aspects of LTE networks, including both the Evolved Universal Terrestrial Radio Access (E-UTRAN) and the Evolved Packet System (EPS). It supports single and heterogeneous multi-cell environments, QoS management, multi-user environment, user mobility, handover procedures, and frequency reuse techniques. Four kinds of network nodes are modeled: user equipment (UE), evolved Node B (eNB), Home Enb (HeNB), and Mobility Management Entity/Gateway (MME/GW). Four different traffic generators at the application layer have been implemented and the management of data radio bearer is supported.

Finally, well-known scheduling strategies (such as Proportional Fair, Modified Largest Weighted Delay First, and Exponential Proportional Fair, Log and Exp rules), AMC scheme, Channel Quality Indicator feedback, frequency reuse techniques, and models for physical layer have been developed [28].

There are four main components in LTE-Sim:

- The Simulator
- The Network Manager
- The Flows Manager
- The Frame Manager

A system level inter cell handover procedure is implemented in the simulator in order to support user mobility. Two types of mobility models are supported;
Random Direction and Random Walk. For each of them, a dedicated class has been developed, extending the basic Mobility Model class, i.e., Random Direction and Random Walk classes. In Mobility Model class *m_speed* and *m_speed direction* variables are used to define the speed and the travel direction of the user, respectively. User speed should be chosen among the values 0, 3, 30, and 120 km/h, equivalent to static, pedestrian, and vehicular scenarios, respectively.

When the Random Direction model is used, the UE randomly chooses the speed direction that remains constant during the time, and moves towards the simulation boundary area. Once the simulation boundary area is reached, the UE chooses a new speed direction. When the Random Walk is used, the UE randomly chooses the speed direction and moves accordingly for a given travel distance that depends on the user speed. The UE changes its speed direction after covering this distance or, as in the previous model, once the simulation boundary area is reached.

As default, the travel distance is equal to 200, 400, 1000 m. when user speed is equal to 3, 30, and 120 km/h, respectively. The user mobility is managed by the Network Manager that, every TTI updates the user position according to the selected mobility model and parameters, and verifies, through the NetworkManager::HandOverProcedure() function, if the handover procedure is necessary. In LTE-Sim both cell re-selection and handover procedures are implemented. Moreover, handover decisions are carried out by the Handover Manager, defined for each UE. Handover management consists of the following steps:

1. For the UE that triggered the handover procedure, the function HandOverManager::SelectTargetENodeB () is used for selecting a new target eNB (Using one of the two algorithms explained below, Position-based or Power-based).
2. All the information about the UE is transferred from the old eNB to the new one.

3. Between the UE and the new target eNB, a new radio bearer is created.
4. The UE updates the list of available sub-channels for downlink and uplink, according to those assigned to the new target eNB.

During the handover, the UE switches to a detached state for a given time interval, so that no flows directed to and coming from the UE can be scheduled; such a time interval is a simulator parameter and can be modified (default value is 30 ms).

Currently LTE-Sim is supporting two algorithms:

- Position-based (if d2 > d1, then choose eNB2 to be your new serving eNB).
- Power-based (if RSRP2 > RSRP1, choose eNB2 to be your new serving eNB).

For the study of the LTE Handover Performance Evaluation, Power-based algorithm is used, but for its simplicity, two parameters are added to carry out the study, these are Hysteresis Margin and the Time to trigger value.

Changes in the code of the LTE-Sim are performed introducing parameters of HOM and TTT. To introduce HOM the following condition is used (Adding a HOM variable):

(RXpower > targetRXpower + HOM)

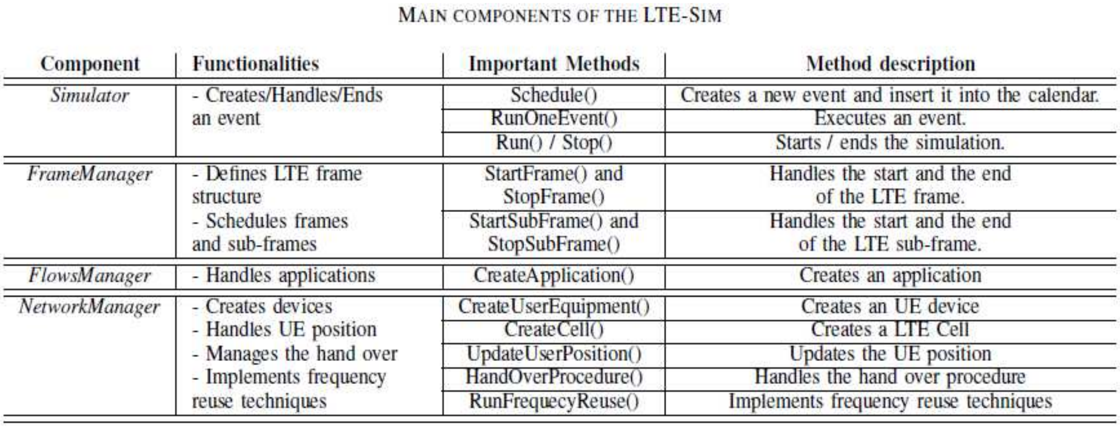
For TTT, a counter associated to each eNB is introduced, that counts the time where the previous condition is guaranteed.

```
If (RXpower > targetRXpower + HOM)
{
  TTT_counter++;

 If (TTT_counter >= TTT_threshold)
 {
   targetRXpower = RXpower;
   targetNode = probableNewTargetNode;
 {

}
```

Another variable is introduced (TTT_counter) for each eNB that keeps trace of the time where the condition (RXpower >targetRXpower + HOM) is guaranteed. Once this time overtakes the TTT_threshold (that is a system parameter) a handover occurs.



MAIN COMPONENTS OF THE LTE-SIM

Component	Functionalities	Important Methods	Method description
Simulator	- Creates/Handles/Ends an event	Schedule()	Creates a new event and insert it into the calendar.
		RunOneEvent()	Executes an event.
		Run() / Stop()	Starts / ends the simulation.
FrameManager	- Defines LTE frame structure - Schedules frames and sub-frames	StartFrame() and StopFrame()	Handles the start and the end of the LTE frame.
		StartSubFrame() and StopSubFrame()	Handles the start and the end of the LTE sub-frame.
FlowsManager	- Handles applications	CreateApplication()	Creates an application
NetworkManager	- Creates devices - Handles UE position - Manages the hand over - Implements frequency reuse techniques	CreateUserEquipment()	Creates an UE device
		CreateCell()	Creates a LTE Cell
		UpdateUserPosition()	Updates the UE position
		HandOverProcedure()	Handles the hand over procedure
		RunFrequecyReuse()	Implements frequency reuse techniques

Figure 15. Main Components of the LTE-Sim [28].

4.5 Modeling and Simulation

The system is modeled and simulated in the dynamic downlink system level simulator LTE-Sim. A radio network consisting of 7 cells of 5 MHz bandwidth with 25 resource blocks and 2 GHz carrier frequency is built.

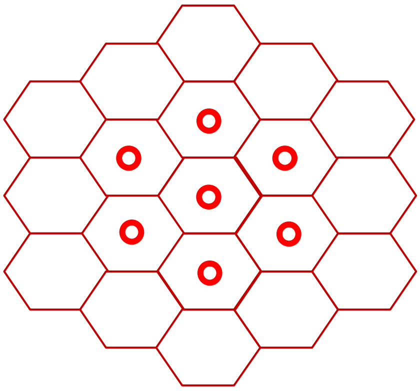


Figure 16. Cell Network Layouts

Each resource block is consisted of 12 subcarriers of size 15 kHz each. A time slot is 0.5 ms. in duration and the transmission time interval (TTI) is 1 ms. A fixed number of users are uniformly distributed over the area with random initialized positions and they are moving at a fixed speed in random directions. The traffic model is defined as infinite-buffer, an ideal greedy source that always has packets to send. Both at the eNB and the UE, 1 antenna is used for transmission and 2 for reception (Single Input Multiple Output).

The most relevant simulation parameters are listed in the next table:

Table 3: Simulation parameters

Parameter	Value
Cellular layout	7 cells
Cell radius	500 m. 1000 m.
Traffic model	INF BUF
BS Tx Power	20 w./43 dBm
Antenna	Onmidirectional with Gain=14 dBi
Channel model	3GPP Typical Urban
Carrier frequency	2 GHz
UE speed	(3 km/h, 30 km/h, 120 km/h)
Number of UE’s	1UE/cell and 3 UE’s/cell
UE direction	Randomly chosen within [0◦, 360◦)
TTI	1 ms.
Subcarrier spacing	15 Khz.
Resource Block	180 Khz
Super frame Time	10 ms.
Noise Figure	2.5
Update time of UE position	1 ms
Noise Spectral Density	-174 dBm
Simulation Time	60 s.
Max, Handover delay	30 ms.
System bandwidth	5 Mhz. 25 RBs/TTI
Hysteresis/Time-to-Trigger	0dB/0ms, 3dB/960ms, 6dB/120ms, 9dB/0ms

The 3GPP common scenarios adopted for simulation are:

- UE speeds at 30 Km/h, 60 Km/h and 120 Km/h.
- Number of users: 1UE/cell, 3 UE’s/cell.
- Cell sizes 500m and 1000 m.

The valid hysteresis values in the simulations vary between 0 dB and 9 dB. The time-to-trigger values for LTE networks are specified by 3GPP. The values taken in this study are: 0, 120 and 960 ms.

The study model of this thesis is shown in figure 18.

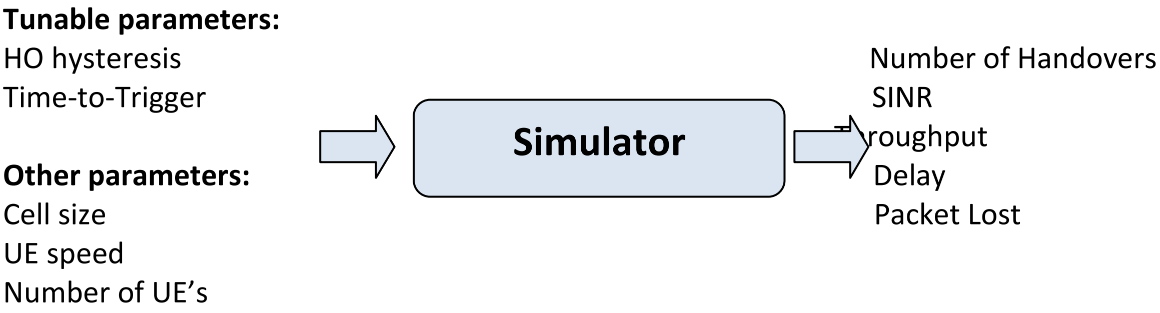


Figure 17. Study model.

The inputs of the study are tunable parameters such as handover hysteresis, time to trigger, cell size, UE speed and number of UE's. The outputs are: Number of handovers, SINR, throughput, delay and packet lost.

4.6 Simulation Results and Performance Evaluation

HO Triggering Setting for 1 UE/System

The case with 1 UE in the whole system is studied. This is the easiest case for handover study in order to confirm the performance of the simulator LTE-Sim.

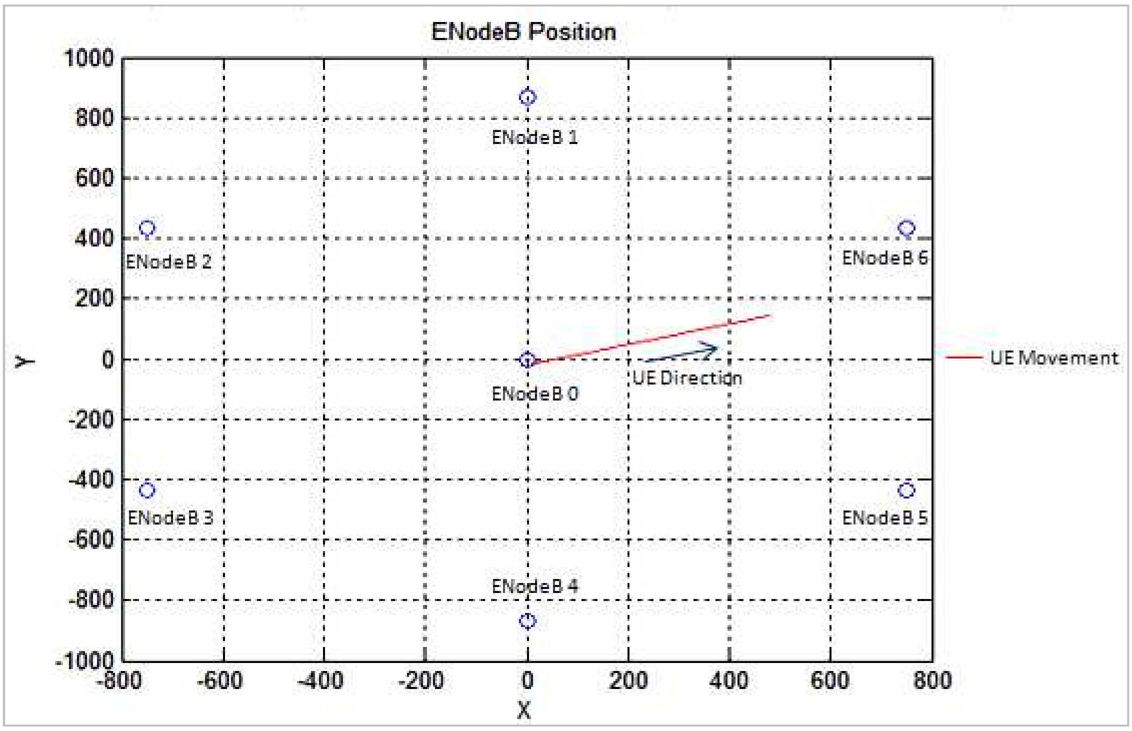


Figure 18. ENodeB's position and UE traveling pattern at 30Km/h.

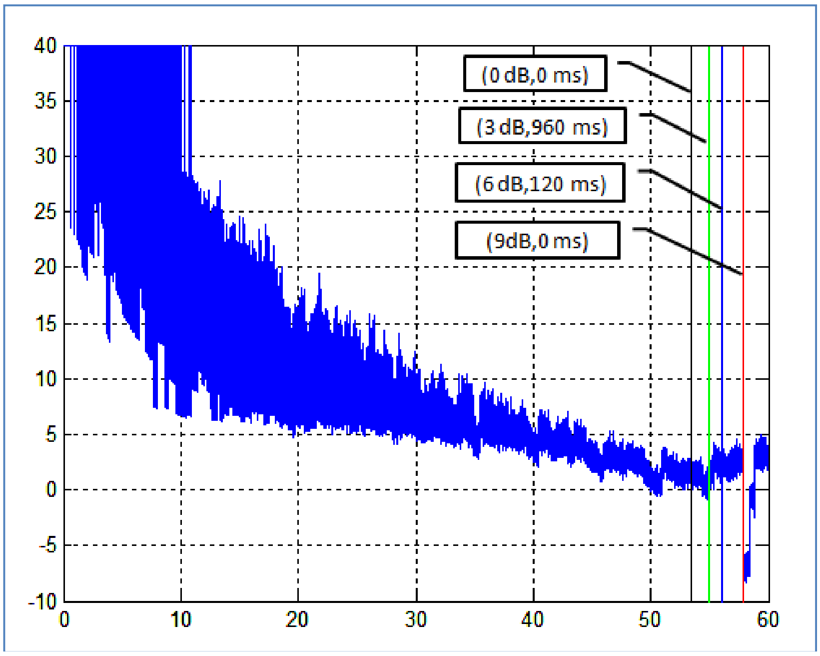


Figure 19. HO metrics with respect of SINR for 1 UE.

The UE performs a HO from ENodeB 0 to ENodeB 6. According to Figure 19, the HO is triggered in different moments depending the configuration of Hysteresis and Time to Trigger used. The evolution for SINR in relation with time is observed.

Scenario 1: HO Triggering Settings for 1 UE/cell at 3, 30, 120 Km/h and Cell Radius 500m.

The case with 1 UE/cell is studied. The evaluation methodology stated is applied to evaluate the performances of different handover triggering settings including (0dB/0ms), (3dB/960ms), (6dB/120ms) and (9dB/0ms).

The evaluation methodology is applied to choose a best triggering setting. Increasing the Hysteresis margin and decreasing values of TTT.

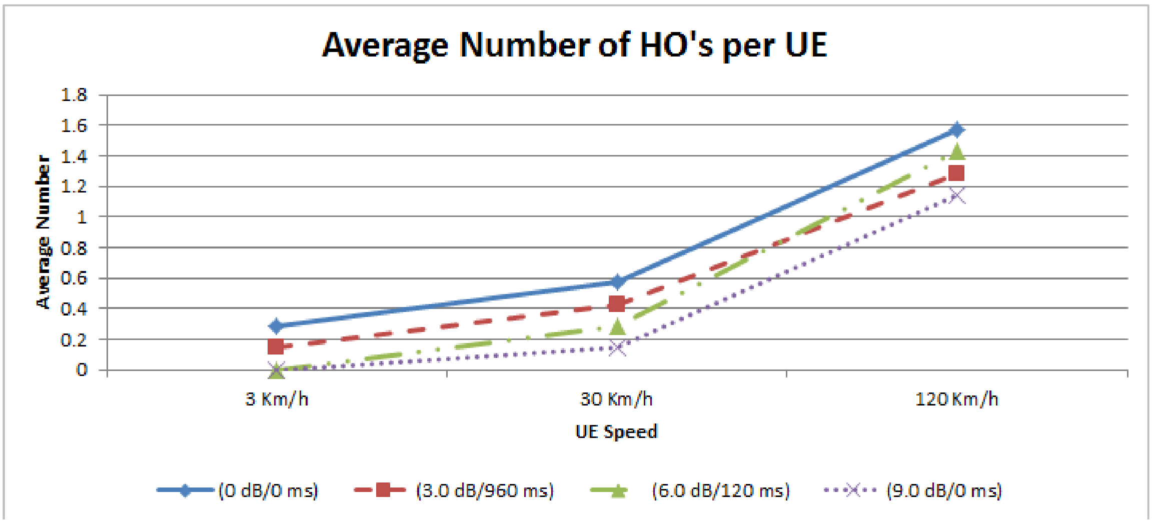


Figure 20. Effect of varying HOM and TTT on the average number of Handovers at the user speeds of 3, 30 and 120 km/h.

For all cases (0dB/0ms) generates the highest number of handovers. For a slow UE, the setting with small hysteresis and long TTT is easier to trigger handovers since it takes a long time for the slow UE to meet the large hysteresis condition. (3dB/960ms) trigger more handovers than other settings for 3km/h. It can be noticed that for, (6dB/120ms) and (9dB/0ms), the number of handovers remain the same.

Although (3dB/960ms) generates the highest number of handovers besides (0dB/0ms) for3km/h, it is still proposed because the handovers are not unnecessary. It is not harmful to generate a few more handovers.

For 30 Km/h, (3dB/960ms) generates more handovers compared with the rest of the configurations. The tendency is similar to the one observed for UE’s moving at 3Km/h. If the hysteresis is large like 9 dB, it is difficult to trigger a handover.

For UE’s going at 120 Km/h (6dB/120ms) triggers more handovers followed by (3dB/960ms) because the hysteresis will be easier to be fulfilled at this speed.

Operators prefer to have less handovers. However, this does not mean to choose the setting which can result in least handovers because a number of necessary handovers are needed.

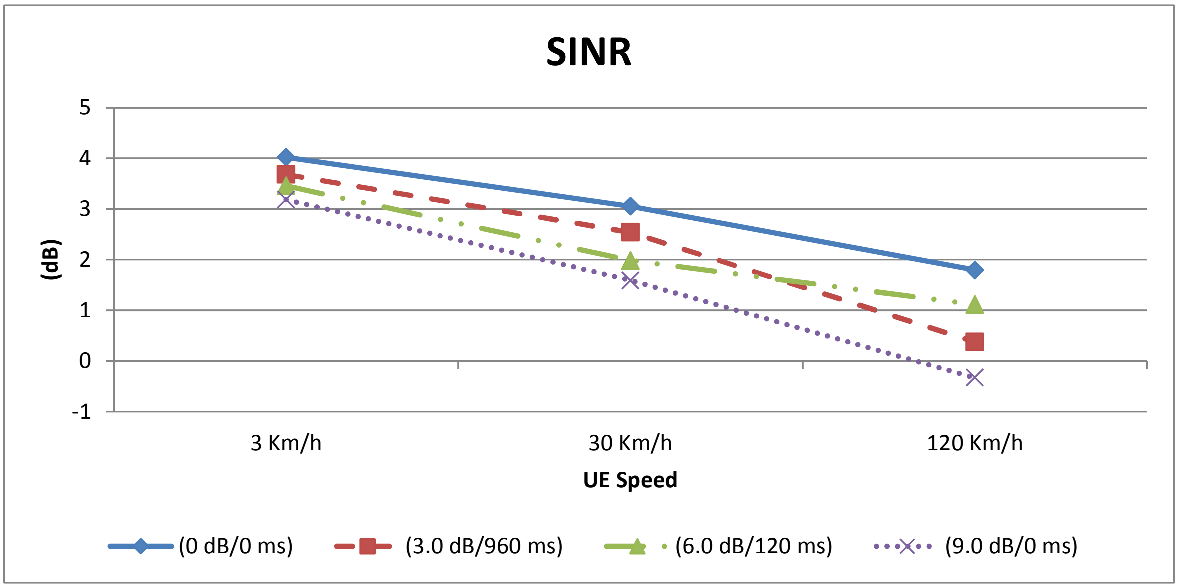


Figure 21. Downlink SINR.

The difference of SINR values for UE's moving at 120 Km/h is relatively larger than UE's moving at slow velocities. (0dB/0ms) performs better for all velocities than other settings because it is always connected to the best cell.

For UE's moving at 3 Km/h, (3dB/960ms) performs better compared to the others. For UE's moving at 30 Km/h the tendency is similar to 3 Km/h but this changes for UE's moving at 120 Km/h, where (6dB/120ms) has a better performance. The lowest values of SINR are obtained for (9dB/0ms) at that velocity.

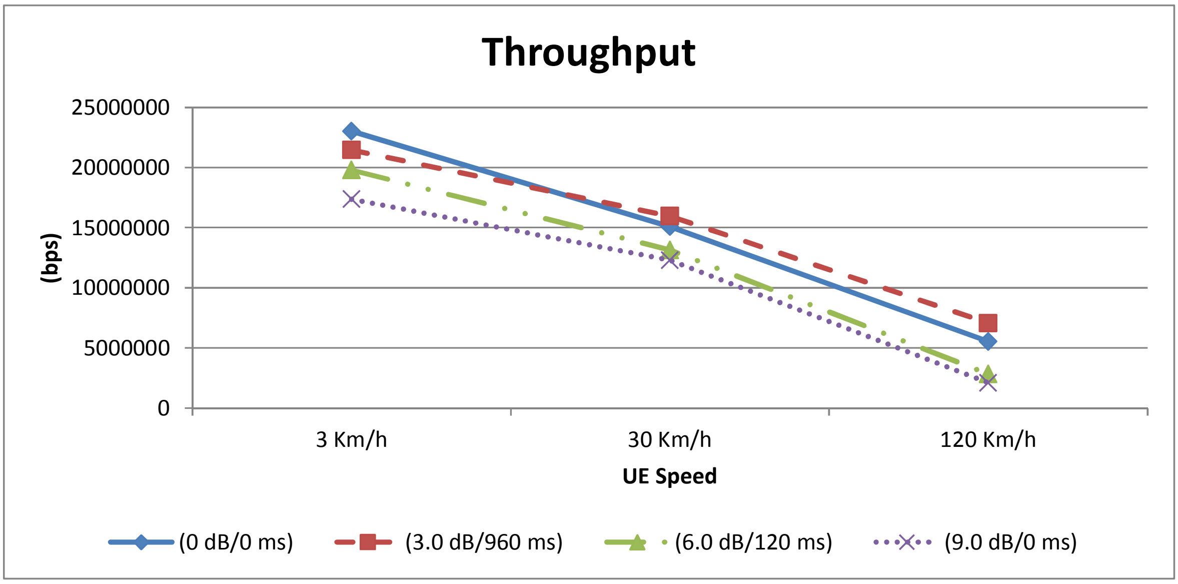


Figure 22. Throughput.

Figure 22, demonstrates that (3dB/960ms) and (0dB/0ms) have the highest throughput (21.45 Mbps and 23.02 Mbps) at 3 km/h because the handover is done for cells that have better channel quality at low speed. The throughput drops to 15.95 and 7.054 Mbps in the case of (3dB/960ms) at 30 and 120 km/h respectively, due to the increase in number of handovers resulting in the drop of the system performance. The same tendency is observed for UE's moving at 30 and 120 Km/h.

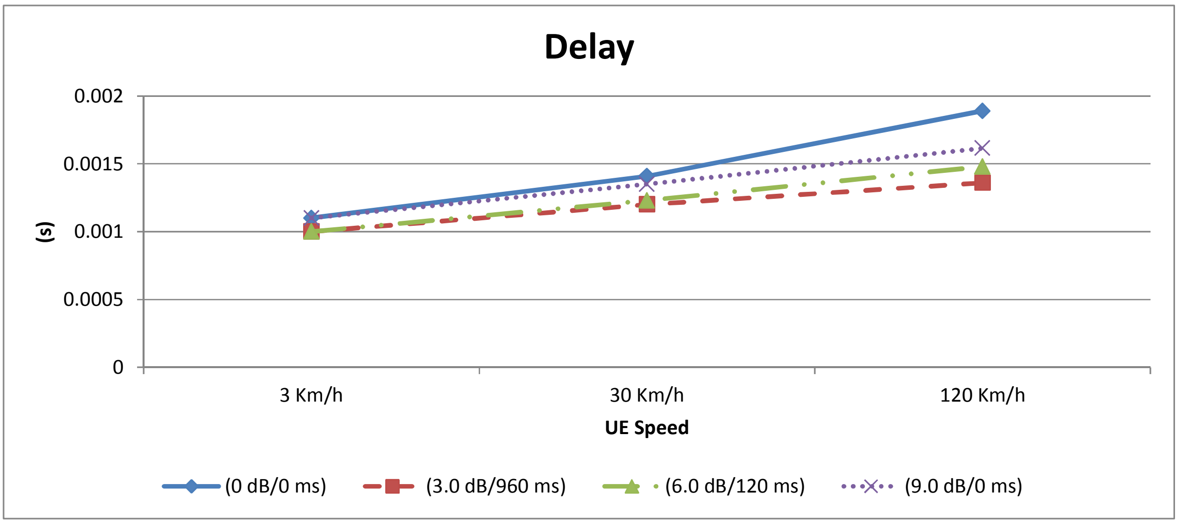


Figure 23. Delay.

Since the handover is more likely to occur frequently as the speed increases, this results in an increasing system delay under all handover settings being evaluated. The (0dB/0ms) and (9dB/0ms) have a slightly higher delay due to lack of TTT mechanism at all speed scenarios as compared with the other handover settings. (3dB/960ms) has the smallest total system delay at 3, 30, 120 km/h.

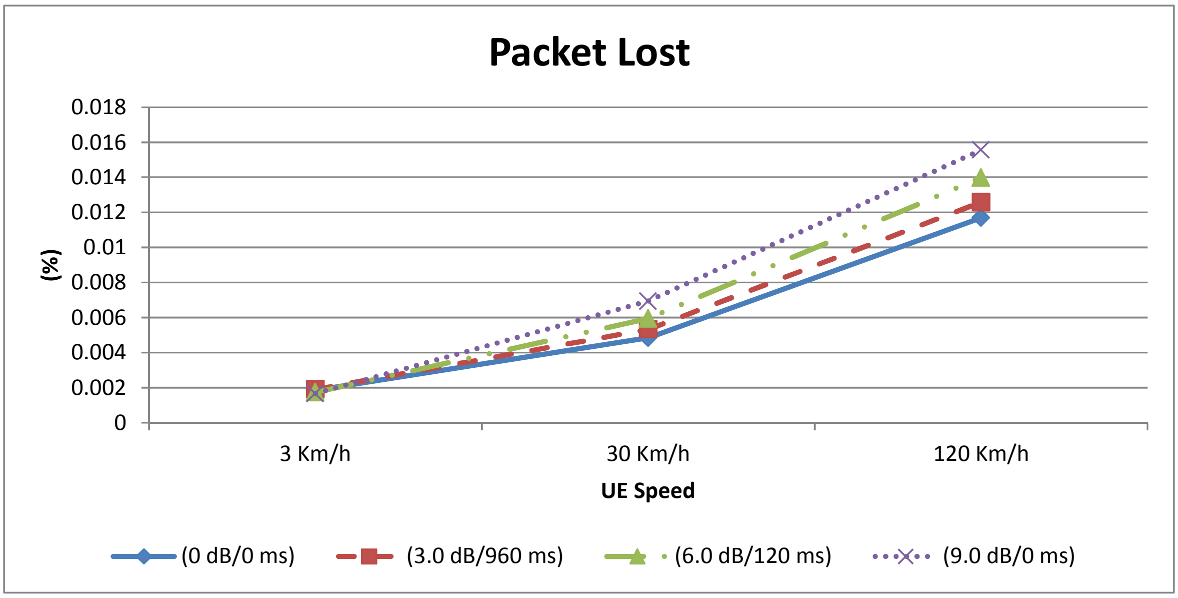


Figure 24. Packet Lost.

According to figure 24, UE's moving at 3Km/h with different handover settings have relatively the same performance. At 30 Km/h and 120 Km/h, (0dB/0ms) and (3dB/960ms) perform better. The packet lost ratio for (9dB/0ms) is 0.006941% and 0.0155% for both velocities.

Scenario 2: HO Triggering setting for 3 UE's/cell at 3, 30 and 120 Km/h and cell radius 1000m.

The tendencies are similar to the ones observed for 1 UE/cell. With larger cell size, relatively smaller hysteresis and larger TTT trigger more handovers because the large hysteresis margin is harder to be fulfilled for bigger cells.

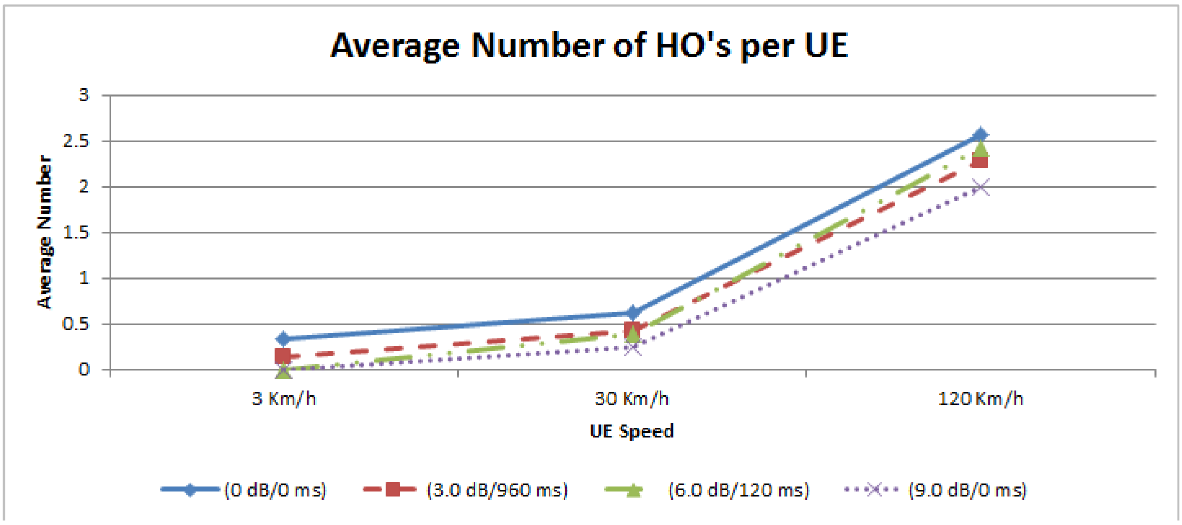


Figure 25. Effect of varying HOM and TTT on the average number of Handovers at the user speeds of 3, 30 and 120 km/h.

For all cases (0dB/0ms) generates the highest number of handovers. For a slow UE, the setting with small hysteresis and long TTT is easier to trigger handovers since it takes a long time for the slow UE to meet the large hysteresis condition. (3dB/960ms) trigger more handovers than other settings for 3km/h. It can be noticed that for, (6dB/120ms) and (9dB/0ms), the number of handovers remain the same.

Although (3dB/960ms) generates the highest number of handovers besides (0dB/0ms) for3km/h, it is still proposed because the handovers are not unnecessary. It is not harmful to generate a few more handovers.

For 30 Km/h, (3dB/960ms) generates more handovers compared with the rest of the configurations. The tendency is similar to the one observed for UE's moving at 3Km/h. If the hysteresis is large like 9 dB, it is difficult to trigger a handover.

For UE's going at 120 Km/h (6dB/120ms) triggers more handovers followed by (3dB/960ms) because the hysteresis will be easier to be fulfilled at this speed.

Operators prefer to have less handovers. However, this does not mean to choose the setting which can result in least handovers because a number of necessary handovers are needed.

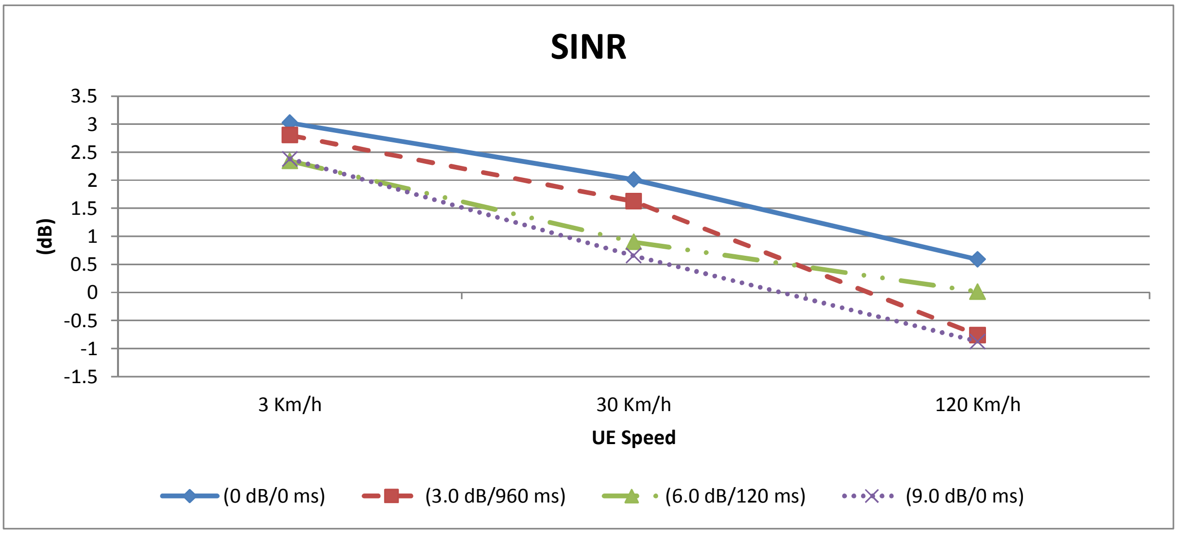


Figure 26. Downlink SINR.

The result is similar to the one obtained for cells of 500m. The difference of SINR values for UE's moving at 120 Km/h is relatively larger than UE's moving at slow velocities. (0dB/0ms) performs better for all velocities than other settings because it is always connected to the best cell.

For UE's moving at 3 Km/h, (3dB/960ms) performs better compared to the others. For UE's moving at 30 Km/h the tendency is similar to 3 Km/h but this changes for UE's moving at 120 Km/h, where (6dB/120ms) has a better performance. The lowest values of SINR are obtained for (9dB/0ms) at that velocity.

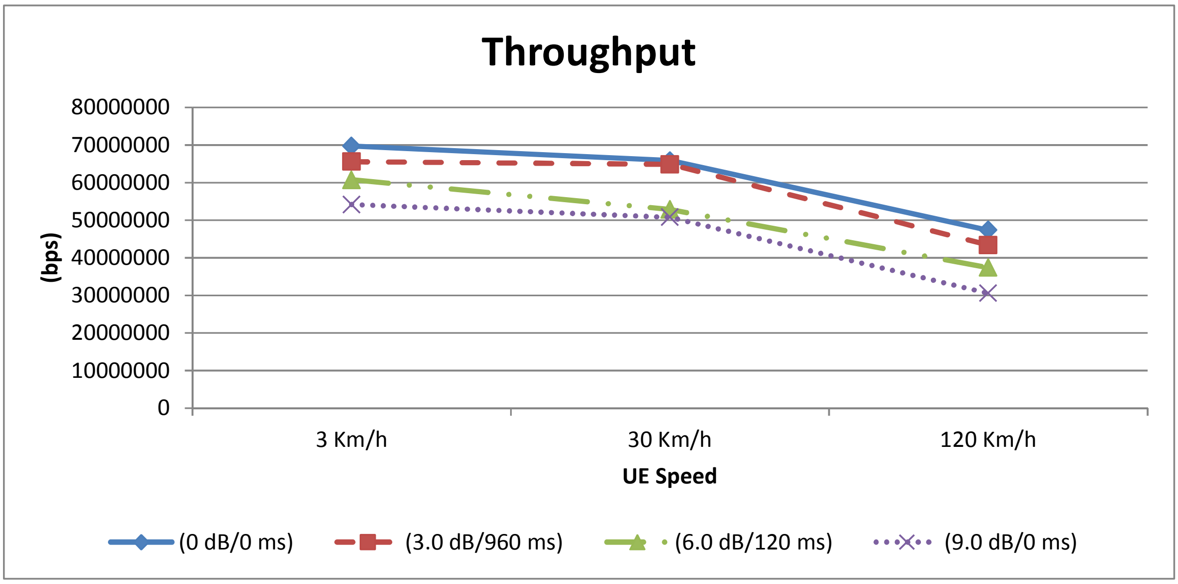


Figure 27. Throughput

Figure 27, demonstrates that (3dB/960ms) and (0dB/0ms) have the highest throughput (65.56 Mbps and 69.73 Mbps) at 3 km/h because the handover is done for cells that have better channel quality at low speed. The throughput drops to 64.84 and 43.37 Mbps in the case of (3dB/960ms) at 30 and 120 km/h respectively, due to the increase in number of handovers resulting in the drop of the system performance. The same tendency is observed for UE's moving at 30 and 120 Km/h.

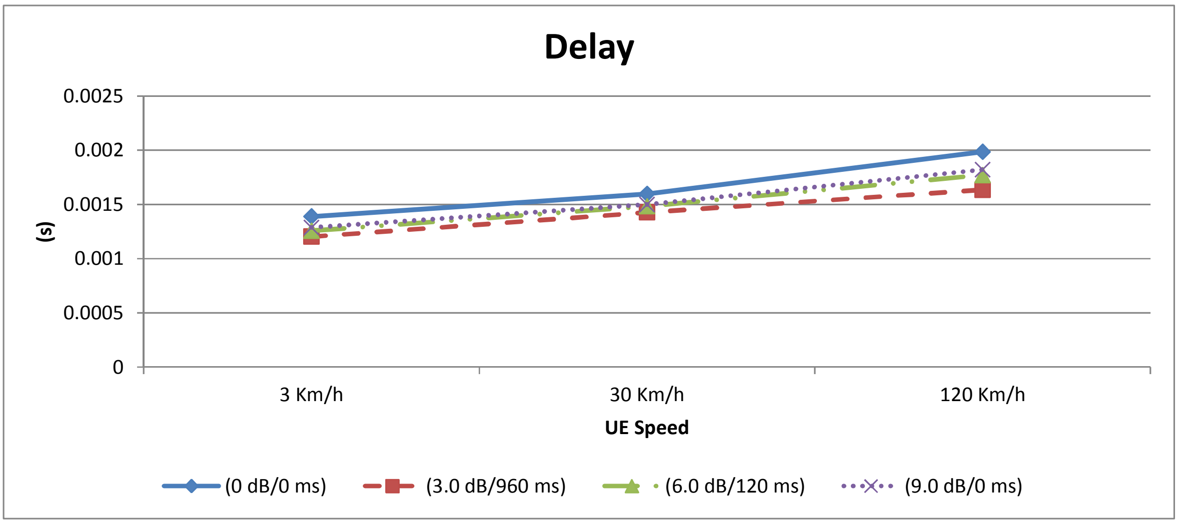


Figure 28. Delay.

Since the handover is more likely to occur frequently as the speed increases, this results in an increasing system delay under all handover settings being evaluated. The (0dB/0ms) and (9dB/0ms) have a slightly higher delay due to lack of TTT mechanism at all speed scenarios as compared with the other handover settings. (3dB/960ms) has the smallest total system delay at 3, 30, 120 km/h.

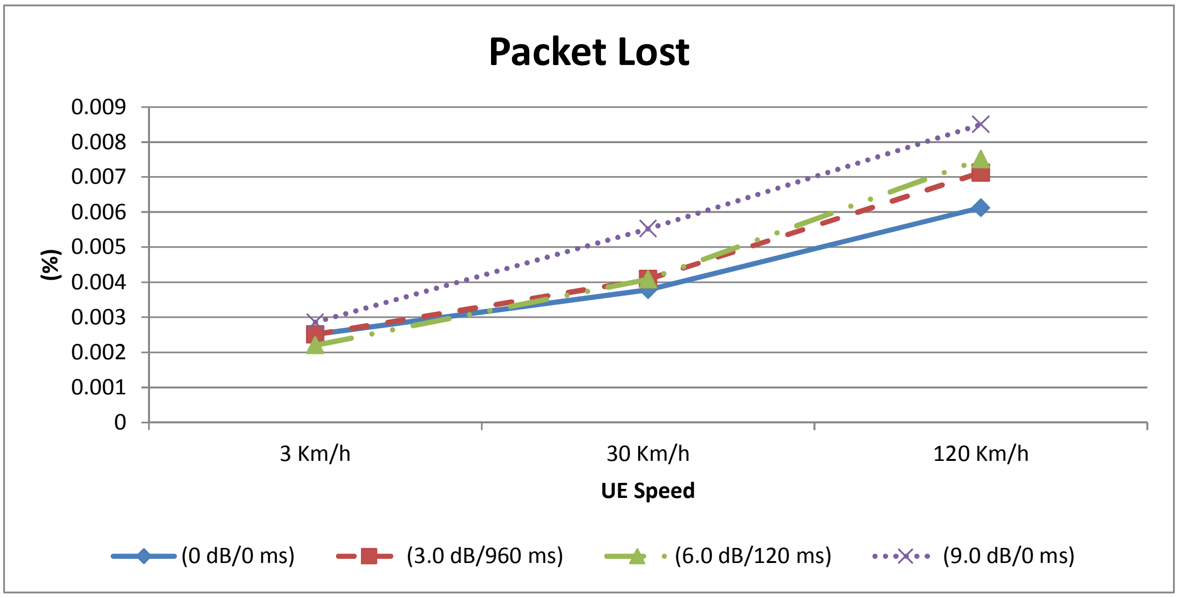


Figure 29. Packet Lost.

According to figure 29, UE’s moving at 3Km/h with different handover settings has relatively the same performance. At 30 Km/h and 120 Km/h, (0dB/0ms) and (3dB/960ms) perform better. The packet lost ratio for (9dB/0ms) is 0.005527% and 0.008501% for both velocities.

As a conclusion, the proposed settings for different UE speeds for cell radius of 500 m. and 1000 m. are shown in tables 3 and 4.

Table 4: Optimal handover triggering settings for cell radius 500 m and 1 UE/cell.

	3Km/h	30 Km/h	120 km/h
Proposed HOM/TTT	3dB/960ms	3dB/960ms	6dB/120ms

Table 5: Optimal handover triggering settings for cell radius 1000 m and 3 UE’s/cell

	3Km/h	30 Km/h	120 km/h
Proposed HOM/TTT	3dB/960ms	3dB/960ms	6dB/120ms

As it can be seen in table 3 and table 4, the tendency is similar and consistent for the two scenarios that have been deployed.

5. Conclusion and Future Work

In this thesis, in order to carry out the handover performance evaluation process, the state of the art of handover in LTE, together with the LTE power budget handover algorithm (PBHA) and the LTE specifications have been studied. The operation and performance of the simulator LTE-Sim have been investigated as well. Moreover, the handover parameters (hysteresis and time to trigger) have been included in the simulator modifying the code in order to carry out the study. The performance of the LTE handover based on the downlink RSRP measurements for the most common 3GPP scenarios has been investigated.

Since the setting of HO triggers is of primary importance for a good performance of the handover procedure, different triggering settings for the selected parameters have been performed. The optimal settings for each scenario have been proposed and performance evaluation has been carried out using the number of handovers, SINR, throughput, delay and packet lost.

The results show that the system load does not affect significantly the optimal setting of handover hysteresis and TTT. It can also be concluded that the optimal triggering setting can improve the performance, thus, by tuning the handover triggering setting, the operator can have some gains. But it can be seen as well that some medium triggering settings, such as (3dB/960ms), have usually good performances for all the scenarios and they can be widely used as a simple way to improve the handover performance. Coverage limitations are the main reasons for a poor performance of the handover.

This thesis has considered for HO performance evaluation simple deployment scenarios due software limitations mainly; however it would be advisable to investigate the handover performance considering more complex scenarios, i.e. larger cells, higher speeds and high loaded systems.

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