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Praise be to Allah, by whose grace good deeds are accomplished, and peace and blessings be upon the most honorable of messengers, our Prophet Muhammad, and upon all his family and companions.

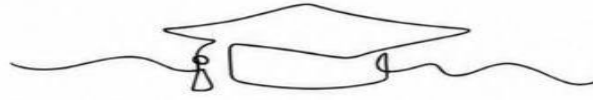
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Dedication

In the name of Allah, the Most Gracious, the Most Merciful.

I dedicate this humble work, first and foremost, to my beloved mother, whose unconditional love, endless sacrifices, sincere prayers, and unwavering support have been the light that guided me throughout my life. Her patience, kindness, and belief in me have been my greatest source of strength. No words can truly express my gratitude for everything she has done for me. May Allah bless her, protect her, and reward her abundantly.

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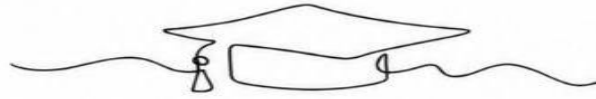
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Symbols and Abbreviations

3GPP	3 rd Generation Partnership Project
API	Application Programming Interface
Clang	Clang Compiler
CMake	Cross-platform Make
DLR	German Aerospace Center
eNodeB	evolved Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FCD	Floating Car Data
GBR	Guaranteed Bit Rate
GCC	GNU Compiler Collection
Git	Git Version Control
GPL	General Public License
GSM	Global System for Mobile Communications
HOF	Handover Failure
HO	Handover
HOM	Handover Margin
IDE	Integrated Development Environment
IDM	Intelligent Driver Model
IP	Internet Protocol
KPI	Key Performance Indicator
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MIT	Mobility Interruption Time
MME	Mobility Management Entity
N311	Timer/Counter for Radio Link Failure
NetAnim	Network Animator
NS-3	Network Simulator 3

OD	Origin-Destination
OS	Operating System
OSM	OpenStreetMap
PF	Proportional Fair
P-GW	Packet Data Network Gateway
PyViz	Python Visualization
QCI	QoS Class Identifier
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RLF	Radio Link Failure
RRC	Radio Resource Control
RRM	Radio Resource Management
RR	Round Robin
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
S1	S1 Interface
S-GW	Serving Gateway
SINR	Signal-to-Interference-plus-Noise Ratio
SUMO	Simulation of Urban Mobility
T310	Timer for Radio Link Failure
TraCI	Traffic Control Interface
TTT	Time-to-Trigger
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
VoIP	Voice over IP
VoLTE	Voice over LTE
X2	X2 Interface



Introduction



Introduction

Telecommunications have experienced rapid and continuous evolution, especially in the field of mobile communications. The emergence of Long-Term Evolution (LTE) technology has marked a significant milestone by providing high data rates, low latency, and improved Quality of Service (QoS) for mobile users. In this context, mobility management has become a fundamental challenge to ensure service continuity when users move between different cells of the network [1].

The handover mechanism is a key aspect of mobility management in LTE networks. It allows the transfer of an ongoing communication session from a serving cell to a target cell without noticeable interruption to the user. Handover decisions are primarily based on radio measurements such as Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and Signal-to-Interference-plus-Noise Ratio (SINR). In addition, handover performance is strongly influenced by control parameters such as Hysteresis and Time-to-Trigger (TTT), which help ensure stable handover execution and reduce unnecessary handovers, commonly known as the ping-pong effect. [2].

Despite the advancements introduced by 3GPP standards, handover performance remains a major challenge, particularly in heterogeneous urban environments. This is mainly due to several persistent issues such as handover failures, the ping-pong effect, excessive signaling overhead, degradation of Quality of Service (QoS), and increased Mobility Interruption Time (MIT). These challenges become more critical in dense networks with varying user speeds and dynamic interference conditions [3].

In this work, we focus on the study of quantized RSRQ-based handover algorithm in a heterogeneous LTE environment. The simulation is performed by coupling the ns-3 simulator with realistic mobility traces generated by SUMO, based on a scenario inspired by the city of M'sila, Algeria. We particularly analyze the impact of the main control parameters (Time-to-Trigger and Hysteresis) on the network's key performance indicators.

This thesis is organized into four chapters as follows:

The first chapter presents a literature review on LTE cellular networks, mobility management, and various handover algorithms.

The second chapter is devoted to a detailed study of handover algorithms in LTE, decision criteria, and control parameters.

The third chapter describes the simulation tools used (ns-3 and SUMO) and their integration.

The fourth chapter presents the simulation scenario, the implementation of the proposed algorithm, and the detailed analysis of the obtained results. A cost function was also proposed for optimal handover parameter selection in our scenario.

Finally, the thesis ends with a general conclusion and some perspectives for future work.



Chapter I

Overview of Handover Algorithms in LTE



I.1 Introduction

Cellular networks enable mobile users to maintain continuous connectivity across geographically distributed areas. These networks are organized into cells, each served by a base station, which enables efficient spectrum utilization and increases network capacity. Modern cellular systems, such as Long Term Evolution (LTE), rely on the Evolved Packet System (EPS), which integrates the E-UTRAN (radio access network) and the Evolved Packet Core (EPC) to manage mobility, resource allocation, and session continuity. The interplay of mobility management, handover mechanisms, and radio metrics such as RSRP, RSRQ, and SINR is fundamental to ensuring uninterrupted communication and efficient network performance under varying mobility and traffic conditions.

I.2 Fundamentals of Cellular Networks

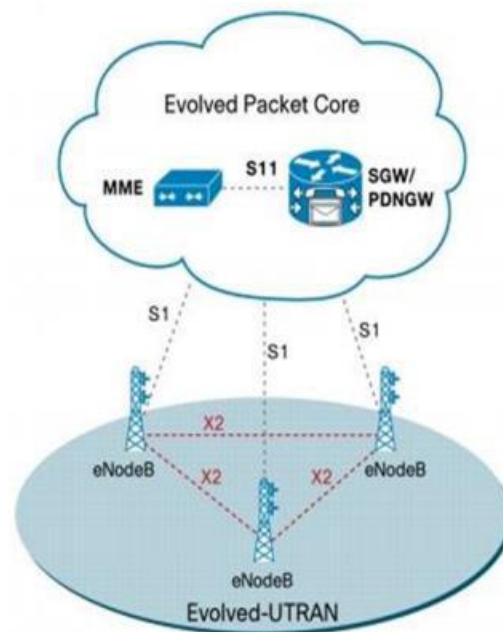


Figure I.1: Architecture of EPS (Evolved Packet System)

Cellular networks are the basis of modern wireless communication systems, allowing mobile users to stay connected while moving across different geographic areas. The network coverage is divided into smaller cells, each served by a base station, which improves spectrum reuse and increases network capacity. In modern systems such as Long-Term Evolution (LTE), the network consists of user equipment, base stations (eNodeB), and core network elements forming the Evolved Packet Core (EPC). These components work together to manage communication, allocate radio resources, and support user mobility. [4]

I.2.1 Mobility Management in Cellular Networks

Mobility management ensures continuous connectivity for users moving between cells in a cellular network. It allows the network to track the location of mobile devices and maintain active communication sessions. This process includes location tracking, authentication, and handover procedures, which transfer the user's connection from one base station to another without interrupting the service.

I.2.1.1 Definition of Mobility Management

Mobility management refers to the mechanisms that allow a cellular network to track mobile users and maintain communication while they move across different cells. Its main goal is to ensure uninterrupted access to communication services.

It mainly includes two processes: [5]

➤ Location Management

Determines the current location of the mobile device within the network.

➤ Handover Management:

Transfers the communication session from one base station to another when the user moves.

I.2.1.2 Architecture of Mobility Management

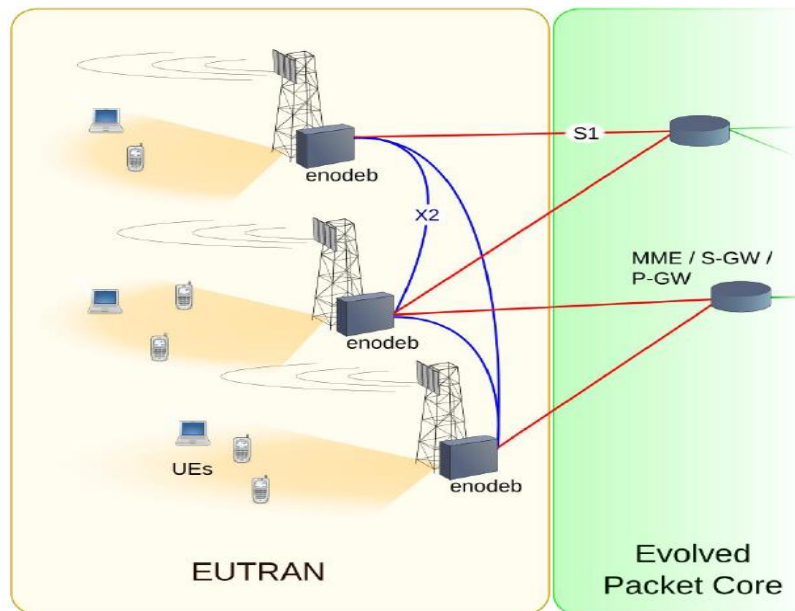


Figure I.2: E-UTRAN Architecture in LTE Networks

In LTE networks, mobility management is implemented within the Evolved Packet System (EPS), which includes the radio access network (E-UTRAN) and the core network (EPC).

The E-UTRAN contains base stations called eNodeB that manage radio communication and handover procedures. The EPC includes entities such as the Mobility Management Entity (MME), Serving Gateway (SGW), and Packet Data Network Gateway (PGW), which handle mobility signaling, data routing, and connectivity with external networks. [6]

I.2.2 Mobility Management at the Network Layer

Mobility management at the network layer allows mobile devices to maintain communication sessions while moving between networks. In IP-based systems such as LTE, special protocols ensure that the device remains reachable even if its point of network attachment changes. Examples include Mobile IP and Proxy Mobile IP, which help maintain continuous communication during mobility.

I.2.2.1 Macro and Micro Mobility

Mobility management can be divided into two categories: [7]

➤ Macro Mobility

Movement across large network regions or different administrative domains, usually involving a change in IP subnet.

➤ Micro Mobility

Movement within a local network area, such as between neighboring base stations. Local mobility mechanisms reduce signaling overhead and improve handover efficiency.

I.2.3 LTE Network Entities

The architecture of Long-Term Evolution (LTE) is based on the Evolved Packet System (EPS), which includes the E-UTRAN and the Evolved Packet Core (EPC).

The eNodeB manages radio communication with user devices and controls mobility procedures. The EPC includes several entities such as the MME for mobility signaling, the

Serving Gateway (S-GW) for data forwarding, and the Packet Data Network Gateway (P-GW) for connecting the LTE network to external networks like the Internet. [8]

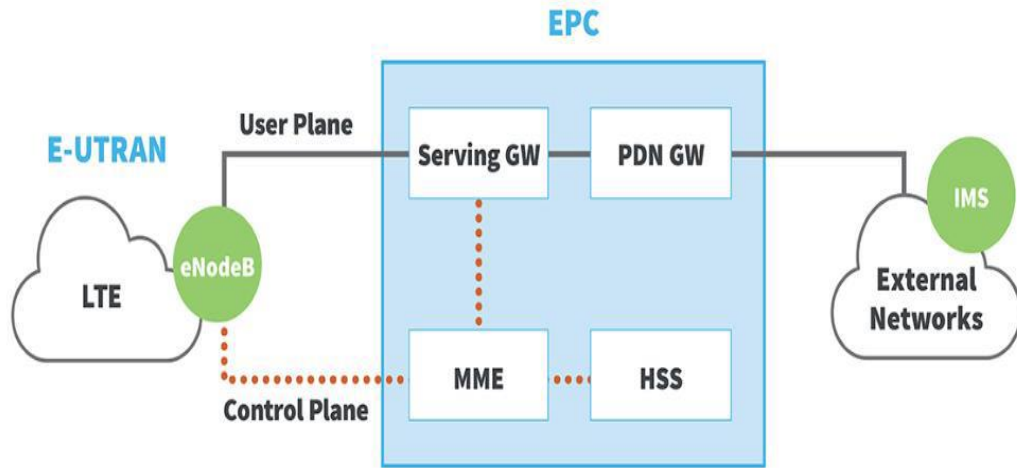


Figure I.3: LTE Functional Architecture (E-UTRAN and EPC)

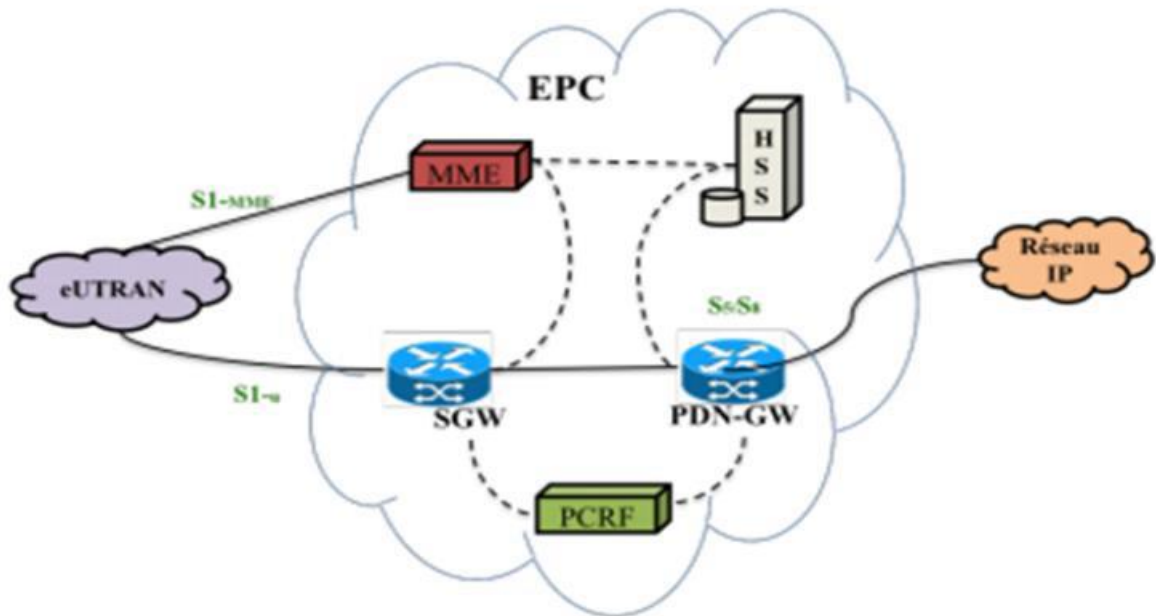


Figure I.4: EPC Core Network Architecture

I.2.4 Quality of Service (QoS)

Quality of Service (QoS) ensures that different types of traffic receive appropriate network resources. LTE networks classify traffic based on requirements such as delay, bandwidth, and reliability. The QoS Class Identifier (QCI) defines the priority level of each traffic flow. LTE also uses logical channels called bearers, which may be Guaranteed Bit Rate (GBR) or Non-GBR, depending on the service requirements. [9]

I.3 Handover Process in LTE

The Handover process in LTE mobile network can be detailed as the following figure

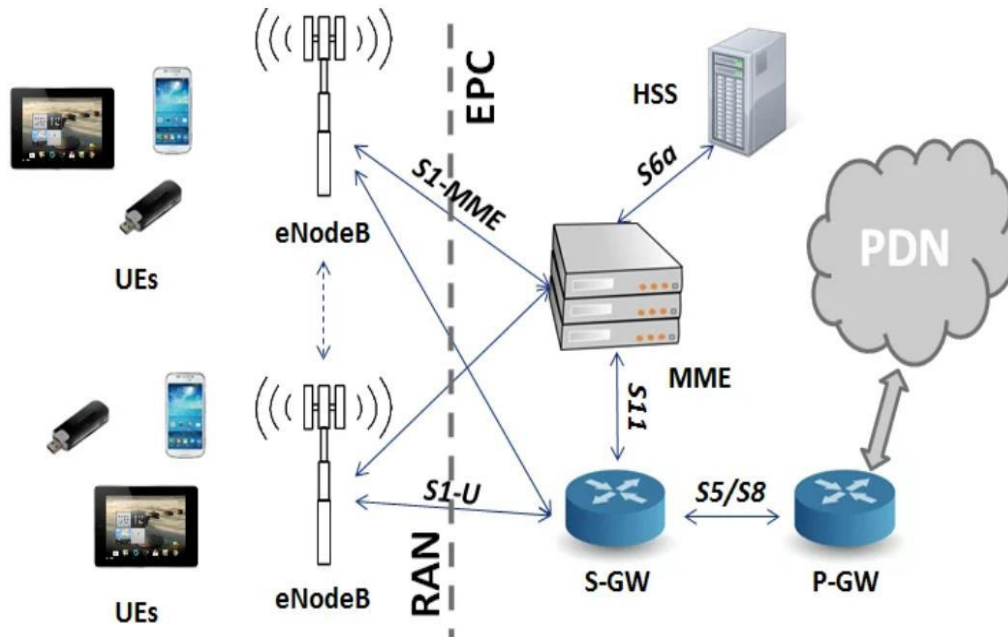


Figure I.5: Detailed LTE Network Architecture

I.3.1 Definition of Handover

Handover is the process of transferring an ongoing communication session from one cell to another when a user moves across the network coverage area. In LTE networks, this mechanism ensures continuous connectivity when the signal from the serving base station becomes weak and a neighboring cell provides better signal quality. [7]

I.3.2 Objectives of Handover

The main objective of handover is to maintain uninterrupted communication for mobile users. It ensures service continuity, maintains the required Quality of Service (QoS), and reduces connection failures. Handover also helps optimize network resources by balancing traffic between cells and improving overall network performance. [9]

I.3.3 Types of Handover

Handover mechanisms are generally classified into two main types: Hard Handover and Soft Handover, depending on how the connection is transferred between base stations.

I.3.3.1 Hard Handover

Hard handover follows a break-before-make approach, where the connection with the serving cell is terminated before establishing a new connection with the target cell. This method is commonly used in LTE networks and can be implemented through X2 or S1 handover procedures. [7]

I.3.3.2 Soft Handover

Soft handover follows a make-before-break approach in which the mobile device temporarily maintains connections with multiple base stations during the transition. This technique was widely used in earlier cellular technologies such as CDMA and UMTS but is generally not used in LTE networks. [9]

I.3.4 Handover Mechanisms in LTE

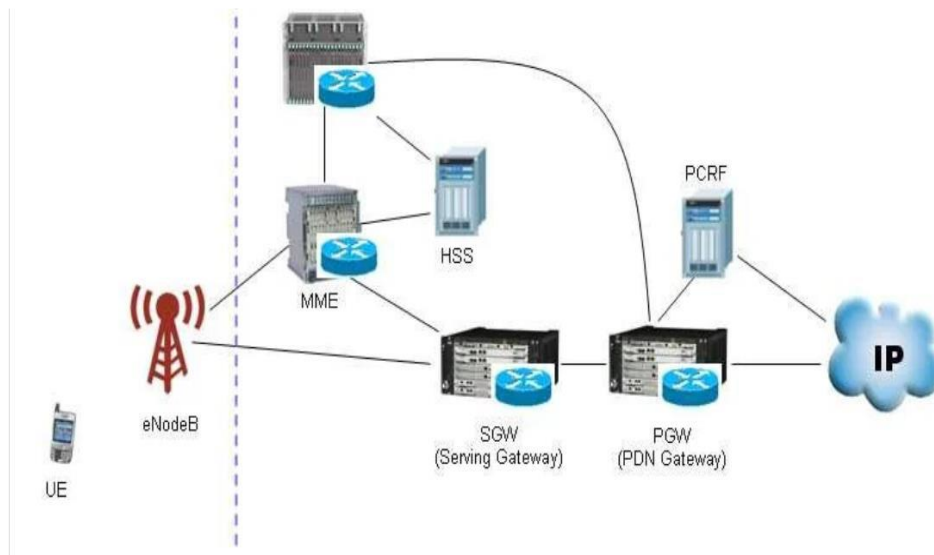


Figure I.6: 4G LTE Network Architecture Components

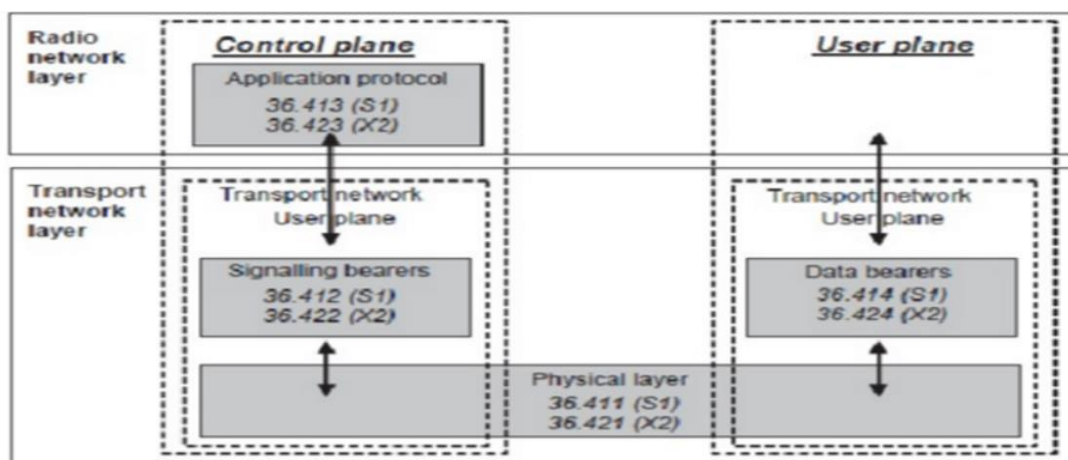


Figure I.7: Model of an E-UTRAN Interface [7].

LTE networks implement handover using two main signaling mechanisms: X2 handover and S1 handover, depending on the available interfaces between network components.

I.3.4.1 X2 Handover

X2 handover occurs when a direct interface exists between neighboring eNodeBs. The base stations exchange signaling messages directly, allowing faster handover execution with reduced latency. [10]

I.3.4.2 S1 Handover

S1 handover is used when a direct X2 connection is not available. In this case, the handover procedure is coordinated through the core network using the Mobility Management Entity (MME). [11]

I.3.5 Handover Categorization

Handover in LTE networks can be categorized according to the network components involved, including Intra-LTE, Inter-LTE, and Inter-RAT handover.

I.3.5.1 Intra-LTE Handover

Intra-LTE handover occurs when a user moves between cells within the same LTE network while remaining connected to the same core network entities. [12]

I.3.5.2 Inter-LTE Handover

Inter-LTE handover occurs when the user moves between LTE cells but experiences a change in core network components such as the MME or the Serving Gateway. [13]

I.3.5.3 Inter-RAT Handover

Inter-RAT handover occurs when the mobile device moves between LTE and another radio access technology such as UMTS or GSM to maintain service continuity.

I.4. Fundamentals of Handover Algorithms

Handover algorithms play a crucial role in mobility management within modern cellular networks, particularly in Long Term Evolution (LTE) systems. These algorithms determine when and to which neighboring cell a mobile device should be transferred in order to maintain continuous connectivity and ensure optimal communication quality.

In LTE networks, handover decisions are generally taken at the eNodeB based on measurement reports sent by the User Equipment (UE). These reports contain several radio measurements and network

parameters that help evaluate the quality of the current connection and the suitability of neighboring cells. Efficient handover algorithms aim to reduce call drops, minimize packet loss, avoid unnecessary handovers such as the ping-pong effect, and improve overall network performance.

The decision process relies on multiple criteria including signal strength, signal quality, interference levels, user mobility, and the load conditions of neighboring cells. By analyzing these parameters, the network can select the most appropriate moment to initiate the handover process and ensure seamless mobility for users. [12]

❖ Definition of a Handover Algorithm

A handover algorithm can be defined as a decision-making mechanism used in cellular networks to determine when a mobile device should be transferred from a serving cell to a target cell. The algorithm analyzes various radio measurements and network conditions to ensure that the handover occurs at the optimal moment.

In LTE networks, handover algorithms are implemented mainly at the base station (eNodeB), which continuously evaluates measurement reports sent by the UE. These reports include parameters related to signal power, signal quality, interference levels, and other mobility indicators.

The main objective of a handover algorithm is to maintain service continuity while optimizing network performance. A well-designed algorithm minimizes unnecessary handovers, prevents connection failures, and ensures that users remain connected to the most suitable base station during mobility. [11]

I.5 Handover Control Parameters and Events

The handover process in LTE networks depends on several control parameters and measurement events that determine when the handover should be triggered. These mechanisms help maintain service continuity while reducing unnecessary handovers caused by signal fluctuations. The most important control parameters include hysteresis, time-to-trigger (TTT), and handover margin (HOM). In addition, LTE defines several measurement events that allow the network to monitor radio conditions and initiate handover decisions. [11]

I.5.1 Key Control Parameters

I.5.1.1 Handover Hysteresis

Hysteresis is used to maintain a minimum difference between the signal received from the serving cell and the target cell before initiating a handover. This parameter helps prevent frequent handovers caused

by small variations in signal quality. In LTE networks, the hysteresis value typically ranges between 0 dB and 30 dB.

I.5.1.2 Time to Trigger (TTT)

Time-to-Trigger (TTT) represents the duration during which the handover condition must remain satisfied before the UE sends a measurement report to the serving eNodeB. This parameter helps reduce unnecessary handovers caused by temporary signal variations. Typical TTT values in LTE range from 0 ms to 5120 ms.

I.5.1.3 Handover Margin (HOM)

The Handover Margin (HOM) represents the minimum signal difference required between the serving cell and a neighboring cell before a handover can be initiated. This margin ensures that the target cell provides better signal conditions than the current serving cell. [14]

I.5.2 Handover Events

I.5.2.1 Overview of Measurement Events (A1–A5)

LTE defines several measurement events used for mobility management based on radio measurements such as RSRP and RSRQ. These events allow the network to monitor variations in serving and neighboring cell conditions and support handover-related decisions. Event A1 indicates that the serving cell quality is above a threshold, whereas Event A2 indicates degradation below a threshold. Event A3 is triggered when a neighboring cell becomes better than the serving cell by a predefined offset. Event A4 occurs when a neighboring cell exceeds a configured threshold, while Event A5 combines both serving cell degradation and neighboring cell improvement conditions. [13]

I.5.2.2 The A3 Event

Event A3 is one of the most commonly used Handover triggering mechanisms in LTE. It occurs when a neighboring cell becomes better than the serving cell by a predefined offset. When this condition remains valid for the configured TTT period, the UE sends a measurement report to the eNodeB, which enables the eNodeB to evaluate and potentially initiate the handover process. [15]

I.5.3 Conditional Handover

Conditional handover is a mechanism where the handover decision is prepared in advance but executed only when predefined conditions are satisfied. This approach reduces handover delay and improves mobility performance, especially in high mobility scenarios.

I.6 Challenges and Undesired Effects in Handover

Although LTE handover mechanisms are designed to maintain seamless connectivity, several issues may affect mobility performance under unstable radio conditions or inappropriate parameter settings. These challenges can reduce communication reliability and impact user experience. [16]

I.6.1 Handover Failure (HOF)

Handover failure occurs when the UE is unable to successfully complete the transition from the serving cell to the target cell. This problem may result from weak radio conditions or incorrect handover timing, leading to connection interruption.

I.6.2 Radio Link Failure (RLF)

Radio Link Failure occurs when the radio connection quality between the UE and the serving cell deteriorates below an acceptable level. In LTE systems, RLF triggers recovery procedures to reestablish connectivity through a suitable neighboring cell. [17]

I.6.3 Ping-Pong Effect

The ping-pong effect describes frequent switching between neighboring cells within a short duration due to unstable signal measurements. This phenomenon may increase unnecessary handovers and reduce network stability. [15]

I.6.4 Signaling Overhead

Signaling overhead represents the additional exchange of control messages required during handover operations. Excessive handovers may increase signaling traffic and consume network resources. [12, 13]

I.6.5 Handover Latency

Handover latency refers to the delay associated with transferring an active connection between cells. High latency may affect service continuity and degrade the quality of real-time communications. [14-16]

I.7 Conclusion

This chapter has provided a comprehensive overview of the fundamentals of cellular networks, highlighting the key architectural elements and operational principles that enable mobile communication. The discussion covered the Evolved Packet System (EPS), including the E-UTRAN and EPC, as well as the critical role of mobility management in maintaining seamless connectivity across cells. Handover mechanisms, both X2 and S1, were examined along with the parameters and algorithms that govern them, such as RSRP, RSRQ, SINR, UE speed, and cell load. Additionally, the importance of Quality of Service (QoS), resource block allocation, and packet scheduling in optimizing network performance was emphasized. Understanding these concepts is essential for analyzing handover efficiency, minimizing service interruptions, and ensuring reliable communication in LTE networks.



Chapter II

Handover algorithms in LTE



II.1 Introduction

LTE networks are designed to provide high data rates and continuous connectivity for mobile users moving across different coverage areas. In such environments, user mobility constantly changes the radio conditions, making it necessary for the network to maintain an optimal connection as the user moves from one cell to another.

Handover is the key mechanism that ensures service continuity by transferring an active connection between cells without interrupting communication. Its performance directly impacts user experience and network efficiency, which is why different handover algorithms have been developed to improve decision accuracy and mobility management in LTE systems.

II.2 Overview of Handover Decision Process

II.2.1 Key Characteristics of LTE Handover

Unlike earlier generations, LTE handover is: [18]

- Network-controlled: The decision is made by the serving eNodeB.
- UE-assisted: The UE performs measurements and reports them to the network.
- X2/S1-based: Handover signaling occurs via X2 interface (preferred) or S1 interface (fallback).

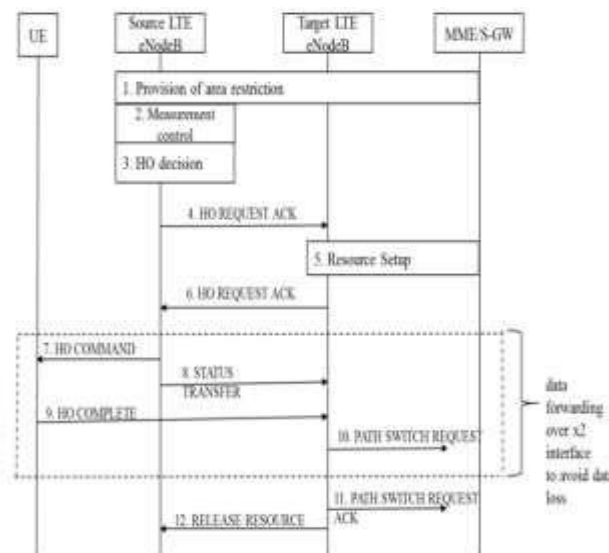


Figure II.1: X2-based LTE handover procedure between source eNodeB and target eNodeB. [19]

II.2.2 Handover Procedure Steps

The handover process in LTE can be divided into three main phases: [20]

II.2.2.1 Measurement Phase

The UE continuously measures radio signals from the serving and neighboring cells. These measurements include parameters such as RSRP and RSRQ. The UE then reports these measurements to the serving eNodeB based on configured events.

II.2.2.2 Decision Phase

The serving eNodeB evaluates the measurement reports and determines whether a handover is necessary. This decision is based on predefined criteria such as signal strength thresholds, hysteresis margins, and time-to-trigger conditions.

II.2.2.3 Execution Phase

Once the decision is made:

- The source eNodeB sends a handover request to the target eNodeB.
- The target eNodeB prepares resources for the UE.
- The UE is instructed to switch to the target cell.
- The UE synchronizes with the target cell and resumes communication.

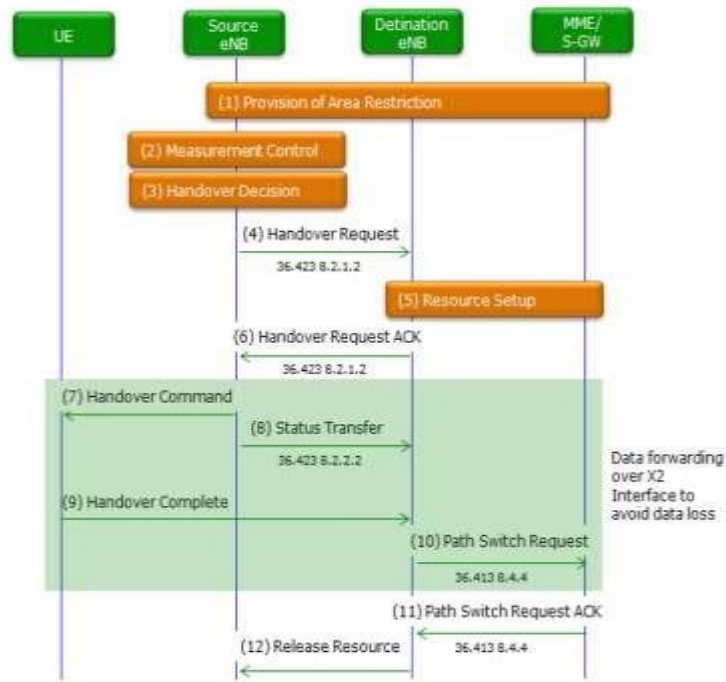


Figure II.2: X2-based handover signaling procedure in LTE. [20]

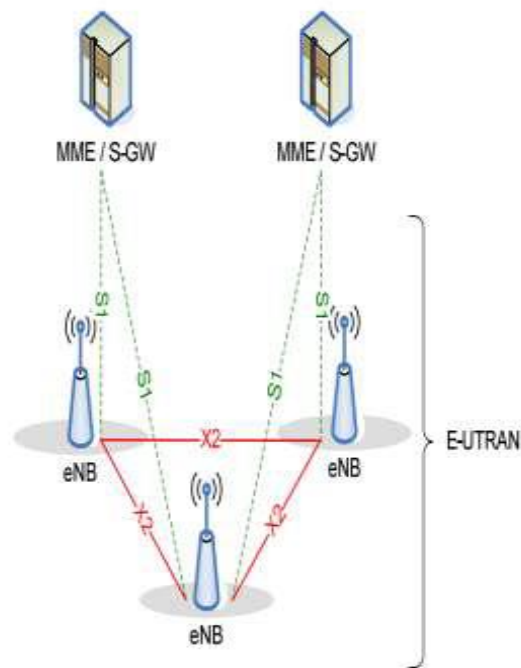


Figure II.3: LTE/E-UTRAN architecture showing the S1 and X2 interfaces involved in handover. [20]

II.3.4 Event-Driven Decision Mechanism

LTE handover decisions are typically triggered by measurement events (e.g., Event A3), which compare signal conditions between serving and neighboring cells. These events ensure that handovers are performed only when necessary, avoiding unnecessary signaling overhead. [21]

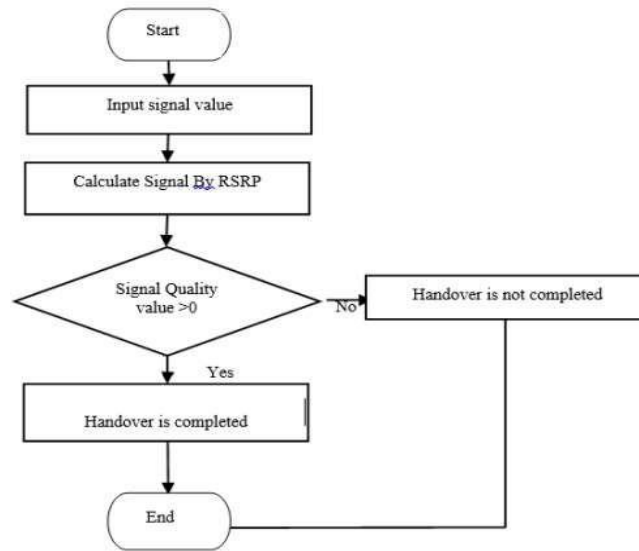


Figure II.4: Simplified flow chart of X2-based handover decision and execution in LTE.

II.3.5 Objectives of the Handover Decision Process

The decision process aims to: [20]

- Maintain high signal quality
- Minimize handover failures
- Avoid unnecessary handovers (ping-pong effect)
- Optimize network resource usage

A well-designed decision process balances responsiveness and stability, ensuring efficient mobility management.

II.4 Handover Decision Criteria

In LTE systems, the handover decision process is inherently multi-dimensional and cannot rely on a single universal metric. Instead, it is based on a set of complementary radio measurements and contextual indicators that collectively describe the state of the radio link, the mobility dynamics of the user, and the operational conditions of the network. The most widely adopted criteria include Reference Signal Received

Power (RSRP), Reference Signal Received Quality (RSRQ), Signal-to-Interference-plus-Noise Ratio (SINR), User Equipment (UE) speed, and cell load. [18]

The primary role of these criteria is to transform a complex and continuously evolving radio environment into quantifiable indicators that enable reliable decision making. A criterion becomes meaningful only if it can determine whether the serving link is degrading, whether a neighboring cell provides a better alternative, and whether the handover will improve communication performance or resource utilization. For this reason, LTE systems rely on filtered measurements combined with hysteresis and time-to-trigger mechanisms to ensure both stability and responsiveness. [19]

From a system-level perspective, each criterion captures a distinct dimension of the mobility problem. Power-based metrics reflect spatial proximity, quality-based metrics capture interference and effective link usability, while contextual indicators introduce awareness of mobility patterns and network load. Their combination enables a balanced trade-off between robustness, sensitivity, and efficiency.

II.4.1 RSRP

RSRP is a fundamental LTE measurement representing the average received power of reference signals transmitted by a cell. It is widely used as a primary indicator of signal strength and forms the basis of many classical handover algorithms. [19]

RSRP mainly reflects large-scale propagation effects such as path loss and shadowing. As the UE moves away from the serving cell, the received power decreases, while neighboring cell signals increase. This predictable behavior makes RSRP highly suitable for tracking user position relative to cells. In practice, RSRP is typically used in relative comparisons rather than as an absolute threshold. For example, in Event A3-based handover, a neighboring cell must exceed the serving cell by a predefined offset before triggering a handover. This approach helps mitigate short-term fluctuations caused by fading [18]. The main advantage of RSRP lies in its simplicity and low computational cost. However, it does not account for interference or noise. As a result, a cell with strong RSRP may still provide poor performance in interference-limited scenarios, particularly in dense network deployments.

II.4.2 RSRQ

RSRQ complements RSRP by incorporating both signal strength and the overall received signal environment, including interference and noise. It provides a more comprehensive indication of link quality. [18]

Unlike RSRP, which reflects propagation conditions, RSRQ captures the impact of interference and network activity. This makes it especially useful in dense deployments where multiple cells operate on the same frequency and interference becomes significant. [22]

In LTE, RSRQ is fully integrated into the measurement reporting framework and can be used in standard handover events. This enables quality-aware decision making, allowing the network to avoid cells that appear strong in terms of power but offer poor effective performance.

However, RSRQ is more sensitive to dynamic network conditions, which can introduce variability. This requires careful tuning of filtering and timing parameters to maintain decision stability while benefiting from improved quality awareness.

II.4.3 SINR

SINR measures the ratio of useful signal power to the combined interference and noise, making it a direct indicator of communication quality and achievable performance. [22]

Compared to power-based metrics, SINR provides a more accurate reflection of whether a link can support reliable and high-throughput communication. Even when signal strength is high, poor SINR can indicate severe interference conditions. [18]

SINR-based handover is particularly relevant in interference-limited environments, where maximizing throughput and link reliability is a priority. By selecting cells with higher SINR, the network can improve overall user experience.

However, SINR tends to fluctuate rapidly due to dynamic interference conditions. Without proper stabilization mechanisms, this can lead to overly sensitive handover decisions. Additionally, LTE standard measurement events are primarily based on RSRP and RSRQ, so SINR is often used as a complementary metric or evaluation parameter rather than a primary trigger.

II.4.4 UE Speed

UE speed is a critical contextual factor that influences how quickly radio conditions change. It determines how long a user remains within the coverage overlap between cells and how rapidly signal conditions evolve. [19]

High-speed users experience rapid signal variations and have limited time for handover execution, increasing the risk of delayed or failed handovers. In contrast, low-speed users allow for more stable measurements and conservative decision strategies.

The effect of speed is closely linked to handover control parameters such as hysteresis and time-to-trigger. Larger values may improve stability for slow users but can delay handover for fast users, while smaller values increase responsiveness but may lead to unnecessary handovers.

Although not always explicitly included in standard decision formulas, UE speed is essential in adaptive algorithms and simulation studies, where it is used to evaluate the robustness of handover strategies under different mobility conditions.

II.4.5 Cell Load

Cell load reflects the level of resource utilization within a cell and introduces a network-centric perspective to handover decision making. [23]

Unlike radio-based metrics, which focus on signal conditions, cell load represents how congested a cell is. Incorporating this criterion enables load balancing, where users are distributed across cells to improve overall network efficiency.

Load-aware handover allows the network to redirect users from heavily loaded cells to less congested ones, even if the latter are not the strongest in terms of signal power. This improves fairness and system-level performance. [21]

However, relying solely on load can degrade radio quality if users are transferred to weaker cells. Therefore, effective strategies combine load considerations with minimum radio quality constraints to maintain both performance and reliability.

II.5 Classification of Handover Algorithms

Handover algorithms in LTE can be categorized according to the dominant principle that governs the transfer decision. This classification is essential in advanced research because it distinguishes between baseline mechanisms rooted in standardized radio measurements and more sophisticated approaches that incorporate adaptation, optimization, or learning capabilities. [23]

At a fundamental level, most LTE handover schemes originate from the comparison of radio measurements between serving and neighboring cells. These include threshold-based decisions, relative comparisons, and event-triggered mechanisms, typically stabilized through hysteresis and time-related controls. However, as LTE networks evolved toward higher density and heterogeneous deployments, these traditional approaches were progressively extended to include load-aware and intelligent strategies. Such extensions aim to address challenges that pure signal-based decisions cannot fully capture, including congestion management, dynamic traffic distribution, and context-aware optimization. [24]

It is important to note that these categories are not strictly mutually exclusive. In practice, a modern handover algorithm may combine multiple principles—for example, an event-triggered mechanism based on RSRP, enhanced by hysteresis control, and further refined using load-awareness or adaptive tuning. Nevertheless, the classification remains analytically valuable, as it reflects the principal conceptual families widely discussed in LTE mobility research.

II.5.1 Threshold-Based

Threshold-based algorithms represent the most basic form of handover decision making. A handover is triggered when one or more measured parameters cross predefined limits, such as when the serving cell signal falls below an acceptable threshold or when a neighboring cell exceeds a minimum requirement. [25]

The primary advantage of this approach is its simplicity. The decision rule is explicit, computationally efficient, and easy to implement in both analytical models and simulation environments. For this reason, threshold-based algorithms are often used as baseline references in LTE studies and provide a clear foundation for understanding mobility behavior. [26]

However, fixed thresholds lack adaptability. They do not inherently account for relative conditions between cells, short-term signal variations, or different mobility scenarios. As a result, they may lead to delayed handovers in some cases or excessive triggering in others. To mitigate these limitations, threshold-based logic is typically combined with additional control mechanisms such as hysteresis and time- to-trigger.

II.5.2 Hysteresis-Based

Hysteresis-based approaches focus on improving decision stability by preventing handovers caused by short-term fluctuations in signal measurements. Instead of triggering a handover as soon as a neighboring cell becomes slightly better, the algorithm requires that the superiority exceeds a defined margin before the transfer is allowed. [25]

This margin introduces a buffer that filters out minor variations due to fading, thereby reducing unnecessary handovers. Its impact is particularly important in mitigating the ping-pong effect, where a UE rapidly switches between adjacent cells due to marginal and unstable differences. [23]

The effectiveness of hysteresis comes with a trade-off. A small margin increases sensitivity but may lead to instability, while a large margin improves robustness but delays necessary handovers. Consequently,

hysteresis is not merely a protective mechanism but a key parameter that directly shapes the balance between responsiveness and stability in LTE mobility management.

II.5.3 Event-Triggered

Event-triggered algorithms rely on predefined conditions that determine when measurement reports should be generated and evaluated. In LTE, this concept is central to the standardized measurement framework defined by 3rd Generation Partnership Project, where events such as A1 through A5 govern reporting behavior. [26]

Among these, Event A3 is particularly significant because it defines a relative condition: a neighboring cell becomes better than the serving cell by a specified offset. This formulation aligns closely with practical handover requirements, as it avoids relying solely on absolute degradation of the serving link.

The main strength of event-triggered approaches lies in their alignment with LTE signaling procedures and their flexibility in configuration. However, their performance depends heavily on parameter tuning. Without appropriate hysteresis and timing controls, even well-defined events may lead to unstable or inefficient handover decisions in dynamic radio environments.

II.5.4 Load-Based

Load-based algorithms extend handover decision making beyond radio measurements by incorporating the level of resource utilization within cells. Instead of selecting a target solely based on signal conditions, these approaches consider whether the candidate cell can provide better service from a resource availability perspective. [27]

This strategy enables load balancing, where users are redistributed from congested cells to less loaded ones. Such redistribution improves overall network efficiency, enhances fairness, and can lead to better system-level performance, particularly in dense and heterogeneous deployments.

However, load-based decisions must be carefully constrained. Transferring a user to a lightly loaded but radio-weak cell can degrade link quality. Therefore, effective designs combine load awareness with minimum radio quality conditions, ensuring that performance gains at the network level do not come at the expense of individual user experience.

II.5.5 AI-Based

AI-based handover algorithms represent a more recent and advanced category, where decision making is driven by data-driven models rather than fixed rules. These approaches aim to learn optimal handover behavior from network conditions, user mobility patterns, or historical performance data. [30]

The key advantage of AI-based methods is their ability to handle complex, multidimensional scenarios. They can simultaneously consider multiple variables—such as signal quality, speed, load, and interference—and adapt decisions dynamically to changing environments. This makes them particularly attractive for self-optimizing networks and future mobility management systems.

Nevertheless, these methods introduce additional challenges. They require training data, careful model design, and validation under realistic conditions. Moreover, their complexity can make them less transparent compared to classical approaches. For LTE-focused research, AI-based handover is best viewed as a promising extension rather than a direct replacement for established algorithms.

II.6 Classical Handover Algorithms

Classical LTE handover algorithms are based on standard radio measurements and relatively direct decision rules. They remain essential in both academic research and simulation studies because they provide interpretable baselines and closely reflect standardized LTE behavior. [27]

Despite differences in their specific criteria, these algorithms share a common structure: the UE performs measurements, the network evaluates a configured condition, and the handover is triggered when that condition is satisfied under stability controls.

II.6.1 RSRP-Based

RSRP-based algorithms use signal strength as the primary decision variable. A handover is typically triggered when a neighboring cell becomes stronger than the serving cell according to a predefined rule. [28]

Their main strength lies in their intuitive behavior: they naturally follow user movement across cell boundaries. This makes them widely used as baseline approaches in LTE simulations.

However, since they ignore interference, they may select cells that are strong in power but suboptimal in performance. As a result, they are often complemented by additional quality-based criteria.

II.6.2 RSRQ-Based

$$RSRQ = \frac{N \times RSRP}{RSSI} \quad (I.1)$$

RSRQ-based algorithms introduce quality awareness into the decision process by considering both signal strength and interference effects. This makes them more suitable for environments where interference significantly impacts performance. [29]

These algorithms can better reflect actual user experience compared to pure power-based approaches. However, their sensitivity to network dynamics may introduce variability, requiring careful parameter tuning.

II.6.3 SINR-Based

SINR-based algorithms rely on a direct measure of link quality. By considering both signal strength and interference, they aim to maximize effective communication performance. [31]

They are particularly useful in dense networks where interference dominates. However, their high variability may lead to instability if not properly controlled, which is why they are often combined with filtering or used as evaluation metrics.

II.6.4 A3 Event-Based

The A3-based algorithm is one of the most representative LTE handover mechanisms. It triggers a handover when a neighboring cell becomes better than the serving cell by a configurable offset. [31]

Its strength lies in combining relative comparison with stability controls such as hysteresis and time-to-trigger. This makes it more robust than simple strongest-cell approaches.

The A3 algorithm is particularly important in simulation environments such as NS-3, where it is widely used as a reference model due to its clarity, configurability, and strong alignment with LTE standards.

II.7 Handover Control Parameters

Handover performance in LTE is not determined solely by the decision criterion, but also by control parameters that regulate how and when decisions are executed. These parameters are essential for balancing responsiveness and stability.

II.7.1 Hysteresis

Hysteresis defines the margin that a target cell must exceed before a handover is allowed. It acts as a buffer against small fluctuations, reducing unnecessary handovers. [28]

A higher hysteresis improves stability but delays handover, while a lower value increases responsiveness but may cause instability.

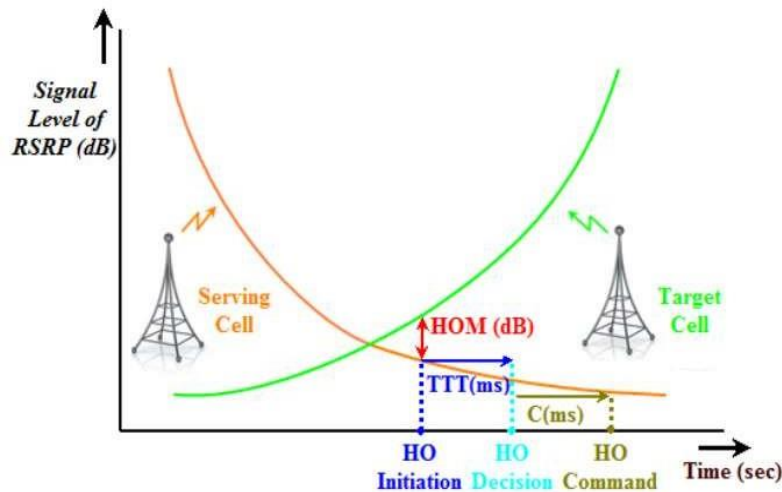


Figure II.5: LTE Hard Handover algorithm [31]

II.7.2 Time-to-Trigger

Time-to-Trigger (TTT) specifies how long a condition must remain valid before triggering a handover. It filters out short-term variations in signal conditions. [32]

Short TTT increases responsiveness, whereas long TTT enhances stability but may delay necessary handovers.

II.7.3 Handover Margin

Handover Margin (HOM) represents the required superiority of the target cell over the serving cell. It is closely related to hysteresis and plays a key role in defining decision sensitivity. [28]

In practice, HOM and TTT are jointly optimized to achieve a balance between reducing unnecessary handovers and avoiding delayed transitions.

II.8 Impact of Parameters on Handover Performance

The performance of handover algorithms in LTE is not determined solely by the decision criterion, but also by the configuration of control parameters that regulate when and how the decision is executed. Parameters such as hysteresis, time-to-trigger (TTT), and measurement filtering play a central role in shaping mobility behavior, affecting handover timing, frequency, and stability. As a result, the same underlying algorithm can exhibit significantly different performance depending on its parameterization. [30]

Empirical observations from simulations using NS-3 confirm that increasing hysteresis reduces the number of handovers by requiring a larger superiority margin before a neighboring cell can trigger a transfer. Similarly, increasing TTT reduces handover frequency by enforcing temporal persistence of the triggering condition. These parameters act as stabilizing mechanisms that suppress reactions to short-term radio fluctuations such as fading. [24]

However, enhanced stability does not necessarily translate into improved overall performance. Large hysteresis values or long TTT settings may delay legitimate handover decisions, allowing the serving link to degrade excessively before the transfer is initiated. This can lead to late handovers, reduced throughput, and increased probability of handover failure, especially in high-mobility or interference-limited environments.

Conversely, aggressive parameter configurations—characterized by small hysteresis and short TTT—improve responsiveness but increase sensitivity to transient variations in radio conditions. This often results in a higher number of handovers, including undesirable ping-pong effects where the UE oscillates between neighboring cells. Simulation studies consistently show that such configurations can significantly increase signaling overhead and reduce system efficiency.

Measurement filtering introduces an additional dimension to performance control. In LTE simulations, radio measurements such as RSRP are typically smoothed using time-averaging techniques to reduce the impact of fast fading. Increasing the filtering duration reduces handover frequency by stabilizing measurement trends, but it may also delay the detection of genuine changes in radio conditions. This effect becomes particularly critical for high-speed users, whose radio environment evolves rapidly.

Overall, parameter tuning in LTE handover is inherently a multi-objective optimization problem. The optimal configuration depends on user mobility, network density, interference conditions, and the desired balance between responsiveness and robustness. Effective handover design therefore requires coordinated adjustment of hysteresis, TTT, and filtering mechanisms rather than treating them independently.

II.9 LTE Handover Events

Handover decisions in LTE are closely tied to measurement reporting events that determine when the User Equipment (UE) should notify the network about significant changes in radio conditions. These events are defined within the LTE measurement framework standardized by 3rd Generation Partnership Project and form the basis of mobility signaling. [25]

It is important to distinguish between event triggering and the actual handover decision. Events define when measurement reports are generated, while the final decision to perform a handover remains under network control. Therefore, events act as the sensing and signaling layer of mobility management.

II.9.1 Event A1

Event A1 is triggered when the serving cell quality becomes better than a predefined threshold. Its role is typically associated with stabilizing the connection by indicating that the serving cell conditions are satisfactory. In practice, A1 can be used to reduce unnecessary measurement activity or to terminate conditions that were previously signaling potential mobility concerns. [32]

II.9.2 Event A2

Event A2 is triggered when the serving cell quality falls below a configured threshold. This event serves as an early indication of link degradation and can initiate increased monitoring of neighboring cells. In many implementations, A2 is used in combination with other events to ensure that handover decisions are made only when both degradation and a suitable target are present. [31]

II.9.3 Event A3

Event A3 is one of the most important triggers in LTE mobility. It occurs when a neighboring cell becomes better than the serving cell by a specified offset. This relative comparison makes A3 particularly effective for intra-LTE handover.

$$RSRP_{\text{target}} > RSRP_{\text{serving}} + \text{HOM} \quad (\text{II.2})$$

The strength of A3 lies in its balance between responsiveness and stability, especially when combined with hysteresis and TTT. It is widely used in both practical LTE systems and simulation environments such as NS-3. [31]

II.9.4 Event A4

Event A4 is triggered when a neighboring cell exceeds a predefined threshold. Unlike A3, it does not directly compare the neighbor with the serving cell, but instead evaluates whether the neighbor alone meets a minimum quality requirement. This makes A4 simpler but less selective, as it does not guarantee that the target is better than the current serving cell. [28]

II.9.5 Event A5

Event A5 combines two conditions: the serving cell becomes worse than a threshold while the neighboring cell becomes better than another threshold. This dual- condition structure makes A5 more restrictive and controlled, ensuring that both degradation and improvement criteria are satisfied before reporting. [32]

As a result, A5 is often used in scenarios where tighter control over handover triggering is required, reducing unnecessary or premature handovers.

II.10 Handover Performance Metrics

Evaluating handover performance in LTE requires a set of key performance indicators (KPIs) that capture reliability, stability, continuity, and data transmission quality. These metrics are essential because the effectiveness of a handover algorithm cannot be assessed solely by its triggering behavior, but must also reflect its impact on user experience and network efficiency. [25]

A comprehensive evaluation framework typically combines event-level metrics with service-level indicators. Event-level metrics describe how often and how reliably handovers occur, while service-level metrics assess whether communication quality is preserved during mobility.

II.10.1 Handover Failure Rate

Handover Failure Rate represents the proportion of handover attempts that do not complete successfully. It is a critical indicator of mobility reliability, as high failure rates suggest poor decision timing, unsuitable target selection, or inadequate execution conditions. [32]

II.10.2 Ping-Pong Rate

Ping-Pong Rate measures the frequency of rapid back-and-forth handovers between cells. It reflects instability in the decision process and is often associated with overly aggressive parameter settings. High ping-pong rates increase signaling overhead and reduce overall system efficiency. [25]

II.10.3 Dropping Ratio

Dropping Ratio quantifies the proportion of sessions that are interrupted before completion due to loss of connectivity. Since maintaining session continuity is a primary objective of handover, this KPI is directly linked to user experience and network reliability. [26]

II.10.4 Handover Delay

Handover Delay represents the time required to complete the handover process. Excessive delay can degrade service continuity and increase the risk of connection failure, particularly in fast-changing radio environments.

II.10.5 Throughput

Throughput measures the effective data transmission rate achieved by the user. It is a key indicator of whether the handover process preserves or improves communication performance rather than merely completing a signaling procedure.

II.10.6 Packet Loss

Packet Loss reflects the proportion of data packets that fail to reach their destination. During handover, packet loss may occur due to buffering delays, signaling gaps, or timing mismatches. Minimizing packet loss is essential for ensuring seamless user experience, especially for real-time applications.

The interaction between control parameters, triggering events, and performance metrics defines the overall effectiveness of LTE handover mechanisms. Parameter tuning directly influences event behavior, which in turn impacts key performance indicators. A well-designed handover strategy must therefore achieve a careful balance between stability, responsiveness, and service quality, taking into account both radio conditions and network-level objectives.

II.11 Comparison of Handover Algorithms

The comparison of LTE handover algorithms cannot be reduced to a single performance indicator such as the number of handovers or signal strength improvement. A meaningful evaluation must consider how each algorithm balances mobility robustness, signaling stability, service continuity, and network efficiency under varying radio and traffic conditions. This is particularly important in LTE systems, where handover is a hard, UE-assisted, and eNodeB-controlled procedure, meaning that incorrect decisions immediately affect ongoing sessions. [33]

In the literature, it is well established that no single handover strategy is universally optimal. Classical signal-based approaches remain widely used due to their simplicity and direct alignment with standardized measurement frameworks, whereas more advanced load-aware and AI-based approaches aim to address limitations related to congestion, heterogeneity, and dynamic optimization requirements. Consequently, comparative analysis should focus on trade-offs rather than absolute superiority. [34]

A practical comparison framework typically considers four main dimensions: decision basis, implementation complexity, stability against ping-pong effects, and suitability for dense or heterogeneous deployments. Under this perspective, LTE handover algorithms can be broadly summarized as follows: [29]

- **RSRP-based methods** rely on received signal strength and are simple and efficient but do not capture interference or load effects.
- **RSRQ-based methods** incorporate quality and interference awareness, improving realism but increasing sensitivity to variations.
- **SINR-based methods** provide a direct link to throughput performance but may fluctuate rapidly under dynamic interference.
- **A3 event-based methods** rely on relative comparison with configurable offsets and are widely adopted due to their robustness and standard compatibility.
- **Load-based methods** introduce resource-awareness and improve balancing but may compromise radio quality if not constrained.
- **AI-based methods** offer adaptive multi-parameter optimization but introduce higher complexity and dependence on training data.

From a classical LTE perspective, RSRP-based and A3 event-based algorithms remain the most practical and widely used baselines. The NS-3 implementation studied in the literature confirms that A3-based handover, grounded in RSRP comparison with hysteresis and time-to-trigger control, provides a transparent and reproducible reference model for mobility evaluation. [32]

RSRQ-based algorithms generally enhance performance in interference-sensitive environments by providing a more realistic view of link quality. However, their sensitivity to network dynamics makes them more dependent on careful parameter tuning and filtering mechanisms. In contrast, SINR-based approaches are more directly related to throughput and link usability but require additional stabilization to prevent excessive sensitivity to interference variations.

A3 event-based algorithms deserve particular emphasis because they combine relative comparison with standardized behavior and configurable robustness. The decision is triggered when a neighboring cell exceeds the serving cell by a defined offset and maintains this superiority over a specified duration, making it significantly more stable than naive strongest-cell selection.

Load-based algorithms shift the focus from purely radio-centric decisions to system-level optimization. By considering cell utilization, they improve resource distribution and reduce congestion in overloaded cells. However, this introduces a trade-off, as prioritizing load balancing may lead to selection of suboptimal radio conditions if not properly constrained.

AI-based approaches extend this concept further by integrating multiple parameters simultaneously, including radio quality, mobility patterns, and traffic load. Their main advantage is adaptability, but their main limitation lies in complexity, interpretability, and validation across diverse scenarios. In practice, their benefits depend strongly on data quality and training conditions. [28]

For research based on NS-3, simpler algorithms remain essential as reference models due to their transparency and alignment with LTE measurement logic. Advanced methods should therefore be interpreted as extensions that are potentially beneficial in specific scenarios such as dense networks or highly dynamic traffic environments, rather than universal replacements.

II.12 Challenges in Handover Algorithms

Despite the maturity of LTE mobility mechanisms, handover design remains a complex problem due to the inherent variability of wireless environments. Radio conditions fluctuate due to fading, interference, mobility, and traffic load, while incorrect decisions may result in ping-pong effects, delayed handovers, or connection

failures. Thus, handover optimization is fundamentally a problem of decision-making under uncertainty. [31]

A primary challenge is the trade-off between responsiveness and stability. Simulation studies in NS-3 demonstrate that low hysteresis and short time-to-trigger values increase responsiveness but significantly raise the number of handovers and ping-pong events. Conversely, high parameter values improve stability but may delay necessary handovers, degrading link quality. This defines a narrow operational region that must be carefully optimized. [31]

Another key challenge is environmental diversity. LTE networks operate across macro, micro, indoor, and heterogeneous deployments, each characterized by different propagation conditions, interference patterns, and user densities. A configuration that performs well in one scenario may fail in

another, making universal parameter settings impractical and motivating adaptive or scenario-specific optimization strategies.

User mobility diversity further complicates the problem. Fast-moving users have limited time in cell overlap regions, making delayed decisions more harmful, while slow-moving users are more susceptible to unnecessary handovers caused by short-term fluctuations. Therefore, a single fixed strategy cannot optimally serve all mobility profiles.

Handover design is also inherently multi-objective. Improving one performance metric often degrades another. For example, optimizing purely for signal quality may increase load imbalance, while prioritizing load balancing may reduce individual radio performance. This trade-off requires careful balancing between user- level and system-level objectives. [27]

Practical deployment constraints add another layer of difficulty. Some theoretical handover models rely on metrics that are not directly available in standardized LTE signaling. As emphasized in the literature, realistic designs must rely on measurable quantities such as RSRP, RSRQ, and load indicators defined within standard frameworks such as those of 3rd Generation Partnership Project.

Simulation limitations also affect research validity. Some NS-3-based studies report incomplete modeling of radio link failures and certain mobility failure

scenarios, which can lead to overly optimistic performance results if not properly considered. This highlights the importance of clearly stating simulation assumptions when interpreting results. [35]

Finally, the emergence of load-aware and AI-based algorithms introduces additional challenges related to complexity, convergence, and generalization. While these approaches offer improved adaptability, they require careful validation to ensure stability, computational feasibility, and consistency across different network conditions. Moreover, fair comparison between algorithms requires consistent simulation setups, identical mobility models, and standardized KPI definitions to avoid misleading conclusions.

II.13 Conclusion

This chapter has presented a comprehensive overview of LTE handover algorithms, starting from the fundamental importance of mobility management in cellular networks to the detailed decision criteria and algorithmic classifications. It has shown that handover is not a simple triggering mechanism but a complex decision process that depends on multiple radio, mobility, and network-related parameters.

The study of classical and advanced handover strategies highlights that no single algorithm is universally optimal. Each approach presents specific advantages and limitations depending on deployment scenarios, user mobility, and network load conditions. Therefore, effective handover design in LTE requires a careful balance between stability, responsiveness, and overall system performance, which will be further explored through NS-3-based implementation and evaluation in the following chapters.



Chapter III

Simulation Tools



III.1 Introduction

Network simulation has become an essential component in the design, analysis, and evaluation of modern communication systems. Developing a full-scale network in a real-world environment often requires significant resources, infrastructure, and time, making it impractical for testing new protocols or algorithms. Therefore, simulation provides a controlled, cost-effective, and reproducible environment to study complex network behavior and evaluate the performance of communication protocols before actual deployment [36, 37].

Simulation tools are widely used in both academic and industrial research to model wired, wireless, and cellular networks. They enable researchers to test new protocols or algorithms under various traffic and mobility conditions, evaluate network performance metrics such as throughput, delay, packet loss, and reliability, and analyze the impact of parameter variations without affecting real network operations [38, 39].

Among the available network simulators, ns-3 Network Simulator has emerged as one of the most popular and widely adopted open-source platforms. It provides a discrete-event simulation environment capable of modeling a wide range of network technologies, including LTE, Wi-Fi, and TCP/IP networks [40]. Its modular architecture and object-oriented design, implemented in C++ and Python, allow researchers to develop new protocols, simulate realistic network topologies, and efficiently analyze simulation results [41]. Compared to its predecessor ns-2, ns-3 offers improved accuracy, better integration with real network stacks, and enhanced scalability for large-scale simulations [42].

In addition to ns-3, Simulation of Urban Mobility (SUMO) is an open-source microscopic traffic simulator used to generate realistic mobility patterns for network nodes, particularly in vehicular environments. Although optional for LTE handover studies, SUMO can be integrated with ns-3 to provide detailed mobility traces in complex and dynamic scenarios [43, 44].

This chapter focuses on the simulation tools used in this study, describing their capabilities as well as the procedures for installation, configuration, and practical use in network modeling. It provides the technical foundation required to understand how communication networks and protocols can be simulated using these tools. Furthermore, this chapter prepares the reader for Chapter 4, which presents the simulation environment and scenario setup used to evaluate handover algorithms in LTE networks.

III.2 NS-3 Network Simulator

III.2.1 Overview of ns-3

The ns-3 Network Simulator is a discrete-event network simulator designed primarily for research and educational purposes. It is an open-source software distributed under the GNU General Public License (GPLv2), which allows researchers and developers to freely use, modify, and extend the simulator for various networking studies [40].

ns-3 was developed as a replacement for ns-2, with the objective of providing a more accurate, scalable, and flexible simulation environment for modern communication networks. Unlike its predecessor, ns-3 is not backward-compatible, as it was redesigned from scratch to better support contemporary networking technologies and research requirements [45].

The simulator models network behavior through a discrete-event approach, where system changes occur only at specific scheduled events in simulation time. This mechanism enables precise modeling of network protocols, node interactions, and data transmission processes, making ns-3 a powerful tool for analyzing network performance under controlled and reproducible conditions [46].

One of the key strengths of ns-3 is its ability to support a wide range of network technologies, including wired and wireless systems such as Wi-Fi, LTE, and Internet-based protocols. This flexibility makes it suitable for studying diverse networking scenarios and evaluating the performance of communication protocols and algorithms [47].

Due to its open-source nature, extensibility, and active research community, ns-3 has become one of the most widely used network simulators in both academic and industrial environments. It provides researchers with a reliable platform for designing, testing, and validating new networking solutions before real-world deployment [40].



Figure III.1: *Logo of ns-3*

III.2.2 Architecture of ns-3

The architecture of the ns-3 network simulator is based on a modular and object-oriented design, which ensures flexibility, scalability, and ease of extension. Unlike monolithic simulators, ns-3 is organized as a collection of independent modules, where each module implements a specific functionality such as core simulation, networking, mobility, or applications. This modular structure allows users to include only the required components for a given simulation scenario, thereby reducing complexity and improving efficiency [48].

At its core, ns-3 relies on a discrete-event simulation engine, in which events such as packet transmissions, protocol operations, or mobility updates are scheduled and executed in chronological order. This mechanism provides an accurate representation of time-dependent network behavior [49].

The architecture of ns-3 is built around several fundamental abstractions:

- **Node:** Represents a network entity such as a user device or base station.
- **NetDevice:** Acts as a network interface responsible for data transmission and reception.
- **Channel:** Represents the communication medium between devices.
- **Packet:** Defines the basic unit of data exchanged within the network.

These components closely resemble real-world network systems, enabling realistic simulation of communication scenarios [50].

In addition, ns-3 follows a layered protocol architecture, similar to actual communication networks, including data link, network, transport, and application layers. This structure enables detailed analysis of end-to-end communication processes.

A key feature of ns-3 is its object and attribute system, which allows flexible configuration of simulation parameters such as transmission power, delay, and queue size. These parameters can be modified at runtime without changing the source code, facilitating experimentation and performance evaluation [48].

To simplify simulation development, ns-3 provides a Helper API, which abstracts complex low-level operations such as installing protocol stacks, configuring devices, and defining mobility models. Furthermore, the simulator includes a tracing system that enables monitoring of events and collection of performance data without modifying the simulation core.

In summary, the architecture of ns-3 combines a discrete-event core, modular structure, and flexible configuration mechanisms, making it a powerful and efficient tool for simulating modern communication networks.

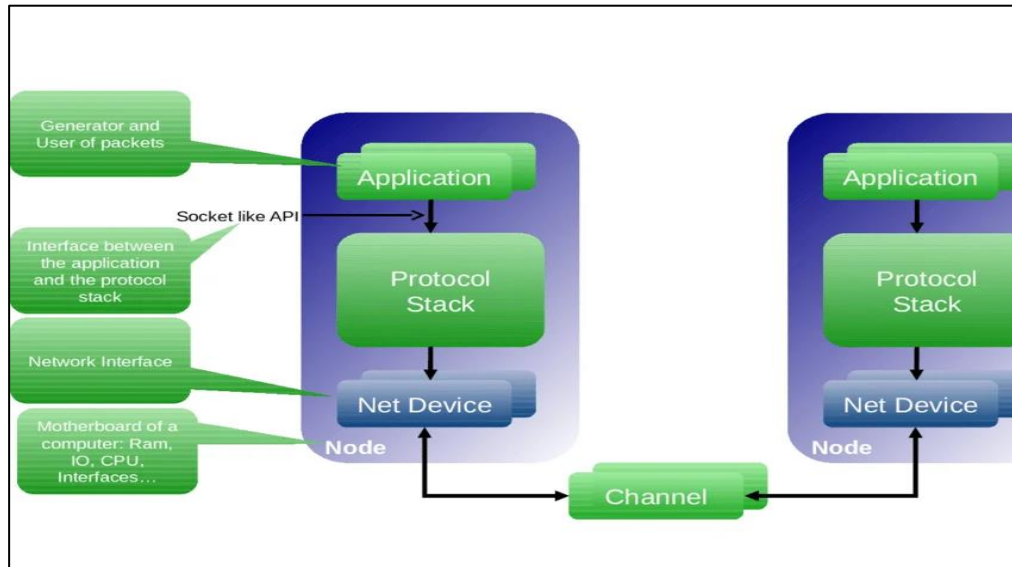


Figure III.2: Architecture of ns-3[51]

III.2.3 LTE Module in ns-3

The LTE module in ns-3 provides a comprehensive simulation framework for modeling Long Term Evolution (LTE) networks, encompassing both the Radio Access Network (RAN) and the Evolved Packet Core (EPC). Developed as an open-source extension of the ns-3 simulator, this module has been widely adopted in academic research for evaluating radio resource management strategies, mobility procedures, and handover algorithms under realistic network conditions [52].

III.2.3.1 Core Components

➤ User Equipment (UE):

Represents mobile terminals capable of connecting to eNodeBs. Each UE performs periodic measurements of neighboring cells, reporting Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) to the serving eNodeB [53].

➤ eNodeB (Evolved Node B):

Acts as the LTE base station, managing radio resources and controlling handover execution. The eNodeB evaluates measurement reports received from UEs and triggers handover procedures based on configurable criteria. It also maintains a neighbor cell list that defines potential target cells for handover [53].

➤ Evolved Packet Core (EPC):

Comprises the Mobility Management Entity (MME) for session and mobility management, along with the Serving Gateway (SGW) and Packet Data Network Gateway (PGW) for data routing and IP

connectivity. The EPC enables end-to-end simulation of LTE networks, including bearer establishment and inter-eNodeB handover signaling [54].

➤ **Radio Resource Management (RRM):**

Implements scheduling algorithms, SINR-based cell selection, and handover decision logic. The RRM entity in each eNodeB processes UE measurements and evaluates handover triggers according to configured parameters [52].

III.2.3.2 Handover Support

The LTE module includes a complete handover framework compliant with 3GPP specifications. Key features include:

- **A3 Event-Based Handover:** The default handover mechanism, triggered when the neighbor cell signal strength exceeds the serving cell by a specified hysteresis margin for a duration exceeding the Time-to-Trigger (TTT) [53].
- **Configurable Parameters:** Handover behavior can be adjusted through parameters such as hysteresis margin, Time-to-Trigger (TTT), and measurement reporting intervals, allowing researchers to evaluate handover performance under different configurations [53].
- **Extensible Architecture:** The module's object-oriented design allows researchers to implement custom handover algorithms by extending existing handover management classes. This extensibility makes ns-3 suitable for studying enhanced handover solutions beyond the standard A3 event-based approach [52].

III.2.3.3 Simulation Workflow

A typical simulation scenario using the LTE module involves:

- **Network Topology Definition:** Creating nodes representing UEs and eNodeBs, configuring their positions, and assigning mobility models [52].
- **EPC and IP Configuration:** Setting up the EPC components and installing IP stacks on UEs to enable end-to-end connectivity [52].
- **Handover Parameter Configuration:** Specifying handover-related parameters according to the scenario requirements [53].
- **Simulation Execution:** Running the discrete-event simulation, during which handover events are triggered based on UE mobility and signal conditions [52-54].
- **Data Collection:** Recording performance metrics such as handover counts, throughput, and SINR for analysis [52-54].

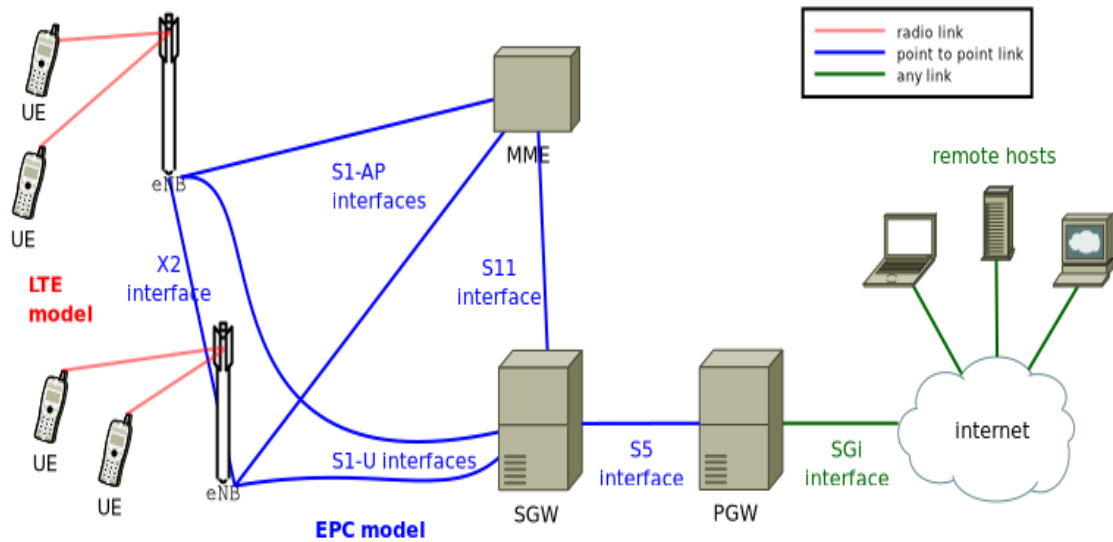


Figure III.3: LTE System Architecture in ns-3[55].

III.2.4 Comparison with Other Simulators

Table III.1: Comparative analysis of ns-3 and other network simulators for LTE and handover studies

Criteria	NS-3	OMNeT++	OPNET (Riverbed Modeler)	MATLAB-based Simulators
License	Open-source (free)	Open-source (free)	Commercial (paid)	Commercial (paid)
Simulation Type	Discrete-event	Discrete-event	Discrete-event	Numerical / event-based
Protocol Realism	High	Medium	High	Low to medium
LTE/5G Support	Native	Extensions required	Built-in	Limited
Mobility & Handover	Advanced	Moderate	Advanced	Limited
PHY Layer Modeling	Detailed	Abstracted	Detailed	Simplified
Ease of Use	Moderate	Easy	Easy	Easy
Flexibility	Very high	High	Low	High
GUI Support	Limited	Strong	Very	Strong
Performance	Very accurate	Good	Very accurate	Depends on model
Research Suitability	Excellent	Very good	Limited	Good (theory)
Cost	Free	Free	Expensive	Expensive

III.3 Installation and Configuration of ns-3

III.3.1 System Requirements

Before installing the ns-3 network simulator, it is essential to ensure that the system meets the necessary hardware and software requirements to guarantee proper compilation and execution of simulations [50].

From a hardware perspective, ns-3 does not require high-end resources; however, a modern computer with at least a dual-core processor, 4 GB of RAM (minimum), and sufficient disk space (approximately 2–5 GB) is recommended for efficient simulation performance [50]. For large-scale LTE or 5G simulations, higher memory capacity (8 GB or more) is preferable [50].

Regarding software requirements, ns-3 is primarily developed for Linux-based operating systems, particularly Ubuntu, which is widely recommended due to its compatibility and community support [50]. Although ns-3 can also be used on Windows (via virtual machines or Windows Subsystem for Linux), Linux remains the preferred environment for stability and performance [50].

The following software dependencies are typically required:

- **C++ compiler** (GCC or Clang) supporting modern C++ standards [50]
- **Python (version 3.x)** for scripting and automation [50]
- **CMake** and **build tools** for compilation [50]
- **Git** for downloading the source code [50]
- Optional tools such as **NetAnim** for visualization and **PyViz** for real-time simulation monitoring [36]

Additionally, some optional libraries may be required depending on the modules used, such as support for LTE, mobility, or external tools integration [50].

Ensuring that these requirements are satisfied helps avoid installation errors and guarantees a stable simulation environment for conducting network performance evaluations [17].

III.3.2 Downloading ns-3

The ns-3 network simulator is a discrete-event simulation tool widely used in academic research and industry for modeling communication networks, particularly wireless and cellular systems. It provides a flexible and extensible environment for protocol design, performance evaluation, and network experimentation [56].

In this work, the standalone version of ns-3.46 was used instead of the all-in-one package in order to allow better control over dependency management and system configuration. Unlike the all-in-one distribution, the standalone version includes only the core simulator, requiring manual installation of the necessary prerequisites.

The simulator can be obtained from the official ns-3 repository, which ensures authenticity, integrity, and compatibility with the latest updates. The following commands illustrate the standard procedure for downloading **ns-3.46**:

```
cd ~
mkdir ns3
cd ns3
wget https://www.nsnam.org/releases/ns-
3.46.tar.bz2
tar -xjf ns-3.46.tar.bz2
cd ns-3.46/
ls
```

These steps perform the following operations:

- Create a dedicated workspace for ns-3
- Download the official archived release using `wget`
- Extract the archive and access the simulator directory

Downloading the simulator from the official source is essential to ensure the correctness and reliability of subsequent simulation experiments.

III.3.3 Building and Configuration

After successfully downloading the source code of **ns-3.46**, the next step consists of configuring and building the simulator to make it ready for execution.

Starting from recent releases, the ns-3 project transitioned from the legacy **Waf build system** to a **CMake-based build system**, improving compatibility with modern development tools and simplifying the build process [57].

III.3.3.1 Configuration

The configuration step prepares the build environment by checking the availability of required dependencies such as:

- C++ compiler (g++ or clang)
- Python 3

- CMake and build tools

```
./ns3 configure --enable-examples --enable-tests
```

- `--enable-examples`: enables example scripts for testing and learning
- `--enable-tests`: enables the test suite for validation

III.3.3.2 Building

Once configured, the simulator is compiled using:

```
./ns3 build
```

This process compiles the source files into object files and links them into executable binaries. CMake internally invokes build tools such as make or ninja to complete the compilation process [60].

After a successful build, the ns-3 simulator and its modules become ready for use.

III.3.3.3 Verification of Installation

To ensure that the installation was completed successfully, the integrated test suite can be executed:

```
./test.py
```

This command runs a comprehensive set of internal tests to validate the correctness of the simulator components. Successful execution indicates that the environment is properly configured and ready for simulation experiments.

III.3.3.4 Technical Discussion

The building and configuration stage is critical in the ns-3 workflow. Any missing dependency or incorrect configuration may lead to compilation failures or incorrect simulation behavior.

The adoption of CMake introduces several advantages over the legacy Waf system, including:

- Improved dependency management
- Better integration with modern IDEs
- Enhanced cross-platform compatibility
- More robust and modular build process

Additionally, the ns3 script provides a simplified interface, easing the transition from Waf to CMake while maintaining usability for researchers and developers [57].

III.4 SUMO Mobility Simulator

III.4.1 Overview of SUMO



Figure III.4: *Logo of SUMO Mobility simulator*

Simulation of Urban MObility (SUMO) is an open-source, microscopic traffic simulation package developed by the German Aerospace Center (DLR) [58]. SUMO allows modeling of individual vehicles and their interactions within road networks, providing detailed representation of traffic dynamics. Each vehicle is assigned a specific route, departure time, and driving behavior, which enables researchers to perform precise analysis of traffic flow, route choice, and congestion patterns [59].

SUMO supports multi-modal traffic, including cars, buses, and pedestrians, making it suitable for urban mobility studies and large-scale network analysis. Its tools allow network generation, traffic demand creation, route calculation, and result evaluation. A notable feature of SUMO is its ability to integrate with external applications using the TraCI (Traffic Control Interface) API, which permits real-time control of simulations and communication with other software, such as network simulators for vehicular communications [58, 59].

Historically, SUMO was developed to fill the gap of a flexible, extensible, and open-source traffic simulation platform. Over time, it has evolved to include advanced capabilities, such as emissions calculation and intelligent traffic control strategies, making it widely used in both academic research and industrial applications [59].

III.4.2 Road Network Generation

Road network generation represents a fundamental phase in the configuration of traffic simulations using Simulation of Urban Mobility (SUMO), as it defines the structural environment in which vehicular mobility is modeled. Within SUMO, the road network is formally represented as a directed graph, where

nodes correspond to intersections or junctions, and edges represent road segments connecting these nodes, enriched with attributes such as lane count, maximum speed, and priority rules [58].

SUMO offers a flexible and extensible framework for network creation, supporting both synthetic and real-world scenarios. On one hand, users can manually construct networks through XML-based definitions, enabling fine-grained control over topology and infrastructure parameters. On the other hand, SUMO allows the importation of real-world geographic data, particularly from OpenStreetMap (OSM), thereby facilitating the generation of realistic urban traffic environments suitable for large-scale simulations [58].

In addition to manual and data-driven approaches, SUMO provides dedicated tools to streamline network generation. The *Netgenerate* utility enables the automatic creation of abstract network topologies, such as grid, random, or spider networks, which are particularly useful for theoretical and comparative studies. Meanwhile, *Netconvert* supports the transformation of external network formats into SUMO-compatible representations, ensuring interoperability with various traffic and geographic data sources [59].

Beyond the geometric structure, road network generation in SUMO also involves the specification of traffic control components, including traffic light systems, right-of-way regulations, and intersection management policies. These elements play a crucial role in shaping vehicle interactions and traffic dynamics. Consequently, the accuracy and level of detail of the generated network significantly influence the validity, realism, and reproducibility of simulation outcomes [58, 59]. the fidelity of the road network is particularly relevant, as it directly determines the mobility patterns of User Equipment (UEs), which in turn affect handover triggering and performance in LTE simulations.

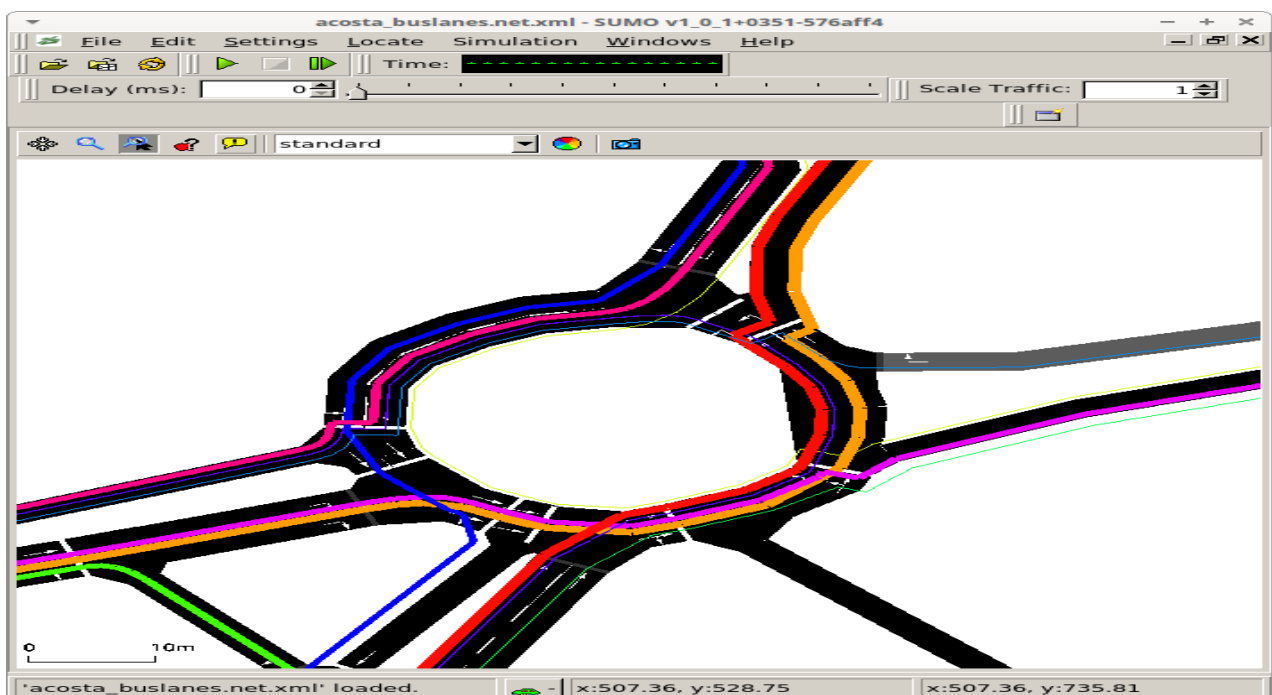


Figure III.5: Example of a road network generated using Simulation of Urban Mobility (SUMO) showing intersections (nodes), roads (edges), and lanes.

III.4.3 Vehicle Mobility Generation

Once the road network has been created, generating vehicle mobility constitutes a critical phase in SUMO-based traffic simulations. This stage determines the movement behavior of vehicles, including their routes, speeds, departure times, and interactions with other vehicles and traffic control infrastructure [60]. Accurate modeling of vehicle mobility is essential for simulating realistic traffic scenarios and for studies involving User Equipment (UE) movement in LTE networks.

III.4.3.1 Traffic Demand Generation Tools in SUMO

SUMO provides a comprehensive suite of tools to generate vehicle mobility. These tools can be classified into two categories: countless (stochastic) and count-based (data-driven) approaches [26].

Table III.2: Traffic Demand Generation Tools in SUMO

Tool	Category	Description
randomTrips.py	Countless	Generates random trips without requiring real-world data. Suitable for theoretical studies and controlled experimental analyses [58].
osmWebWizard	Countless	A graphical interface that generates traffic demand from OpenStreetMap (OSM) data with simplified configuration parameters, ideal for rapid scenario prototyping [60].
JTRROuter	Countless	Generates random routes according to specified turning ratios (e.g., 25% right, 50% straight, 25% left). Particularly suitable for Manhattan-style grid networks [61].
DUARouter	Count-based	Computes routes based on Origin-Destination (OD) pairs, considering congestion and dynamic rerouting. Uses iterative equilibrium assignment to achieve realistic traffic distributions [58].
OD2Trips	Count-based	Converts OD matrices into trip files, enabling integration of real-world mobility survey data into simulations [61].
DFRouter	Count-based	Generates routes based on flow data, suitable when real traffic count measurements are available [60].

➤ **Remark:**

Count-based tools generally produce more realistic travel patterns and emissions data, whereas countless tools provide simplicity, faster execution, and flexibility for theoretical studies [61].

III.4.3.2 Mobility Models

SUMO implements a variety of microscopic models to govern individual vehicle behavior, including car-following and lane-changing models.

Table III.3: *Vehicle Mobility Models Parameters*

Parameter	Description	Typical Range
MaxSpeed	Maximum vehicle speed	13.9 – 33.3 m/s (50–120 km/h)
Accel	Maximum acceleration	0.8 – 3.0 m/s ²
decel	Maximum deceleration	3.0 – 6.0 m/s ²
MinGap	Minimum gap to leading vehicle	1.0 – 2.5 m

➤ **Intelligent Driver Model (IDM):**

The default car-following model calculates vehicle acceleration based on current speed, relative speed to the leading vehicle, and the desired gap. Key parameters include maximum speed, maximum acceleration, comfortable deceleration, and minimum gap [60][62].

➤ **LC2013 Model:**

The default lane-changing model accounts for both strategic lane selection (following planned routes) and tactical lane changes (to gain speed advantage) [58].

III .4.3.3 Floating Car Data (FCD) Output

To utilize SUMO vehicle mobility outputs in network simulators such as ns-3, SUMO provides the `--fcd-output` option. This generates an XML file containing detailed information for each vehicle at every simulation timestep [63].

Table III.4: *Key Attributes of FCD Output*

Attribute	Description
x, y	Vehicle coordinates (meters or longitude/latitude)
Z	Elevation (if available)
Angle	Vehicle orientation (0–360°, 0° = North, clockwise)
Speed	Instantaneous speed (m/s)
Type	Vehicle type (car, bus, bicycle, pedestrian, tram, etc.)
Slope	Road slope at vehicle position (if enabled)
acceleration	Current acceleration (if enabled via <code>--fcd-output.acceleration</code>)
Emissions	CO ₂ , NO _x , and other pollutants (optional via <code>--fcd-output.attributes</code>)

III.5 Integration of SUMO with ns-3

Integrating SUMO (Simulation of Urban Mobility) with ns-3 enables researchers to combine microscopic vehicle mobility with network-level simulation. This setup allows studying how realistic vehicular movement can influence network performance, including handover in LTE [58][64]

III.5.1 Coupling Method

The coupling between SUMO and ns-3 is commonly implemented through co-simulation frameworks, allowing real-time data exchange. A widely used approach is the Traffic Control Interface (TraCI) [64, 65].

Key aspects include

- **Bidirectional communication:** Vehicle states such as position, speed, and lane information are exchanged between SUMO and ns-3.
- **Step-wise simulation:** Both simulators progress in discrete timesteps, ensuring synchronized updates.
- **Topology mapping:** Each SUMO vehicle is linked to a corresponding ns-3 node representing User Equipment (UE) or network-capable vehicles.

This configuration facilitates realistic co-simulations where vehicle mobility can influence network behavior, including handover in LTE, without detailing its internal mechanisms.

III.5.2 Synchronization Mechanism

Synchronization ensures that both simulators maintain temporal consistency and prevents timing-related errors [58, 65].

Common approaches include:

- **Master-slave synchronization:** SUMO typically acts as the master updating vehicle positions, while ns-3 acts as the slave computing network events.
- **Timestep alignment:** Both simulators advance in consistent timesteps (e.g., 0.1 s or 1 s).
- **Event-driven synchronization:** Certain vehicle events in SUMO can trigger corresponding network computations in ns-3.

These mechanisms allow efficient co-simulation between SUMO and ns-3, with vehicle movements potentially impacting network operations, including handover in LTE.

III.5 Conclusion

The simulators ns-3 and SUMO are key tools for modeling LTE mobility, where SUMO provides realistic mobility through detailed vehicular movement patterns, while ns-3 simulates LTE network behavior and handover mechanisms. Their integration enables the joint analysis of network performance under dynamic mobility scenarios, highlighting the strong interaction between user movement and communication behavior. This combined framework provides a flexible and accurate approach for studying LTE networks, making simulation a fundamental methodology for performance evaluation rather than a supporting tool. Overall, the effectiveness of simulation studies depends not only on the choice of tools, but also on how they are used and integrated. Therefore, combining network modeling with realistic mobility simulation represents an essential approach for obtaining accurate and reliable results in communication network research.



Chapter IV

Simulation and Results



IV.1 Introduction

Evaluating the performance of handover algorithms in Long Term Evolution (LTE) networks is a critical aspect of mobility management research. The handover process has a direct impact on Quality of Service (QoS), service continuity, and the overall user experience. Although 3GPP standards provide well-defined handover mechanisms, identifying the optimal configuration of control parameters such as Time-to-Trigger (TTT) and Hysteresis remains a major challenge, particularly in dense and heterogeneous urban deployments [66, 67].

This chapter presents the simulation framework and results of evaluating a quantized RSRQ-based handover algorithm. The study considers a realistic urban scenario inspired by the city of M'sila, Algeria, comprising a central tri-sector macro cell and eighteen micro cells deployed around it. Mobility traces for 100 user equipment's (UEs) are generated using SUMO and imported into the ns-3 LTE module to conduct the simulations.

This chapter further details the proposed detection mechanisms for Handover Failures (HOF) and the Ping-Pong effect, both based on a 2-second time window. The detection threshold for both HOF and ping-pong events is set to 2 seconds. System performance is evaluated using several Key Performance Indicators (KPIs), including total handover count, Ping-Pong rate, handover failure rate, RSRQ signal quality, and Mobility Interruption Time (MIT), under varying Time-to-Trigger (TTT) and hysteresis configurations.

Through this experimental study, the research aims to examine the interactions among these parameters and to identify the optimal trade-off between minimizing unnecessary handovers and avoiding handover failures in realistic urban conditions [68, 69].

IV.2 Experimental Scenarios & Configuration Framework

This chapter presents the experimental scenarios and simulation configurations adopted in this study, including the network layout and street map data description.

IV.2.1 Mobility Configuration

❖ Cell deployment

The simulation was conducted using map data from the M'sila University Pole area. The map was extracted from OpenStreetMap (OSM) and processed using the QGIS platform for cell deployment. The

positions of the macro and micro cells were then extracted as Cartesian coordinates and exported to a CSV file, which was used in ns-3 simulations, as illustrated in the following figures.

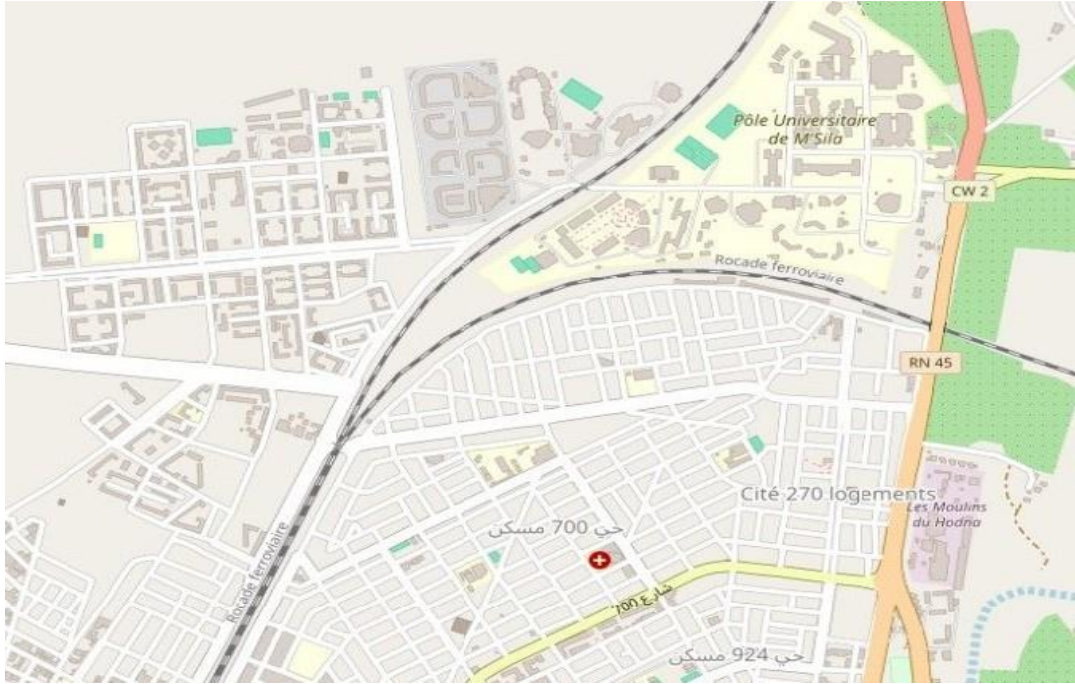


Figure IV.1: Map of the M'sila University Pole area extracted from OpenStreetMap (OSM)

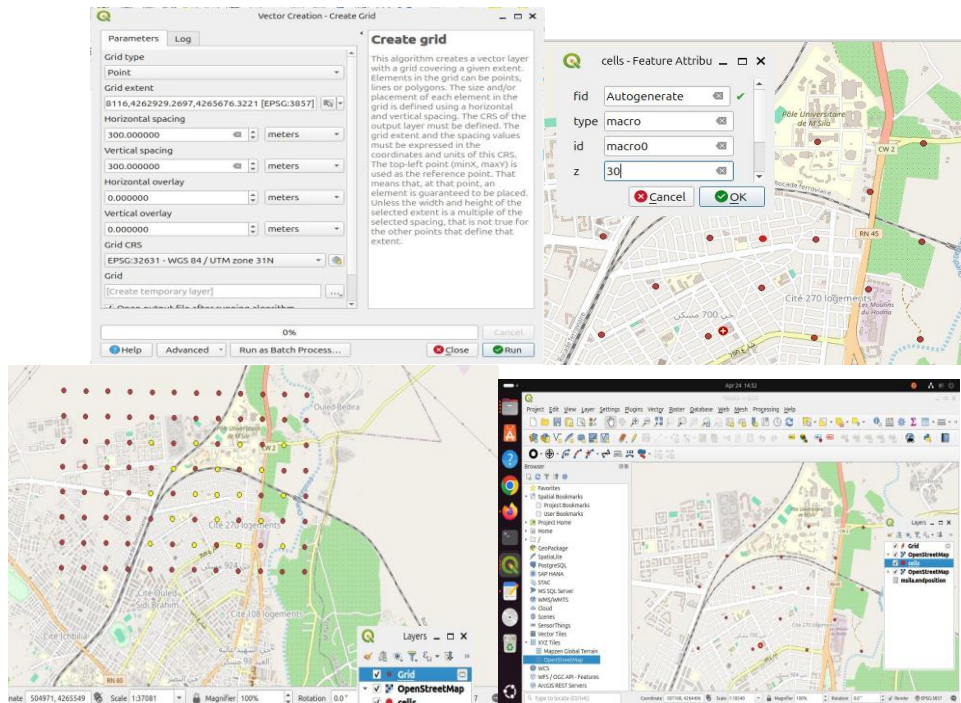


Figure IV.2: Extraction Steps of 1 Macro & 18 Micro Cells Coordinates in M'sila Area Using QGIS

❖ Mobility generation (SUMO)

A mobility scenario was created in SUMO using map data extracted from OpenStreetMap (OSM) for the M'sila University Pole area. The road network was imported into SUMO, and vehicle routes were generated to reflect realistic urban mobility patterns. A total of 100 vehicles were initiated, with a maximum speed set to 13.9 m/s (50 km/h), consistent with urban speed limits. The resulting mobility traces were exported in NS-2 format and directly imported into ns-3 using the Ns2MobilityHelper class, which assigned each vehicle to a User Equipment (UE), as illustrated in Figures IV.17, and IV.19.

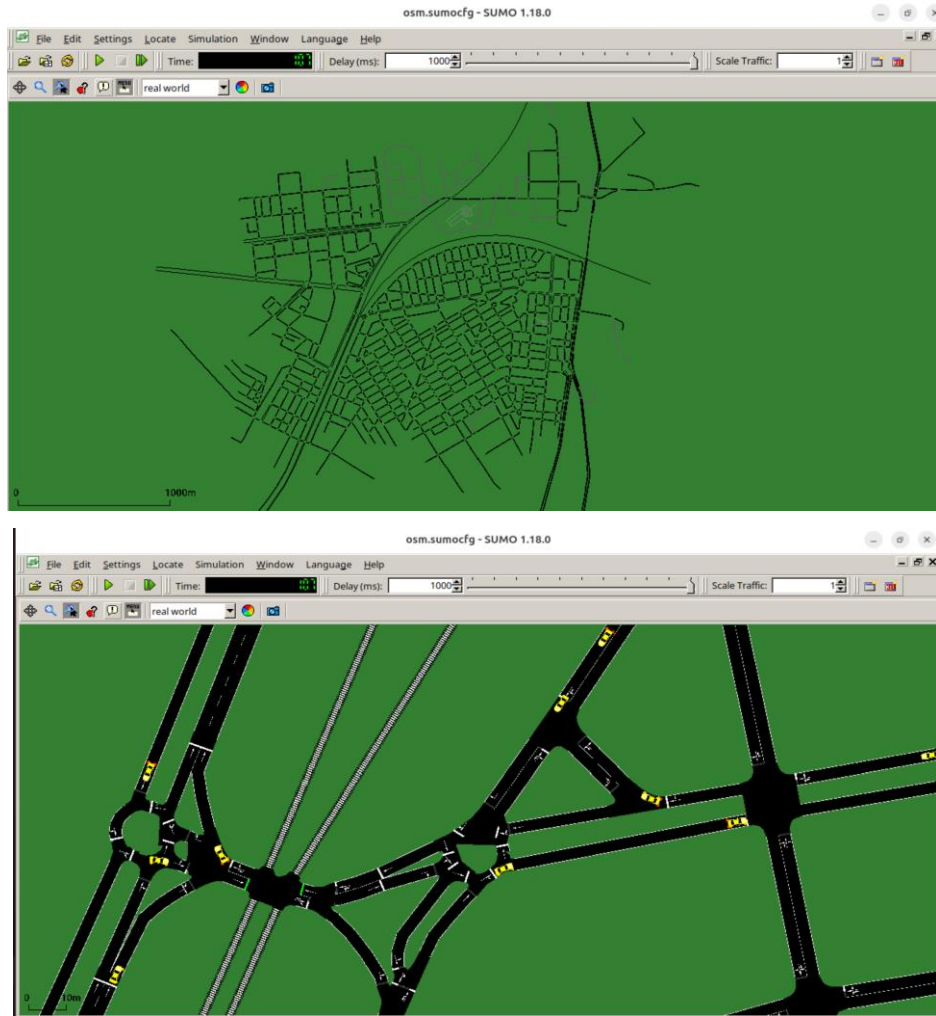


Figure IV.3: SUMO mobility simulation in the M'sila University Pole area

IV.2.2 Cell settings

In this scenario, a network architecture based on a central macrocell is adopted, with eighteen (18) microcells deployed around it to reflect realistic cellular network deployments.. The inter-site distance between adjacent microcells is set to approximately 300 meters, ensuring a balance between coverage and capacity. The adopted cell distribution within the study area is illustrated in the corresponding figure.

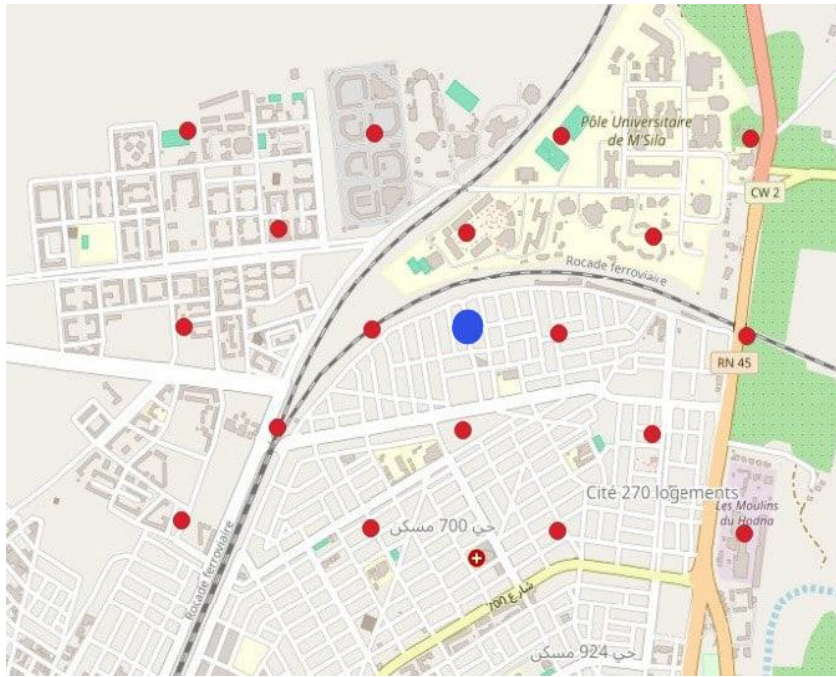


Figure IV.4: Simulation Cell Positions (M'sila)

- The following table contains the configuration information of the macro and micro cells in the simulated scenario

Table IV.1: Macro and Micro Cell Configuration Parameters

Parameter	Macro Cell	Micro Cell	Unit
Tx Power	15	40	dBm
Antenna height	30	30	M
Bandwidth	20	20	MHz
Scheduler	RrFfMacScheduler (Round Robin)	RrFfMacScheduler (Round Robin)	---
Frequency	2.6	2.6	(GHz)
Pathloss Model	3GPP UMi Street Canyon	3GPP UMi Street Canyon	---

IV.2.3 Simulation data collection

In this study, the **quantized RSRQ** metric is adopted as the basis for handover decision-making, as it represents the actual measurement reported by the user equipment (UE) to the serving base station. Unlike RSRP, which reflects only the received signal power from a single cell, RSRQ provides a more comprehensive indication of radio link quality by incorporating both signal strength and interference effects, as it is derived from RSRP and RSSI.

User mobility is first generated using the **SUMO simulator**, and the resulting mobility traces are then imported into the **ns-3** environment to conduct the simulation under a predefined movement scenario. During the simulation, the quantized RSRQ values perceived by each UE from all surrounding cells are periodically recorded.

The simulation time is discretized into fixed intervals of **120 ms**, at which serving-cell RSRQ measurements are sampled, quantized to 0–34 index values, and stored. These collected data are subsequently used to analyze network behavior and evaluate the performance of the handover mechanism by tracking the evolution of signal quality over time within a defined observation window.

The simulation is conducted with 100 mobile users using the **3GPP UMi Street Canyon** propagation model at **2.6 GHz** with **20 MHz** bandwidth, a **Round Robin scheduler**, and an RSRQ-based handover algorithm. The simulation duration was set to 400 s.

The UMi-Street Canyon model is adopted not because the M'sila University Pole itself resembles a dense urban canyon, but to create a high-interference, worst-case environment that stresses the handover algorithm beyond real campus conditions.

IV.3 Handover Failure

In this thesis, handover failures (HOF) are detected using a time threshold of 2 seconds. The classification of handover failures is performed according to the following criteria:

Too Late Handover: Occurs when a radio link failure (RLF) happens while the handover is still in progress (before completion). The UE then reconnects to a cell other than the source cell within 2 seconds.

Too Early Handover: Occurs when a successful handover is completed, but an RLF happens within 2 seconds afterwards, and the UE reconnects back to the previous source cell.

Wrong Cell Handover: Occurs when a successful handover is completed, followed by an RLF within 2 seconds, and the UE reconnects to a third cell (neither the source nor the target cell).

Both Too Early and Wrong Cell handover failures are aggregated in this study under the composite metric Too Early Handover, since they are primarily caused by insufficient signal quality from the target cell after the handover is executed.

IV.4 Ping Pong

In this thesis, ping-pong handover is detected using a 2-second time window. A ping-pong event is defined as a sequence where the User Equipment (UE) successfully completes a handover from a source

cell to a target cell, and within 2 seconds thereafter successfully completes another handover back to the original source cell, without experiencing any Radio Link Failure (RLF) during this period.

IV.5 Simulation results

This study utilized the standard **A3 event** handover mechanism commonly adopted in LTE-Advanced systems. Handover decisions are based on **quantized RSRQ** measurements (0–34 index, mapping -19.5 dB to -3.0 dB in 0.5 dB steps) and performance was evaluated using different parameter combinations of **Time-to-Trigger** [80, 100, 160, 320, 640, 800, 1200, 2000 ms] and **Hysteresis** [1.0, 2.0, 3.0, 4.0 dB]:

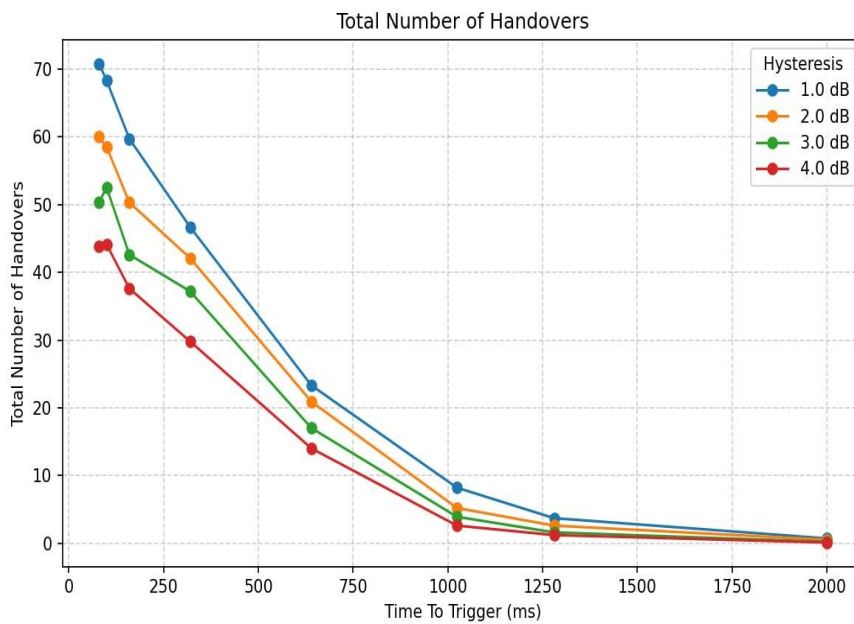


Figure IV.5: Total number of Handovers

The results presented in Figure IV.5 demonstrate that **Time-To-Trigger (TTT)** and **Hysteresis** have a direct impact on the handover behavior in the network.

The number of Handovers decrease at higher TTT values, demonstrating inverse behavior. This occurs because a higher TTT requires the UE to maintain the handover condition for a longer period before reporting to the serving eNodeB, thereby filtering out short-term signal variations. In addition, increasing the hysteresis value further reduces the number of handovers occurrences by enforcing a larger signal quality margin between the target and serving cells before a handover decision is triggered.

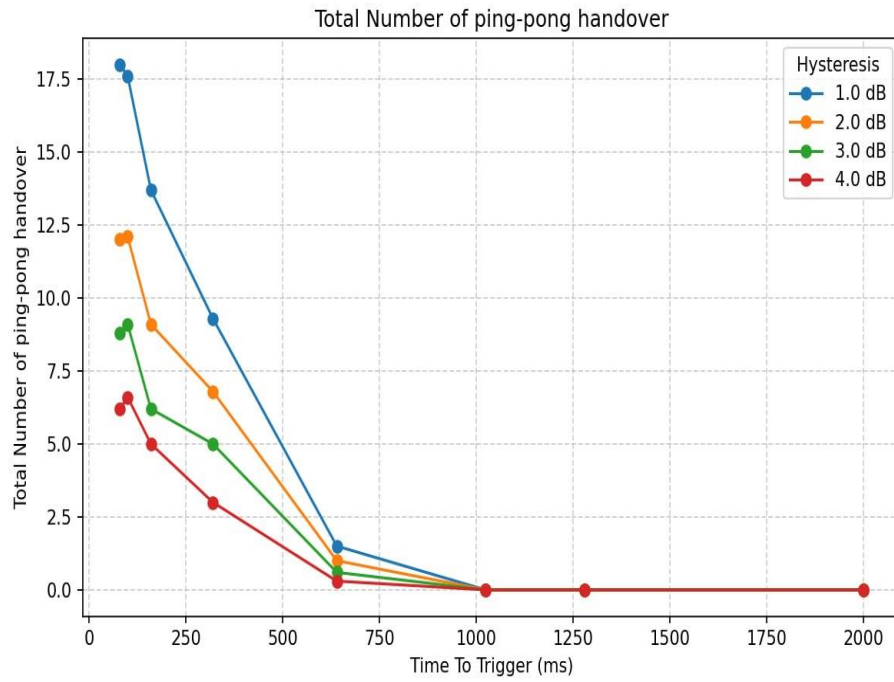


Figure IV.6: Average number of Ping-Pong Handover

In Figure IV.6, a sharp decrease in ping-pong events is observed as TTT increases, approaching zero at higher values. This behavior indicates that longer TTT values effectively mitigate rapid and unnecessary back-and-forth handovers between cells. Furthermore, higher hysteresis values contribute to reducing ping-pong handovers by enforcing a stricter signal difference condition between the serving and target cells.

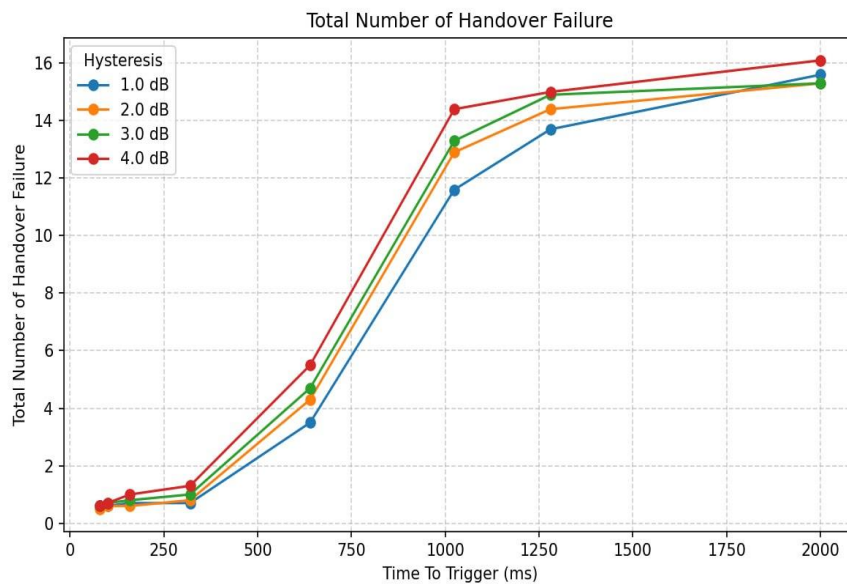


Figure IV.7: Total Number of Handovers Failure

The Figure VI.7 illustrates the impact of **Time-to-Trigger (TTT)** and **Hysteresis** values on the total number of **handover failures** in the simulated environment. The results reveal a strong positive correlation between increasing TTT values and the number of handover failures. At low TTT values (80 to 320 ms), the number of failures remains relatively low across all hysteresis levels.

However, the number of handover failures increases noticeably as TTT rises, with a sharp surge observed starting from 640 ms. This upward trend continues significantly beyond 1000 ms, reaching the highest failure rates at the maximum tested TTT value of 2000 ms.

Higher hysteresis values generally result in an increased number of handover failures, particularly in the medium-to-high TTT range. The 4.0 dB hysteresis configuration consistently recorded the highest number of failures across most points, while the 1.0 dB setting achieved relatively better performance. It is noteworthy that the performance difference among the various hysteresis values narrows considerably at very high TTT values (1250–2000 ms), where the curves nearly converge.

Overall, the figure highlights that **Time-to-Trigger (TTT)** exerts a significantly stronger and more dominant influence on handover failure rates compared to the hysteresis parameter within the evaluated range.

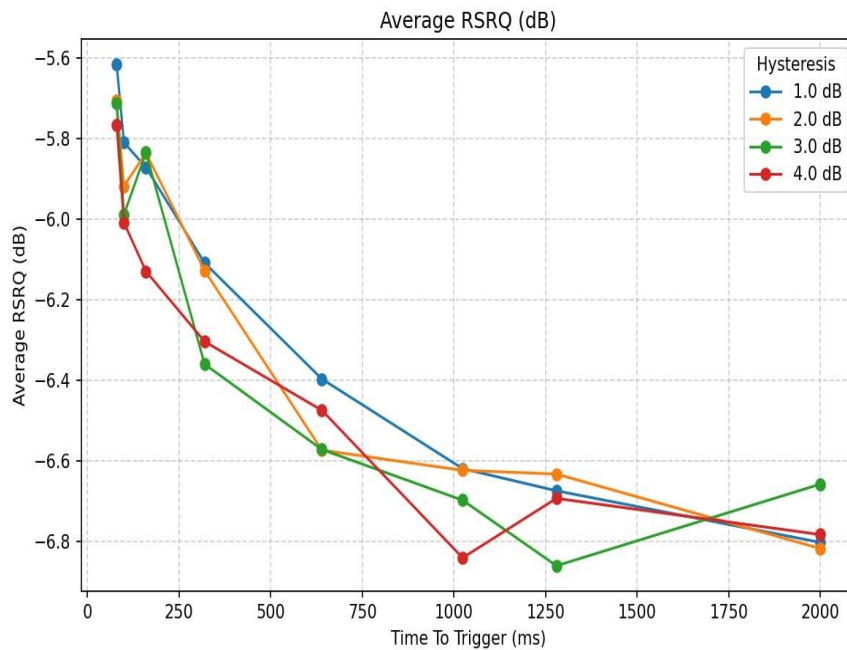


Figure IV.8: Average number of RSRQ (dB)

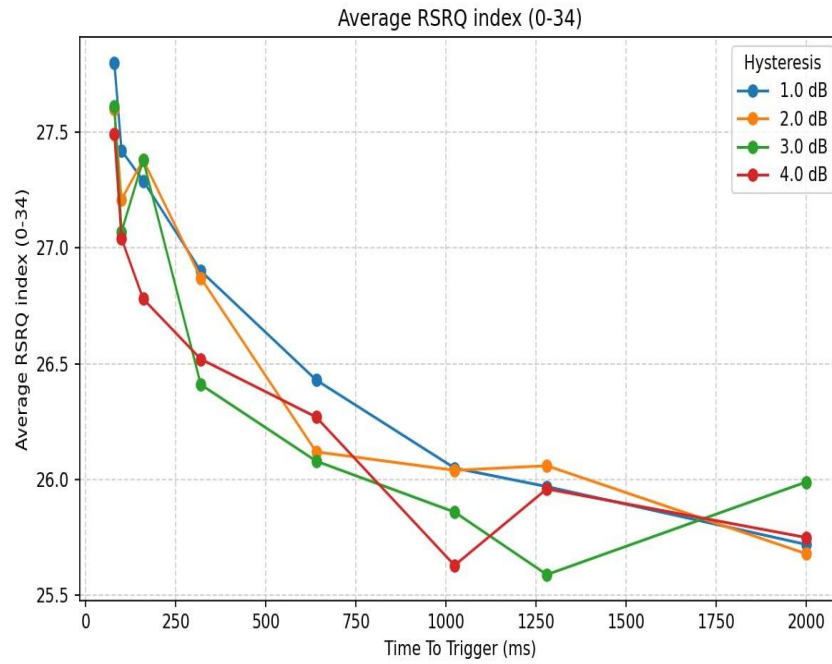


Figure IV.9: Average RSRQ index (0- 34)

The figures IV.8 and IV.9 illustrate the impact of Time-to-Trigger (TTT) and hysteresis on RSRQ, showing a consistent decrease in average RSRQ as TTT increases. At low TTT values (80–250 ms), the average RSRQ reaches its best levels. As TTT increases, the average RSRQ begins to decline gradually, with a sharper drop observed after 250 ms. This decline continues until it reaches its lowest values at high TTT settings, particularly after 1000 ms. The curves also exhibit significant convergence at the highest TTT values (1750–2000 ms). Regarding hysteresis, lower values (especially 1.0 dB) maintain better average RSRQ in the mid-range, while higher values (3.0 and 4.0 dB) result in worse average RSRQ.

The degradation of average RSRQ with increasing Time-to-Trigger (TTT) is a deterministic consequence of the handover delay inherent to the A3 event mechanism. During the TTT interval, the UE remains attached to a deteriorating serving cell while the handover condition is already satisfied. This delay allows the serving cell's signal quality to decline further before handover execution, resulting in systematically lower recorded RSRQ samples. Higher hysteresis requires the neighboring cell to be sufficiently stronger than the serving cell before handover is considered, delaying the initial satisfaction of the A3 condition. At sufficiently long TTT values (≥ 640 ms in this scenario), the serving cell RSRQ may fall below the Radio Link Failure threshold before handover completes, triggering Handover Failures and further degrading average RSRQ due to recovery procedures.

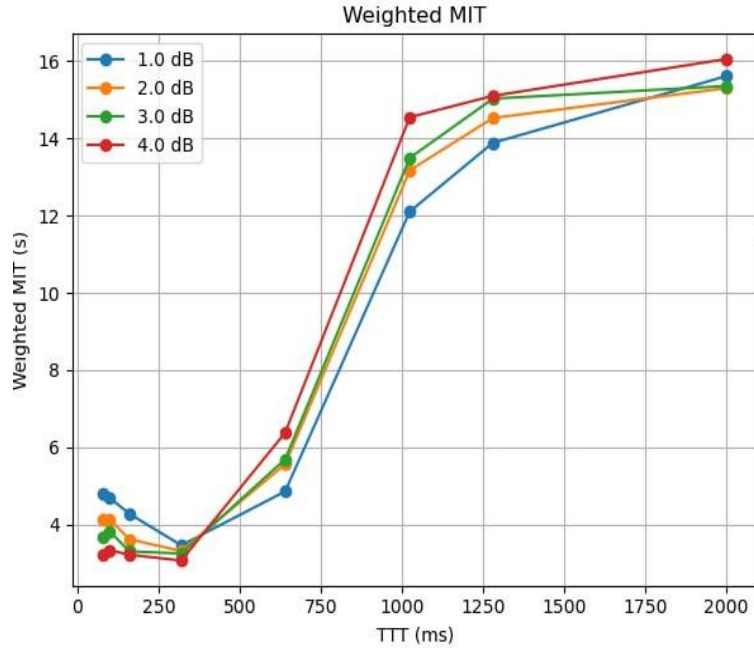


Figure IV.10: Average Weighted MIT

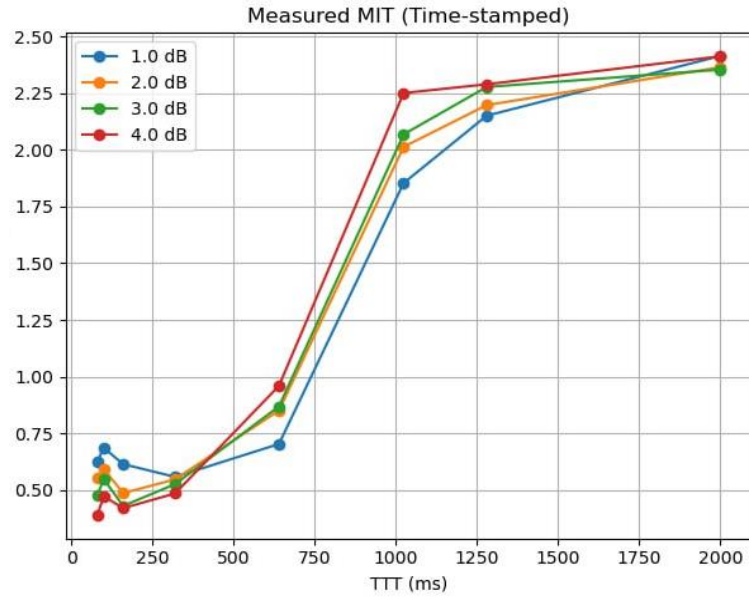


Figure IV.11: Average Measured MIT (Time-stamped)

The figures IV.10 and IV.11 illustrate the methodology and results of the Mobility Interruption Time (MIT) calculation used in this study. The weighted MIT defined by the following equation:

$$MIT_{Weighted} = N_{HO} \times 0.06 \text{ s} + N_{HOF} \times 1.0 \text{ s} \quad (IV.3)$$

Where, N_{Ho} is the total number of handovers and N_{HOFs} is the total number of handover Failures (Too Late + Too Early).

Meanwhile, the actual Mobility Interruption Time (MIT) measured from the ns-3 simulator is calculated as follows:

$$MIT_{measured} = \sum_{Handovers} (t_{end} - t_{start}) + \sum_{HOFs} (t_{reconnect} - t_{RLF}) \quad (IV.4)$$

Where, $t_{end} - t_{start}$ represents the interruption duration associated with successful handovers, and $t_{reconnect} - t_{RLF}$ represents the recovery duration associated with handover failures, measured from the Radio Link Failure (RLF) event until reconnection.

The weighted MIT provides a standardized comparison framework based on fixed upper-bound estimates, while the measured MIT validates the underlying assumptions. Both metrics exhibit consistent trends, confirming the realism of the proposed weighting approach, as shown in the figures.

MIT values remain relatively low and stable at small Time-to-Trigger values (80–320 ms). However, as TTT increases beyond 500 ms, a sharp rise in MIT is observed for all hysteresis configurations. This increase continues significantly, reaching the highest values at TTT = 2000 ms.

It is also noted that higher hysteresis values (particularly 4.0 dB) generally result in higher MIT compared to lower values (1.0 dB), especially in the medium-to-high TTT range. The behavior is consistent between the weighted and measured MIT graphs, which validates the proposed formula in the thesis.

This analysis highlights that extending the Time-to-Trigger (TTT) significantly increases the overall time cost associated with handover operations. This rise is mainly due to the increased number of handover failures and the delay in handover execution.

IV.5.2 Optimal parameter configuration

The evaluation of the quantized RSRQ-based handover algorithm under varying Time-to-Trigger (TTT) and hysteresis values highlights the necessity of precise parameter tuning to balance handover efficiency, mobility stability, and signal quality. In accordance with 3GPP specifications for event A3-based handover, the TTT parameter serves as a temporal filter to suppress short-term fluctuations, while hysteresis enforces a minimum signal quality margin between serving and target cells. Their joint adjustment directly influences the trade-off between minimizing unnecessary handovers and avoiding late or failed handover events.

Simulation results indicate that low TTT values (80–100 ms) combined with small hysteresis margins lead to frequent handover triggering and increased ping-pong behavior. While these configurations

maintain relatively strong RSRQ levels, they incur higher signaling load and reduced mobility stability. In contrast, large TTT values (≥ 640 ms) significantly delay handover execution, resulting in increased mobility interruption time (MIT) and a higher incidence of late handovers. At higher values (≥ 1024 ms), degradation in handover performance becomes more pronounced, with increased failure events and reduced RSRQ stability.

Table IV.2: Comparative Performance Metrics for Selected TTT–Hysteresis Configurations

Configuration (TTT, Hys)	Mean HO Count	Mean Ping- Pong	Mean Too Late HO	Mean HOF	Avg. RSRQ (dB)	Avg. RSRQ Index	Measured MIT (s)
80 ms, 1 dB	70.8	18.0	0.6	0.6	- 5.62	27.8	0.624
100 ms, 3 dB	52.5	9.1	0.6	0.7	- 5.99	27.07	0.548
160 ms, 2 dB	50.3	9.1	0.6	0.6	- 5.84	27.38	0.486
320 ms, 3 dB	37.2	5.0	0.7	1.0	- 6.36	26.41	0.526
640 ms, 2 dB	20.9	1.0	4.1	4.3	- 6.57	26.12	0.851
1024 ms, 4 dB	2.6	0.0	14.4	14.4	- 6.84	25.63	2.25

For high-mobility environments, the configuration TTT = 160 ms, Hysteresis = 2 dB provides the most suitable setting for the RSRQ-based handover algorithm. This parameter set enables fast adaptation to rapidly varying signal conditions, reducing the likelihood of late handovers while maintaining stable RSRQ levels (≈ -5.8 dB). The measured Mobility Interruption Time remains low (≈ 0.49 s), which is essential for preserving service continuity during frequent cell transitions. These results confirm that the 160 ms / 2 dB configuration offers an effective trade-off between responsiveness, signal quality, and mobility stability, making it particularly well-suited for vehicular and other high-speed mobility scenarios in heterogeneous LTE deployments. In this case study, the evaluated parameter settings represent robust configurations for heterogeneous LTE networks, achieving a balance between efficiency, stability, and quality in line with 3GPP mobility management principles.

As summarized in Table IV.5.2, the comparative analysis confirms that the configuration (160 ms, 2 dB) represents an optimal trade-off between handover efficiency, mobility interruption, and signal quality.

IV.5.3 Cost Function for Optimal Handover Parameter Selection

● Normalization

To ensure each KPI contributes proportionally to the cost function, raw values are normalized using the maximum observed values from the simulation dataset:

Metric	Maximum Value	Parameter Configuration
<i>HO</i>	70.8	TTT=80 ms, Hyst=1 dB
<i>PP</i>	18.0	TTT=80 ms, Hyst=1 dB
<i>HOF</i>	16.1	TTT=2000 ms, Hyst=4 dB
<i>MIT</i>	2.412573	TTT=2000 ms, Hyst=4 dB
<i>RSRQ Index</i>	27.8	TTT=80 ms, Hyst=1 dB
<i>RSRQ Index</i>	25.63	TTT=1024 ms, Hyst=4 dB

● Weighted Cost Function

For urban vehicular mobility scenarios (≤ 50 km/h), the following weights are applied:

$$HO_{norm} = 0.18$$

$$PP_{norm} = 0.15$$

$$HOF_{norm} = 0.32$$

$$MIT_{norm} = 0.25$$

$$RSRQ_{norm} = -0.10$$

● Normalization Formulas

$$HO_{norm} = \frac{HO}{70.8} \quad (IV.5)$$

$$PP_{norm} = \frac{PP}{18.0} \quad (IV.6)$$

$$HOF_{norm} = \frac{HOF}{16.1} \quad (IV.7)$$

$$MIT_{norm} = \frac{MIT}{2.412573} \quad (IV.8)$$

$$RSRQ_{norm} = \frac{RSRQ_{idx} - RSRQ_{min}}{RSRQ_{max} - RSRQ_{min}} \quad (IV.9)$$

● The cost function is defined as

$$C = 0.18 \cdot \frac{HO}{70.8} + 0.15 \cdot \frac{PP}{18.0} + 0.32 \cdot \frac{HOF}{16.1} + 0.25 \cdot \frac{MIT}{2.412573} - 0.10 \cdot RSRQ_{norm} \quad (IV.10)$$

Table IV.3 presents the ranking of all evaluated TTT and Hysteresis configurations based on the proposed weighted cost function. The lowest cost value indicates the optimal trade-off among the five KPIs. As shown below.

Table IV.3: Cost Function Ranking of TTT and Hysteresis Configurations

Rank	TTT (ms)	Hyst (dB)	HO	PP	HOF	MIT (s)	RSRQ_idx	Cost
1	160	3	42.6	6.2	0.8	0.430	27.38	0.1319
2	160	2	50.3	9.1	0.6	0.486	27.38	0.1341
3	160	4	37.6	5.0	1.0	0.420	26.78	0.1356
4	80	4	43.8	6.2	0.6	0.388	27.49	0.1368
5	320	4	29.8	3.0	1.3	0.485	26.52	0.1402
6	80	3	50.4	8.8	0.6	0.475	27.61	0.1495
7	320	3	37.2	5.0	1.0	0.526	26.41	0.1555
8	100	4	44.1	6.6	0.7	0.472	27.04	0.1577
9	320	2	42.1	6.8	0.8	0.547	26.87	0.1640
10	80	2	60.0	12.0	0.5	0.553	27.60	0.1795

The configuration with TTT=160 ms and hysteresis = 3 dB and 4 dB achieves the best trade-off for urban vehicular mobility scenarios. The selected TTT value is sufficiently large to suppress short-term signal fluctuations caused by shadowing and fast fading, thereby reducing unnecessary handovers and ping-pong effects. Simultaneously, it remains short enough to prevent excessive handover delays that may lead to radio link failures (RLFs), which become more significant when the TTT parameter increases to 640 ms or higher. Consequently, configurations within the 160 ms TTT category consistently achieve the highest rankings in the overall cost-function evaluation.

This behavior is consistent with mobility optimization principles defined in 3rd Generation Partnership Project LTE/5G mobility management studies, where moderate TTT values are preferred in low-to-medium vehicular mobility environments because they provide a balance between handover stability and responsiveness.

IV.6 Conclusion

In this chapter, the results and analyses of the RSRQ-based handover algorithm in a heterogeneous LTE environment were presented. The findings demonstrate the significant impact of Time-to-Trigger and Hysteresis on all performance metrics. Increasing these parameters reduced the total number of handovers and ping-pong events, but at the cost of higher handover failure rates, degraded RSRQ, and longer mobility interruption times.

A weighted cost function was proposed. The optimal configuration for dense urban vehicular mobility (≤ 50 km/h) is TTT = 160 ms with Hysteresis = 3 dB. These results confirm the fundamental trade-off inherent in handover mechanisms and highlight the importance of precise parameter tuning for mobility optimization in dense urban LTE deployments.



Conclusion



Conclusion

In this work, we have studied and evaluated the performance of a quantized RSRQ-based handover algorithm in heterogeneous LTE networks. Using the ns-3 simulator coupled with the SUMO mobility generator, we designed a realistic urban scenario inspired by the city of M'sila (Algeria), consisting of one central tri-sector macro cell and eighteen irregularly distributed micro cells. The main objective was to analyze the impact of the key control parameters, namely Time-to-Trigger (TTT) and hysteresis, on the major performance indicators of the handover process.

In the first chapter, we presented a detailed state of the art on LTE cellular networks, mobility management, and existing handover algorithms.

The second chapter was dedicated to an in-depth study of handover mechanisms in LTE, decision criteria (RSRP, RSRQ, SINR), measurement events, as well as control parameters and their effects on network performance.

In the third chapter, we described the simulation tools used (ns-3 and SUMO), their architecture, features, and the integration method between the two simulators.

The fourth chapter focused on the implementation of the simulation scenario, the quantized RSRQ-based handover algorithm, and the detailed analysis of the results according to various combinations of TTT and hysteresis values.

The obtained results highlighted the fundamental trade-off in handover parameter configuration: while increasing TTT and hysteresis values significantly reduces the number of handovers and the ping-pong effect, it leads to higher handover failure rates, degraded signal quality, and increased Mobility Interruption Time. These findings confirm the effectiveness of the quantized RSRQ-based approach in dense urban environments.

As perspectives for future work, we propose to implement and compare intelligent handover algorithms based on Artificial Intelligence (Machine Learning and Deep Learning), to integrate cell load balancing, or to extend this study to 5G NR networks. Furthermore, the realization of a real testbed would allow the validation of simulation results under real conditions.

These directions and others can form promising research axes in the field of mobility management in next-generation mobile networks.



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Abstract

Long Term Evolution (LTE) networks require efficient handover mechanisms to ensure seamless connectivity and service continuity for mobile users. This work presents the implementation and evaluation of handover algorithms in heterogeneous LTE networks using the ns-3 network simulator coupled with realistic mobility traces generated by SUMO. The study focuses on the impact of key handover control parameters, namely Hysteresis and Time-to-Trigger (TTT), on network performance. A simulation scenario based on the M'sila University Pole area was analyzed using performance metrics such as handover failure, ping-pong effect, RSRQ, and Mobility Interruption Time (MIT). The obtained results show that proper parameter tuning can improve mobility performance and reduce unnecessary handovers. In addition, a cost function approach was proposed to determine the optimal handover parameter configuration for the studied LTE environment.

Key words: Mobility managements, Handover algorithms, LTE, NS-3 simulator

ملخص

تتطلب شبكات الجيل الرابع LTE اليات تسليم Handover فعالة لضمان استمرارية الاتصال وجودة الخدمة أثناء تنقل المستخدمين بين الخلايا. يهدف هذا العمل إلى دراسة وتنفيذ خوارزميات التسليم في شبكات LTE غير المتجانسة باستخدام محاكي الشبكات ns-3 مع دمج بمحاكي الحركة SUMO لتوليد مسارات تنقل واقعية. ركزت الدراسة على تأثير أهم معاملات التحكم في التسليم، والمتمثلة في الهسترة (Hysteresis) وزمن التفعيل (TTT)، على أداء الشبكة. تم إجراء محاكاة اعتمادًا على منطقة القطب الجامعي بولاية المسيلة، مع تحليل مؤشرات الأداء مثل فشل التسليم، وتأثير Ping-Pong، وجودة الإشارة RSRQ، وزمن انقطاع الاتصال MIT أظهرت النتائج أن الضبط المناسب لمعاملات التسليم يساهم في تحسين أداء التنقل وتقليل عمليات التسليم غير الضرورية. كما تم اقتراح دالة كلفة لاختيار أفضل إعدادات لمعاملات التسليم في بيئة LTE المدروسة.

الكلمات المفتاحية: إدارة التنقل، خوارزميات التسليم، الجيل الرابع LTE، محاكي

NS-3