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THEME

Planning and Optimization of 5G-Based Massive MIMO in Mobile Radio Networks

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ملخص

تتناول هذه الأطروحة موضوع **تصميم وهندسة شبكات الهاتف المحمول من الجيل الخامس (5G)** باستخدام تقنية **Massive MIMO**وتستعرض تطور شبكات الاتصالات من الجيل الثاني (2G) إلى الجيل الخامس(5G) ، مع تحليل لمبادئ عمل تقنيةMassive MIMO ، ومناقشة لأدوات التصميم مثل برنامج **Atoll**المستخدم في التنبؤ بالتغطية اللاسلكية.

يشمل المشروع **محاكاة عملية** في مناطق حضرية جزائرية، ويعتمد على منصة **iManager MAE من هواوي** لتقييم مؤشرات الأداء الرئيسية (**KPIs**) مثل التغطية، وسرعة النفاذ، وعمليات التسليم بين الخلايا .(**Handovers**) ومن خلال دمج تقنيات **تشكيل الحزم الذكي (Beamforming)** ونشر الخلايا الصغيرة(**Small Cells**) ، يهدف هذا العمل إلى **تعزيز سعة الشبكة وأدائها**.

تسلّط الدراسة الضوء على التحديات الواقعية التي تواجه مهندسي الشبكات، وتقترح حلولاً قابلة للتوسّع لتحسين **بنية الاتصالات المتنقلة للجيل القادم**.

الكلمات المفتاحية :الجيل الخامس، Massive MIMO، تصميم الشبكات، Beamforming، الخلايا الصغيرة، Atoll، iManager MAE، مؤشرات الأداء، الجزائر، تغطية الشبكة، تسليم المكالمات، سعة الشبكة.

ABSTRACT

This thesis addresses the design and engineering of fifth-generation (5G) mobile networks using Massive MIMO technology. It reviews the evolution of communication networks from the second generation (2G) to 5G, with an analysis of the operating principles of Massive MIMO and a discussion of design tools such as the Atoll software used for wireless coverage prediction.

The project includes a practical simulation in Algerian urban areas and relies on Huawei's iManager MAE platform to evaluate key performance indicators (KPIs) such as coverage, access speed, and handovers between cells. By integrating technologies like smart beamforming and the deployment of small cells, the work aims to enhance the capacity and performance of the network.

The study highlights the real-world challenges faced by network engineers and proposes scalable solutions to improve the architecture of next-generation mobile communications.

Keywords :5G, Massive MIMO, Network Design, Beamforming, Small Cells, Atoll, iManager MAE, Key Performance Indicators (KPIs), Algeria, Network Coverage, Call Handover, Network Capacity.

RÉSUMÉ

Ce mémoire traite de la conception et de l'ingénierie des réseaux mobiles de cinquième génération (5G) en utilisant la technologie Massive MIMO. Il retrace l'évolution des réseaux de télécommunications du deuxième (2G) au 5G, en analysant les principes de fonctionnement de la technologie Massive MIMO, et en abordant les outils de conception tels que le logiciel Atoll, utilisé pour la prévision de la couverture sans fil.

Le projet inclut une simulation pratique dans des zones urbaines en Algérie, et s'appuie sur la plateforme iManager MAE de Huawei pour évaluer les indicateurs clés de performance (KPI), tels que la couverture, la vitesse d'accès et les handover (transferts entre cellules). En intégrant des technologies comme la formation de faisceaux intelligente (Beamforming) et le déploiement de petites cellules (Small Cells), ce travail vise à améliorer la capacité et la performance du réseau.

L'étude met en lumière les défis réels auxquels sont confrontés les ingénieurs réseau, et propose des solutions évolutives pour améliorer l'architecture des communications mobiles de prochaine génération.

Mots-clés :5G, Massive MIMO, Conception de réseaux, Formation de faisceaux (Beamforming), Petites cellules, Atoll, iManager MAE, Indicateurs clés de performance (KPI), Algérie, Couverture réseau, Handover (transfert d'appel), Capacité du réseau.

DEDICATION

All praise and thanks are due to Allah, the Source of knowledge and guidance, whose mercy granted us the strength to complete this work.

We humbly dedicate this work:

To our mothers,
whose unwavering love, endless patience, and heartfelt prayers have always been our greatest source of strength. Your presence is a blessing that gives meaning to every success.

To our fathers,
true examples of perseverance, dignity, and discipline. Your belief in hard work and values shaped our paths and inspired us never to settle for less than our best.

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significant depth and realism to this work. We also appreciate the high level of professionalism and collaboration shown throughout.

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With all our gratitude,
Mohamed Anis and **Mohcin Adlane**

TABLE OF CONTENTS

Abstract **i**

Acknowledgment **iv**

Dedication **iv**

Table of contents **ix**

List of Figures **xii**

List of tables **xiii**

Abbreviations list **xiv**

I General Introduction **1**

I.1 General Introduction 1

II Evolution of mobile network **3**

II.1 Introduction 3

II.2 The second generation of Mobile phone 4

II.2.1 GSM network subsystems 4

II.2.2 global system for mobile (GSM) network interfaces 5

II.2.3 GSM with packet switch capability 5

II.2.4 Access modes 6

II.2.5 Channels in second generation (2G) 6

II.2.6 Antenna type of 2G 7

II.3 The third generation of mobile phones 8

II.3.1 Architecture of third generation (3G) 9

II.3.2 Antenna types in 3G networks 11

II.4 The fourth generation of mobile phones . . . 14
II.4.1 Fourth Generation Presentation . . . 14
II.4.2 Architecture of fourth generation (4G) . . . 14
II.4.3 LTE network architecture overview . . . 15
II.4.4 LTE Network Interfaces . . . 15
II.4.5 Techniques and characteristics of long term evolution (LTE) technology . . . 16
II.4.6 LTE Frequency bands . . . 16
II.5 LTE-Advanced . . . 17
II.5.1 Principal features . . . 17
II.5.2 Key technologies . . . 17
II.5.3 Applications and benefits . . . 18
II.6 The Fifth Generation . . . 18
II.6.1 The 5G network architecture . . . 19
II.6.1.1 User equipment . . . 19
II.6.1.2 The radio access network . . . 19
II.6.1.3 The core network of 5G . . . 20
II.6.2 Antenna Type of 5G . . . 22
II.6.3 Protocol layers of the 5G access stratum . . . 22
II.6.3.1 Radio resource control . . . 22
II.6.3.2 Packet data convergence protocol . . . 25
II.6.3.3 Radio link control . . . 25
II.6.3.4 Medium Access Control . . . 25
II.6.4 Physical channels . . . 25
II.7 Conclusion . . . 26

III Massive MIMO for 5G Radio Network Performance 28
III.1 Introduction . . . 28
III.2 Evolution of antennas in 4G . . . 29
III.3 From MIMO to massive MIMO . . . 30
III.3.1 Principle of Massive MIMO . . . 30
III.3.2 Functioning of Massive MIMO . . . 31
III.3.3 General characteristics of Massive multiple input multiple output (MIMO) systems . . . 32
III.3.3.1 Time diversity . . . 33
III.3.3.2 Spatial diversity . . . 33
III.3.3.3 Space-time diversity . . . 33
III.3.3.4 Spatial multiplexing . . . 33
III.3.3.5 Small cells . . . 33

III.3.3.6 Millimeter waves . . . 35
III.3.4 Beamforming and massive MIMO . . . 35
III.3.4.1 Digital beamforming . . . 36
III.3.4.2 Analog beamforming . . . 36
III.3.4.3 Hybrid beamforming . . . 37
III.4 Channel estimation . . . 38
III.5 Linear pre-coding techniques . . . 41
III.6 Key Benefits of Massive MIMO . . . 43
III.7 Future directions and challenges in Massive MIMO . . . 43
III.7.1 Future Directions . . . 44
III.7.2 Research Challenges . . . 44
III.8 Conclusion . . . 45

IV Planning and optimization in 5G network 46
IV.1 Introduction . . . 46
IV.2 5G Network planning coverage and capacity . . . 46
IV.2.1 Coverage planning . . . 47
IV.2.2 Capacity planning . . . 47
IV.2.3 Radio propagation models . . . 48
IV.2.4 Link budget . . . 49
IV.2.5 Radio parameters configuration . . . 51
IV.2.5.1 NR PCI planning . . . 51
IV.2.5.2 physical cell ID (PCI) planning in 5G new radio (5GNR) . . . 52
IV.2.5.3 Avoiding PCI confusion . . . 53
IV.2.5.4 The performance of the random access channel . . . 54
IV.2.5.5 5GNR network relationship – neighbor planning . . . 55
IV.3 5G Network optimization . . . 56
IV.3.1 5GNR radio access network (RAN) key performance indicator (KPI)s . . . 56
IV.3.1.1 Accessibility KPIs . . . 56
IV.3.1.2 Retainability KPIs . . . 58
IV.3.1.3 Mobility KPIs . . . 59
IV.3.1.4 Availability KPIs . . . 61
IV.3.2 Drive Testing in mobile networks . . . 61
IV.3.2.1 Types of drive test (DT) . . . 62
IV.3.2.2 DT parameters . . . 62
IV.3.2.3 The importance of DT . . . 66
IV.4 Conclusion . . . 67

V Planning and Optimization: Application and Results 68
V.1 Application in planning in 5G network 68
V.1.1 Atoll Software 68
V.1.2 Creation of project 68
V.1.3 General configuration parameters 70
V.1.4 Propagation model used 72
V.1.5 Traffic parameters 72
V.1.6 Predictions and simulations 75
V.1.7 Network deployment and Optimization Scenarios 76
V.1.7.1 Upgrade from 4G to fifth generation (5G) network 77
V.1.7.2 Cells deployment and scenarios 80
V.1.7.3 Simulation Results 90
V.2 Application in optimization in 5G network 91
V.2.1 iMANAGER MAE platforme interface 91
V.2.1.1 KPI Analysis 92
V.2.1.2 MAE capacity visibility 92
V.2.1.3 Monitoring and KPI insight 94
V.2.2 Case Study: LTE Accessibility Analysis 95
V.2.2.1 Accessibility Issue Observed Under High Load 95
V.2.2.2 Retainability Analysis 96
V.2.2.3 Handover Success Rate Analysis 97
V.2.3 Conclusion 99

VI general conclusion 100
VI.1 General Conclusion 100

LIST OF FIGURES

II.1 Cellular network evolution. 4
II.2 General architecture of GSM. 5
II.3 Sector antennas. 7
II.4 General architecture of universal mobile telecommunications system (UMTS) network. 9
II.5 NodeB with sector antennas. 10
II.6 Sector antennas used in 3G networks. 12
II.7 Omnidirectional antenna configuration. 12
II.8 Panel antennas used in 3G and 3G+ networks. 13
II.9 General architecture of a 4G LTE network. 15
II.10 Channel 5G network architecture. 19
II.11 Architecture of the radio access network 5G. 20
II.12 Architecture of the 5G core network (5GCN). 21
II.13 Massive MIMO antenna used in 5G base stations. 22
II.14 Plane Protocol Stack. 23
II.15 5G RRC states. 24

III.1 Propagation models for different antenna configurations: (a) single input single output (SISO), (b) single input multiple output (SIMO), (c) multiple input single output (MISO), and (d) MIMO. 29
III.2 llustration of the evolution from conventional 4G antenna systems to 5G Massive MIMO beamforming. 32
III.3 D-BLAST system. 34
III.4 Heterogeneous network consisting of a macro cell and several small cells to ease data traffic of the macro cell. 34
III.5 Beamforming: directional signal transmission in 5G Massive MIMO Systems. 35
III.6 digital beamforming (DBF) Beamforming. 36

III.7 analog beamforming (ABF) principle. 37
III.8 Hybrid beamforming. 38
III.9 Time slot with channel estimation for frequency division duplexing (FDD) and time division duplexing (TDD) systems. 39
III.10CSI-RS transmission and feedback mechanism in a MIMO system. 40

IV.1 System Gain-Loss Profile for a Link Budget. 50
IV.2 PCI generation and distribution concept. 52
IV.3 PCI planning example illustrating collision risks. 53
IV.4 Example of PCI confusion due to neighboring cells using the same PCI. 53
IV.5 NR-PRACH procedure. 55
IV.6 Key connection setup success rates during LTE drive test: (a) radio resource control (RRC) setup success rate (service), (b) evolved radio access bearer (ERAB) setup success rate (all). 57
IV.7 Service Drop Rate (All) [5]. 58
IV.8 KPIs mobility flow. 59
IV.9 Intra-frequency handover out success rate. 60
IV.10 Inter-RAT Handover Out Success Rate. 61
IV.11 Plots of key downlink radio measurements observed during LTE drive testing: (a) reference signal received power (RSRP), (b) reference signal received quality (RSRQ), (c) SINR, (d) received signal strength indicator (RSSI), and (e) channel quality indicator (CQI) [61]. 63
IV.12 Distribution of serving cell DL E-utra absolute radio frequency channel number (EARFCN)s by percentage. 66

V.1 Illustrations of project templates and coordinate systems. 69
V.2 New transmitter's general tab 71
V.3 Okumura-Hata propagation. 73
V.5 General tab of a new user. 73
V.4 5GNR tab of a new service. 74
V.6 Dense urban environment. 74
V.7 Traffic map in Alger Centre. 75
V.8 Clutter classes model. 77
V.9 Broadband and Internet service configurations in LTE and 5GNR networks 78
V.10 Video and voice call configuration properties. 79
V.11 Advanced user profile. 79
V.12 Standard user profile. 80
V.13 Different environment types modeled in the radio network planning: (a) Dense Urban Area, (b) Rural Area, (c) Suburban Area, and (d) Urban Area. 81
V.14 Downlink coverage prediction with LTE transmitters. 83

V.15 Downlink Coverage prediction with 5G transmitters. 84
V.16 small cell deployments LTE 85
V.17 LTE DL Coverage Before and After Optimization. 86
V.18 5G DL Coverage. 87
V.19 Various maps for La Grande Poste zone analysis. 88
V.20 Various maps for university of Algiers zone analysis. 89
V.21 5G DL quality before and after optimization. 89
V.22 Coverage map showing LTE and 5G NR deployment with macro and small cells in central Algiers. 90
V.23 iMANAGER MAE platform interface. 92
V.24 KPI Analysis interface description. 93
V.25 KPI Results Display Panel Interface. 93
V.26 huawei imanager mae (MAE) Capacity visibility interface. 93
V.27 Real time KPI monitoring interface. 94
V.28 KPI insight for performance monitoring. 94
V.29 Accessibility degradation in high load conditions. 95
V.30 Accessibility improvement after `qRxLevMin` tuning. 96
V.31 ERAB drop rate root cause. 97
V.32 Intra-frequency handover failure visualization. 98
V.33 Target cell radio deaf detection. 98

LIST OF TABLES

II.1 GSM network interfaces and their functions 5
II.2 GSM Band Frequency Allocations 8
II.3 Antenna types, supported bands, and usage remarks. 13
II.4 LTE Network Interfaces, Connections, and Functions. 16
II.5 Essential LTE Bands in MHz. 17
II.6 Comparison between 4G (LTE) and 4G+ (LTE-Advanced) 18
II.7 Physical channels in 5G mobile networks 26

III.1 Comparison between traditional MIMO and Massive MIMO 31

IV.1 5G network planning considerations 47
IV.2 5G Network Enhancement Techniques 48
IV.3 Link budget parameters. 50
IV.4 Peak DL speeds. 65
IV.5 Peak UL speeds 65

V.1 LTE Cell Parameters Configuration 82
V.2 5GNR cell configuration: PCI and physical random access channel (PRACH) allocation 83
V.3 Small Cell Configuration: PCI and PRACH Allocation 85
V.4 Comparison between demand and simulation results (Mbps) 90

ABBREVIATIONS LIST

2G second generation

3G third generation

4G fourth generation

5G fifth generation

5GCN 5G core network

5GNR 5G new radio

ABF analog beamforming

BLER block error rate

BSC base station controller

BTS base transceiver station

CDMA code-division multiple access

CN core network

CQI channel quality indicator

CSI channel state information

DBF digital beamforming

DL downlink

DMA direct memory access

DMRS demodulation reference signal

DT drive test

EARFCN e-utra absolute radio frequency channel number

EDGE enhanced data rates for GSM evolution

ERAB evolved radio access bearer

E-UTRAN evolved universal terrestrial radio access network

FDD frequency division duplexing

FDMA frequency division multiple access

GPRS general packet radio service

GSM global system for mobile

HSDPA high-speed downlink packet access

HSUPA high-speed uplink packet access

KPI key performance indicator

LTE long term evolution

MAC medium access control

MAE huawei imanager mae

MIMO multiple input multiple output

MISO multiple input single output

ML machine learning

MMSE minimum mean square error

MS mobile station

NSS network switching subsystem

OFDM orthogonal frequency division multiplexing

PCI physical cell ID

PDCP packet data convergence protocol

PDCP packet data convergence protocol

PRACH physical random access channel

PSS primary synchronization signal

QAM quadrature amplitude modulation

QoS quality of service

RACH random access channel

RAN radio access network

RF radio frequency

RLC radio link control

RNC radio network controller

RRC radio resource control

RSRP reference signal received power

RSRQ reference signal received quality

RSS radio subsystem

RSSI received signal strength indicator

SIMO single input multiple output

SINR signal to interference plus noise ratio

SISO single input single output

SMS short message service

SVD singular value decomposition

TAC tracking area code

TDD time division duplexing

TDMA time division multiple access

UE user equipment

UMTS universal mobile telecommunications system

UTRAN universal terrestrial radio access network

CHAPTER I

GENERAL INTRODUCTION

I.1 General Introduction

In the rapidly evolving world of telecommunications, the transition from legacy systems such as 2G and 3G to advanced paradigms like 5G represents not merely a generational shift but a transformative leap in the way wireless systems are conceptualized, designed, and optimized. This project emerges as a direct response to the growing complexity of mobile radio networks and the increasing demand for ultra-reliable, low-latency, and high-capacity communications in modern urban environments. The core of this research revolves around the planning and optimization of a 5G mobile network architecture grounded on Massive MIMO (Multiple Input Multiple Output) technology, with practical deployment scenarios conducted in partnership with the national operator Mobilis and Huawei's engineering support. The objective is to develop an integrated, performance-driven model that combines theoretical advancements with real-world engineering practices, supported by the deployment of tools such as Atoll for radio network planning and Huawei iManager MAE for performance monitoring and KPI-based analysis.

Massive MIMO is positioned as a cornerstone of 5G radio access networks (RAN), enabling high spectral efficiency through spatial multiplexing and beamforming techniques. By equipping base stations with a high number of antenna elements, this technology allows the simultaneous transmission of independent data streams to multiple users, significantly improving throughput, coverage, and system robustness. However, the implementation of such a system is not without its challenges. The increased dimensionality introduces difficulties in channel estimation, inter-cell interference mitigation, and real-time adaptation to varying user mobility profiles and network loads. Thus, the project does not limit itself to idealized models but actively engages with the physical constraints and optimization variables observed in dense Algerian urban areas such as Algiers. By integrating propagation models like Okumura-Hata and applying them to site-specific morphology and clutter classes, the project ensures that radio link budget, signal-to-interference-plus-noise ratio (SINR), and reference signal received power (RSRP) predictions are accurately represented.

A significant portion of the work involves simulating the entire network planning cycle within Atoll: defining eNodeB and gNodeB parameters, selecting appropriate antenna types (e.g., sectorized or Massive MIMO panels), configuring PRACH formats, PCI allocation, and drive-test data interpretation. These simulations are then validated through KPI extraction and real-time monitoring on the iManager MAE platform, which provides a powerful interface for accessibility, retainability, and mobility performance evaluations. Particular attention was given to metrics such as RRC connection setup success rate, ERAB drop rate, and inter-frequency handover success, each of which serves as a critical indicator of network reliability and user experience.

The practical component is further enriched through the study of physical layer aspects such as synchronization signal block (SSB) allocation, PRACH detection performance, and the impact of PCI collision and confusion scenarios on initial access procedures. The research applies 3GPP-compliant planning rules including mod3, mod4, and mod30 constraints to reduce PRACH-related interference and enhance network stability. Additionally, uplink and downlink resource blocks are analyzed for optimal scheduling in urban macro and small cell deployments, addressing the need for coverage-extension strategies via dense cell layering. Beamforming mechanisms—whether analog, digital, or hybrid—are investigated in their ability to dynamically shape radiation patterns and steer energy toward user equipment (UE) with high precision, thereby improving SINR and reducing multi-path fading effects.

The KPI-based optimization approach leveraged within MAE integrates not only statistical indicators but also geo-referenced drive test logs, providing spatial insight into network weak zones. Scenarios involving poor radio conditions, such as low RSRQ or excessive BLER (Block Error Rate), are diagnosed, and corrective actions such as downtilt adjustments, antenna azimuth reconfiguration. Furthermore, advanced KPI correlations are used to identify root causes behind accessibility degradation, retainability instability, and mobility failures. These include issues like radio link failures due to poor uplink quality, delayed handover due to suboptimal neighbor relations, and load balancing anomalies in high-traffic hotspots [1].

CHAPTER II

EVOLUTION OF MOBILE NETWORK

II.1 Introduction

The success of wired networks, along with the need of the users to transcend the limitations of wired connectivity and users' desire for greater freedom, has been a great driving force behind the development of another type of network: mobile networks. Mobile networks provide a great advantage by eliminating the need for cabling and offering users a more dynamic environment. Users are permitted to stay connected to the network while they move within a specified geographical area. The evolution of mobile networks has continued, creating several generations: 2G , 3G, and 4G [2].

Mobile networks are wireless networks in which at least two terminals can communicate without the utilization of wired links. Thanks to this type of network, a user (subscriber) can be connected to the network while moving in a more or less extended geographical area, and that is why we speak about mobility. These networks are based on a radio wave connection and use the radio interface as the transmission medium. The development of the mobile network has occurred in several phases: The 2G network, launched at the end of 90th, is still operational. It signifies the transition from analog to digital. From a usage perspective, 2G suffices for making calls and sending short message service (SMS) , and even multimedia messaging service (MMS). The data rates that are typically found in 2G are 9.6 Kbits/s. This network has undergone three successive upgrades in the form of the GPRS network, also referred to as 2.5G, and the enhanced data rates for GSM evolution (EDGE) network (general packet radio service (GPRS) evolution), also referred to as 2.75G [3].

The 3G network, which operates exclusively on the 900 MHz and 2100 MHz frequency bands, has a data rate of 1.9 Mbits/s. It has also experienced three successive boosts with 3G+ (also named HSPA), H+ (HSPA+), and H+ Dual Carrier (DC-HSPA+). These are UMTS evolutions for the sake of having better data rates: 3.6 Mbits/s for 3G +, 5 Mbits/s for H+, and 10 Mbits/s for H+ Dual Carrier. These enhancements have made it possible to use the Internet more, like being able to stream videos instantly without loading times.

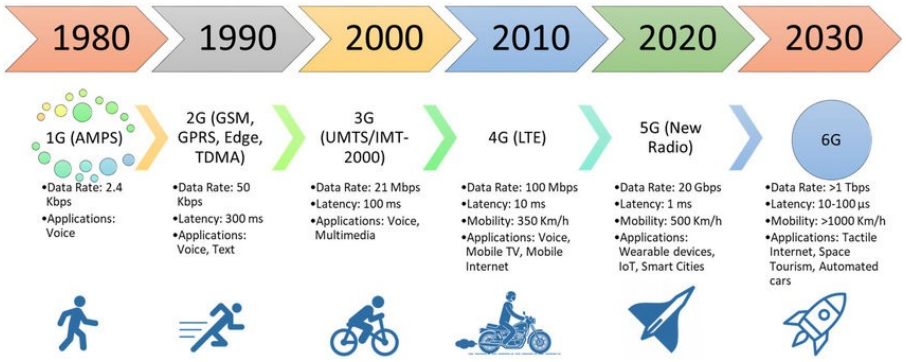


Figure II.1: Cellular network evolution.

LTE, which is popularly known as 4G , provides users with very high-speed internet browsing. Downloading large files, streaming HD videos, live streaming, and much more are possible because of 4G 's high data rates [4]. Figure II.1 summarizes the evolution of cellular network from 2G to 5G the arrival of 5G represents a leap toward ultra-high-speed connectivity, ultra-low latency, and support for massive machine-type communications (mMTC), [5].

II.2 The second generation of Mobile phone

The introduction of digital technology by the 2G, called also of mobile phones marked a significant advancement over the first generation (1G). This change made it possible for data to be transmitted simultaneously with voice. These days, users can share a single transmission channel thanks to mechanisms like frequency division multiple access (FDMA) and time division multiple access (TDMA) [4]. The general diagram of the GSM network architecture is depicted in Figure II.2 [6].

II.2.1 GSM network subsystems

The GSM network is composed of three main subsystems. The radio subsystem (RSS) is responsible for the radio communication between the mobile device and the network, ensuring the transmission and reception of signals over the air interface. The network switching subsystem (NSS) handles essential network functions such as call routing, subscriber mobility management, and overall subscriber data handling. Finally, the operational support system (OSS) plays a crucial role in overseeing, managing, and controlling the entire GSM network, enabling operators to monitor performance and maintain system integrity [7].

The RSS forms the access layer of the GSM network, facilitating wireless communication between users and the core infrastructure. The mobile station (MS) enables end-user access to network services. It communicates wirelessly with the base transceiver station (BTS), which serves as the interface between the user and the GSM infrastructure. Multiple BTSs are coordinated by the base station controller (BSC), which handles functions such as frequency assignment, power control, and seamless mobility across coverage areas [7].

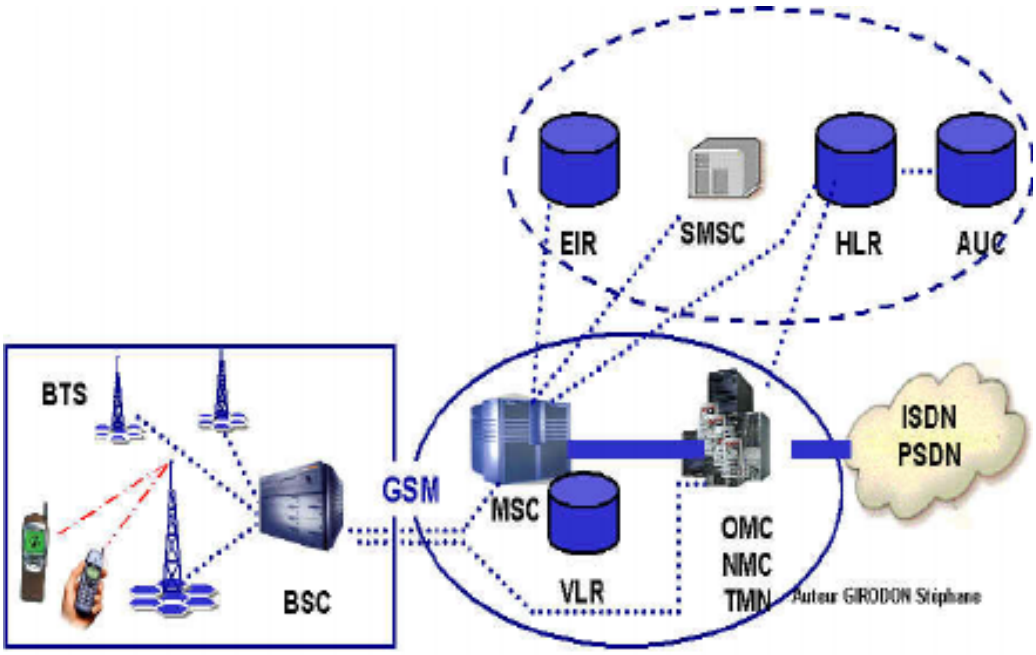


Figure II.2: General architecture of GSM.

II.2.2 GSM network interfaces

Interfaces in the GSM radio subsystem play a vital role in ensuring modularity, interoperability, and efficient communication between different network components. By standardizing the exchange of signaling and traffic data between the MS, BTS, and BSC , these interfaces enable flexible network expansion, simplified maintenance, and vendor-independent integration. This structured connectivity enhances system performance, scalability, and reliability, which are essential for delivering consistent mobile services across diverse geographic areas. Table II.1 outlines the key GSM interfaces that link different network entities for seamless communication [8].

Table II.1: GSM network interfaces and their functions

Interface	**Between**	**Function**
Um	MS ⟷ BTS	Radio interface, wireless communication between the user and the network
Abis	BTS ⟷ BSC	Carries data and signaling between the station and its controller
A	BSC ⟷ MSC	Interface for signaling and traffic between the controller and the switch
MAP	BSC ⟷ HLR/VLR/AUC/EIR	Signaling protocol for subscriber and mobility managemen

II.2.3 GSM with packet switch capability

As new technologies have emerged, the GSM standard has undergone two significant changes [9]:

- GPRS: Is a GSM extension that enables packetized data transport and provides mobile internet

access. This maximizes network efficiency by ensuring that data is transmitted only when needed. Theoretical GPRS bandwidth can reach up to 114 kbps, allowing simultaneous voice and data usage. Its billing, based on data volume rather than connection time, offers users greater flexibility and cost control [9].

- EDGE: Another development of GSM, called EDGE, included the eight-Phase Shift Keying (8-PSK) modulation, enabling the expansion of data capacities. This standard is seen as a step toward 3G and may theoretically achieve speeds of up to 384 kbps for stationary stations and 144 kbps for rapidly moving mobile stations. Even while EDGE offers higher-value debits, its coverage is typically more constrained than it was under earlier standards [9].

II.2.4 Access modes

Methods of access refer to the strategies used to organize and manage communication channels in mobile telecommunications systems, particularly to avoid interference and maximize the efficiency of spectral resources. Here are some of the main axis techniques used in 2G networks [9]:

Time Division Multiple Access(TDMA) and **Frequency Division Multiple Access(FDMA)** are two fundamental access methods used in early generations of mobile communication systems. TDMA enables multiple users to share the same frequency channel by allocating unique time slots to each user, allowing them to transmit or receive data in an organized sequence. This technique, widely used in GSM networks, optimizes spectrum utilization and reduces mutual interference. On the other hand, FDMA divides the available radio spectrum into separate frequency bands, assigning each user a dedicated frequency. While predominantly used in analog systems such as AMPS, FDMA was also integrated into early GSM deployments to manage RF channels efficiently. Together, these techniques laid the groundwork for modern multiple access schemes.

II.2.5 Channels in 2G

In 2G networks, channels are classified based on their specific function, such as voice communication, data transmission, signaling, and network monitoring. These channels are categorized as follows according to their specific functions:

- Common Control Channels (CCCH): It is used for managing communication and include channels for call setup, synchronization, and user mobility management. For instance, the random access channel (RACH) allows a mobile phone to establish a connection with the BTS.

- Broadcast Control Channel (BCCH): Is a downlink-only channel used by the base station to continuously transmit essential system information to all mobile stations within its coverage area. This includes details such as the network identity, location area code, and available frequency channels. The BCCH enables mobiles to identify and select appropriate cells, facilitating network access and handover decisions.

- Traffic Channel (TCH): is responsible for carrying user-specific information, such as voice. Unlike control channels, TCHs are allocated dynamically when a call or data session is initiated

and released once it ends, ensuring efficient use of radio resources. In GSM, separate TCHs exist for full-rate and half-rate transmission, balancing quality and capacity depending on network conditions.

- Standalone Dedicated Control Channel (SDCCH): Is a signaling channel used for transmitting small amounts of data, such as SMS messages and critical control information required during call setup, authentication, location updates, and registration. It operates independently of traffic channels and is essential during the pre-connection phase, ensuring reliable communication between the mobile station and the network before a dedicated traffic channel is assigned [10].

II.2.6 Antenna type of 2G

A sector antenna is widely used in 2G networks to divide the cell area into sectors, usually three 120° sectors or six 60° sectors, each covered by a directional antenna. This improves frequency reuse and reduces interference, which is crucial in the limited frequency spectrum used by GSM. Figure II.3 illustrate the shape of sector antenna used in 2G [11]. Sector antennas are simpler, mainly supporting voice and SMS over narrow bandwidth.



Figure II.3: Sector antennas.

Sector antennas operate on several frequency bands depending on the region. Table II.2 summarizes these frequency bands. Where, the 900 MHz and 1800 MHz bands are most used in Europe, Africa, and Asia, while the 850 MHz and 1900 MHz bands are common in North and Latin America.

Table II.2: GSM Band Frequency Allocations

Band Name	Uplink (Mobile to Network)	Downlink (Network to Mobile)
GSM 900	890 – 915 MHz	935 – 960 MHz
GSM 1800 (DCS)	1710 – 1785 MHz	1805 – 1880 MHz
GSM 850	824 – 849 MHz	869 – 894 MHz
GSM 1900 (PCS)	1850 – 1910 MHz	1930 – 1990 MHz

II.3 The third generation of mobile phones

The third generation of mobile networks, commonly referred to as 3G or UMTS, was introduced to create a unified global communication standard. Its core objectives included enabling seamless international roaming, improving support for data services, and reducing the costs of mobile terminals and infrastructure through economies of scale. Two major technological families emerged within 3G. The UMTS, developed as an evolution of GSM and widely adopted worldwide, and CDMA2000, derived from the IS-95 standard and primarily deployed in North America and parts of Asia. Both technologies use a code-division multiple access (CDMA) radio interface, which enables multiple users to share the same frequency spectrum efficiently [4].

UMTS, developed under the 3rd Generation Partnership Project (3GPP), was launched with Release 99 and became the foundation for 3G services in most GSM-based markets. It integrates a new radio access network with the existing GPRS core and was designed to significantly enhance both data and voice capabilities. UMTS allows for higher spectral efficiency and wider frequency bands compared to GSM, resulting in improved service quality and support for multimedia applications. It delivers data rates exceeding 144 Kbps and, under optimal conditions, can reach speeds up to 2 Mbps. This advancement paved the way for the development of more sophisticated mobile services, such as video calls, mobile TV, and high-speed web browsing [4].

To further improve performance, especially for data-centric applications, the high-speed downlink packet access (HSDPA) technology was introduced. Often labeled 3.5G, HSDPA significantly enhances downlink data rates—up to 10 Mbps—offering a smoother experience for users engaging in activities such as video streaming, file downloads, and mobile browsing. One of HSDPA's main advantages is that it can be integrated into existing UMTS infrastructure, enabling operators to upgrade their networks with minimal investment. Complementing HSDPA is high-speed uplink packet access (HSUPA), known as 3.75G, which focuses on improving uplink performance. It enables theoretical upload speeds of up to 5.8 Mbps while maintaining similar downlink capabilities as HSDPA, around 14 Mbps. This enhancement is especially valuable for users who frequently send media files—such as images, videos, and large documents—through mobile networks. HSUPA has contributed significantly to the development of mobile internet by supporting richer, more interactive communication experiences [4].

By the end of 2017, Algeria recorded 21.592 million 3G subscribers, representing a penetration rate of 51.17%, underscoring the importance of third-generation services in expanding access to mobile connectivity and data-driven applications. Overall, the evolution from UMTS to HSDPA and HSUPA marked a turning point in the history of mobile networks, enabling faster,

more reliable, and more interactive mobile communications on a global scale [4].

II.3.1 Architecture of 3G

The 3G of mobile communication systems, represented by the UMTS, introduced significant advancements in data transmission capabilities and service integration. The architecture of UMTS is structured into two main components: the RAN, known as universal terrestrial radio access network (UTRAN), and the core network (CN). Figure II.4 illustrates the general architecture of a UMTS network [12], highlighting the interaction between these two main subsystems. The CN is responsible for routing voice and data, mobility management, and interfacing with external networks such as the Internet and the public switched telephone network (PSTN).

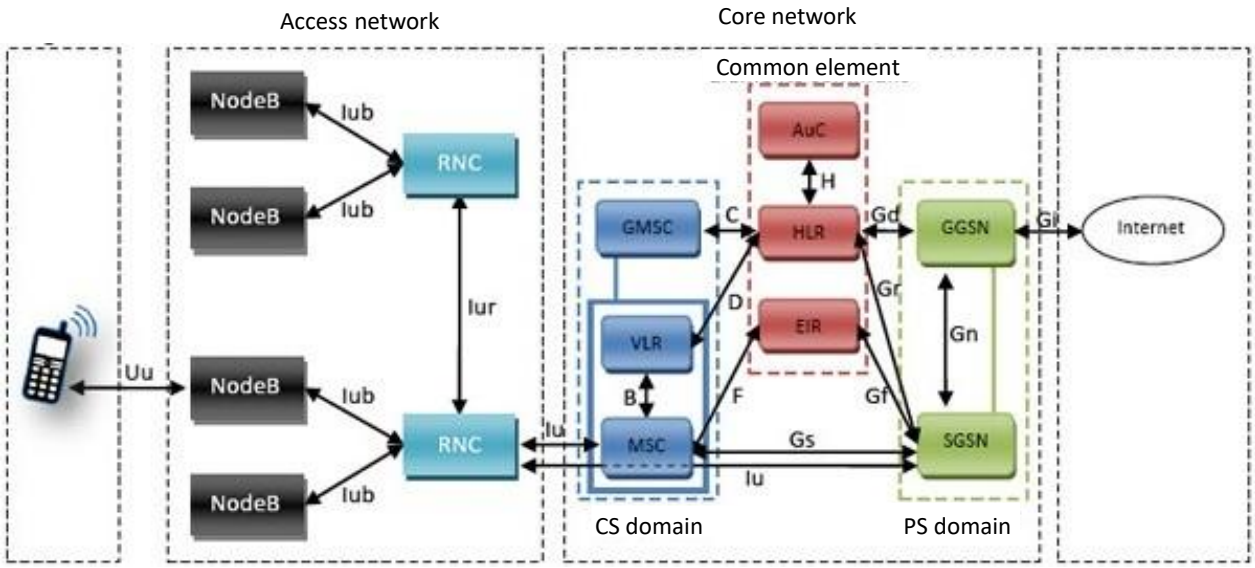


Figure II.4: General architecture of UMTS network.

The UTRAN's main role is to transfer the data generated by the user. It acts as a gateway between the user equipment and the CN via the Uu and Iu interfaces. However, it is also responsible for other functions:

- *Security:* It ensures the confidentiality and protection of the information exchanged over the radio interface by using encryption and integrity algorithms.
- *Mobility:* The access network allows for the estimation of the user's geographical position.
- *Radio resource management:* The access network is responsible for allocating and maintaining the radio resources required for communication.
- *Synchronization:* It also maintains the mobile devices' reference time base to enable proper transmission and reception of information.

The UTRAN access network is composed of several elements: one or more base stations (called NodeB), radio network controller (RNC), and communication interfaces between the various elements of the UMTS network [12].

The main role of the NodeB is to perform radio transmission and reception functions for one or more cells within the UMTS access network, in communication with user equipment (UE). It operates at the *physical layer* of the OSI model and is responsible for tasks such as encoding, decoding, modulation, and demodulation [12]. The NodeB ensures the physical connectivity between the mobile user and the RNC, and plays a critical role in managing resources such as transmission power and signal quality. There are generally two types of NodeB based on their antenna configuration [12]:

- Omnidirectional NodeB covers a cell in all directions with a single antenna.
- Sectorized NodeB uses multiple directional antennas to cover the cell in sectors (commonly three sectors of 120° each).

Figure II.5 shows a typical NodeB configuration with sector antennas [12].

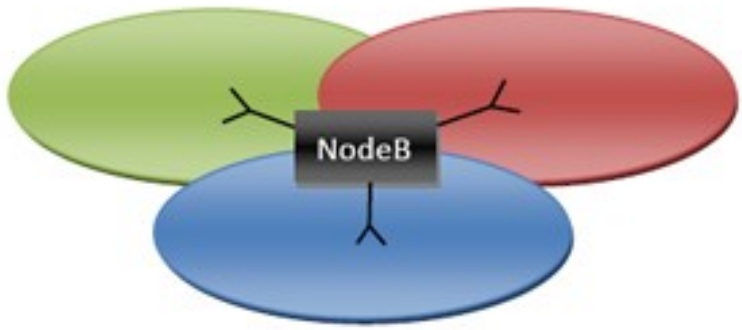


Figure II.5: NodeB with sector antennas.

- Communication interfaces: Several types of communication interfaces coexist within the UMTS network:

- Uu: Interface between user equipment and the UTRAN access network. It enables communication with UTRAN via CDMA technology.
- Iu: Interface between the UTRAN access network and the UMTS CN. It allows the RNC to communicate with the SGSN.
- Iur: Interface that allows two RNCs to communicate.
- Iub: Interface that enables communication between a NodeB and a RNC.

RNC The main role of the RNC is to route communications between the NodeB and the UMTS CN. It operates at layers 2 and 3 of the OSI model (power control, code allocation) [12]. The RNC serves as the access point for all services towards the CN [12]

- Communication channels: The three types of channels employed in the 3G UMTS mobile network to facilitate communication between the network and the UE are physical, transport, and logical channels.

- Physical channels: are on the physical layer of the OSI model and carry user and control data across the air interface. They allow for the actual transmission of radio signals between UE and NodeB. Most significant examples include P-CCPCH (system information broadcasting), S-CCPCH (paging and control), and DPCH (dedicated voice/data).
- Transport channels: define how information is transmitted between the physical and data link layers. They deal with coding, timing, and multiplexing of data. For instance, BCH is employed for broadcasting system information, forward access channel (FACH) and RACH for shared downlink and uplink access respectively, whereas DCH is used solely for a single user's traffic.
- Logical channels: categorize the type of content being transferred—control or user information. These operate above the transport layer and define what kind of information each stream carries. BCCH carries control information, PCCH manages paging, and DCCH and DTCH deal with dedicated signaling and user information.

Together, these channels form a layered system enabling efficient, reliable mobile communication in the 3G network, from access to ongoing voice or data sessions [13].

II.3.2 Antenna types in 3G networks

Different types of antennas are used in mobile communication networks depending on environmental conditions and coverage requirements. The three main types commonly deployed in 3G networks are **sector antennas**, **omnidirectional antennas**, and **panel antennas**.

- Sector antennas: Are directional antennas typically used in urban, suburban, and semi-rural environments. They are usually installed in sets of three, each covering 120°, to provide full 360° coverage. These antennas offer a good balance between coverage range, capacity, and interference management. Sector antennas are compatible with technologies like wide CDMA and can be upgraded to support MIMO, enhancing data throughput and spectral efficiency [14]. As shown in Figure II.6, these antennas are mounted with a directional focus to serve specific coverage sectors effectively [14].



Figure II.6: Sector antennas used in 3G networks.

- Omnidirectional antennas: Radiate signals uniformly in all horizontal directions. They are mainly used in low-density or rural areas where wide-area coverage is needed with fewer base stations. Although they provide less capacity compared to sector antennas, their ability to cover large areas makes them ideal for expansive regions with low user density. Figure II.7 illustrates a typical omnidirectional antenna [14], often installed on towers in open environments.

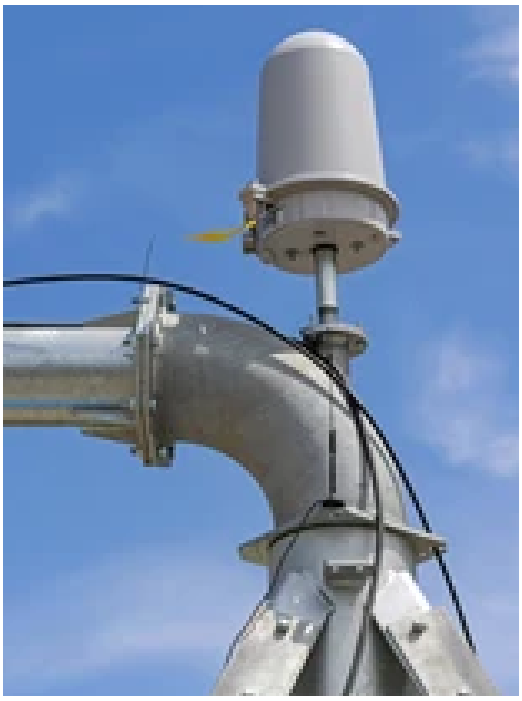


Figure II.7: Omnidirectional antenna configuration.

- Panel antennas Are flat and can be either directional or sectorial. They are commonly mounted on rooftops or towers and are widely used in 3G+ networks such as HSPA+. These antennas support MIMO configurations, which significantly enhance network performance. Due to their simple structure and ease of installation, panel antennas are a popular choice for both temporary and permanent deployments. Figure II.8 shows a typical panel antenna designed for use in 3G+ systems [14].



Figure II.8: Panel antennas used in 3G and 3G+ networks.

In 3G mobile networks, antenna selection is crucial to ensure optimal coverage, capacity, and service quality. Different antenna types are chosen based on deployment environments and frequency band availability. Each type is associated with specific technical characteristics and operational advantages. Table II.3 summarizes the key antenna types used in 3G networks [14], along with their compatible frequency bands and typical usage scenarios.

Table II.3: Antenna types, supported bands, and usage remarks.

Antenna Type	**Compatible Bands**	**Remarks**
Sector Antenna	900, 1800, 2100 MHz (B8, B1, B2)	Most commonly used on 3G macro sites; supports multiple frequency bands.
Omnidirectional Antenna	900 MHz (B8), sometimes 2100 MHz (B1)	Mainly used for wide rural coverage; radiates in all horizontal directions.
Panel Antenna	Multi-band: 850/900/1800/2100 MHz	Very common in urban deployment; easily configured for various bands.
MIMO Antenna (3.5G)	2100 MHz (B1), sometimes 900 MHz (B8)	Used with HSPA+ for higher throughput and performance.
Indoor Antenna (DAS)	Depends on repeater band (usually 2100 MHz)	Used inside buildings for indoor coverage extension.

II.4 The fourth generation of mobile phones

II.4.1 Fourth Generation Presentation

In comparison to earlier generations, the fourth generation of mobile networks, or 4G, represents a significant advancement. The definition of 4G has changed over time in response to a new wave of hazy attempts to commercialize mobile services. The Union Internationale des Telecommunications (UIT), which oversees the creation of cellular data standards, has pointed out that the word "4G" is not precisely defined. Consequently, several mobile operators have started to offer 4G services based on advanced 3G designs, even if these services don't always meet the rigorous requirements of 4G [15].

LTE is a technology developed by the 3GPP standardization organization. Its main goal is to enhance the UMTS standard for 3G cellular networks in order to get ready for the fourth-generation transition. The main goals of LTE technology are as follows [15]:

- **Improvement of spectrum efficiency:** This enables very high-bandwidth data transport with theoretical speeds of up to 50 Mbps.
- **Gained coverage:** LTE aims to provide wider coverage compared to earlier technologies.
- **Improved call capacity:** The number of calls that can be managed by a cell is more than that of the UMTS.
- **Reduced latency:** The network's response time, or latency, is significantly reduced. This improves the user experience.

4G is distinguished by its all-IP architecture, which means it uses an access network known as evolved universal terrestrial radio access network (E-UTRAN) and a network core that only sends data packets. 4G mostly relies on voice over Internet protocol (VoIP) for voice transmission, in contrast to 3G, which uses circuits for voice.

II.4.2 Architecture of 4G

The 4G, called also LTE, represents a major evolution toward an all-IP network, offering higher data rates, reduced latency, and improved capacity. It is composed of the E-UTRAN for radio access and the EPC for core operations. Figure II.9 shows the general structure of a 4G LTE network [16].

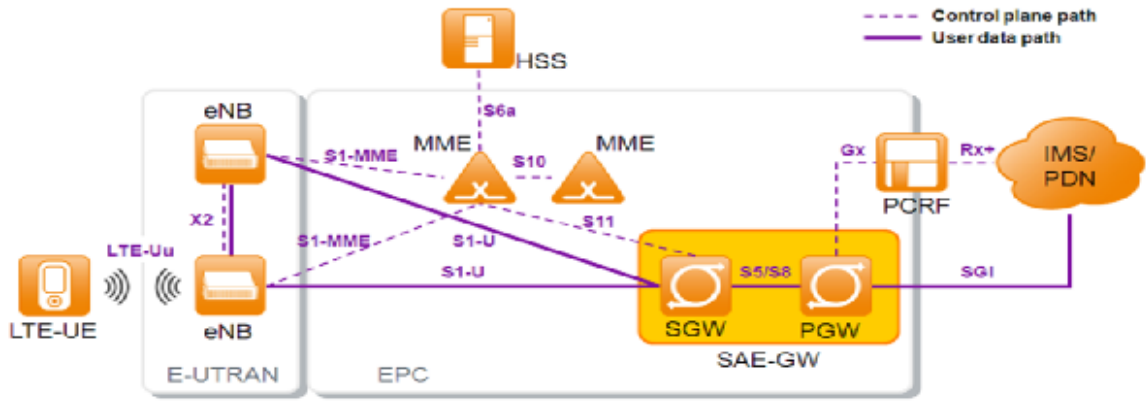


Figure II.9: General architecture of a 4G LTE network.

II.4.3 LTE network architecture overview

LTE network architecture is defined to provide data at high speed and low-overhead signaling to support mobile communications. LTE fundamentally relies on two primary domains: E-UTRAN and evolved packet core (EPC). Together, they constitute the evolved packet system (EPS) to provide seamless data communication and mobility.

E-UTRAN is the radio access part of the LTE network. It is made up of UE such as phones and tablets, and the eNodeB (evolved Node B), which is a base station. LTE-Uu is the UE-eNodeB interface. LTE-Uu accommodates advanced radio technology such as orthogonal frequency division multiplexing (OFDM) for downlink and SC-FDMA for uplink, together with MIMO and dynamic resource allocation. It enhances data rate and spectral efficiency while reducing latency and power consumption.

The eNodeBs are interconnected through the X2 interface, responsible for coordination and handover among cells. There is a link between each eNodeB and the EPC via the S1 interface, split into two halves: S1-MME for control/signaling and S1-U for user data.

The essential operations of the network are managed by the EPC. It consists of several components: mobility management entity (MME), srving gateway (SGW), Packet Gateway (PGW), home subscriber server (HSS), and policy and charging rules function (PCRF). The MME authenticates the users, manages the sessions, and handles mobility procedures. It gets subscriber information via the S6a link while communicating with the HSS [15].

II.4.4 LTE Network Interfaces

The LTE architecture incorporates a set of well-defined interfaces to ensure seamless communication between its components. These interfaces manage both control and user planes, enabling functions such as mobility management, session handling, and data transfer. Table II.4 summarizes the key interfaces in LTE and their respective roles within the network [15].

Table II.4: LTE Network Interfaces, Connections, and Functions.

Interface	Connection	Function
LTE-Uu	UE ⟷ eNodeB	Radio interface between the UE and the eNodeB
X2	eNodeB ⟷ eNodeB	Supports inter-cell handover
S1-MME	eNodeB ⟷ MME	Control plane (signaling) interface
S1-U	eNodeB ⟷ SGW	User plane (data traffic) interface
S11	MME ⟷ SGW	Session control interface
S5/S8	SGW ⟷ PGW	Data transfer and mobility management
SGi	PGW ⟷ Internet/IMS	Connection to external data networks
S6a	MME ⟷ HSS	Authentication and retrieval of user information
Gx	PCRF ⟷ PGW	QoS and charging policy enforcement
Rx	PCRF ⟷ PDN	Service coordination and policy control

II.4.5 Techniques and characteristics of LTE technology

This section presents the key characteristics of LTE technology, including its bandwidth capabilities, data rates, modulation techniques, and the use of multiple antennas to enhance performance and network efficiency.

- Bandwidth: LTE uses hertzian frequency bands, whose bandwidth can range from 1.4 MHz to 20 MHz. The theoretical binary bit rate can reach 300 Mbit/s in "downlink" (téléchargement) mode on a 20 MHz channel.

- Real-world debits: Although "real 4G " may provide consumers with speeds of up to 1 Gbit/s, actual performance may differ depending on a number of factors, including network congestion and distance from the base station.

- Methods of modulation: The Orthogonal Frequency Division Multiple Access (OFDMA) multiplexage is used to maximize frequency use and minimize interference. This method makes it possible to divide the spectrum into sub-carriers, which increases the network's efficiency.

- Multiple antennas: By using multiple antenna techniques, which are similar to those used in Wi-Fi and WiMax, it is possible to multiply parallel communication channels, increasing the network's total bandwidth and reach [15].

II.4.6 LTE Frequency bands

This table highlights the most essential 4G LTE frequency bands, offering global compatibility, wide coverage, and high capacity for both urban and rural deployments.

In the field of mobile telecommunications, 4G is a significant advancement that offers higher data transfers, faster speeds, and enhanced capacity to handle large numbers of users at once. Thanks to technologies like LTE, users can enjoy an enhanced mobile experience that encourages the creation of creative applications and multimedia services [17].

Table II.5: Essential LTE Bands in MHz.

Band	Frequency	Uplink	Downlink	Main usage
B1	2100	1920–1980	2110–2170	Common in Europe, Asia, and Africa
B3	1800	1710–1785	1805–1880	Most widely used LTE band worldwide
B7	2600	2500–2570	2620–2690	High-capacity band, ideal for urban areas
B20	800 (DD)	832–862	791–821	Excellent coverage in Europe, rural and indoor
B28	700 (APT)	703–748	758–803	Broad area coverage, used in many regions
B8	900	880–915	925–960	Complementary coverage in Europe and Asia
B38/B40	TDD 2300/2600	TDD	TDD	TDD networks in Asia, good for high throughput

Abbreviation: Digital Dividend (DD)

II.5 LTE-Advanced

4G+, also referred to as LTE-Advanced, is an advancement of 4G technology that aims to enhance mobile networks' performance by increasing data debits, decreasing latency, and increasing network capacity. Here is a thorough overview of the features and technology related to 4G+.

II.5.1 Principal features

4G+ introduces several enhancements over the standard 4G technology. One of its key features is carrier aggregation (also known as porteuses aggregation), which allows the combination of multiple frequency bands to boost data transmission capacity. For example, by aggregating two 20 MHz bands, theoretical speeds of up to 300 Mbit/s or more can be achieved. This technology contributes to the significantly higher data rates offered by 4G+—under optimal conditions, speeds may reach up to 1 Gbit/s. In practice, users typically experience download rates well above those of standard 4G, greatly improving performance for bandwidth-intensive activities such as HD video streaming and online gaming. Additionally, 4G+ delivers reduced latency, which is vital for real-time applications like augmented reality, online gaming, and video conferencing. Moreover, thanks to spectrum optimization and increased network capacity, 4G+ supports a greater number of simultaneous users—an essential advantage in high-density environments [15].

II.5.2 Key technologies

This table presents the main technical improvements that distinguish 4G+ from standard 4G networks.

Table II.6: Comparison between 4G (LTE) and 4G+ (LTE-Advanced)

Feature	**4G (LTE)**	**4G+ (LTE-Advanced)**
Max Speed	~150 Mbps	Up to 1 Gbps
Modulation	64-QAM	256-QAM
Carrier Aggregation	Not supported or basic	2–5 carriers combined
MIMO	2×2 MIMO	Up to 4×4 or 8×8 MIMO
Latency	~50 ms	<30 ms
IoT Capability	Basic	Enhanced for massive IoT
Efficiency	Standard	Higher spectral efficiency

II.5.3 Applications and benefits

Among the various advantages offered by **4G+**, several key applications stand out. *Video streaming* benefits from the capabilities of **4G+**, which enables high-definition playback without affecting memory, thus providing a seamless user experience. *Teletravail and collaboration* are enhanced as applications like video conferencing and file sharing take advantage of increased bandwidth and reduced latency. *internet of things (IoT)* sees improved support, with **4G+** capable of managing a large number of connected devices and ensuring efficient communication between them. *Online games* also perform more smoothly due to the high data speeds and low latency made possible by **4G+** advancements.

Compared to the **4G** standard, **4G+** represents a significant evolution, offering higher data rates, lower latency, and better user management capabilities. By leveraging technologies such as port aggregation, MIMO, and quadrature amplitude modulation (QAM), **4G+** is well-positioned to meet the growing demands for mobile connectivity while enabling innovative applications and advanced multimedia services [15].

II.6 The Fifth Generation

One of the most recent breakthroughs in wireless communications is the advent of 5G mobile phone technology. The primary objective of 5G is to significantly enhance both the speed and reliability of wireless networks. Engineers specializing in network optimization are closely observing the transformative impact that 5G is expected to have on global communication systems.

5G enables ultra-fast data transmission over wireless connections, with theoretical speeds reaching up to 20 Gbit/s—surpassing the performance of many wired broadband systems. Moreover, it achieves ultra-low latency, often less than or equal to 1 millisecond, which is crucial for real-time applications such as autonomous vehicles and remote surgery. In addition to its speed and responsiveness, 5G leverages advanced antenna technologies, facilitating exponential growth in wireless data transmission and laying the groundwork for a new era of fil-free (wireless) communication systems [18].

II.6.1 The 5G network architecture

The network structure of 5G mobile technology marks a considerable advancement compared to earlier generations. This structure consists of three fundamental elements: the RAN, the CN, and the user devices, as illustrated in Figure II.10 [19].

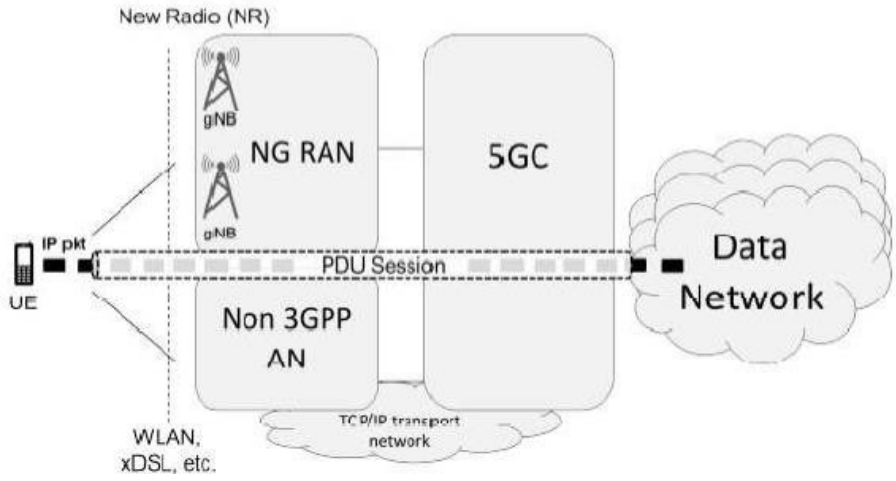


Figure II.10: Channel 5G network architecture.

II.6.1.1 User equipment

UE is essential. It includes all devices that connect to the 5G network to utilize its services and applications, such as smartphones, tablets, laptops, IoT devices, connected vehicles, and other 5G-compatible devices. These devices connect to 5G network base stations (gNB) to access the services offered, and they can also communicate with other network components like Wi-Fi access points, gateways, content servers, and management systems [19].

II.6.1.2 The radio access network

The RAN serves as a conduit for data and signaling between user devices and the CN. In the context of 5G, this access is facilitated by advanced base stations that are crucial for linking mobile devices to the 5GCN. Mobile devices can connect to these base stations through either 5G or 4G radio links. When utilizing 5G, the base station is designated as a gNB, whereas for 4G connections, it is referred to as an ng-eNB, which is specifically engineered to interact with the 5GCN.

The gNB performs functions akin to those of the traditional eNB, albeit with significant distinctions. For example, in 5G, quality of service (QoS) management is executed on a per-flow basis instead of relying on bearers, which allows for a more accurate distribution of resources tailored to the unique requirements of each data stream. Additionally, the capability for network slicing over the radio interface promotes effective segmentation and resource allocation across various services and applications, thereby enhancing the user experience within the 5G network.

The overall architecture of the 5G Radio Access Network is illustrated in Figure II.11 [19], highlighting the roles and interfaces of gNBs and ng-eNBs in connecting UE to the 5GCN.

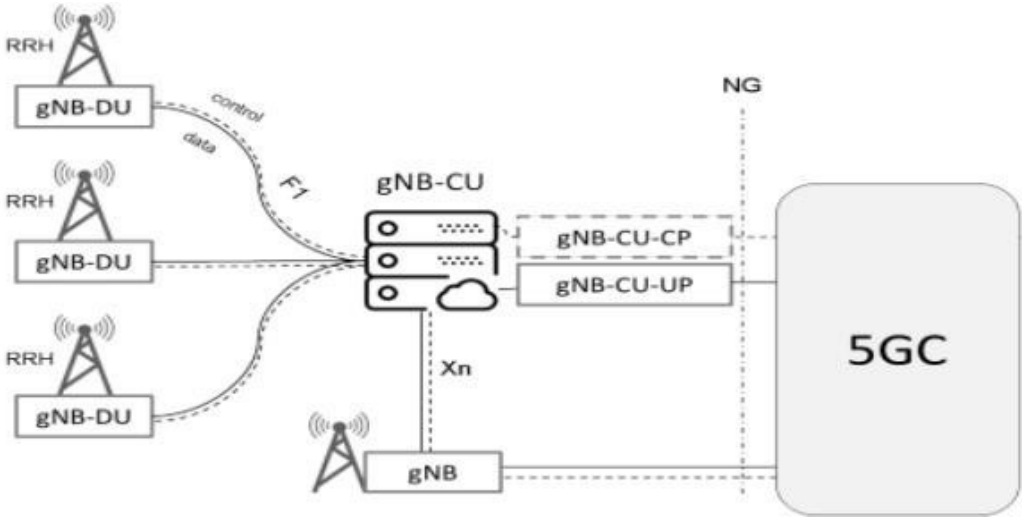


Figure II.11: Architecture of the radio access network 5G.

II.6.1.3 The core network of 5G

The 5GCN is structured around a service-based architecture, which is consistent with the principles of cloud computing. This methodology provides enhanced flexibility, scalability, and efficiency in the delivery of services. The 5GCN is responsible for critical functions including user authentication, data security, session management, and traffic aggregation for devices that are connected. The architecture of the 5GCN is illustrated in Figure II.12, showing the key functional components and their interactions as described in [19].

The 5GCN consists of several essential components that work together to deliver advanced communication services:

- Access and Mobility Function (AMF): This function manages the control plane signaling related to UE, including registration, connection, reachability, mobility, and access authentication. It facilitates UE access to the network and cooperates with other functions such as the SMF and AUSF. The AMF also inherits part of the functionalities of the 4G MME.
- Session Management Function (SMF): This is a key component responsible for managing and controlling user sessions. It handles the configuration and supervision of NG tunnels, assigns IP addresses via DHCP, manages QoS, and redirects traffic in accordance with security policies and application demands. The SMF also interfaces with the AMF and UPF.
- User Plane Function (UPF): This component manages the transmission of NG-U tunnels and related data path services, such as traffic anchoring, QoS enforcement, and policy application. A single UE may be associated with multiple UPFs, either grouped in one slice or distributed across several slices. The UPF integrates functionalities previously handled by the SGW and PGW in 4G.

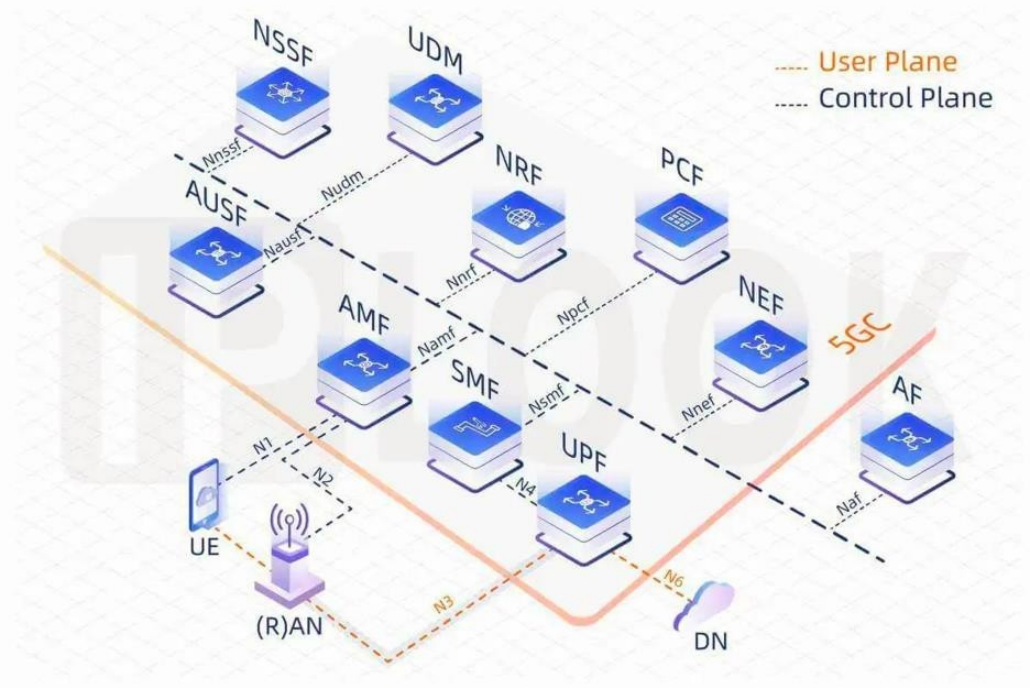


Figure II.12: Architecture of the 5GCN.

- Authentication Server Function (AUSF): A critical component for 5G security, the AUSF ensures authentication of users and mobile devices, making sure that only authorized equipment can access the network.
- Network Slice Selection Function (NSSF): Responsible for selecting the most appropriate network slice instance and the corresponding AMF for a given UE, based on the service requirements.
- Unified Data Management (UDM): Acts as a repository for user-related information, such as identifiers, AMF details, and SMF assignments for active sessions. It aims to centralize UE configuration data, allowing network functions (NFs) to operate in a stateless manner, thereby improving architectural flexibility. The UDM integrates functionalities from the 4G HSS.
- Network Repository Function (NRF): A fundamental element of the 5G core, the NRF plays a vital role in discovering NFs and supporting signaling processes during initial UE registration, as well as slice selection.
- Policy Control Function (PCF): Provides policy rules to other control plane functions, particularly the SMF, for traffic and QoS management.
- Network Exposure Function (NEF): Allows third-party applications to access network capabilities and UE/network events, enabling edge computing use cases and external integrations.
- Application Function (AF): Serves as an application server interacting with other control

plane functions to support diverse application-level services. It can be operated either by the network provider or by trusted third parties [20].

II.6.2 Antenna Type of 5G

Figure II.13 shows a 5G mobile network antenna system equipped with Massive MIMO technology [21]. These advanced antennas form a core component of modern 5G base stations and are designed to manage multiple data streams simultaneously. Massive MIMO greatly enhances network capacity, efficiency, and data speeds through a technique called beamforming, which allows the system to direct signals precisely toward individual users. The large rectangular panels visible in the image are antenna arrays capable of serving multiple users at the same time, thereby improving coverage and minimizing interference — especially in dense urban environments.



Figure II.13: Massive MIMO antenna used in 5G base stations.

II.6.3 Protocol layers of the 5G access stratum

The architecture of the 5G access stratum includes four main layers: RRC, packet data convergence protocol (PDCP), radio link control (RLC), and medium access control (MAC). These layers operate between the UE and the gNB to ensure secure signaling, efficient data transmission, and robust error handling. Figure II.14 illustrates their hierarchical relationship [22].

II.6.3.1 Radio resource control

The RRC layer in 5GNR is a vital component of the control plane architecture. It facilitates signaling between the UE and the RAN, playing a central role in the management and allocation of radio resources such as frequency, bandwidth, and transmission power.

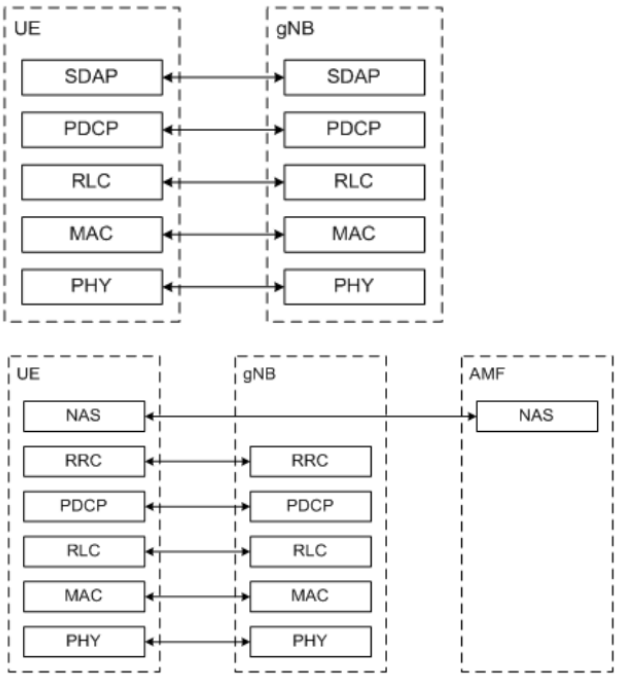


Figure II.14: Plane Protocol Stack.

Operating exclusively in the control plane, the RRC layer works in conjunction with the user plane (UP) to ensure secure and efficient transmission of data, while maintaining appropriate QoS levels and enforcing security mechanisms. Its responsibilities directly impact network performance, connection stability, and overall user experience [23].

- Functions: The 5G RRC layer is responsible for a wide range of control and management functions that are essential to maintaining efficient and secure communication between the UE and the 5G network. One of its key roles is handling UE measurement reporting, where the UE reports signal strengths from neighboring cells, enabling the network to make decisions about handovers and optimal cell selection. It also manages key security mechanisms, ensuring that all communications between the UE and the network are encrypted and protected against unauthorized access. Another critical function is broadcasting system information to the Non-Access Stratum (NAS), such as available radio resources and system parameters. Additionally, the RRC layer plays a vital role in QoS management, ensuring that data flows are prioritized and delivered according to their required service levels. It also handles radio resource allocation and control, assigning frequency and bandwidth resources to UEs based on real-time network conditions. Finally, the RRC layer supports mobility management, allowing the UE to perform smooth handovers and cell reselections, thereby ensuring continuous service and connection stability as users move across different cells [23].

- RRC States: Based on its network connection status, a UE can be in one of the various operational states known as the 5GNR RRC states. These states, which are crucial for controlling the radio resources allotted to the UE, are specified in the 5GNR standard. According to the Figure II.15, the 5GNR protocol has three primary RRC states figure [24].

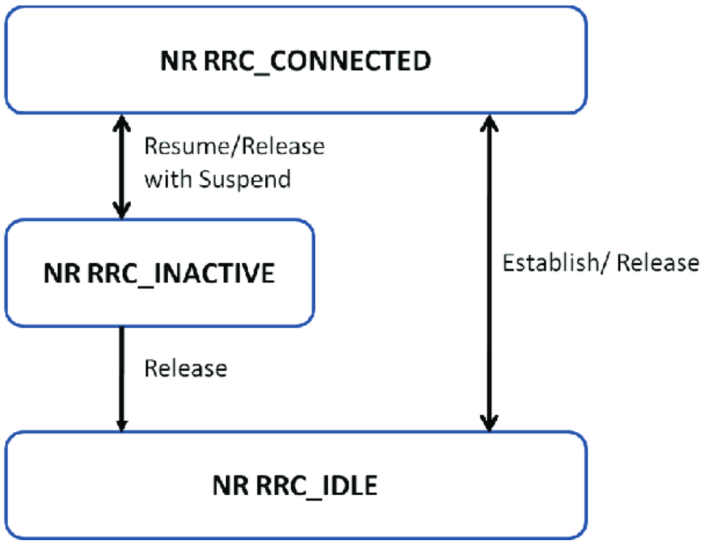


Figure II.15: 5G RRC states.

- **RRC-IDLE:** In the RRC-IDLE state, the UE is not actively connected to the 5G network and does not have any dedicated radio resources assigned. However, the UE remains partially aware of its surroundings by periodically scanning for available cells and monitoring broadcast channels. While idle, the UE performs Public Land Mobile Network (PLMN) selection and engages in cell reselection to ensure it remains camped on the most suitable cell based on signal quality and mobility criteria. This state allows the UE to conserve battery life while maintaining readiness to establish a connection when needed [23].

- **RRC-INACTIVE:** The RRC-INACTIVE state is unique to 5GNR and offers a balance between connectivity and power efficiency. In this state, the UE maintains a lightweight connection with both the 5GCN and the Next Generation Radio Access Network (NG-RAN), without requiring active radio resource allocation. Although no user data is exchanged, the UE retains its context in the network, enabling rapid resumption of communication when needed. It continues to support cell reselection mobility, and the network can reach the UE via RAN-based paging mechanisms. This state reduces signaling overhead while still allowing for fast response times [23].

- **RRC-CONNECTED:** In the RRC-CONNECTED state, the UE is fully connected to the 5G network with dedicated radio resources allocated for communication. This is the state where active unicast data transmission occurs between the UE and the network, encompassing both user data and signaling messages. While connected, the UE participates in handover procedures to maintain service continuity across cells and is subject to dynamic QoS management based on its traffic profile. This state provides full access to network services and enables features such as beamforming, carrier aggregation, and precise mobility control [23].

II.6.3.2 Packet data convergence protocol

The PDCP layer sits above RLC and is crucial for optimizing data transfer and maintaining security in 5G. One of its key responsibilities is header compression, which reduces overhead by eliminating redundant protocol information, allowing more efficient bandwidth usage. PDCP also ensures data confidentiality through encryption (ciphering) on a per-packet basis, so intercepted packets do not expose the entire session. In addition, it provides integrity protection, safeguarding data against tampering and replay attacks. Through these functions, PDCP strengthens both the performance and the security of the 5G radio interface [23].

II.6.3.3 Radio link control

The RLC layer is responsible for ensuring the reliable transmission of data over the radio interface. It performs error correction using Automatic Repeat reQuest (ARQ), where packets are retransmitted until correctly received. RLC also handles segmentation and reassembly, dividing large data units into smaller packets for transmission and reconstructing them at the receiver. Additionally, it includes duplicate detection to prevent redundant packet delivery and supports re-establishment procedures to quickly recover communication in case of link disruptions. Positioned between the PDCP and MAC layers, RLC ensures ordered and dependable delivery of user and control data [23].

II.6.3.4 Medium Access Control

The MAC layer in 5G plays a vital role in managing both data transmission and radio resource allocation. It receives data from the upper layers and encapsulates it with headers containing addressing, control, and error detection information. The MAC layer controls access to the shared communication medium using techniques such as CSMA/CA, ensuring efficient channel utilization. It also provides flow control mechanisms to prevent receiver overload by regulating the data rate through buffering and acknowledgments. Furthermore, the MAC layer supports unicast and multicast addressing, enabling targeted or group data delivery across the network. It works closely with the RLC layer to coordinate transmission opportunities [23].

II.6.4 Physical channels

In the context of 5G cellular networks, physical channels are communication channels that operate at the physical layer of the network architecture. These channels are responsible for carrying the actual user data and control information between the UE and the NodeB. Table II.7 summarize the main types of 5G physical channels on the base station.

These physical channels are essential components of the 5G air interface, facilitating the exchange of information between the network infrastructure and the user devices for efficient and reliable communication. In the pursuit of seamless connectivity and enhanced user experiences,

Table II.7: Physical channels in 5G mobile networks

Channel	Direction	Detailed Description
PDSCH (Physical Downlink Shared Channel)	Downlink	Provides a shared data channel for transmitting user data, such as video, audio, or other application data from the base station to UE.
PUSCH (Physical Uplink Shared Channel)	Uplink	Carries user data from the UE to the base station, enabling UEs to transmit their data to the network.
PDCCH (Physical Downlink Control Channel)	Downlink	Carries control information that is used to manage the transmission on the physical channels, such as resource allocation, power control commands, and scheduling information.
PUCCH (Physical Uplink Control Channel)	Uplink	Used for transmitting uplink control information from the UE to the base station. It includes ACK/NACK, scheduling requests, and other control signals.
PRACH	Uplink	Enables UEs to initiate communication with the network when no dedicated resource is assigned. Essential for establishing a connection.
PBCH (Physical Broadcast Channel)	Downlink	Broadcasts necessary parameters from the base station to UEs for synchronization and initial access to the network.

the PRACH plays a key role. The 5GNR PRACH serves as the gateway for UE to initiate communication with the network, making it a critical component of the 5GNR architecture. However, its efficiency is profoundly influenced by the surrounding interference conditions. Intra-cell interference arises when multiple UEs within the same cell attempt to access the network simultaneously, leading to contention for the PRACH resources. Conversely, inter-cell interference emerges when UEs from neighboring cells contend for the same PRACH resources, leading to contention across cell boundaries. These interference scenarios introduce complexities in PRACH detection, impacting network efficiency, latency, and overall QoS.

II.7 Conclusion

The evolution from 2G to 5G has marked a profound transformation in mobile communications, driven by the increasing demand for higher data rates, lower latency, and more reliable connectivity. Each generation introduced new capabilities that addressed the shortcomings of the previous one: 2G digitized voice and introduced basic data services; 3G enabled mobile internet and multimedia; and 4G brought high-speed connectivity and real-time communication support.

The introduction of 5G represents a paradigm shift, not just in speed and capacity, but in the network's ability to support diverse and demanding applications across various industries. In this chapter, we explored the key characteristics, architecture, and enabling technologies of 5G, highlighting its potential to transform the digital landscape.

One of the cornerstone technologies behind 5G's enhanced performance is **Massive MIMO**, which plays a crucial role in improving spectral efficiency, capacity, and coverage. In the next chapter, we will examine Massive MIMO in depth, exploring its principles, benefits, and its central role in next-generation radio networks.

CHAPTER III

MASSIVE MIMO FOR 5G RADIO NETWORK PERFORMANCE

III.1 Introduction

Over the past two decades, developments in wireless telecommunications have accelerated, particularly with the shift from simple single antenna, SISO, systems to multi-antenna, MIMO systems, which were widely adopted with the fourth generation. In 4G , MIMO technology played a key role in improving network capacity and connectivity quality, but faced challenges when the demand for data increased exponentially. Here came the turn of 5G, which introduced more sophisticated technologies, most notably Massive MIMO, which relies on huge numbers of antennas to improve spectral efficiency and provide better coverage.

Traditional MIMO technology is a significant advancement. As opposed to SISO systems, which employ a single antenna on both the transmit and receive ends of the communication link, MIMO systems employ multiple antennas on both ends. This technique seeks to improve transmissions spectrum efficiency, capacity, and dependability without using more power or bandwidth. The phenomena of multipath propagation, in which signals bounce off different obstacles before reaching the receiver, is its primary tenet. MIMO cleverly takes advantage of these multipaths to boost performance, whereas in traditional systems they lead to interference. The overall system throughput can be increased by transmitting numerous data streams at once using a mix of techniques like spatial diversity and spatial multiplexing [25]. Traditional MIMO systems, often referred to by configurations such as 2x2 or 4x4 (two antennas at the transmitter and two at the receiver, etc.), lay the foundations for more advanced generations such as Massive MIMO, used in 5G [26].

Additionally, several antennas can simultaneously send and receive multiple spatial streams thanks to MIMO. To improve signal strength and dependability, smart antennas mix data streams that arrive at different times and through multiple paths using spatial diversity. Antennas can offer additional variety to improve communication range and stability when there are more antennas than spatial streams [27].

III.2 Evolution of antennas in 4G

The progression of wireless communication systems has been marked by continuous advancements in antenna technologies and signal processing methods. This evolution, aimed at improving spectral efficiency, reliability, and data throughput, has transitioned from basic SISO configurations to more sophisticated MIMO architectures [28].

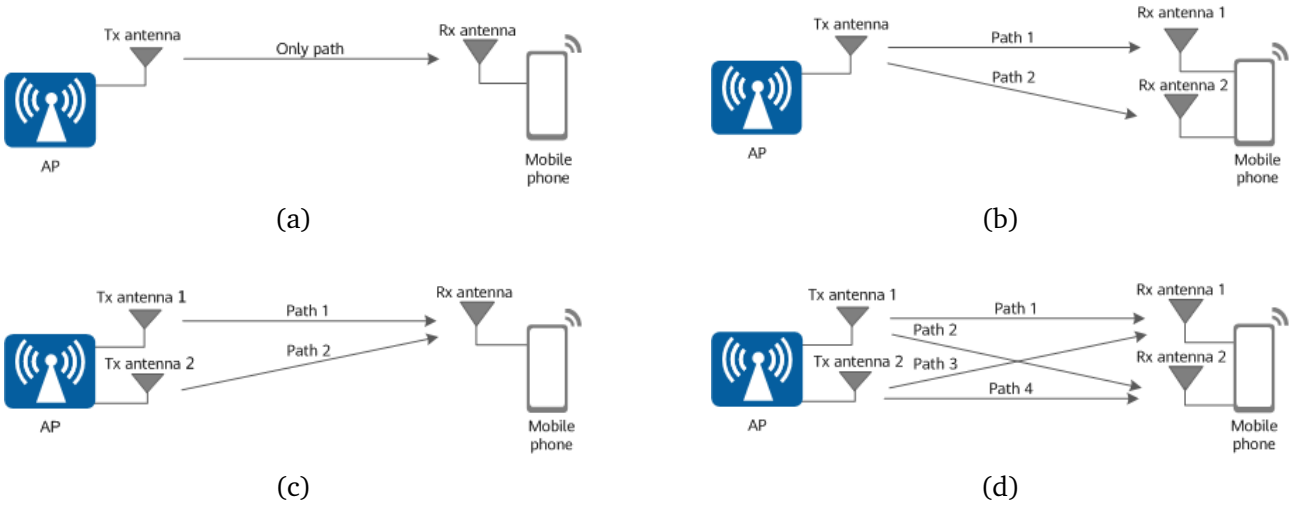


Figure III.1: Propagation models for different antenna configurations: (a) SISO, (b) SIMO, (c) MISO, and (d) MIMO.

- **SISO:** SISO transmits a single signal and literally creates a special path between the Tx and Rx antennas. Every signal is sent over a single spatial stream in a wireless system.Apparently, such transmission is unreliable and rate limited, As shown in Figure III.1(a) [28].

- **SIMO:** To achieve higher reliability, SIMO is introduced. That is, one antenna is added on the receiver (STA), so that two signals can be received concurrently. As shown in the figure III.1(b), two signals containing the same data are sent from one Tx antenna. If one signal is partially lost, the receiver may still obtain complete data from the other signal. Although the capacity remains unchanged (there is still one path in use), the reliability is doubled. This mode is also known as receive diversity.

- **MISO:** Given the presence of only one Rx antenna, the signals sent from the two Tx antennas must carry the same data and be combined as one signal on the receiver. This mode, referred to as MISO or transmit diversity, actually delivers the same effect as SIMO, as illustrated in Figure III.1(c).

- **MIMO:** The transmission capacity is dependent on the number of Tx and Rx antennas, as demonstrated by the previous analysis on SIMO and MISO. Therefore, by sending and receiving two signals independently, it is possible to double the rates by employing two antennas on both the transmitter and the receiver. Using multiple antennas on both the transmitter and the receiver is known as MIMO. Differentiating signals delivered to or received from different spatial positions is made possible by MIMO technology, which allows many antennas to broadcast

and receive spatial streams (multiple signals) concurrently. Through the use of technologies like space diversity and spatial multiplexing, MIMO increases system capacity, coverage range, and SNR without using additional bandwidth. These advantages make MIMO a key enabler for high-capacity wireless systems [28].

A number of multi-user MIMO technology types are derived from MIMO as multi-user transmission technologies have advanced. Single-user-type MIMO is called:

Single-user MIMO (SU-MIMO): to make it easier to distinguish various MIMO modes. The following are the primary multi-user types of MIMO technology:

Multi-user MIMO (MU-MIMO): permits the transmitter to send data to several users at once. Wi-Fi 6 expands the number of MU-MIMO users to eight, whereas Wi-Fi 5 only supports MU-MIMO with four users.

Cooperative MIMO (CO-MIMO): enables neighboring transmitters to provide data to numerous users at once by combining several wireless devices into a virtual multi-antenna system.

III.3 From MIMO to massive MIMO

Massive MIMO builds upon the principles of standard MIMO by enabling simultaneous data transmission to multiple users, thereby increasing the number of parallel data streams. This dramatically enhances network capacity and efficiency. Moreover, the use of advanced beamforming techniques allows for more focused signal transmission, which improves signal quality and reduces interference. This technology is a cornerstone in the development of 5G networks, providing the infrastructure required to support ultra-reliable, low-latency communication. Its ability to accommodate large numbers of users, particularly in densely populated areas, helps mitigate network congestion while maintaining high-speed connections. In addition to boosting data throughput, Massive MIMO improves spectral efficiency and ensures more stable connections even in interference prone environments. It also plays a critical role in reducing latency an essential requirement for applications such as virtual reality and autonomous vehicles. By delivering stronger and more precise signal coverage, Massive MIMO significantly enhances the overall user experience. In essence, Massive MIMO is a transformative enabler for next-generation wireless systems, ensuring they are equipped to meet the demands of an increasingly connected and data-driven world [29].

The advantages of Massive MIMO are often highlighted through direct comparisons with traditional MIMO systems [30]. A detailed performance comparison between traditional and Massive MIMO technologies is presented in Table III.1.

III.3.1 Principle of Massive MIMO

The fundamental principle of Massive MIMO is the deployment of a large number of antennas at the base station to establish multiple spatial channels between the transmitter and users. These channels enable the simultaneous transmission and reception of multiple data streams, effectively

Table III.1: Comparison between traditional MIMO and Massive MIMO

Technical Content	**Traditional MIMO**	**Massive MIMO**
Number of antennas	≤ 8	≤ 100
Channel angle value	Uncertain	Deterministic with matrix field growth
Channel matrix	Low demand	High demand
Channel capacity	Low	High
Diversity gain	Low	High
Link stability	Low	High
Resistance to noise	Low	High
Array resolution	Low	High
Antenna correlation	Low	High
Coupling	Low	High
SER (Symbol Error Rate)	High	Low
Pilot pollution	No	Yes

increasing both data capacity and throughput. In Massive MIMO systems, the number of antennas typically exceeds the number of users, allowing for highly efficient parallel communications. As a result, Massive MIMO holds significant promise for enhancing the performance of cellular networks, making it a cornerstone technology for 5G deployments and future upgrades.

Beyond capacity improvements, Massive MIMO enables each antenna to serve multiple users concurrently on the same frequency band, a capability achieved through beamforming a signal processing technique that directs transmission energy toward specific users or spatial regions. This targeted transmission improves signal quality and reduces interference, thereby enhancing overall network performance.

According to 3GPP Release 15, 5G new radio (NR) initially supports configurations of up to 32 antennas (32×32 MIMO). This number is expected to increase in future releases, with systems using 64 antennas or more to meet the growing demands for capacity, reliability, and spectral efficiency. Overall, Massive MIMO is a key enabler of 5G and beyond, addressing critical challenges in wireless communication by significantly improving link capacity, spectral utilization, and network reliability [31–33].

III.3.2 Functioning of Massive MIMO

Massive MIMO extends the principles of traditional MIMO by employing a significantly larger number of antennas, often dozens or even hundreds at the base station. This increase in antenna count allows for a more effective exploitation of spatial diversity, leading to several key benefits:

- **Enhanced capacity:** With more antennas, Massive MIMO can serve multiple users simultaneously in the same time-frequency resource, significantly increasing the overall capacity of the network.
- **Improved signal quality:** The large number of antennas enables better spatial filtering, which helps to mitigate interference and enhance the quality of the signals received. This

results in higher data rates and more reliable connections.

- **Robustness to fading:** The diversity provided by the numerous antennas allows the system to average out the effects of fading and multipath propagation, leading to more stable and consistent performance, even in challenging environments.
- **Energy efficiency:** Massive MIMO can achieve higher energy efficiency by focusing the transmitted energy in the direction of the users, rather than broadcasting it in all directions. This beamforming capability reduces interference and improves the overall performance of the network.
- **Scalability:** The architecture of Massive MIMO is inherently scalable, allowing network operators to add more antennas as demand increases without a significant overhaul of the existing infrastructure.

This development reflects the natural evolution of antenna systems from conventional 4G configurations, characterized by limited spatial capabilities, to advanced 5G Massive MIMO beamforming architectures, which enable highly focused and efficient signal transmission [34, 35]. As illustrated in Figure III.2, this transition highlights the shift toward higher spatial efficiency and energy-focused transmission in modern cellular networks [31].

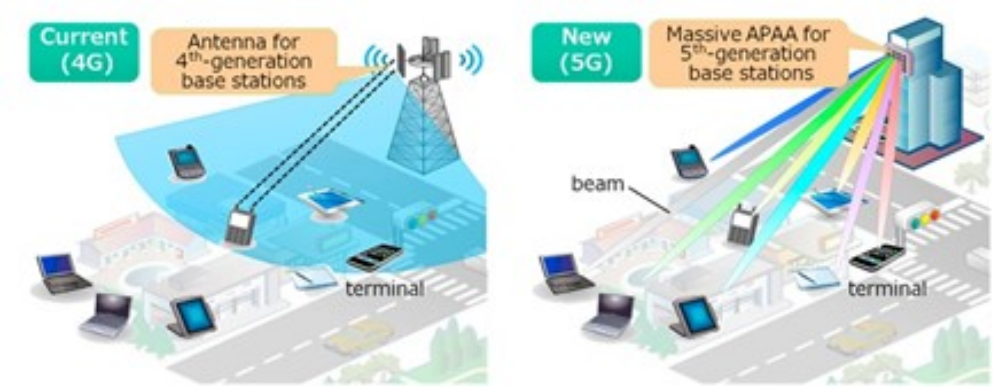


Figure III.2: llustration of the evolution from conventional 4G antenna systems to 5G Massive MIMO beamforming.

III.3.3 General characteristics of Massive MIMO systems

Channel diversity is exploited when the dispersive nature of the channel is used to send several replicas of the same signal to the receive. The more replicas the receiver receives, the less likely it is that all of them will have undergone strong attenuation thus improving the quality of the radio link. Exploiting channel diversity is only useful when the channel is subject to strong attenuation

Otherwise, exploiting this diversity will simply use up spectral, temporal or spatial resources all equally scarce and precious, for almost no gain. Channel selectivity must therefore be studied beforehand [36].

III.3.3.1 Time diversity

Exploiting the channel's temporal diversity means sending the same signal several times at different moments. In practice, this involves distributing the useful data over time (for example, by applying channel coding and temporal interleaving) to enable the receiver to recombine the different versions and reconstruct the original signal. However, to make the most of this temporal diversity, it is essential that two instances of the same signal be separated by at least the channel coherence time, which defines the period during which the channel is considered static [36].

III.3.3.2 Spatial diversity

Spatial diversity can be exploited when a signal is transmitted from several distinct points in space. In order to effectively benefit from this type of diversity, the distance d between each antenna in the same antenna array must be at least half a wavelength (See Equation III.1), ensuring that the signals are sufficiently decorrelated.

$$d > \frac{\lambda}{2} \tag{III.1}$$

This spatial separation is necessary for the diversity to be properly exploited. Additionally, any electromagnetic coupling between antennas may degrade the system's performance and reduce the effectiveness of spatial diversity [36].

III.3.3.3 Space-time diversity

Spatio-temporal diversity is an example of a combination of diversity techniques. In This technique sends time-delayed signal versions via several transmitting antennas. In this way, a higher level of diversity is achieved [37].

III.3.3.4 Spatial multiplexing

The principle of spatial multiplexing is to arrange the sequence of information along the spatial axis. The system then transmits N_t times as many useful symbols per time unit as a SISO system. Such a system was proposed by Foschini in 1996, the architect of the first MIMO system, is called D-BLAST [38], as illustrated in Figure III.3 [39].

III.3.3.5 Small cells

Currently, the concept of a heterogeneous network is frequently associated with the use of so-called small cells [36].These cells are characterized by their limited coverage radius, which enables them to offer high data throughput to users, a direct consequence of fewer terminals sharing the available time and frequency resources. As a result, small cells can effectively complement macro cells, which provide wider coverage but lower throughput, and they can also be used for

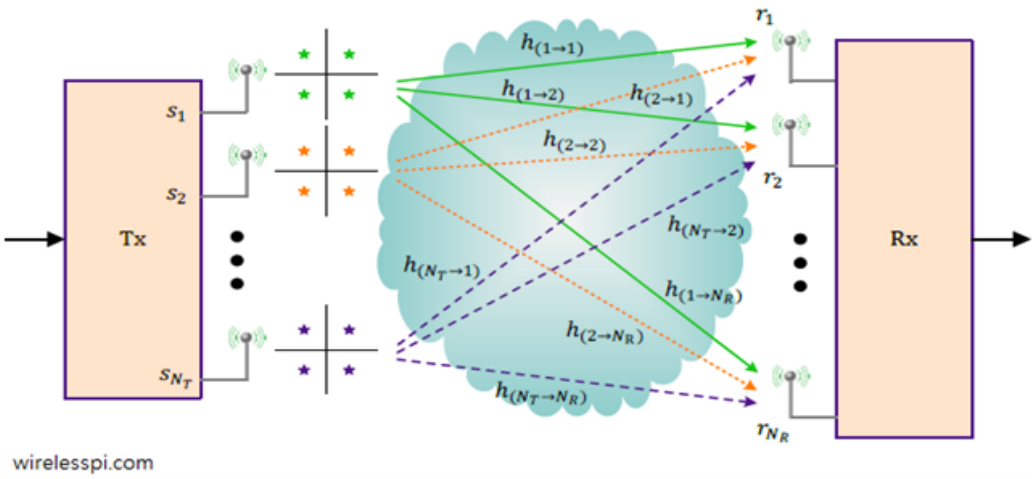


Figure III.3: D-BLAST system.

data offloading when the transmission of information is redirected from the macro cell to the small cell.

The densification of networks through the deployment of these small cells aligns perfectly with the objectives of 5G, particularly in enhancing energy efficiency, mainly due to the reduced cell size, and in meeting future demands for higher data throughput. However, such densification also introduces the need for a backhaul infrastructure that can sustain the increased data rates.

These backhaul links are illustrated in Figure(III.4) [40], connecting macro cells, small cells, remote radio heads (RRHs), and relays. In this context, the use of Massive MIMO as a wireless backhaul solution is particularly attractive. It suggests that, in the long term, the BS may be dedicated primarily to signaling and backhaul functions, while small cells handle the actual data transmission [41].

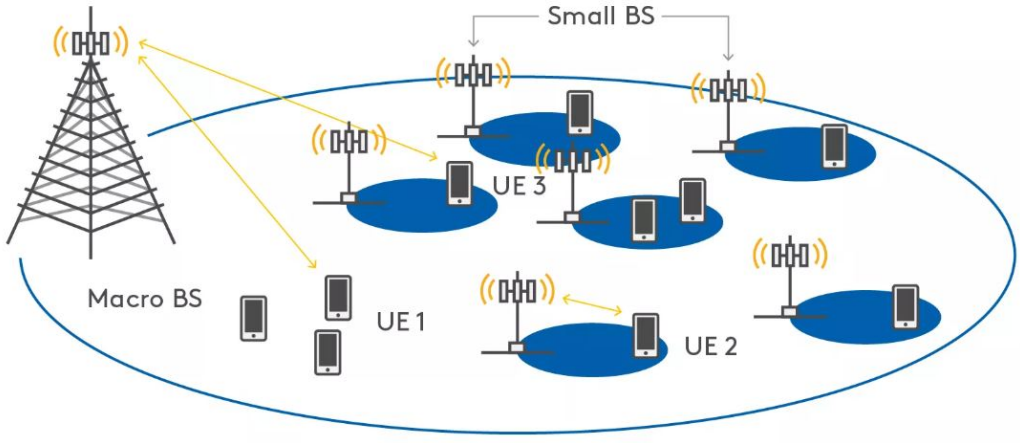


Figure III.4: Heterogeneous network consisting of a macro cell and several small cells to ease data traffic of the macro cell.

III.3.3.6 Millimeter waves

The reduction in cell size brought about by the densification of networks means that very high-frequency systems (>6 GHZ) for future communications. Indeed, covering a large area is no longer possible due to high free-space losses at these frequencies free space at these frequencies, but very wide frequency bands can be used, thus decouple the data rate [41].

III.3.4 Beamforming and massive MIMO

Beamforming is an advanced antenna technique that focuses wireless signals in specific directions rather than broadcasting them uniformly across a wide area. This directional transmission improves signal strength and reduces interference. Beamforming plays a crucial role in conjunction with Massive MIMO to enhance network throughput and capacity.

In Massive MIMO systems, the large number of antennas allows for three-dimensional (3D) beamforming, which steers beams both horizontally and vertically toward individual users. This capability significantly improves data rates and network capacity, especially in dense urban environments with high-rise buildings, where precise spatial targeting is essential for optimal performance [32].

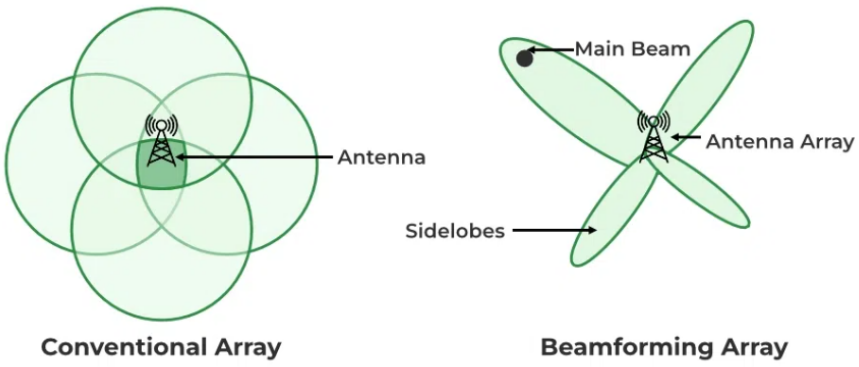


Figure III.5: Beamforming: directional signal transmission in 5G Massive MIMO Systems.

It is a traffic signaling system for cellular base stations that identifies the most efficient path for data transmission to a particular user. It allows the signal to be filtered to create a direct connection between the device and the transmitting antenna, in other words, to have a directed signal see figure III.5 [42]. At the massive MIMO base station, signal processing algorithms map out the best transmission route over the air to each user. They can then send individual data packets in many different directions, sending them back from buildings and other objects in a perfectly coordinated pattern. This improves the stability and strength of the transmitted signal, particularly in congested areas such as public and reduces interference for nearby users. Depending on the situation and technology [43].

There are several ways of implementing beamforming for 5G networks.Three different architectures is discussed in the following subsections:

III.3.4.1 Digital beamforming

DBF is a signal processing technique in which the signal is precoded in the baseband before being transmitted via the radio frequency (RF) front-end. This enables the formation of multiple independent beams(typically one per user) from the same set of antenna elements, as illustrated in FigureIII.6. In the context of LTE/4G, DBF corresponds to (MU-MIMO), and in 5G networks, it remains a fundamental component of the radio access strategy.

To support MU-MIMO, the base station must incorporate several digital transmission chains, each dedicated to a specific user. This allows simultaneous transmission to multiple users using the same physical resources (the same frequency and time slots), effectively increasing spectral efficiency. DBF is implemented in LTE Advanced Pro and plays an even more prominent role in 5G NR. It significantly enhances overall cell capacity by enabling concurrent data streams to be transmitted to multiple users using shared physical resource blocks (PRBs), while minimizing interference through spatial separation and beam-level control [44], Figure III.6 illustrates the functional structure of digital beamforming [44]. It shows how baseband signals are digitally precoded per user, passed through multiple digital-to-analog converters and RF chains, and transmitted via an antenna array to form focused beams directed at specific users. Each beam can be dynamically adapted based on channel conditions, user mobility, and scheduling requirements, showcasing the flexibility and intelligence of DBF in 5G radio access.

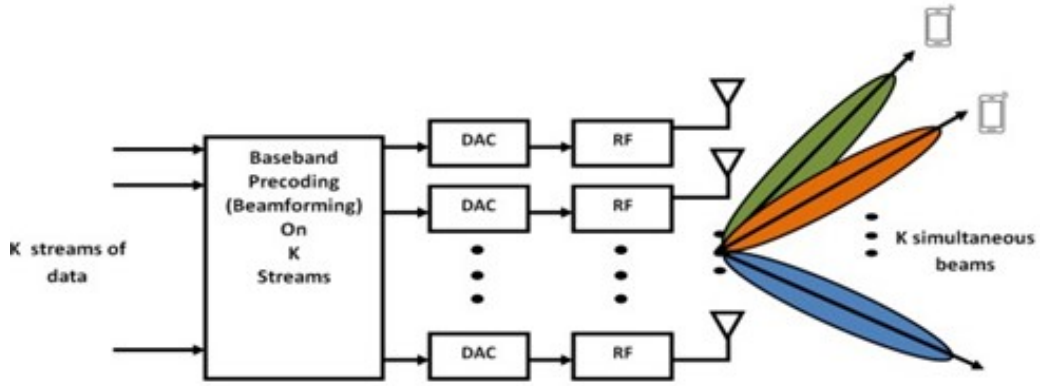


Figure III.6: DBF Beamforming.

III.3.4.2 Analog beamforming

ABF is a simpler beamforming technique, primarily suited for single-user applications. In ABF, the same signal is distributed to all antenna elements, with analog phase shifters applied at the RF stage to steer the beam in a desired direction. By adjusting the phases of the signals fed to each antenna element, the radiated waves are combined constructively in a specific direction, enhancing the signal strength toward the intended user.

This approach follows the principle of phase gratings, a well-established concept in wave propagation and antenna theory. The key distinction between ABF and DBF lies in the processing

domain: DBF applies phase and amplitude adjustments at the baseband level across multiple data streams (K streams), enabling support for multiple users and streams simultaneously. In contrast, ABF performs phase shifting after the digital-to-analog conversion (DAC), and is limited to a single data stream per user [44], As illustrated in Figure III.7, the ABF architecture consists of a single baseband processing chain feeding a digital-to-analog converter, followed by an RF chain connected to an array of phase shifters [44]. These phase shifters are used to apply different phase offsets to the signal sent to each antenna element, enabling beam steering in a specific direction. This hardware-efficient structure makes ABF attractive for millimeter-wave applications and small form-factor devices, though at the cost of reduced spatial flexibility compared to digital beamforming.

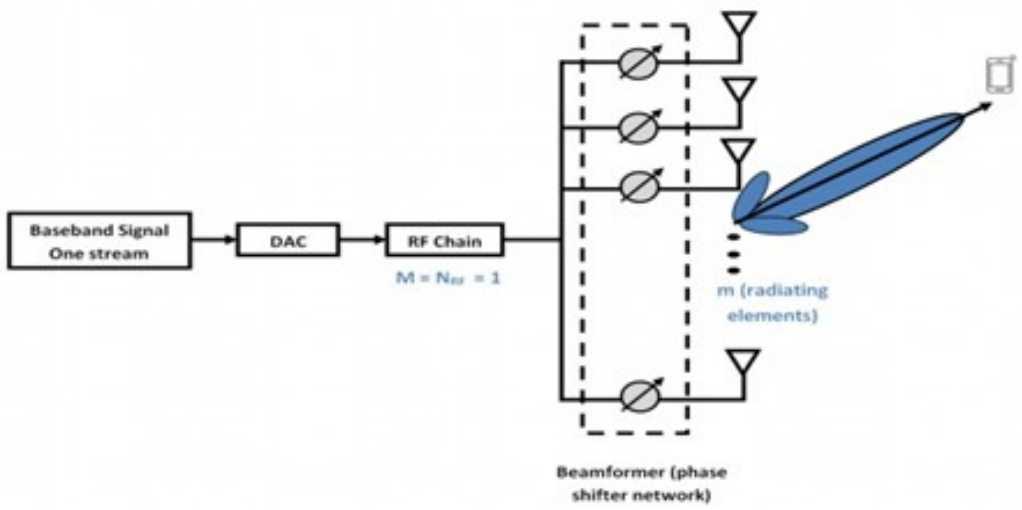


Figure III.7: ABF principle.

III.3.4.3 Hybrid beamforming

Hybrid beamforming combines both analog and digital techniques to achieve an optimal balance between performance and complexity. In millimeter-wave 5G base stations, a common strategy is to apply analog beamforming for initial coarse beam steering, followed by digital beamforming within each analog beam. This digital processing can support either SU-MIMO or MU-MIMO, depending on the scenario [45], Figure III.8 illustrates the architecture of hybrid beamforming [44]. It shows how a limited number of digital baseband processing chains are connected to a larger number of antenna elements via analog phase shifters. The digital stage handles baseband precoding for multiple users or streams, while the analog stage performs beam steering using phase shifts applied at the RF domain. This approach enables multi-user support and beamforming flexibility while reducing hardware complexity compared to full digital beamforming.

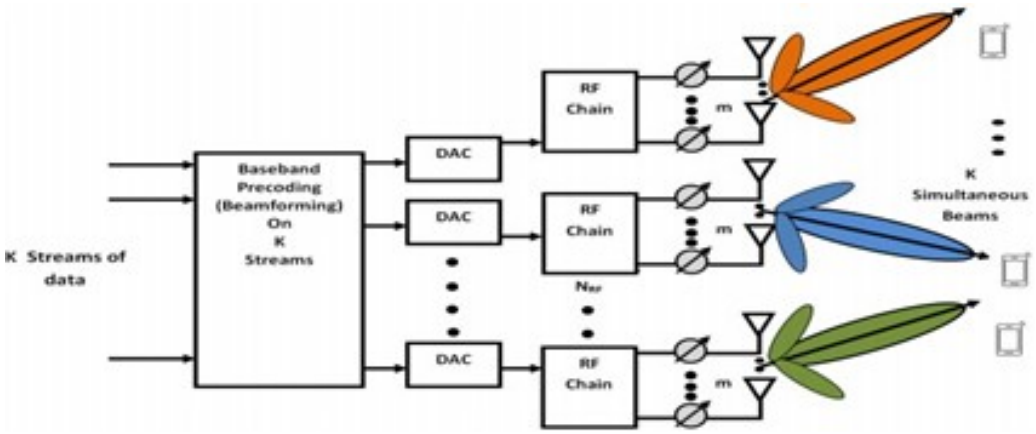


Figure III.8: Hybrid beamforming.

III.4 Channel estimation

Massive MIMO systems fundamentally rely on spatial multiplexing, which necessitates accurate channel state information (CSI) at the base station. In the uplink, users transmit known training sequences, allowing the base station to estimate each user's channel response. However, obtaining precise CSI for downlink transmission is more challenging, as the base station must acquire knowledge of the forward channel in advance.

In TDD systems, channel reciprocity is assumed meaning the uplink and downlink channels are considered identical within a given coherence interval. This allows the base station to use the uplink channel estimates for downlink transmissions. While TDD offers a significant advantage in reducing feedback overhead, calibration between the transmitter and receiver hardware chains is essential to preserve reciprocity [46].

In contrast, FDD systems do not benefit from channel reciprocity. Instead, they operate in a closed-loop manner: users send training sequences for uplink channel estimation, while downlink channel estimation requires the base station to transmit pilots, followed by limited CSI feedback from the users. This process is both bandwidth- and computation-intensive, especially as the number of antennas increases.

Consequently, the training overhead in TDD systems scales with the number of users, whereas in FDD systems it scales with the number of base station antennas, making TDD more favorable for large-scale antenna deployments. Figure(III.9) illustrates the time-slot structure used for channel estimation in both FDD and TDD architectures [47].

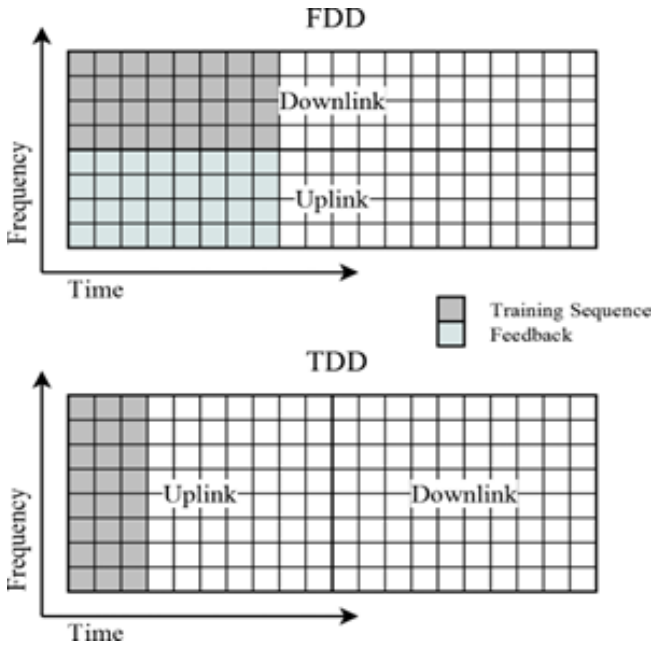


Figure III.9: Time slot with channel estimation for FDD and TDD systems.

Despite the adoption of FDD in the current LTE standard, integrating FDD into Massive MIMO systems presents significant challenges. One major issue arises from the need for orthogonality among downlink pilot signals. In Massive MIMO, where the base station may have hundreds of antennas, achieving this orthogonality requires a proportional increase in time-frequency resources. Consequently, the number of orthogonal training sequences becomes a limiting factor, and supporting a large number of antennas would demand hundreds of times more resources than in conventional MIMO systems.

Moreover, each terminal must estimate a channel response for every base station antenna, increasing the computational burden and energy consumption at the user end. This feedback requirement adds latency and degrades the performance, especially in mobile scenarios. Additionally, quantization errors due to limited feedback capacity and CSI aging, caused by the time delay between estimation and application, further deteriorate the accuracy of CSI In [48], the issue of non-ideal CSI is examined, highlighting the trade-off between the benefits of large antenna arrays and the overhead required to estimate high-dimensional channel vectors in FDD-based systems.

These challenges underscore a key problem in scaling up antenna arrays: new constraints emerge that were not significant in conventional MIMO. To address these issues, most Massive MIMO systems adopt TDD, which leverages channel reciprocity. In TDD, the channel estimates obtained from uplink transmissions can be reused for downlink, drastically reducing the need for downlink pilot transmission. This is especially advantageous because, in TDD, the required pilot overhead is independent of the number of base station antennas. Alternatively, some research has proposed FDD schemes that function under reduced CSI accuracy [49].

Furthermore, both the base station and mobile devices in a MIMO network must be tightly coordinated. The base station transmits channel (CSI-RS) enable UE to measure the propagation

characteristics of the channel. The UE then computes the CSI, which includes information about signal scattering, fading, and power loss over distance, and sends it back to the base station.

This CSI is critical for efficient transmission: it allows the base station to exploit spatial multiplexing, enabling simultaneous and independent communication with multiple users. At the receiver side, the MIMO decoder performs advanced signal processing, using the CSI to reconstruct the transmitted data streams accurately. The channel transfer function is typically represented in matrix form and relies on CSI acquisition, as illustrated in Figure III.10 [50], where the CSI-RS is sent by the gNB and the UE responds with feedback for accurate downlink data transmission.

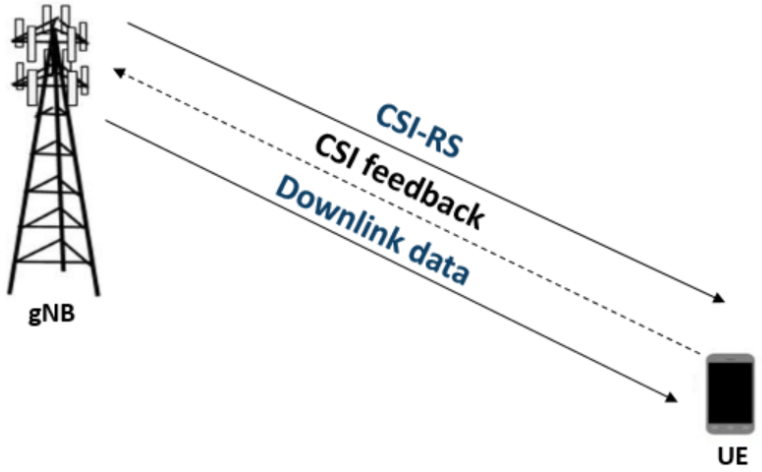


Figure III.10: CSI-RS transmission and feedback mechanism in a MIMO system.

The **channel transfer matrix**, defines the relationship between transmitted and received signals as follows:

$$[R] = [H] \times [T] \tag{III.2}$$

Here, $[R]$ denotes the set of signals received by the antenna elements at the base station, $[T]$ represents the transmitted data streams, and $[H]$ is the channel matrix, encapsulating the characteristics of the wireless propagation paths (e.g., attenuation, fading, and phase shifts).

To recover the original transmitted data, the receiver must estimate the channel matrix $[H]$ using the acquired CSI and then compute the inverse of this matrix, enabling the reconstruction of the transmitted signal as:

$$[T] = [H]^{-1} \times [R] \tag{III.3}$$

This process, however, is computationally demanding, especially as the number of antennas in the MIMO system increases. The estimation of each channel coefficient becomes more complex and contributes significantly to the system overhead.

It should be noted that this formulation is a simplification. In practice, CSI acquisition and channel estimation techniques vary depending on the duplexing mode (TDD vs FDD), the carrier

frequency (e.g., sub-6 GHz or mmWave), and the mobility of the UE. These factors influence not only the accuracy but also the latency and overhead of CSI feedback.

Consequently, modern research is increasingly exploring machine learning (ML) techniques, particularly neural networks and autoencoders, to improve CSI estimation, compression, and feedback accuracy in Massive MIMO environments [32].

III.5 Linear pre-coding techniques

Linear pre-coding techniques, sometimes referred to as beam, have been widely developed over the last few decades. It is considered an advantageous way to exploit the full diversity of the chain. For MU-MIMO systems, assuming a flat fading channel, the techniques of pre-coding are used to form a beam signal via the target user all by reducing interference from other users. In general, in addition to capacity optimization of singular value decomposition (SVD), the methods of linear pre-coding can be classified according to two approaches: zero forcing (ZF) such as ZF and the regularized ZF method (RZF)/minimum mean square error (MMSE). This approach seeks to minimize among users and leads to a centralized architecture in which the base collects the channel response from all users to form the pre-coding matrix. The conjugate pre-coding approach is based on the report algorithm maximum ratio (MR), to maximize the useful signal strength on the receiving side.

This approach generally uses the channel response conjugate as pre-coders, to allow for pre-coded signals from different antennas of add "in phase" to the location of the receptor, this phenomenon is also called spatial focus. The conjugate pre-coding approach often leads to decentralized architecture in which antenna processing is feasible. The computational complexity is greatly reduced compared to the ZF approach. In this part, the different pre-coding techniques are presented, in which each OFDM subcarrier is considered as a subchannel with flat fainting. A transmission scenario of a BS with M transmitting antennas and K users of a single antenna is considered. One perfect synchronization is assumed between the base station and users [51].

- Singular value decomposition: SVD-based pre-coding strategies are thought to be the best ways to maximize system performance. Actually, a collection of independent, parallel links could make up the channel MIMO; the maximum number of links would be equal to the minimum number of sending and receiving antennas. Applying SVD to the channel matrix creates parallel channels with perfect CSI.

$$H_p = U \rho D_p V_p^H \tag{III.4}$$

The matrix $\mathbf{U}_p \in \mathbb{C}^{M \times M}$ is employed at the transmitter as a pre-coding matrix, while $\mathbf{V}_p \in \mathbb{C}^{K \times K}$ is applied at the receiver as a post-coding matrix. This configuration enables the transmission of signals through independent beams, which correspond to the vectors of the channel correlation matrix $\mathbf{H}_p^H \mathbf{H}_p$. The power allocated to each beam is given by the squared singular values, represented by $\mathbf{D}_p^2$.

However, SVD technique presents a notable drawback in terms of high computational com-

plexity. Furthermore, the post-coding matrix must be conveyed to the UE in order to enable proper decoding of the received signals [51].

- Maximum ratio: With the maximum ratio (MR), the base station wants to maximize the signal-to-noise ratio (SNR) received from each stream while ignoring the effect of received multi-user signal interference because there is no active attenuation of interference. Next, the precoding matrix is given by:

$$\mathbf{F}_{\mathrm{MR}} = \alpha_{\mathrm{MR}}\mathbf{H}^{H} \tag{III.5}$$

Where α_{MR} is a normalizing scalar that controls the transmit power and the resulting SNR. The MR technique maximizes the transmission matrix gain; however, as it ignores the impact of multi-user interference, it performs poorly in high-interference environments [52].

- Zero forcing: ZF is a linear precoding technique designed to eliminate interference, including both inter-user and inter-symbol interference. The ZF precoding matrix is defined as the pseudo-inverse of the channel matrix:

$$\mathbf{F}_{\mathrm{ZF}} = \alpha_{\mathrm{ZF}}\mathbf{H}^{H}(\mathbf{H}\mathbf{H}^{H})^{-1} \tag{III.6}$$

where α_{ZF} is a normalization factor that ensures the total transmit power constraint is satisfied.

The key difference between ZF and Maximum Ratio Transmission (MRT) lies in the inversion of the channel Gram matrix, $\mathbf{H}\mathbf{H}^{H}$, which enables ZF to effectively cancel multi-user interference. However, this advantage comes at the cost of higher computational complexity due to the matrix inversion. In the context of Massive MIMO, the channel matrices exhibit favorable properties such as asymptotic orthogonality, allowing for significant simplification of the inversion operation and making ZF more computationally feasible [52].

- Regularized zero forcing and MMSE: In addition to MR and ZF precoding, a more flexible linear pre-coding scheme called RZF can be employed. RZF lies between MR and ZF, combining characteristics of both. The RZF pre-coding matrix is given by:

$$\mathbf{F}_{\mathrm{RZF}} = \alpha_{\mathrm{RZF}}\mathbf{H}^{H}\left(\mathbf{H}\mathbf{H}^{H} + \beta_{\mathrm{reg}}\mathbf{I}_{KN}\right)^{-1} \tag{III.7}$$

Here, β_{reg} is the regularization parameter, which can be tuned to balance between signal amplification (as in MR) and interference suppression (as in ZF). α_{RZF} is a normalization factor to ensure transmit power constraints are met.

When β_{reg} is optimized to minimize the Mean Square Error (MSE), the RZF precoding approach becomes particularly effective in scenarios with noise and interference. The MSE is defined as:

$$\mathbb{E}\left\|\mathbf{u} - \frac{1}{\sqrt{P}}\hat{\mathbf{u}}\right\|^{2} \tag{III.8}$$

where P is a power normalization constant, $\mathbf{u}$ denotes the original symbols intended for the

users, and $\hat{\mathbf{u}}$ represents the received signals after precoding and transmission. Minimizing this error yields the well-known MMSE precoder, which is robust in environments with limited channel knowledge and high levels of noise or interference [52].

III.6 Key Benefits of Massive MIMO

Massive MIMO has emerged as a transformative technology in modern wireless communication systems, offering a multitude of benefits that significantly enhance network performance and user experience [33]. The key advantages include:

- **Increased Spectral Efficiency:** One of the primary advantages of Massive MIMO is its ability to greatly enhance spectral efficiency. By utilizing a large number of antennas at the BS, Massive MIMO enables the simultaneous transmission to multiple users over the same time and frequency resources, thereby maximizing spectrum utilization. This leads to higher network capacity and faster data rates for end-users.
- **Improved Coverage:** Massive MIMO extends the coverage area of wireless networks by leveraging beamforming techniques and multiple antennas to focus signal power more effectively. This allows for stronger and more reliable signal reception, especially in challenging environments such as rural areas or deep indoor locations where signal degradation is common.
- **Reduced Interference:** Through spatial filtering and beamforming, Massive MIMO significantly mitigates inter-user and inter-cell interference. The base station can steer beams precisely towards intended users while minimizing leakage to others, resulting in cleaner transmission and enhanced signal quality across the network.
- **Increased Energy Efficiency:** Beamforming not only improves signal quality but also contributes to energy savings. By concentrating transmission power in the desired direction rather than broadcasting omnidirectionally, Massive MIMO reduces overall power consumption, thereby increasing the energy efficiency of the network.
- **Enhanced User Experience:** The combination of higher data rates, improved reliability, and lower latency contributes to a better user experience. Users benefit from fewer dropped calls, consistent data throughput, and a more seamless connectivity experience, especially in dense urban scenarios or high-demand environments.

III.7 Future directions and challenges in Massive MIMO

As the adoption of Massive MIMO continues to accelerate in advanced wireless networks, ongoing research explores both the future potential of the technology and the key challenges that must be addressed to ensure its full realization.

III.7.1 Future Directions

This section outlines promising directions for future research and highlights the main technical and practical challenges that researchers must overcome [53].

- **Beyond 5G and 6G:** Massive MIMO is expected to play a central role in the evolution of wireless networks beyond 5G, particularly in shaping the vision of 6G. Future research will focus on enhancing massive MIMO capabilities to meet the stringent requirements of ultra-reliable low-latency communications (URLLC), extreme connectivity, and significantly higher spectral efficiency.
- **Millimeter-Wave Massive MIMO:** The integration of millimeter-wave (mmWave) frequencies with massive MIMO is a key area of interest for enabling ultra-high-speed communication in dense urban environments. Future work will explore hybrid beamforming techniques, hardware-efficient architectures, and robust propagation models to overcome challenges such as path loss and blockage at mmWave bands.
- **Intelligent Massive MIMO:** The application of Artificial Intelligence (AI) and ML to massive MIMO is a rapidly growing research area. AI-enabled MIMO systems can dynamically optimize beamforming, scheduling, and resource allocation, adapting in real-time to network conditions and user mobility.
- **Massive MIMO for IoT:** As the number of IoT devices continues to grow, future research will investigate the application of massive MIMO in supporting massive connectivity, low-power communication, and low-latency services in dense IoT scenarios.
- **Massive MIMO in Satellite Communications:** With the emergence of non-terrestrial networks and 6G satellite systems, massive MIMO is poised to enhance satellite communication by enabling high-throughput, low-latency links and seamless integration with terrestrial networks.

III.7.2 Research Challenges

While massive MIMO offers unprecedented improvements in wireless network capacity, efficiency, and reliability, several critical challenges must be addressed to enable its widespread deployment and practical implementation [53]. These include:

- **Hardware Complexity and Cost:** Deploying large-scale antenna arrays poses significant challenges in terms of hardware cost, design complexity, and energy consumption. Future research will aim to develop low-cost, scalable, and energy-efficient hardware solutions, including compact RF front-end components and advanced antenna array designs.
- **Channel Estimation and Feedback Overhead:** Accurate CSI is essential for massive MIMO performance. However, in FDD systems, the overhead associated with pilot signals and

feedback is significant. Research will continue to explore efficient channel estimation techniques, such as compressive sensing and downlink (DL), to reduce overhead and improve estimation accuracy.

- **Interference Management and Coexistence:** In dense deployments, inter-cell and intra-cell interference can degrade system performance. Advanced interference mitigation techniques, such as coordinated beamforming, dynamic spectrum allocation, and interference alignment, will be critical research areas moving forward.
- **Mobility and Handover Management:** High-mobility environments, such as vehicular networks, introduce challenges in maintaining stable connections and performing efficient handovers. Future work will explore predictive beam tracking, fast handover protocols, and mobility-aware scheduling algorithms.
- **Security and Privacy:** As the number of connected devices and the complexity of wireless systems grow, ensuring data security and user privacy becomes increasingly important. Future research will focus on developing lightweight encryption schemes, secure beamforming techniques, and authentication mechanisms tailored for massive MIMO architectures.

III.8 Conclusion

From prior generations antenna systems were quite basic, MIMO propelled the development of 4G networks, and finally 5G networks are now built upon the foundations of massive MIMO technology. Due to the increase in antennas, intricate beam steering, and channel estimation, the efficiency with which Massive MIMO can serve numerous users is unparalleled. Especially in conjunction with AI and mmWave frequencies, Massive MIMO is predicted to be crucial in 6G networks adding to the growing in the communications industry, mastering this technology prepares you for future challenges.

CHAPTER IV

PLANNING AND OPTIMIZATION IN 5G NETWORK

IV.1 Introduction

5G is the latest generation of mobile networks, offering ultra-fast speeds, low latency, and support for massive device connectivity. To ensure efficient deployment, two key phases are involved: network planning and optimization. Planning in 5G involves determining the ideal locations for base stations, calculating coverage and capacity, and selecting suitable frequency bands. Due to the use of higher frequencies (like mmWave), planning requires precision. Engineers often use professional tools like Atoll, a powerful radio planning software that simulates coverage, predicts signal quality, and helps design optimal network layouts. Once deployed, the network enters the optimization phase, this includes adjusting parameters, balancing traffic, and enhancing performance in real time. Tools like Huawei iMaster assist operators by using AI and automation to monitor KPIs, detect issues, and implement self-optimizing solutions. Together, planning with Atoll and optimization with iMaster ensure a high-performance 5G network that meets user demands efficiently.

IV.2 5G Network planning coverage and capacity

Planning a 5G network is a foundational step in deploying a next-generation mobile communication system. With ambitious goals such as ultra-fast speeds, ultra-low latency, and massive connectivity, the success of 5G hinges on strategic planning. This process ensures that the network meets both the performance expectations of users and the technical requirements of operators. At the core of 5G planning lie two essential domains: coverage planning and capacity planning. While these domains serve different purposes, they are inherently interconnected and must be managed together to create a robust and sustainable network [54].

IV.2.1 Coverage planning

Coverage planning is a fundamental aspect of 5G network deployment that focuses on ensuring that the radio signal is both available and strong enough throughout the entire geographical area intended for service. This involves designing the network so that users can maintain continuous and reliable connectivity, regardless of their location or movement within the coverage zone. The goal is not only to extend the signal reach but also to maintain its quality, even in challenging environments. These include urban settings with high-rise buildings that can obstruct signals, rural areas with wide-open spaces that require larger coverage per site, and complex environments like underground tunnels, shopping malls, subways, and dense indoor environments where traditional signal propagation is limited. To achieve optimal coverage, engineers consider various factors summarized in Table IV.1 [54].

Table IV.1: 5G network planning considerations

Category	**Description**
Frequency Band Selection	
Low frequencies (<1 GHz)	Example: 700 MHz — Excellent for long-distance propagation and indoor penetration.
Mid frequencies (1–6 GHz)	Example: 3.5 GHz — Good compromise between coverage and capacity.
mmWave (>24 GHz)	Very high data rates, but short range and poor indoor penetration.
Cell Types	
Macro cells	Cover large geographic areas; typically used for outdoor coverage.
Micro/Pico cells	Used in high-density urban zones to improve coverage locally.
Femto cells	Small cells installed indoors to extend indoor network coverage.
Propagation Models	
Environment simulation	Takes into account terrain, building density, and vegetation.
Planning tools	Software such as Atoll, iBwave, and Planet simulate and predict coverage.
Technical Parameters	
Configuration details	Includes transmit power, antenna height, tilt angle, polarization type, and more.

The main goal is to minimize coverage gaps (so-called "white zones") while avoiding unnecessary overlap between cells.

IV.2.2 Capacity planning

Capacity planning in 5G networks focuses on ensuring that the infrastructure can accommodate the expected traffic load while maintaining high service quality and avoiding network congestion. As mobile data usage continues to grow rapidly due to high-definition video streaming, real-time

gaming, cloud applications, and the IoT, effective capacity planning becomes increasingly essential. To address these challenges, capacity planning involves planning all parameters summarized in Table IV.2 [54].

The goal is to maintain consistent service quality, even under high traffic demand.These two types of planning coverage and capacity must be tightly integrated to ensure a high-performing, scalable, and optimized 5G network that meets both user needs and technical or economic constraints.

Table IV.2: 5G Network Enhancement Techniques

Category	**Description**
Network Densification	
Small Cells	Used to offload traffic from macro base stations in high-density areas.
Cell Size Reduction	Decreases user load per cell, improving performance and reducing interference.
Advanced Technologies	
Massive MIMO	Supports multiple data streams simultaneously using arrays of antennas.
Beamforming	Directs radio signals towards users, improving signal strength and spectral efficiency.
Carrier Aggregation	Combines multiple frequency bands to increase total available bandwidth and throughput.
DSS (Dynamic Spectrum Sharing)	Dynamically allocates spectrum between 4G and 5G networks, optimizing resource use.
Traffic Forecasting	
User Behavior Analysis	Considers usage patterns such as video streaming, gaming, and IoT demands.
Load Estimation	Projects needs based on user count, peak usage hours, and anticipated traffic during special events.

IV.2.3 Radio propagation models

This section introduces the most widely used radio propagation models for wireless network planning. These models help predict signal behavior over distance and terrain, enabling accurate coverage estimation. Each model—such as FSPL, Hata, and COST-231—caters to specific environments and frequencies, supporting efficient 2G to 4G network design [55].

1. **Free space path loss model:** The Free space path loss (FSPL) model is a theoretical model used to predict the path loss of a radio signal in free space. It assumes no obstacles between transmitter and receiver (Line-of-Sight, LoS).

$$\text{FSPL (dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \quad \text{(IV.1)}$$

Where: d is the distance in meters, f is the frequency in Hz, c is the speed of light in vacuum ($\approx 3 \times 10^8$ m/s).

Use cases: Satellite communication, LoS links, point-to-point wireless systems.

2. **COST-231 Hata model:** An extension of the Hata model for frequencies up to 2 GHz, developed under the COST European framework.

$$L = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_t) - a(h_r) + \big(44.9 - 6.55\log_{10}(h_t)\big)\log_{10}(d) + C \quad \text{(IV.2)}$$

Where C is an environment-dependent correction factor (urban: 3 dB, suburban/rural: 0 dB).

Use Cases: 3G, 4G network design in urban/suburban areas.

3. **Okumura Model:** Based on extensive measurements, used in urban and suburban areas over 100 MHz–3 GHz.

$$L = L_0(f, d) + G(h, f) \quad \text{(IV.3)}$$

Where: $L_0(f, d)$ is the basic path loss, $G(h, f)$ is a gain correction factor depending on antenna height and frequency.

Use Cases: Urban macrocell design, general-purpose planning.

IV.2.4 Link budget

When planning a long road trip to a remote destination, one of the first considerations is the fuel requirement. One considers the storage capacity and rate of consumption to calculate the fuel required to not only reach the destination, but to also arrive with some level of reserve or margin of safety—accounting for the unforeseeable. A very similar process is involved in planning an RF telemetry link. One begins with the output power capacity of the transmitter and sums the system gains and losses to determine the level of power actually delivered to the receiver. To ensure a reliable link, the level of power available to the receiver should be in excess of that required for a minimum level of performance. An account of all the various gains and losses between the transmitter and the receiver is referred to as the link budget. The system factors involved in this accounting are illustrated in Figure IV.1 [56].The link budget parameters are summarized in Table IV.3.

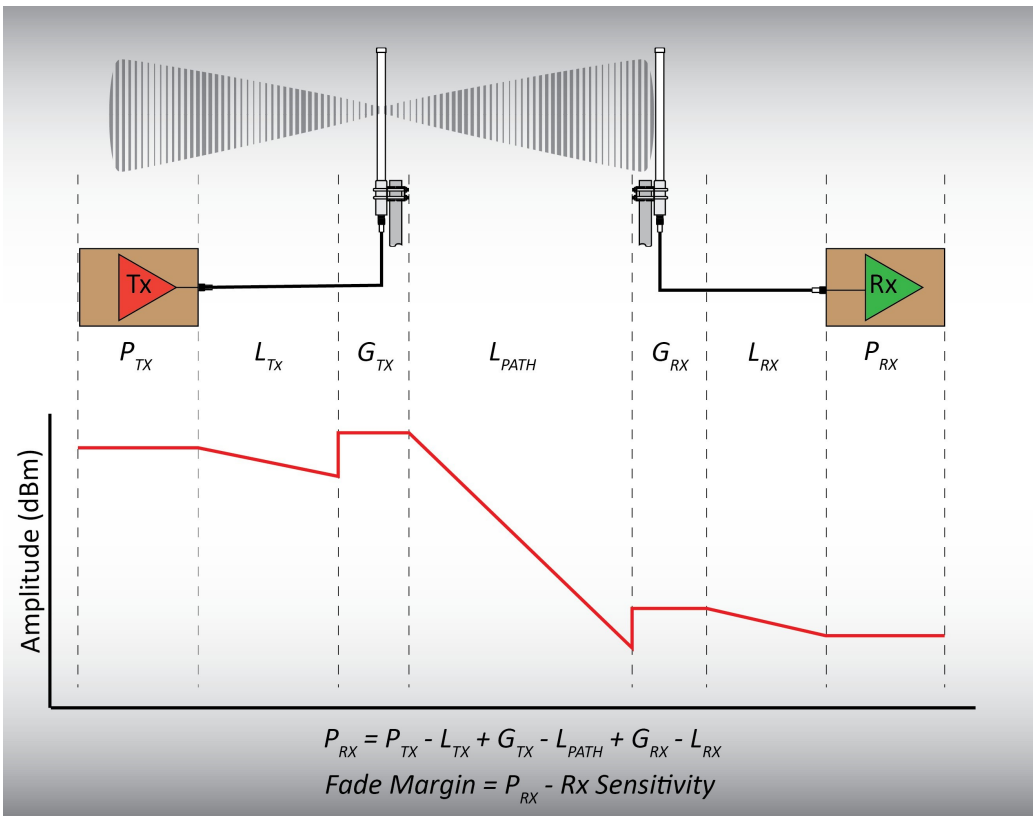


Figure IV.1: System Gain-Loss Profile for a Link Budget.

Table IV.3: Link budget parameters.

Parameter	Description
PTX	The transmit power in dBm.
LTX	The total system loss in dB at the transmitter.
GTX	The antenna gain in dBi at the transmitter.
LPATH	The total propagation losses in dB between the transmit and receive antennas.
GRX	The antenna gain in dBi at the receiver.
LRX	The total system loss in dB at the receiver.
PRX	The receive power in dBm.

- The level of received power in excess of that required for a specified minimum level of system performance is referred to as the **fade margin**. It provides a margin of safety in the event of temporary attenuation or fading of the received signal power.
- The minimum required received power level used for the link budget is often tied to the **receiver's sensitivity**, which specifies the minimum RF input power required to produce a usable output signal. Typical receiver sensitivity values range from –90 to –120 dBm.
- A **link budget** provides a quick, simplistic assessment of a link's viability and is best used as a preliminary design tool. It gives only theoretical approximations and does not account for many real-world variables.

- All link budgets should be **verified via empirical measurements** before committing to installation. Analysis is no substitute for real-world data.
- For mission-critical RF telemetry links, the design goal should be a minimum fade margin of **20 to 30 dB**.
- If calculations or measurements indicate a fade margin of less than **10 dB**, the following improvement measures should be considered:
  - **Use a higher-gain antenna** on one or both ends of the link. Ensure compliance with regulations (e.g., FCC) regarding maximum radiated power.
  - **Increase antenna elevation** at one or both ends. Even a small change (as little as half a wavelength) can significantly improve signal reception if path obstructions or multipath effects are present.
  - **Add a repeater site** to the path. This helps mitigate large path loss, the most significant factor in a link budget.
- There are many **online calculators and software tools** available for link budget and path loss estimation—some are more reliable than others and should be chosen carefully.

IV.2.5 Radio parameters configuration

IV.2.5.1 NR PCI planning

In 5GNR networks, each cell is identified by a **PCI**, which is essential for distinguishing cells on the radio side. The PCI plays a crucial role in several processes, including synchronization, demodulation, and handover signaling. Poor PCI planning can lead to performance issues, such as synchronization failures and degraded service quality.

The PCI planning for 5GNR is very similar to PCI planning for LTE and scrambling code planning for 3G UMTS. Bad or incorrect planning can adversely affect the synchronization procedure, demodulation, and handover signaling, ultimately degrading network performance. However, PCI planning should be simpler for 5GNR compared to LTE because there are double the number of PCIs available for allocation.

In 5GNR, there are **1008 unique PCIs** available, compared to **504 in LTE**. The formulation for calculating the PCI is based on the following parameters [57]:

- $N_{\mathrm{ID}}^{(1)}$: This represents the **Secondary Synchronization Signal (SSS)** and its range is from $\{0, 1, \ldots, 335\}$.
- $N_{\mathrm{ID}}^{(2)}$: This represents the **primary synchronization signal (PSS)** and its range is from $\{0, 1, 2\}$.

The PCI is calculated using the formula:

$$\text{PCI} = 3 \times N_{\text{ID}}^{(2)} + N_{\text{ID}}^{(1)} \tag{IV.4}$$

This means that for each value of $N_{\text{ID}}^{(2)}$, there are 336 possible values of $N_{\text{ID}}^{(1)}$, resulting in a total of 1008 unique PCIs. Proper planning and allocation of these PCIs are critical to ensuring efficient network operation and minimizing interference among cells. The principle of PCI planning is illustrated in Figure IV.2 [57].

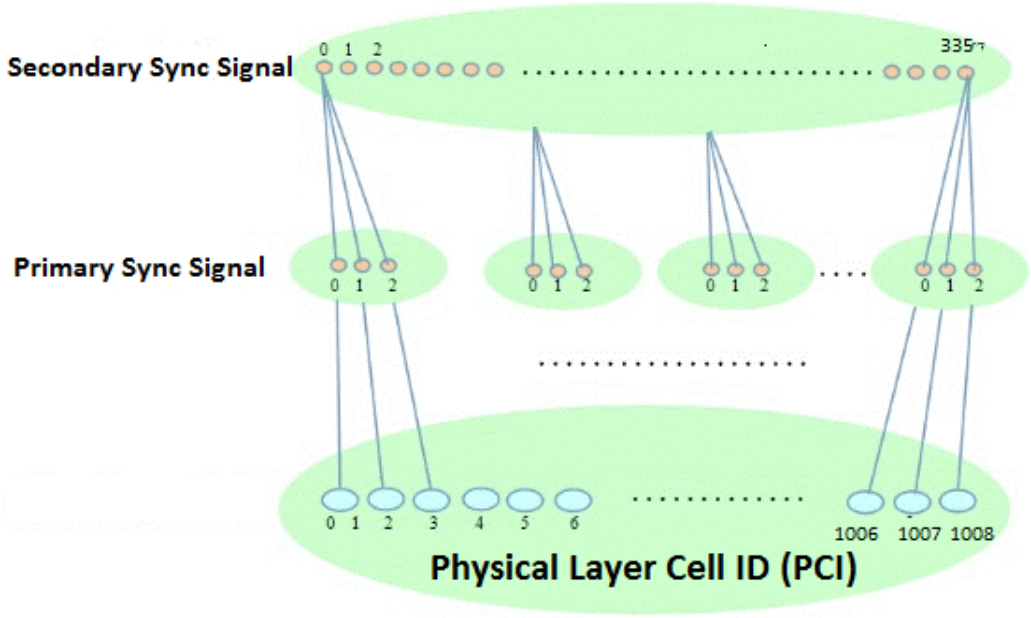


Figure IV.2: PCI generation and distribution concept.

IV.2.5.2 PCI planning in 5GNR

5G PCI planning should be done keeping the following aspects in mind [57]:

- **Avoiding PCI collision:** As part of this principle of network planning, neighboring cells must not be allocated the same PCI. If neighboring cells share the same PCI, only one of them can be synchronized by the UE during the initial cell search in overlapping areas. However, this cell may not be the most appropriate one, leading to incorrect cell selection. This issue is referred to as a *PCI collision*. To prevent this, sufficient physical separation between cells using the same PCI must be ensured, so that a UE never receives the same PCI from more than one cell. This can be achieved by maximizing the PCI re-use distance.
- **Consequences of PCI Collision:**
  - Delay in downlink (DL) synchronization in overlapping zones.
  - Increased block error rate (BLER) and decoding failures of physical channels scrambled using PCI.
  - Handover failures due to ambiguity in PCI-based identification.

An illustration of these PCI planning principles is shown in Figure IV.3 [57].

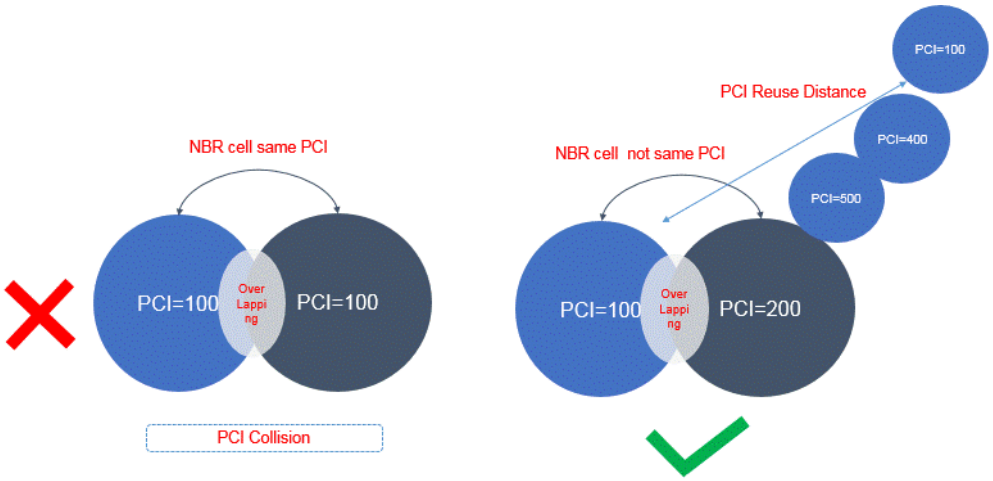


Figure IV.3: PCI planning example illustrating collision risks.

IV.2.5.3 Avoiding PCI confusion

Under this principle of network planning, two neighboring cells of the same cell must not be allocated the same PCI. If they are, the base station will not be able to determine the correct target cell when processing a handover request from a UE. This leads to a confusion situation. To avoid this, PCI allocation must be done such that a cell does not have multiple neighbors using the same PCI. Furthermore, the physical separation between cells using the same PCI should be sufficiently large to prevent neighbor confusion. An illustration of this confusion scenario is presented in Figure IV.4 [57].

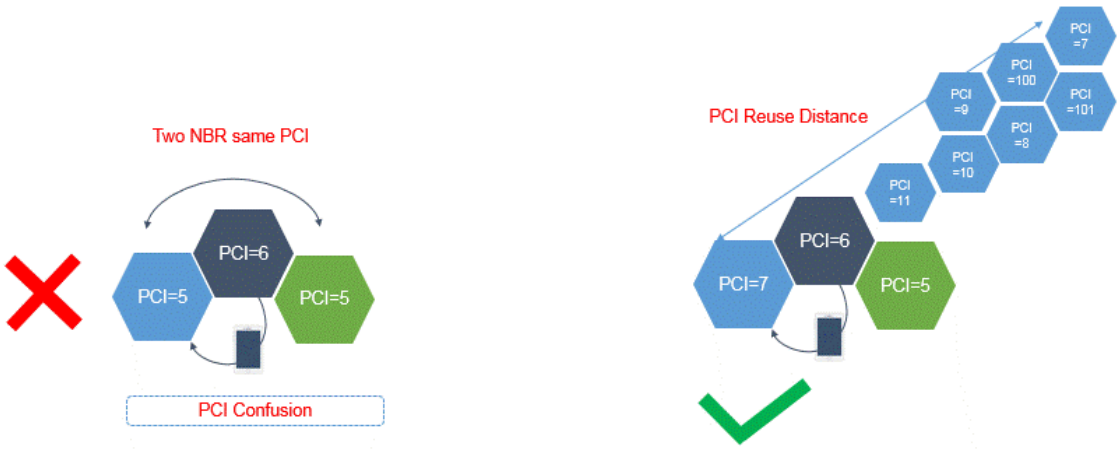


Figure IV.4: Example of PCI confusion due to neighboring cells using the same PCI.

Based on the design of various physical layer signals such as PSS, demodulation reference signal (DMRS), and **SRS!** (**SRS!**), as well as channels like **PUSCH!** (**PUSCH!**) and **PUCCH!** (**PUCCH!**) and their time-frequency allocations, PCI planning must adhere to certain modulus rules to min-

imize interference. These rules are necessary to avoid resource conflicts and signal interference during initial access, channel estimation, and uplink/downlink transmissions.

To reduce interference, a UE should not simultaneously receive multiple PCIs with the same result under the following modulus operations: **PCI Mod 3**, **PCI Mod 4**, **PCI Mod 30**.

These modulus operations are based on how synchronization and reference signals are generated and allocated in the physical layer. If two or more neighboring cells use PCIs that result in the same value under these modulus rules, it can lead to serious interference.

To illustrate, let us consider the case of PCI Mod 3. If neighboring cells are assigned PCI values such as 25 and 28, both produce the same result when divided by 3:

$$25 \bmod 3 = 1, \quad 28 \bmod 3 = 1$$

This means that both cells would transmit the same PSS sequence (since only three PSS values exist). As a result, the UE may confuse the origin of the signal, leading to synchronization delays, incorrect cell selection, and degraded overall performance. This situation is referred to as **PCI collision** under Mod 3.

Therefore, careful planning is essential to ensure that neighboring cells do not share the same Mod 3, Mod 4, or Mod 30 result, thereby reducing potential interference and ensuring reliable 5G network operation.

This can lead to interference, as both PCIs yield the same Mod 3 value.

- **Why Mod 3:** The PCI Mod 3 rule is based on the relationship between the PCI and the PSS. There are 3 PSS values (0, 1, 2) that are reused throughout the network. Cells with the same Mod 3 result will transmit the same PSS. If a UE receives the same PSS from multiple cells, it may cause delays in cell acquisition and misleading channel estimation. This affects synchronization delay and degrades user experience.
- **Why Mod 4:** The PCI Mod 4 rule is related to the subcarrier positions of the DMRS for PBCH. These subcarriers are determined using Mod 4 computation. If neighboring cells use PCIs with the same Mod 4 result, it may lead to DMRS-to-DMRS interference, impacting downlink performance.
- **Why Mod 30:** The DMRS for PUCCH, PUSCH, and SRS are based on Zadoff-Chu sequences, which are organized into 30 root sequence groups. These groups are associated with PCI values. Therefore, neighboring cells should not have PCIs with the same Mod 30 result to avoid uplink inter-cell interference.

IV.2.5.4 The performance of the random access channel

In the pursuit of seamless connectivity and enhanced user experience, the PRACH plays a key role. The 5GNR PRACH serves as the gateway for the UE to initiate communication with the network,

making it a critical component of the 5GNR architecture. However, its efficiency is profoundly influenced by surrounding interference conditions:

Intra-cell interference: Arises when multiple UEs within the same cell attempt to access the network simultaneously, leading to contention for the PRACH resources.

Inter-cell interference: Emerges when UEs from neighboring cells contend for the same PRACH resources, causing contention across cell boundaries.

These interference scenarios introduce complexities in PRACH detection, impacting network efficiency, latency, and overall QoS. An overview of the NR-PRACH procedure is illustrated in Figure IV.5 [58].

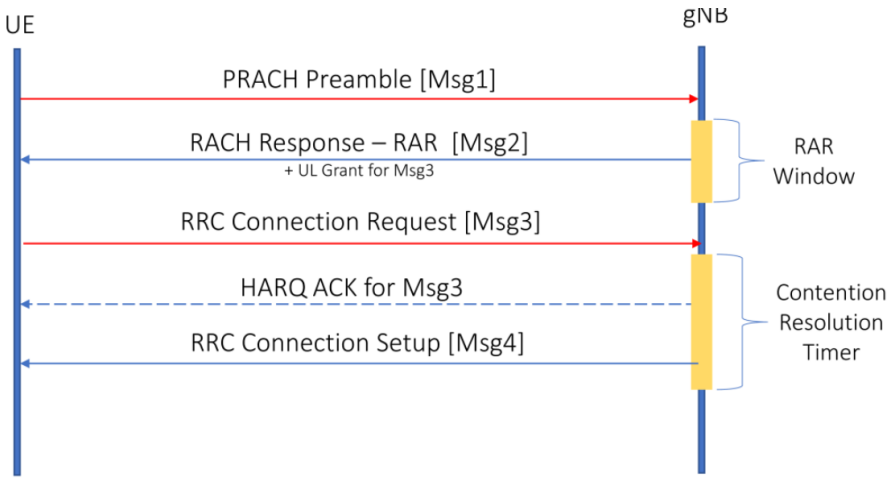


Figure IV.5: NR-PRACH procedure.

The random access process is illustrated in Figure IV.5. The UE randomly selects a preamble from a list of parameters broadcasted through the SIB2 and transmits it over the PRACH, using an initial power level based on a basic downlink pathloss estimation. If no response is received from the gNB, the UE retries the transmission with a higher power level.

IV.2.5.5 5GNR network relationship – neighbor planning

5GNR network planning involves the configuration of specific neighbor relationships to optimize handover performance and idle mode cell reselection. These relationships are essential for managing interference, blacklisting specific cells, and applying power offsets to influence UE behavior during cell selection and reselection in IDLE mode.

The relevant system information blocks (SIBs) for neighbor cell configuration include [59]:

- **SIB3:** Contains intra-frequency neighbor cell information.
- **SIB4:** Used for inter-frequency neighbor cells within the same RAT.
- **SIB5:** Contains neighbor information for inter-RAT cells such as LTE.

- **SIB24:** Introduced in 3GPP Release 15 to support cell reselection for 5GNR cells.

Depending on the deployment architecture, neighbor relationships in 5GNR networks can be categorized as follows:

- **Standalone deployment:** (called also NR–NR neighbors) a 5GNR cell can have intra-frequency neighbors (same ARFCN) or inter-frequency neighbors (different ARFCNs).
- **Non-standalone deployment:** (called also NR–LTE neighbors) in dual-mode deployments, an NR cell may consider an LTE cell as a valid inter-RAT neighbor to enable mobility and reselection between the technologies [59].

IV.3 5G Network optimization

IV.3.1 5GNR RAN KPIs

In both LTE and 5G networks, KPIs play a crucial role in evaluating and optimizing network performance. Although 5G introduces new use cases and advanced capabilities, the fundamental principles of KPI analysis remain consistent with those in LTE. Therefore, understanding LTE KPIs provides a solid foundation for performance management in next generation networks. Typically KPI can be categorized into following subcategories:

IV.3.1.1 Accessibility KPIs

- RRC setup success rate: Is a key accessibility KPI used to evaluate the efficiency of the initial connection establishment between the UE and the eNodeB. This metric is calculated based on measurements taken at different points during the RRC connection procedure.

Specifically, the eNodeB collects the number of RRC connection attempts (denoted as Point A) upon receiving the `RRC Connection Request` message from the UE. The number of successful RRC connection setups is recorded at Point C, after the eNodeB has sent the `RRC Connection Setup Complete` message and received the appropriate response from the UE, Figure IV.6a [5].

The RRC setup success rate is calculated as follows:

$$\text{RRCS-SR} = \left(\frac{\text{Number of successful RRC connections at Point C}}{\text{Number of RRC connection attempts at Point A}} \right) \times 100 \qquad \text{(IV.5)}$$

This KPI is crucial for evaluating the accessibility performance of the LTE network, as a low success rate could indicate signaling issues, resource shortages, or configuration errors within the radio access network [5].

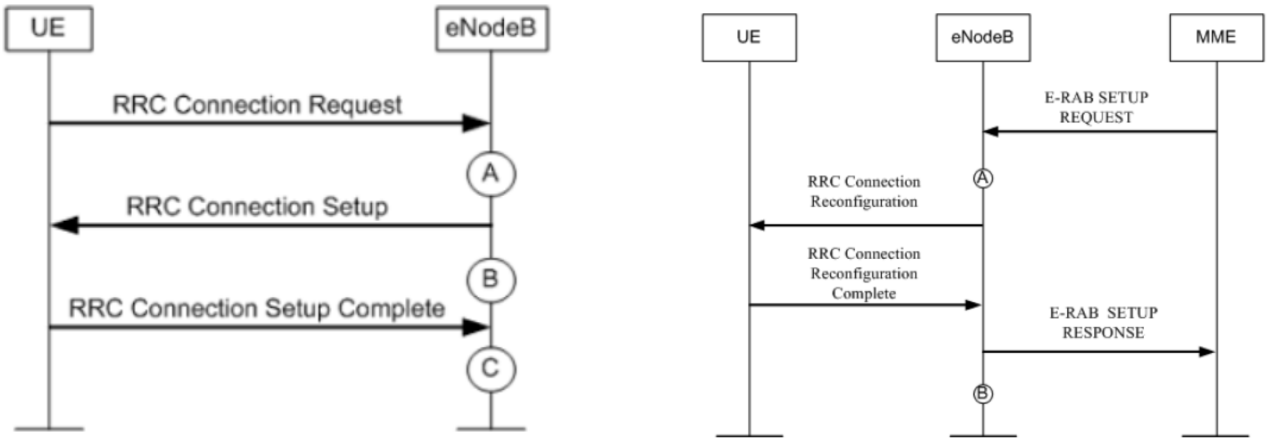
- ERAB setup success rate: This KPI is measured at the eNodeB level using two main counters: (i) the number of ERAB setup attempts (denoted as Point A) and the number of successful ERAB

setups (denoted as Point B); (ii) The success rate provides insight into the network's ability to allocate radio and CN resources needed to support service requests as shown in Figure IV.6b [5].

The ERAB setup success rate is calculated as follows:

$$\text{ERABS-SR} = \left(\frac{\text{Number of successful E-RAB setups at Point B}}{\text{Number of E-RAB setup attempts at Point A}} \right) \times 100 \tag{IV.6}$$

A high ERAB setup success rate indicates efficient service accessibility within the cell or radio network, while a low rate may suggest issues related to resource allocation, signaling failures, or CN constraints [5].



(a) RRC setup success rate (service). (b) ERAB setup success rate (All).

Figure IV.6: Key connection setup success rates during LTE drive test: (a) RRC setup success rate (service), (b) ERAB setup success rate (all).

- Call setup success rate: Reflects the end-to-end success of the initial connection procedure and is influenced by several key stages in the call setup process. Specifically, it is calculated as the product of the following KPIs:

- **RRC Setup Success Rate:** Measures the success of the initial radio connection establishment between the UE and the eNodeB.
- **S1 signaling connection success rate:** Evaluates the success of the signaling connection between the eNodeB and the CN (MME) over the S1 interface.
- **ERAB Setup Success Rate:** Reflects the ability to successfully establish the bearer for user services.

The Call Setup Success Rate is calculated as follows:

$$\text{CSSR} = \text{RRCS-SR} \times \text{S1SR} \times \text{ERABS-SR} \tag{IV.7}$$

A low CSSR may indicate failures at any stage in the call setup chain, requiring detailed troubleshooting across the RANand CN [5].

IV.3.1.2 Retainability KPIs

Retainability KPIs measure the network's capability to maintain ongoing services without unexpected drops or interruptions. They assess how reliably the network retains user sessions such as calls or data connections once they are established.

- Call drop rate (VoIP): Occurs when the established E-RAB is released abnormally, leading to an unexpected termination of the call before it is completed by the user. This KPI reflects the retainability performance of the network and is particularly critical in real-time services such as VoIP.

Each E-RAB is associated with specific QoS parameters, and maintaining these bearers throughout the call session is essential to ensure service continuity. When an abnormal release of the VoIP E-RAB happens, it is typically identified through specific signaling procedures initiated either by the eNodeB or the CN [5].

Two main signaling procedures are used to identify and manage call drops:

- **E-RAB Release Indication:** This message indicates that the eNodeB has released the E-RAB abnormally.
- **UE Context Release Request:** Sent by the eNodeB to the MME when it decides to release the UE context due to radio link failure or other abnormal conditions.

- Service drop rate (All): Is a comprehensive retainability KPI that is used to evaluate the rate of abnormal disconnections for all types of services in a specific cell or cluster. This includes services such as VoIP, data, video, and other types of E-RAB sessions. It reflects the network's overall ability to maintain established sessions across various service categories. A high drop rate may indicate issues in radio conditions, handover mechanisms, or insufficient QoS parameters (see Figure IV.7)
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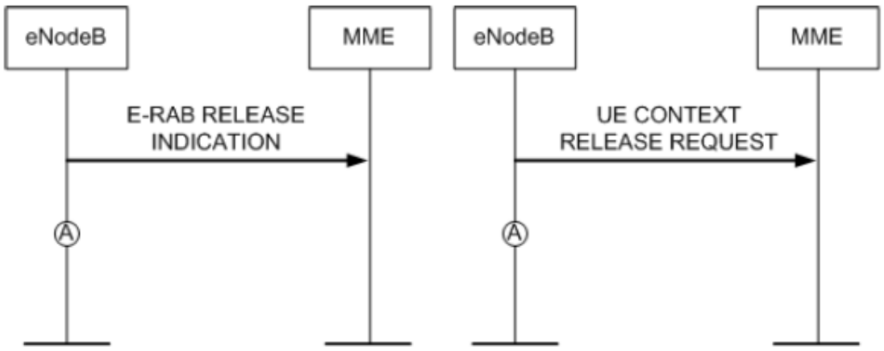


Figure IV.7: Service Drop Rate (All) [5].

The service call drop rate is defined as:

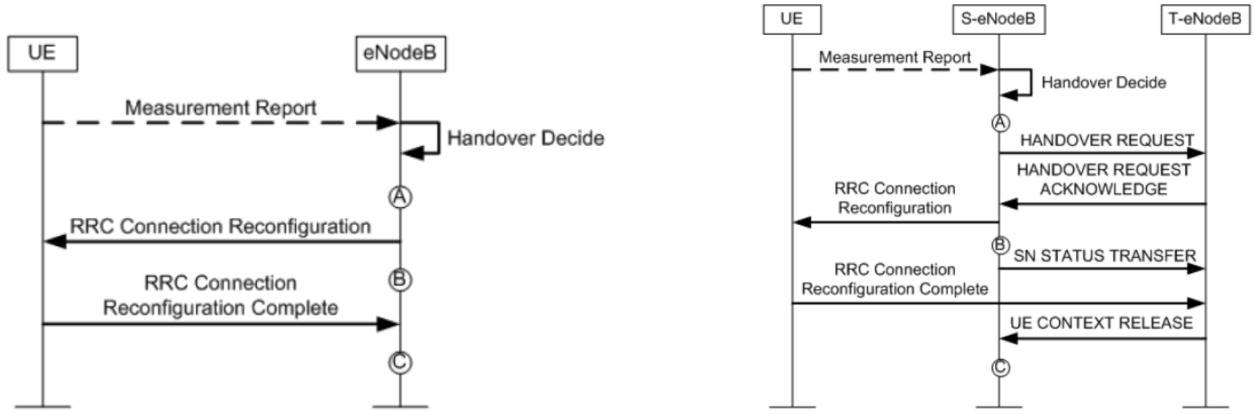
$$\text{Service-CDR (\%)} = \left(\frac{\text{Number of Abnormal E-RAB Releases}}{\text{Total E-RAB Releases}} \right) \times 100 \tag{IV.8}$$

This KPI includes the contribution of VoIP service drops as a subset, making it suitable for evaluating general network stability and user experience across all services [5].

IV.3.1.3 Mobility KPIs

Assess the network's ability to handle user movement across cells or coverage areas without service degradation. They primarily focus on handover success, interruption rates, and service continuity during mobility.

- Intra-frequency handover out success rate: Displays the success rate of intra-frequency handovers from the local serving cell or radio network to a nearby intra-frequency neighboring cell or radio network. Intra-frequency handovers can occur either within the same eNodeB or between different eNodeBs operating on the same frequency. An intra-frequency handover scenario is depicted in the Figure IV.8 (a).



(a) (b)

Figure IV.8: KPIs mobility flow.

At point B, no handover attempt is counted yet. The handover attempt is only registered when the source eNodeB sends an RRC Connection Reconfiguration message to the UE. This message indicates that the eNodeB has decided to initiate the handover. The number of handover attempts from the source cell is counted by the eNodeB at this point.

Point C is where the handover success is calculated. A successful handover is recorded when the source eNodeB receives the RRC Connection Reconfiguration Complete message from the UE. This confirms that the UE has successfully connected to the target cell. An example of an intra-frequency handover between eNodeBs Figure IV.8 (b).

The intra-frequency inter-eNodeB handover scenario is illustrated in the following Figure IV.9 [5]. Mathematically, it could be written as Equation IV.9.

$$\text{IntraFreqHOOut-SR (\%)} = \frac{\text{IntraFreqHOOut Success}}{\text{IntraFreqHOOut Attempt}} \times 100 \tag{IV.9}$$

- Inter-frequency handover Out success rate Similarly, inter-frequency handovers follow the same signaling principle as intra-frequency ones, but occur between cells operating on different

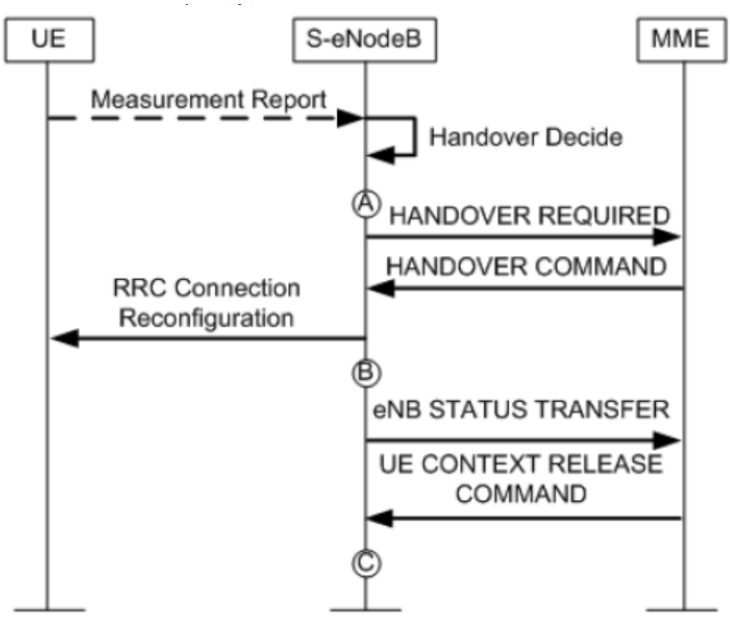


Figure IV.9: Intra-frequency handover out success rate.

frequencies. Handover attempts and successes are still counted at Points B and C respectively (Figure IV.9). The inter-frequency handover Success Rate is given by [5]:

$$\text{InterFreqHOOut-SR (\%)} = \frac{\text{InterFreqHOOut Success}}{\text{InterFreqHOOut Attempt}} \times 100 \tag{IV.10}$$

- Inter-RAT Handover Out Success Rate (LTE to WCDMA)

This KPI reflects the network's ability to maintain service continuity when transitioning from 4G to 3G due to coverage limitations or mobility conditions. The handover attempt is initiated when the LTE eNodeB sends the *RRC Connection Reconfiguration* message including inter-RAT mobility information to the UE. The success is counted when the source LTE eNodeB receives confirmation of successful UE context release from the WCDMA RNC or the MME, indicating that the UE has been successfully handed over and attached to the 3G cell. Figure IV.10 aboutinter-RAT handover out success Rate [5].

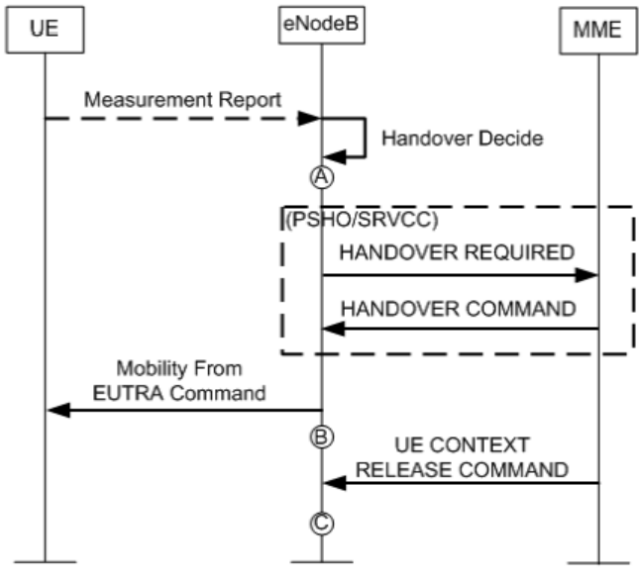


Figure IV.10: Inter-RAT Handover Out Success Rate.

the inter-frequency handover Success Rate given by:

$$\text{IRATHO-L2W-SR (\%)} = \frac{\text{IRATHO-L2W Success}}{\text{IRATHO-L2W Attempt}} \times 100 \tag{IV.11}$$

IV.3.1.4 Availability KPIs

These KPIs reflect the readiness and operability of the network to provide services. Availability indicates whether network elements are functioning correctly and accessible for service delivery at any given time.

- E-UTRAN Cell Availability is a KPIs that measures the proportion of time an LTE cell is operational and capable of providing service. It is defined as the ratio between the total time the cell is available and the total measurement period, expressed as a percentage:

$$\text{E-UTRAN Cell Availability (\%)} = \frac{\text{Cell Available Time}}{\text{Total Measurement Time}} \times 100 \tag{IV.12}$$

A cell is considered available when the eNodeB is able to support E-RAB services within that cell. This KPI is crucial for evaluating the operational readiness of the radio access network, ensuring continuous service delivery, and maintaining overall network stability [5].

IV.3.2 Drive Testing in mobile networks

DT is essential for assessing coverage, capacity, and QoS in LTE networks. It simulates real user experiences using mobile devices and measurement tools in a test vehicle to collect key performance data. These campaigns evaluate session continuity and communication quality, providing GPS-tagged metrics for both voice and data services [60]. The main goal is to validate RF design,

detect coverage gaps, and support network optimization by reducing drop rates and improving service accessibility [61].

The mobile devices used during the DT are typically configured to operate in one of the following modes:

- **Idle Mode**: The UE remains powered on without initiating any sessions, allowing the assessment of idle mode behaviors such as cell reselection and paging.
- **Dedicated Mode (Long Call)**: A continuous voice or data session is maintained throughout the test route to evaluate session stability and handover performance.
- **Dedicated Mode (Short Call)**: A series of short voice calls are made and released during the test to assess call setup success rate and call drop rate.

IV.3.2.1 Types of DT

- Single site verification: Is a DT conducted along a predefined route to verify the coverage footprint and quality of the network. Each sector of the site is tested for uplink and downlink throughput, intra-site and inter-site handovers, and Inter-Radio Access Technology (I-RAT) handovers. Tools such as MapInfo or Google Earth are commonly used to visualize and follow the drive routes during testing, helping to ensure accurate network assessment across the cluster [61]. During this DT, two main tests are performed:

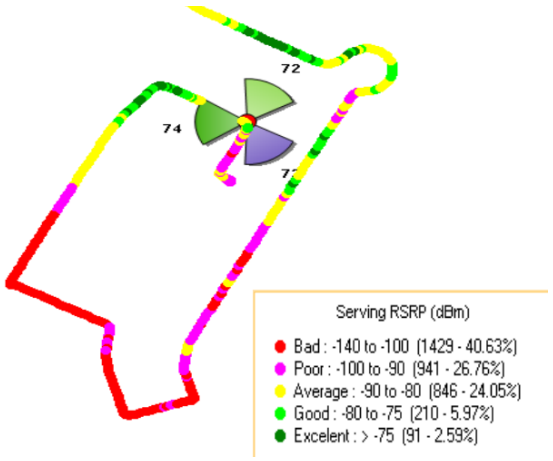
- **Stationary test**: This involves checking throughput or voice call performance while the vehicle is stationary in each sector to ensure all functions are working correctly. This static test is also useful in hotspot areas.
- **Mobility test**: This test checks the coverage footprint and network quality while the vehicle is moving across different sectors. It also includes validation of handover functionality during mobility.

- Cluster DT: Performed when multiple sites located within the same area are grouped as a cluster. DT is done along predefined routes to evaluate network performance across these grouped sites.

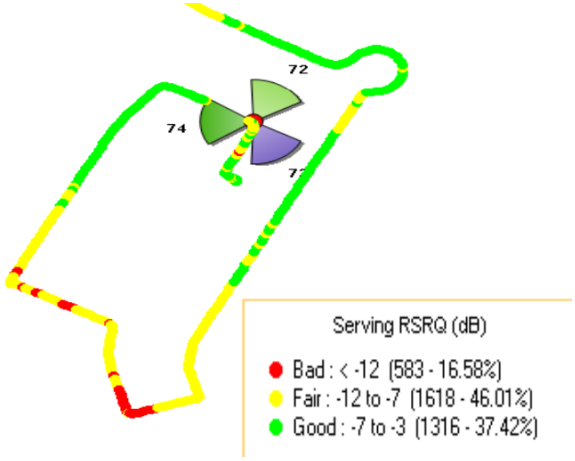
IV.3.2.2 DT parameters

In the context of evaluating and optimizing cellular network performance, analyzing a set of physical and logical parameters is essential, particularly during DTs. The following subsections present a detailed overview of the key indicators used:

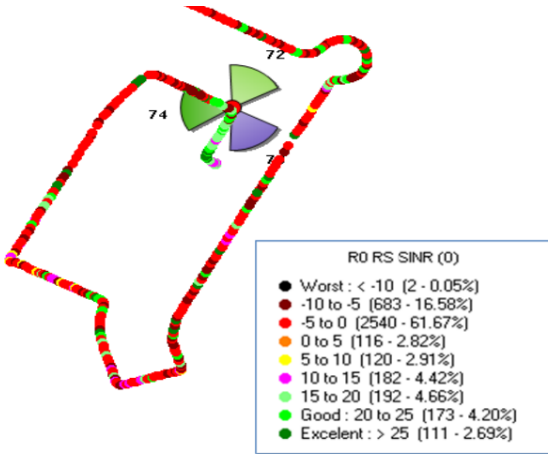
- Physical Cell ID: As previously discussed, the PCI is a key parameter used to uniquely identify a cell in the mobile network. It plays a critical role in synchronization and cell identification during signal acquisition by UE [61].



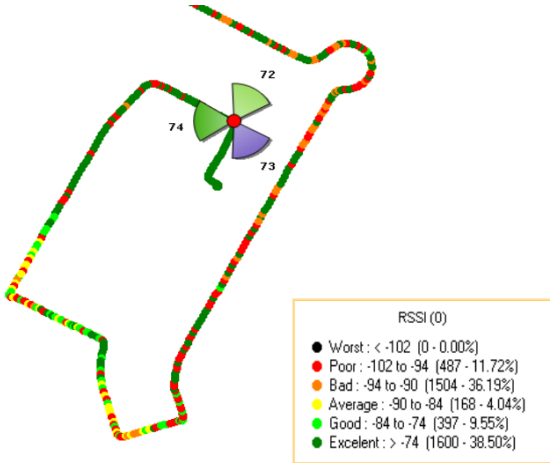
(a) RSRP



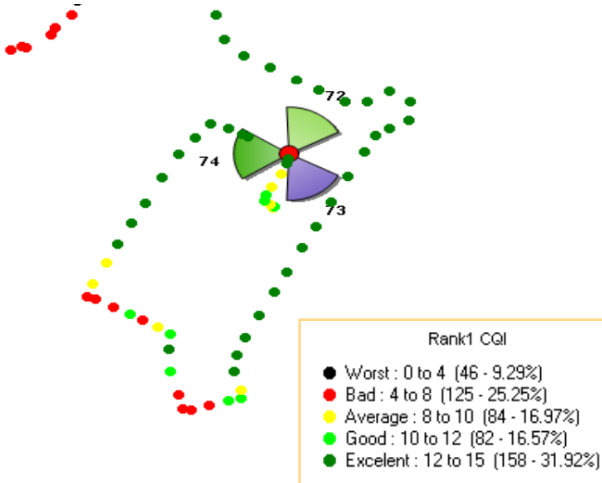
(b) RSRQ



(c) SINR



(d) RSSI



(e) CQI

Figure IV.11: Plots of key downlink radio measurements observed during LTE drive testing: (a) RSRP, (b) RSRQ, (c) SINR, (d) RSSI, and (e) CQI [61].

- RSRP: Represents the received power of the reference signal and is one of the most fundamental physical layer measurements for the UE. It is calculated as:

$$\text{RSRP (dBm)} = \text{RSSI (dBm)} - 10 \times \log_{10}(12 \times N) \tag{IV.13}$$

Where, N is the number of resource blocks, which depends on the bandwidth.

RSRP provides a linear average of the power of downlink reference signals across the channel bandwidth. It enables the UE to estimate path loss and optimize transmission power accordingly. It is used in both idle and connected modes, with a typical range of -44 dBm to -140 dBm. RSRP values are plotted and categorized into standard quality ranges, with the percentage and number of samples in each range used to evaluate signal coverage performance [61]. Figure IV.11a illustrates the distribution of RSRP measurements collected during DT [61].

- RSRQ: Measures the quality of the received reference signal and is defined by Equation IV.14 as follows:

$$\text{RSRQ} = \frac{\text{RSRP}}{\text{RSSI}/N} \tag{IV.14}$$

RSRQ represents the ratio of desired signal power to total received power (including interference and noise). It is crucial for mobility decisions, particularly at the cell edge where signal strength alone is insufficient [61]. RSRQ is measured in connected mode, typically ranging from -3 dB to -19.5 dB. Figure IV.11b illustrates a histogram of RSRQ values collected during DTs [61].

- Signal to interference plus noise ratio (SINR): Quantifies the relationship between the received signal power and the sum of interference and noise, as defined in Equation (IV.15):

$$\text{SINR} = \frac{S}{I + N} \tag{IV.15}$$

Where S is the average received signal power, I is the interference power, and N is the noise power.

This metric is crucial for evaluating LTE wireless connection quality and directly impacts system capacity and data throughput. SINR is used to evaluate the quality of the received signal by comparing it to the surrounding interference and noise, providing a clear indicator of channel usability [61], Figure IV.11c about SINR plot and ranges.

- RSSI: Represents the total received wide-band power, including contributions from the serving cell, adjacent cell interference, and background noise. It is mathematically expressed in Equation (IV.16) as:

$$\text{RSSI} = 12 \times N \times \text{RSRP} \tag{IV.16}$$

RSSI reflects the total received wideband power, including signal, interference, and noise, and helps in understanding the interference level in the network [61], Figure IV.11d about RSSI plot and ranges.

- CQI: Is a measurement of downlink channel quality experienced by the UE. It ranges from 1

to 15, with higher values indicating better channel conditions. CQI is determined in connected mode only and depends on RF conditions. A high CQI value allows the network to apply higher modulation and coding schemes, thereby increasing the achievable throughput [61], , Figure IV.11e about CQI Plot and ranges.

- Block error rate (BLER) Is the ratio of erroneous blocks to the total transmitted blocks and is determined using cyclic redundancy check (CRC) (Euqation IV.17).

$$\text{BLER} = \frac{\text{Number of erroneous blocks}}{\text{Total number of blocks transmitted}} \tag{IV.17}$$

It is used to determine the appropriate CQI value. The UE reports the CQI that ensures a Block error rate (BLER) less than or equal to 10%. High BLER degrades system efficiency and throughput [61].

- Downlink throughput: Refers to the data rate from the network to the UE. LTE supports up to 2x2 MIMO, enabling higher data rates. The goal is to achieve average user throughput per MHz that is 3 to 4 times higher than that of HSDPA (Release 6), potentially exceeding 300 Mbps. Throughput scales with spectrum bandwidth and signal quality [61], as shown in Table IV.4.

Table IV.4: Peak DL speeds.

Modulation scheme	**Antenna configuration**	**Data rates (Mbps)**
64 QAM	SISO	100
	2x2 MIMO	172
	4x4 MIMO	326

- Uplink throughput: UL throughput refers to the data rate from the UE to the network. Typically, the UE uses a single Tx antenna, while the eNodeB has two Rx antennas. With MIMO-capable UEs, higher uplink throughput can be achieved. LTE targets uplink rates over 50 Mbps, significantly surpassing the 5.76 Mbps of UMTS. Uplink performance also scales with bandwidth and transmit power [61], as shown in Table IV.5.

Table IV.5: Peak UL speeds

Modulation Scheme	**Data Rates (Mbps)**
QPSK	50
16 QAM	57
64 QAM	86

- Latency: Measures the time delay in transmitting data packets. LTE achieves lower delays than 3G , with user-plane latency below 10 ms and control-plane latency under 100 ms. Low latency is achieved through fewer network nodes, shorter Transmission Time Interval (TTI), and faster signaling. This enables efficient spectrum usage and supports real-time applications [61].

- Tracking area code (TAC): Identifies the location area in which the UE resides. The MME uses TAC to track the UE's location for paging and mobility management. Each tracking area includes one or more E-UTRAN cells [61].

- E-UTRA absolute RF channel number EARFCN: It is a unique number representing the downlink or uplink frequency channel. This parameter is essential for configuring and analyzing LTE cells, especially during frequency planning and drive tests [61]. Figure IV.12 illustrates the distribution of serving cell DL EARFCNs observed during drive testing, showing the proportions of frequencies 625, 1075, 2200, and 5815 under different scenarios.

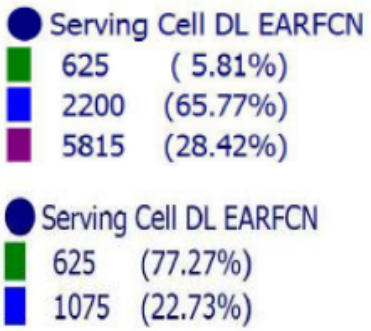


Figure IV.12: Distribution of serving cell DL EARFCNs by percentage.

IV.3.2.3 The importance of DT

DT plays a vital role in the telecommunications industry by enabling the assessment, optimization, and maintenance of mobile network performance. It significantly contributes to the overall cellular health of the network, offering essential benefits for both operators and end-users, which are [62]:

- **Enhanced network performance:** By identifying weak signal areas and performance bottlenecks, cellular DT empowers operators to take targeted actions to improve network coverage, reduce dropped calls, and boost data speeds.
- **Improved user experience:** A robust and well-maintained network ensures that users experience reliable connectivity and faster data speeds, resulting in increased customer satisfaction.
- **Efficient resource allocation:** DT data assists network operators in making informed decisions about infrastructure investments. It helps allocate resources more efficiently, which is essential in a competitive market environment.
- **Network planning and expansion:** Cellular DT is instrumental in planning new cell tower locations, optimizing existing ones, and expanding network coverage into previously underserved areas.
- **Troubleshooting and issue resolution:** When network issues arise, DT data helps operators pinpoint the root causes and take corrective actions promptly.

IV.4 Conclusion

The planning and optimization of 5G networks are essential to achieving high performance, reliability, and service continuity. This chapter covered the key architectural elements of 5G, including user equipment, the RAN, and the 5GCN, each playing a crucial role in delivering ultra-fast and low-latency services. Coverage and capacity planning were explored through radio propagation models and link budget analysis, which serve as foundational tools for network design. Particular attention was given to PCI planning and the importance of avoiding PCI collisions using Mod 3, Mod 4, and Mod 30 rules. Optimization techniques were then examined through the lens of KPIs, including accessibility, retainability, mobility, integrity, and utilization. DT was presented as a practical method to validate network performance and adjust configurations based on real-world measurements. Overall, effective 5G deployment depends on a combination of theoretical planning and empirical validation to ensure optimal service quality and user experience.

CHAPTER V

PLANNING AND OPTIMIZATION: APPLICATION AND RESULTS

V.1 Application in planning in 5G network

In this practical section, we focused on applying radio network planning using Atoll, a professional tool widely used in the telecommunications industry to design, simulate, and optimize mobile networks before deployment. As part of our project, we utilized Atoll to plan a 4G /5G network in the Alger Centre area of the capital city. This allowed us to understand the real-world planning process, from map configuration and site deployment to network performance evaluation across multiple scenarios.

V.1.1 Atoll Software

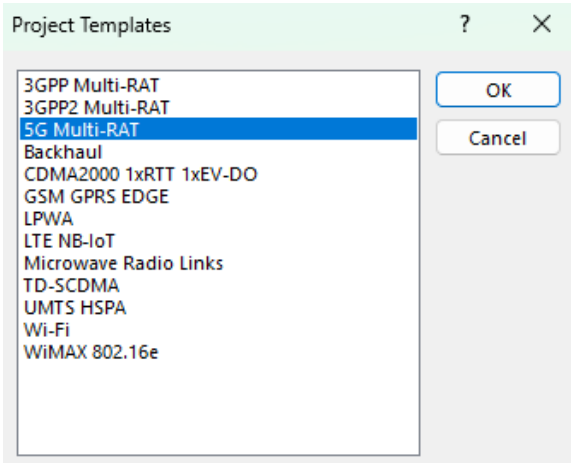
Atoll is a professional radio network planning and optimization software developed by Forsk, widely used by telecommunication engineers and operators to design, simulate, and analyze wireless networks across multiple technologies, including 2G, 3G, 4G and 5G. The software offers an integrated environment that combines geographic data, advanced propagation models, prediction algorithms, and engineering tools to accurately assess coverage, capacity, and interference. By enabling detailed simulations of realistic network behavior, Atoll plays a crucial role in the planning phase, helping to reduce deployment costs, minimize field testing, and accelerate the rollout of new sites. As such, it is an essential tool for building high-performance, reliable, and scalable radio access networks.

V.1.2 Creation of project

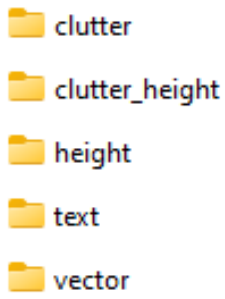
At the initial stage of the project, we began by creating a new Atoll project and selecting 5GNR as the radio access technology. This selection determined the specific parameters and configurations relevant to 5G networks. We then imported the essential geospatial datasets required for accurate network planning (Figure V.1 (a) and (b)). These included the digital elevation model

(DEM), which provides terrain altitude data crucial for modeling signal propagation; the clutter file, which classifies land use types (e.g., urban, forest, water) to estimate signal attenuation; and various vector files containing geographic features such as roads, buildings, and administrative boundaries.

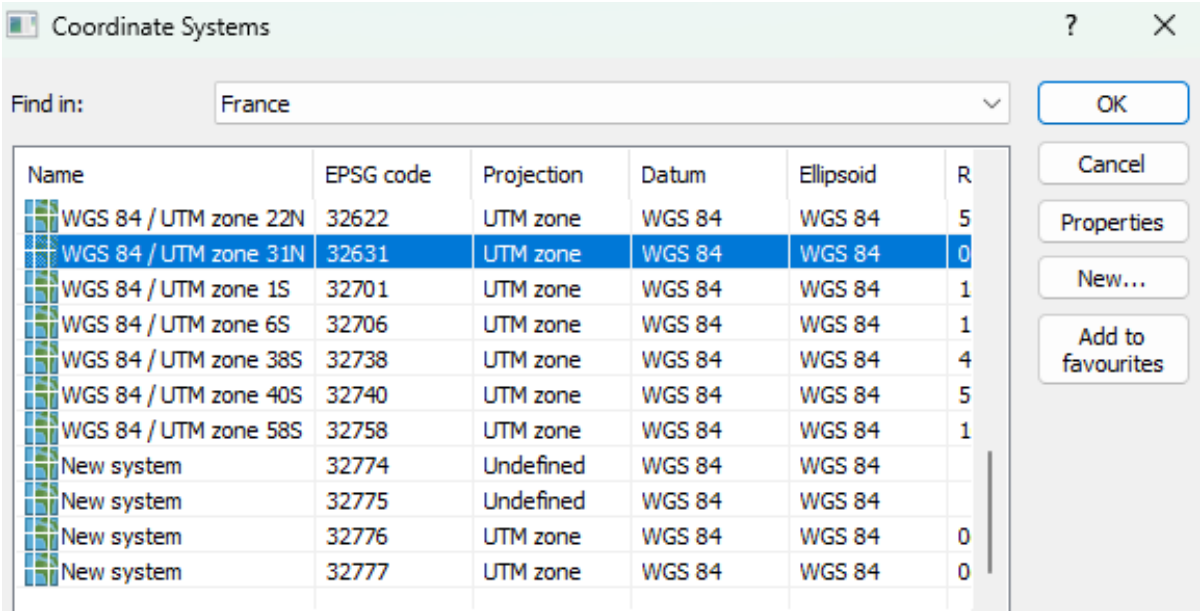
Once the data were imported, we configured the map projection parameters to set the correct coordinate reference system (Figure V.1 (c)). This step ensures that all spatial layers are properly aligned within the project environment, which is critical for maintaining geographic accuracy and enabling precise calculations. After completing these foundational steps, we proceeded to the detailed configuration phase, including the definition of sites, transmitters, and cells, which constitute the core elements of the network design.



(a) Project template 1



(b) Project template 2



(c) Coordinate systems

Figure V.1: Illustrations of project templates and coordinate systems.

V.1.3 General configuration parameters

In Atoll, radio network design is structured around the configuration of multiple hierarchical layers, including sites, transmitters, and cells. Each of these layers contains a set of parameters that define the physical and operational characteristics of the network components. Configuration steps are as follows:

Site configuration: This involves specifying the base station's physical attributes, including the site name, geographic coordinates (X/Y), and altitude. Accurate site definition is crucial for ensuring correct positioning within the project's geospatial environment.

Transmitter configuration: Transmitters are associated with specific sites and include detailed settings such as the transmitter name, frequency band, and antenna location, Figure V.2 illustrates the general tab used to configure a new transmitter in Atoll. The configuration also accounts for hardware-related transmission and reception losses, including those introduced by Tower-Mounted Amplifiers (TMA) and feeder cables. The antenna section allows selection between broadcast and beamforming antennas; however, if both are defined, only the broadcast antenna is used for path loss calculations. Additional parameters include antenna height, number of antenna elements, azimuth, and mechanical downtilt.

Cell configuration: Each transmitter can support one or more cells, potentially across different technologies. Key parameters include the cell name (automatically derived from the associated transmitter), carrier frequency, PCI, and maximum transmission power. Cells are assigned to specific network layers and can be configured as Primary Cell (PCell) or Secondary Cell (SCell) for uplink or downlink operations.

Advanced 5G NR configurations include parameters such as the Cell Individual Offset (CIO), Cell Selection Threshold, SS/PBCH numerology, traffic numerology, and MIMO support (e.g., SU-MIMO or MU-MIMO for uplink and downlink). The configuration also allows the definition of traffic parameters, including the number of users per link, traffic load percentages, and maximum load thresholds. Additionally, PRACH root sequences can be assigned, and neighboring cells both intra and inter-technology can be defined to support mobility management and handover procedures.

Then, each transmitter can support one or more cells, potentially from different radio technologies. The configuration of these cells is a critical aspect of network planning, as it defines the operational parameters that influence performance, interference, and user experience. Key configuration elements include:

- **Name:** Automatically generated by Atoll based on the transmitter's name, with a suffix in parentheses.
- **Carrier:** Defines the frequency band assigned to the cell.
- **PCI:** A unique identifier ranging from 0 to 1007.
- **Max Power (dBm)**: The maximum transmit power of the cell.

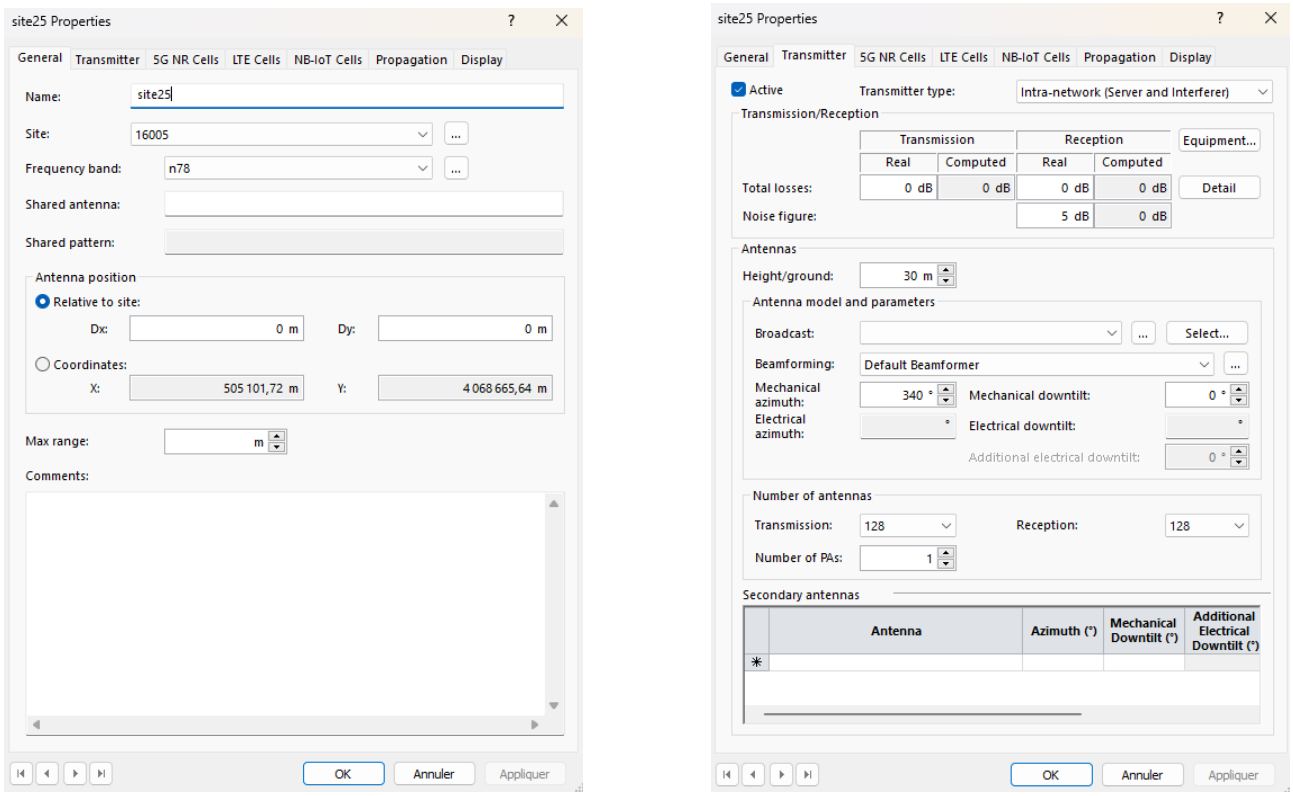


Figure V.2: New transmitter's general tab .

- **Layer**: Indicates the network layer to which the cell belongs, which is important for serving cell determination.
- **Cell Type**: Specifies whether the cell is a PCell, Secondary Uplink Cell, or Secondary Downlink Cell.
- **Cell Individual Offset (CIO)**: A 5G NR parameter used to bias the ranking of potential serving cells during the selection process.
- **Cell Selection Threshold**: Sets the minimum SS-RSRP threshold based on layer priority, influencing cell selection.
- **SS/PBCH Numerology**: Defines the subcarrier spacing for synchronization signals
- **Traffic Numerology**: Defines the subcarrier spacing for traffic channels such as PDCCH, PDSCH, and PUSCH.
- **Diversity Support (DL/UL):** Specifies the antenna diversity technique used in downlink and uplink.
- **Number of MU-MIMO Users (DL/UL):** Indicates the average number of users sharing resources through MU-MIMO in both directions.
- **Number of Users (DL/UL):** Represents the number of connected users in downlink and uplink.

- **Traffic Load (DL/UL):** Defines the percentage of current traffic load.
- **Max Traffic Load (DL/UL):** Sets the maximum allowable traffic load percentage.
- **PRACH RSIs:** Configures the random access root sequences assigned to the cell.
- **Neighbours:** Allows the definition of intra- and inter-technology neighbor cells to support mobility and handover strategies.

This extensive level of configuration enables precise control over network behavior, facilitating optimization for performance, capacity, and user experience.

V.1.4 Propagation model used

For this project, the Okumura-Hata propagation model was selected due to its reliability and widespread use in cellular network planning. This model is particularly well-suited for urban, suburban, and rural environments, operating within frequency ranges from 150 MHz to 1500 MHz, and can be adapted for higher frequency bands through specific extensions. Based on extensive empirical measurements, the Okumura-Hata model provides dependable predictions of path loss across diverse terrains, making it a common standard in the radio planning of mobile networks.

Due to its simplicity, proven effectiveness, and compatibility with the characteristics of the urban area studied, the Okumura-Hata model was chosen as the propagation model for our network design. Figure V.3 shows Okumura-Hata propagation model configuration.

V.1.5 Traffic parameters

In network planning and simulation, accurately modeling traffic parameters is essential to obtain reliable results. Atoll provides the capability to define various services such as voice, mobile internet access, and others, which can be categorized as either circuit-switched (voice) or packet-switched (data), depending on the radio access technology and application type. Within the service configuration window, users can specify the service type (voice, data, or broadband) and select the supported technologies accordingly. Figure V.4 illustrates the 5GNR configuration tab in Atoll for defining new services, including throughput values and modulation settings. Both DL and UL directions allow setting average, minimum, and maximum throughput values, as well as defining the lowest and highest modulation and coding schemes.

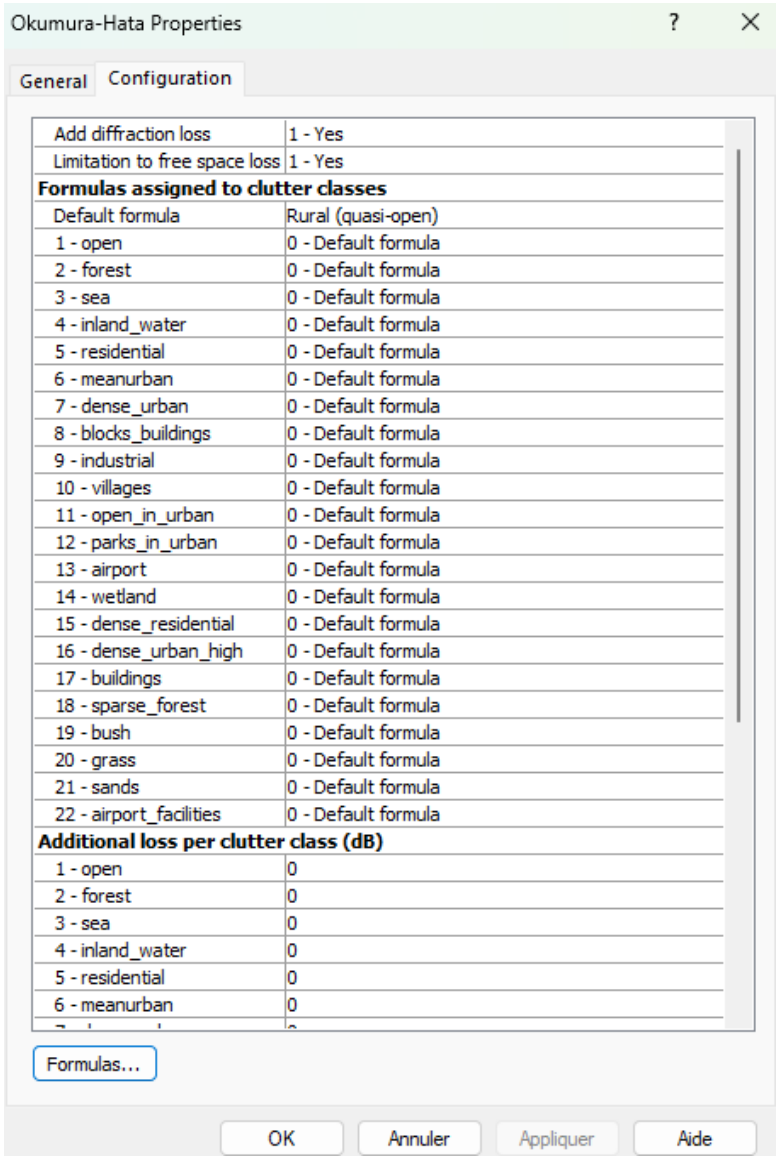


Figure V.3: Okumura-Hata propagation.

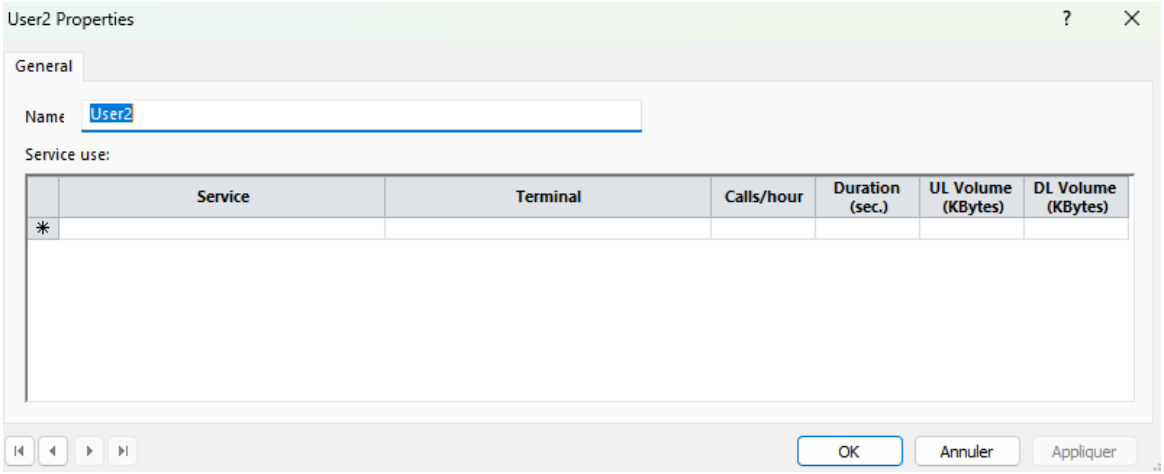


Figure V.5: General tab of a new user.

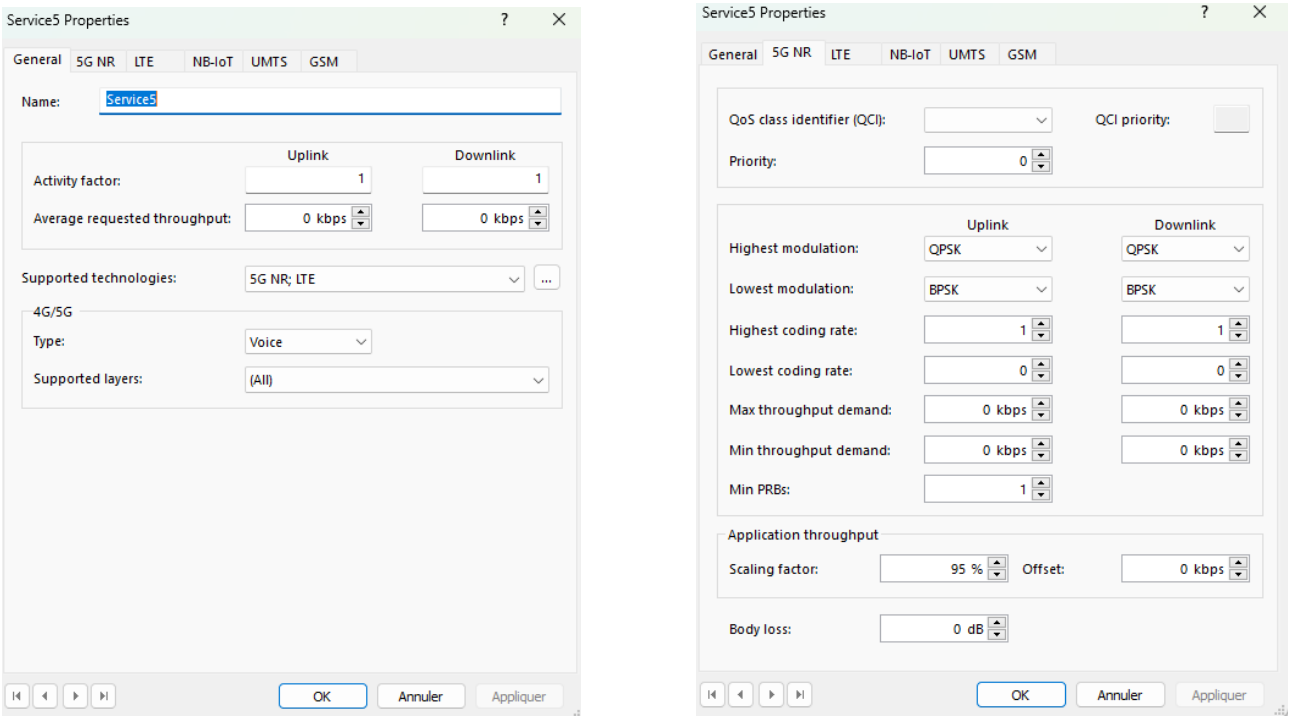


Figure V.4: 5GNR tab of a new service.

After configuring services, the next step involves creating user profiles to assign these services to different user types. For each user profile, parameters such as terminal type (5G or 4G device), the number of calls or requests per hour, and either call duration or UP/DL data volumes must be specified. Figure V.5 shows the general tab of a user profile, where device type and traffic parameters can be configured.

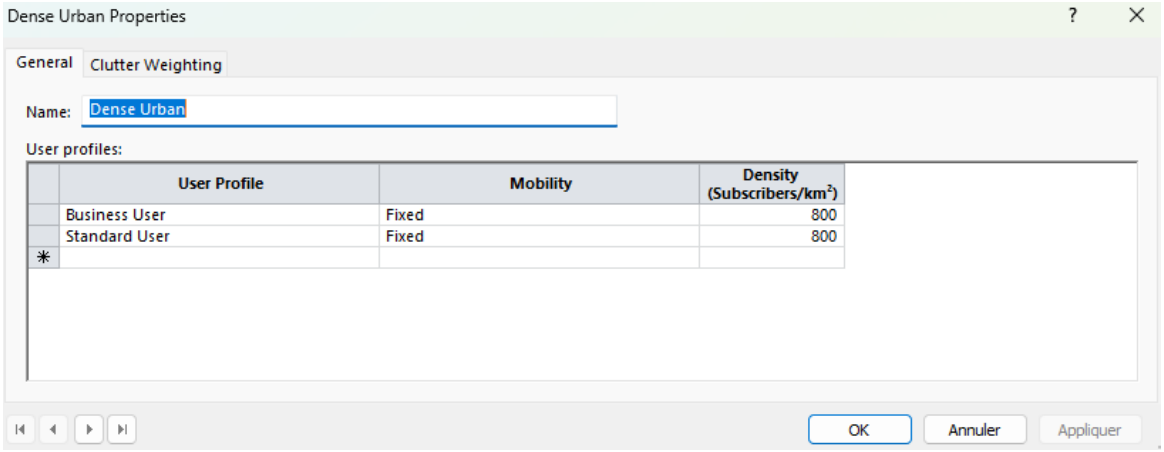


Figure V.6: Dense urban environment.

Moreover, various environmental settings are defined to represent subscriber density and mobility characteristics for each user profile. Figure V.6 illustrates the environmental settings used to model a dense urban environment, including user distribution and mobility behavior. For example, in a residential area, the number and type of users can be adjusted to reflect realistic scenarios. Finally, the spatial distribution of users within the coverage area is modeled using traf-

fic maps. Figure V.7 displays an example of a traffic map used in the Alger centre area, where user profiles are distributed geographically to simulate realistic network load. These maps, combined with environment parameters, determine how many users of each profile are located in specific locations on the map, enabling precise traffic load simulations.

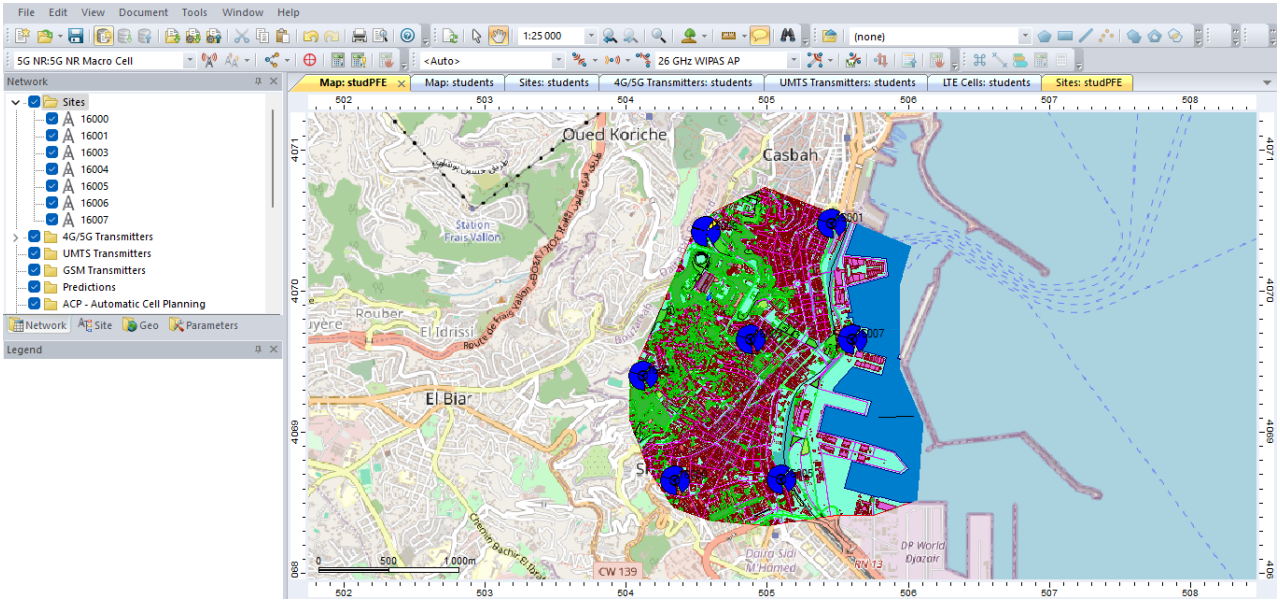


Figure V.7: Traffic map in Alger Centre.

V.1.6 Predictions and simulations

Atoll offers various types of coverage predictions that enable detailed analysis of signal levels, signal quality, and overall network capacity. For each pixel within the coverage area, Atoll determines the serving cell using the standard cell selection mechanism. Based on the type of prediction configured, it then calculates the required effective signal or network parameter. Pixels are visually colored if they meet the display threshold conditions set in the prediction parameters. A summary of the main prediction types is as follows:

- **Uplink and Downlink Network Coverage Prediction:** This predicts the effective signal levels of different signal types within the studied network area. It can also be used to identify the best serving cells and cell-edge areas for those servers.
- **UL and DL Network Quality Prediction:**This predicts interference levels and signal-to-interference-plus-noise ratios (C/(I+N)) in the network area. For the downlink, C/(I+N) is calculated for various channels considering their transmission powers and the interference received from neighboring cells on corresponding resource elements. In the uplink, C/(I+N) uses terminal power after power control and uplink noise rise values stored in cell properties or simulation results.
- **UL and DL Service Areas Prediction:** This calculates and displays service areas (bearers) based on C/(I+N) for each pixel. The coverage is limited by bearer selection thresholds

defined for the highest and lowest bearers of the selected service.

- **UL and DL Network Capacity Prediction:** This calculates channel throughputs and cell capacities based on C/(I+N) and bearer calculations for each pixel. When Monte Carlo simulation results are available, Atoll can also display cumulative cell throughputs.

To deepen network capacity understanding, Atoll can perform network simulations that integrate modeled network services and user distributions defined by traffic maps. The simulation process involves several steps:

a. Generating a realistic user distribution using traffic maps weighted by a Poisson distribution.

b. Selecting the technology: For each simulated mobile user, Atoll identifies the serving cell across available technologies.

c. Modeling network regulation mechanisms according to the technologies deployed.

User rejection can occur at different stages:

- During the “Best Server Determination” if there is no coverage.
- During UL or DL calculations if the quality is too low to support any coding scheme, resulting in no service.
- During “Radio Resource Management” due to:
  - Scheduler saturation (user not selected for resource allocation),
  - Resource saturation (all cell resources exhausted), or
  - Backhaul saturation (cell’s maximum S1 interface throughput exceeded while meeting minimum throughput demands).

V.1.7 Network deployment and Optimization Scenarios

This section presents two case studies exploring different 4G /5G deployment strategies. The first focuses on upgrading an existing LTE network to integrate 5G NR, while the second involves a complete 4G /5G deployment using both macro and small cells to enhance coverage and capacity, especially in dense urban areas. In addition to deployment, several optimization actions were carried out—such as antenna azimuth adjustments, SINR improvement, and PCI planning—to boost overall performance. These scenarios reflect real-world challenges and demonstrate the effective use of planning tools in modern mobile networks.



Figure V.8: Clutter classes model.

Both case studies are conducted in the same geographic area, located in central Algiers, the capital of Algeria. Figure V.8, This region includes a mix of residential, commercial, and open public areas, which makes it a suitable location for evaluating different network planning strategies.

V.1.7.1 Upgrade from 4G to 5G network

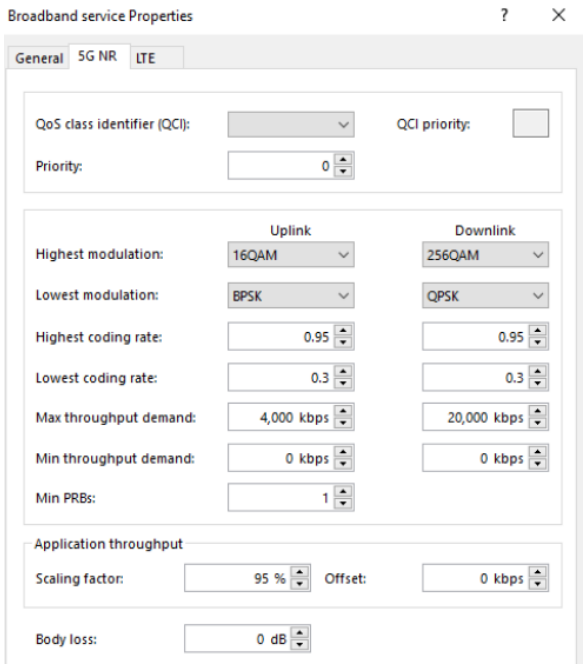
The first case study focuses on the upgrade of an existing 4G LTE network to a 5G NR network in a realistic and practical manner. The process involves initially designing a standalone 4G LTE network, which is then enhanced by overlaying a 5G NR layer on top of the existing infrastructure. This simulates a common migration path adopted by many operators worldwide.

The first step to initiate the network design is to define the services that will be covered in the simulations and predictions. Firstly, a new broadband service type named “Broadband service” was created, this is obviously a packet switched service. This service supports both LTE and 5G NR technologies and its configuration is shown in the images below.

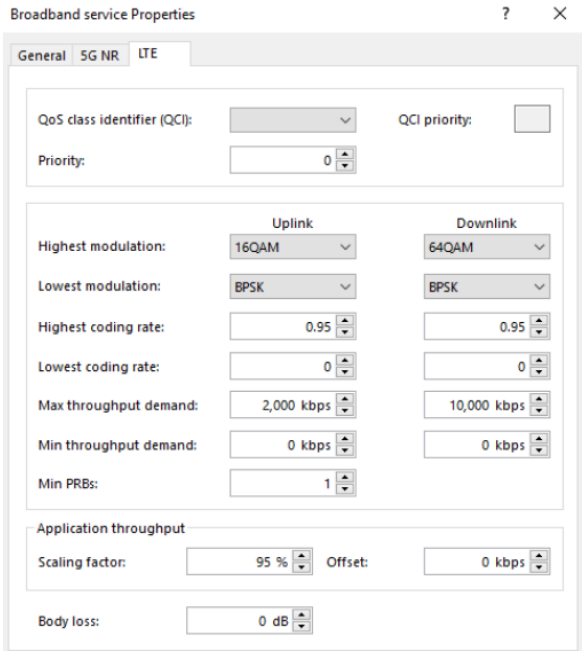
As illustrated in Figures V.9 (a), V.9 (b) and V.9 (c), the maximum and minimum throughput demands differ between the two technologies, with 5G NR being more demanding. However, the general configuration indicates that the average required throughput remains constant regardless of the technology, set at 1000 kbps for uplink and 4000 kbps for downlink. The remaining services were predefined in Atoll and left unchanged. These services include Internet, Voice Call, and Video Call.

The Internet service, classified as a data service, is only supported in LTE. It is characterized by significantly lower average throughput requirements compared to the Broadband service, specifically 200 kbps for uplink and 400 kbps for downlink. Since this service is not supported by 5G NR, only the LTE-specific properties are defined and presented in the figure below.

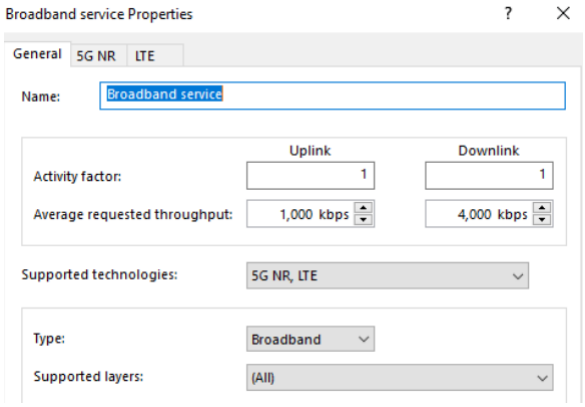
This figure V.9 (d) clearly demonstrates that the Internet service is significantly less demanding in terms of throughput compared to the Broadband service.



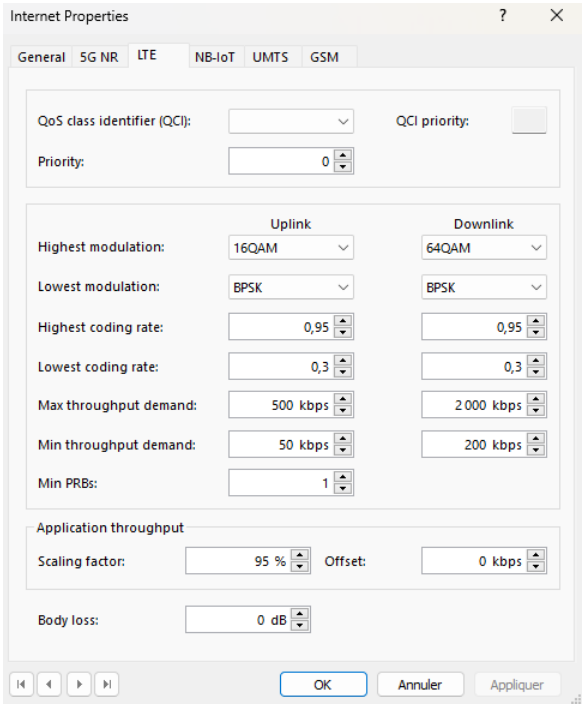
(a) 5GNR Broadband service



(b) LTE Broadband service



(c) General tab of Broadband properties



(d) LTE Internet properties

Figure V.9: Broadband and Internet service configurations in LTE and 5GNR networks

Regarding the other two services Voice Call and Video Call both are categorized as voice-type services and are only supported by LTE technology. The primary distinction between them lies in their throughput requirements and activity factors. The Video Call service demands higher throughput than the Voice Call service (Figure V.10).

In addition, the Voice Call service is configured with an activity factor of 0.4 for both the uplink

and downlink, which indicates the probability of user activity during simulations. Activity factors play a crucial role in network planning, as they define how often users are likely to be active when using the service. Moreover, the Video Call service is assigned a higher priority than the Voice Call service.

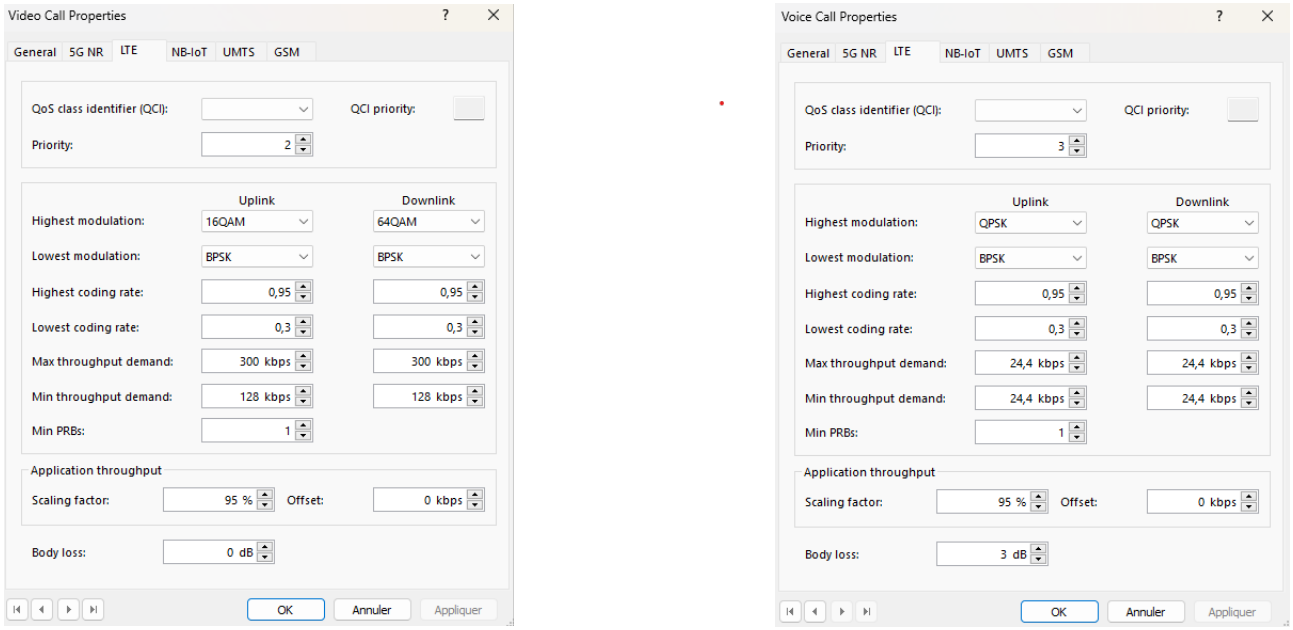


Figure V.10: Video and voice call configuration properties.

Once the services have been modeled, the subsequent step involves defining the user profiles that utilize these services. In this context, two distinct user types were established: the Advanced User and the Standard User.

The advanced user represents a profile characterized by frequent mobile data usage, including activities such as checking emails, streaming videos, sharing photos, as well as occasionally making voice and video calls. Figure V.11 shows the configuration of the advanced user profile.

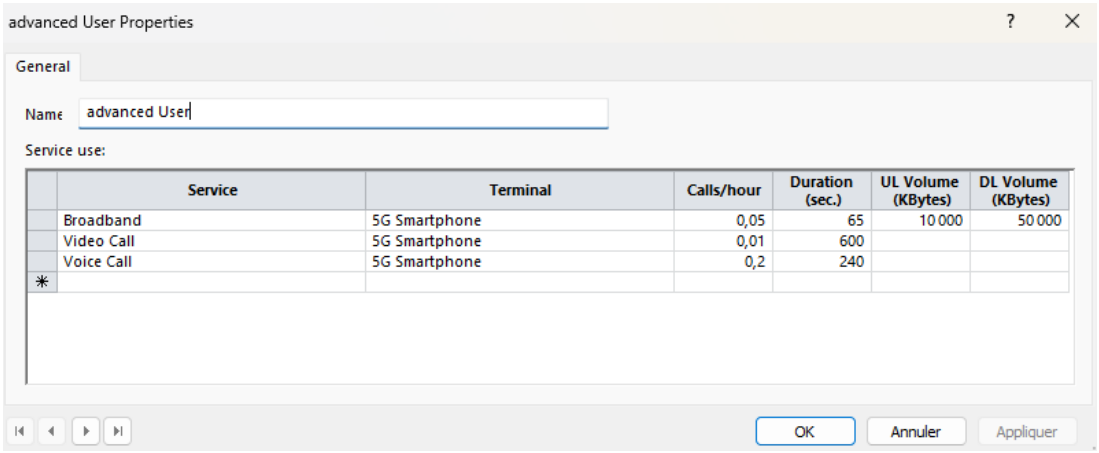


Figure V.11: Advanced user profile.

As illustrated in Figure V.11, the advanced uer generates a high volume of activity within the

Broadband service, consuming 50 MB in the downlink and 10 MB in the uplink every 65 seconds, which corresponds to a broadband session approximately every 20 hours (0.05 calls/hour). In addition, this user makes a 4-minute voice call (240 seconds) approximately once every 5 hours (0.2 calls/hour), and a 10-minute video call (600 seconds) roughly once every 100 hours (0.01 calls/hour). All services are accessed through a 5G smartphone, reflecting the advanced usage patterns and high data demand of this profile.

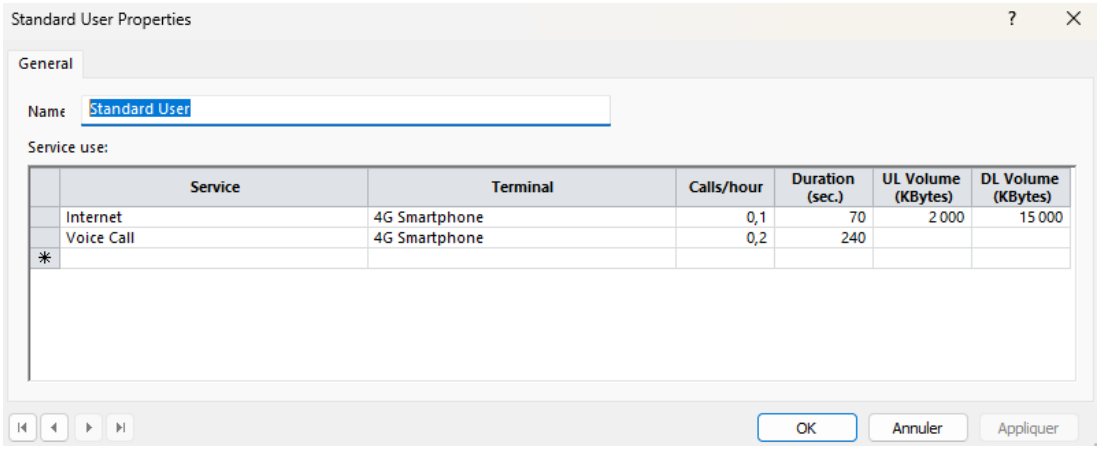


Figure V.12: Standard user profile.

In contrast, the standard user profile engages less frequently with mobile data compared to the Advanced User. Figure V.12 presents the configuration of the Standard User profile used for basic internet and voice services. This user performs internet browsing using a 4G smartphone, consuming 15 MB in the downlink and 2 MB in the uplink during a 70 second session that occurs every 10 hours (0.1 calls/hour). Additionally, this user makes 4 minute voice calls (240 seconds) once every 5 hours (0.2 calls/hour). The Standard User is a casual phone user who checks their phone periodically to make calls and reply to accumulated messages or emails, explaining the higher downlink data compared to uplink.

To do so, a traffic map (Figure V.7) and the environments are created. In each environment, the number and type of users are defined. This traffic map includes four different environments: Dense Urban, Urban, Suburban, and Rural (Figure V.13). The user distribution is as follows: Dense Urban areas are mainly occupied by Advanced Users due to high data demand. Urban areas feature a balanced mix of Advanced and Standard Users. Suburban areas are mostly populated by Standard Users, with a few Advanced Users. In Rural areas, Standard Users dominate, and overall traffic is low.

V.1.7.2 Cells deployment and scenarios

The site locations have been chosen to cover as much area as possible but also taking into account the possible interference from the neighbour sites, To make it as realistic as possible.

- **LTE Macro Cell Deployment:** In the context of radio network planning, a foundational LTE macro cell layer was deployed to ensure extensive coverage and balanced user distribution

Name: Dense Urban

User profiles:

	User Profile	Mobility	Density (Subscribers/km²)
	advanced User	Pedestrian	800
	Standard User	Pedestrian	800
*			

(a)

Name: Rural

User profiles:

	User Profile	Mobility	Density (Subscribers/km²)
	Standard User	Pedestrian	20
*			

(b)

Name: Suburban

User profiles:

	User Profile	Mobility	Density (Subscribers/km²)
	Standard User	Pedestrian	200
*			

(c)

Name: Urban

User profiles:

	User Profile	Mobility	Density (Subscribers/km²)
	advanced User	Pedestrian	400
	Standard User	Pedestrian	400
*			

(d)

Figure V.13: Different environment types modeled in the radio network planning: (a) Dense Urban Area, (b) Rural Area, (c) Suburban Area, and (d) Urban Area.

throughout the target area [ilide.info-], a total of 21 LTE transmitters were strategically distributed over 7 existing base station sites. These sites were selected based on real geographical data, with the objective of minimizing inter site interference while maximizing signal reach, particularly in suburban and semi-rural zones.

The deployment utilized E-UTRA band 20 (800 MHz) due to its favorable propagation characteristics, which make it ideal for wide-area coverage. Each LTE cell was configured with the following technical parameters:

- Maximum Transmission Power: 43 dBm
- Scheduling Algorithm: Proportional Fair
- DL/UL Diversity Scheme: Transmit/Receive Diversity with SU-MIMO
- Cyclic Prefix Type: Normal

- Cell Offset/Selection Threshold: 0 dB

To ensure efficient resource allocation and reduce interference, EARFCN values and PRACH Root Sequence Index (RSI) were automatically assigned using Atoll's integrated planning tools. This automation helped achieve optimal frequency reuse across the LTE layer. As representative examples, a subset of LTE site configurations was selected and is presented in the following table V.1 to illustrate the PCI and PRACH resource allocation strategy used during the LTE macro cell deployment.

Table V.1: LTE Cell Parameters Configuration

Site	Carrier	Physical Cell ID	PRACH RSI
16000-1	20MHz EARFCN 6250	13	81–90
16000-2	20MHz EARFCN 6250	14	516–525
16000-0	20MHz EARFCN 6285	12	25–34
16003-2	10MHz EARFCN 6100	19	34–43
16004-0	10MHz EARFCN 6200	2	24–33
16005-1	10MHz EARFCN 50	4	588–597

In my implementation, this LTE macro layer served as the baseline coverage network, providing consistent downlink coverage throughout the area of interest. The effectiveness of the deployment was verified during the simulation phase using Atoll, where the DL RSRP coverage map (Figure V.14) confirmed strong and uniform signal strength across nearly all evaluation zones.

- **5GNR macro cell deployment:** To increase overall network capacity and enable the delivery of enhanced 5G services particularly enhanced Mobile Broadband (eMBB) and low latency applications a layer of 5G NR macro cells was deployed in co-location with existing LTE sites. These cells operate within band n78 (3.3–3.8 GHz), selected for its suitability in providing high data throughput in urban and dense urban environments.

  Each 5G macro cell was configured with the following parameters:

  - Maximum Transmission Power: 50 dBm
  - DL/UL Diversity Scheme: SU-MIMO and MU-MIMO
  - Scheduling Algorithm: Proportional Fair
  - SS/PBCH Numerology: Subcarrier spacing of 15 kHz

  To align with the strategic importance and traffic load of each site, bandwidths were adapted dynamically, ranging between 50 MHz, 60 MHz, and 80 MHz. Furthermore, PCIs and PRACH resources were automatically generated using Atoll's planning tools, followed by manual optimization to prevent identifier collisions and improve handover performance. As representative examples, a subset of site configurations was selected and presented in the following table V.2 to illustrate the PCI and PRACH resource allocation strategy used during the 5G NR deployment.

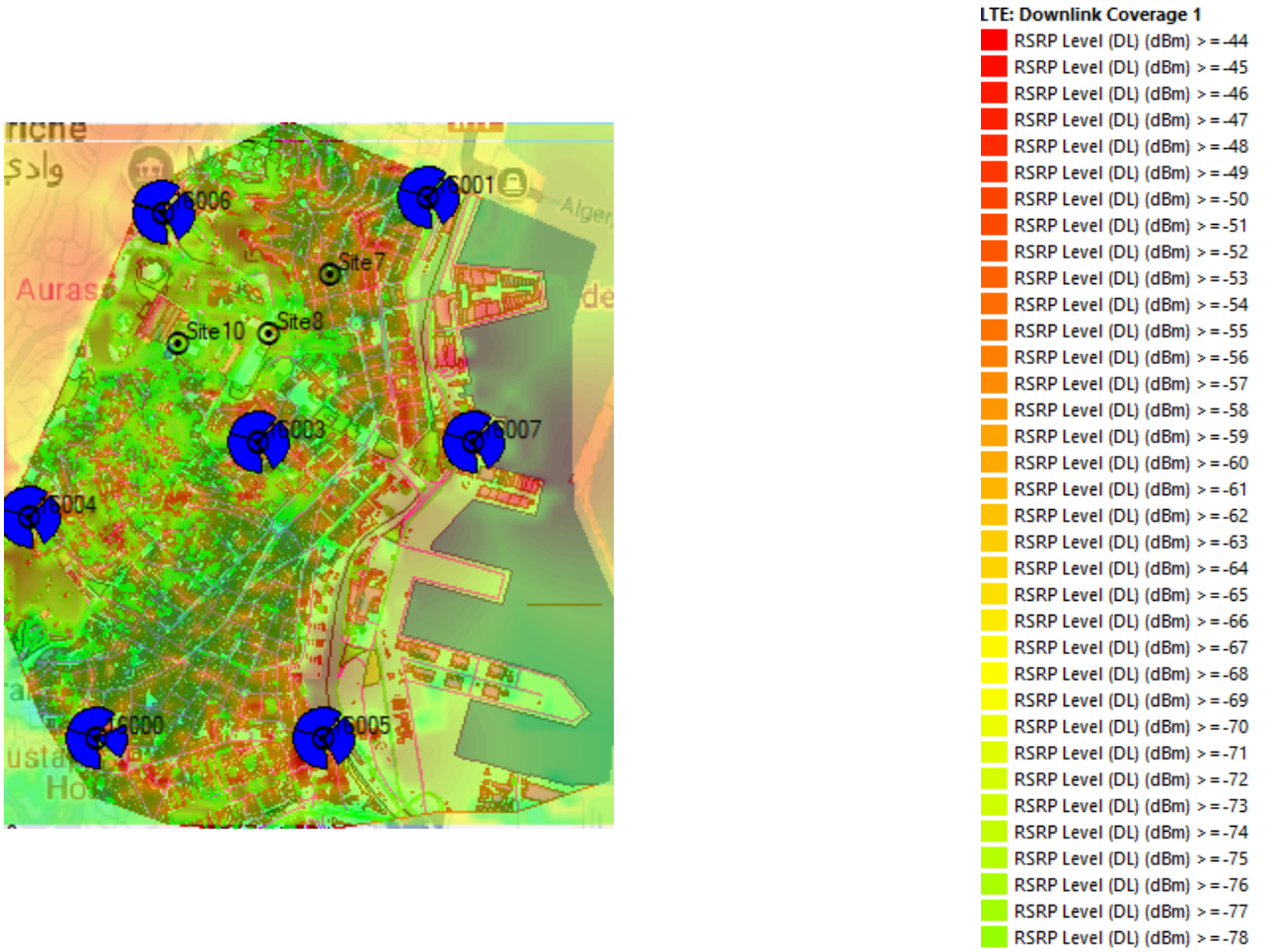


Figure V.14: Downlink coverage prediction with LTE transmitters.

Table V.2: 5GNR cell configuration: PCI and PRACH allocation

Site	Carrier	PCI	PRACH
16000-1	50MHz NR - ARFCN 621667	132	437–446
16000-2	50MHz NR - ARFCN 621667	134	0–9
16001-0	ARFCN 625000	9	95–104
16003-2	60MHz NR - ARFCN 629000	0	486–495
16004-0	80MHz NR - ARFCN 628667	261	276–285
16005-1	50MHz NR - ARFCN 621667	284	557–566

This 5GNR overlay on top of the LTE macro layer resulted in a significant enhancement in network throughput and responsiveness, particularly in high-demand urban zones. The deployment was validated through simulation, as illustrated by the 5G NR DL RSRP coverage map Figure V.15, which demonstrates strong signal availability and performance across the core areas of interest especially where macro cells are reinforced by small cell deployments.

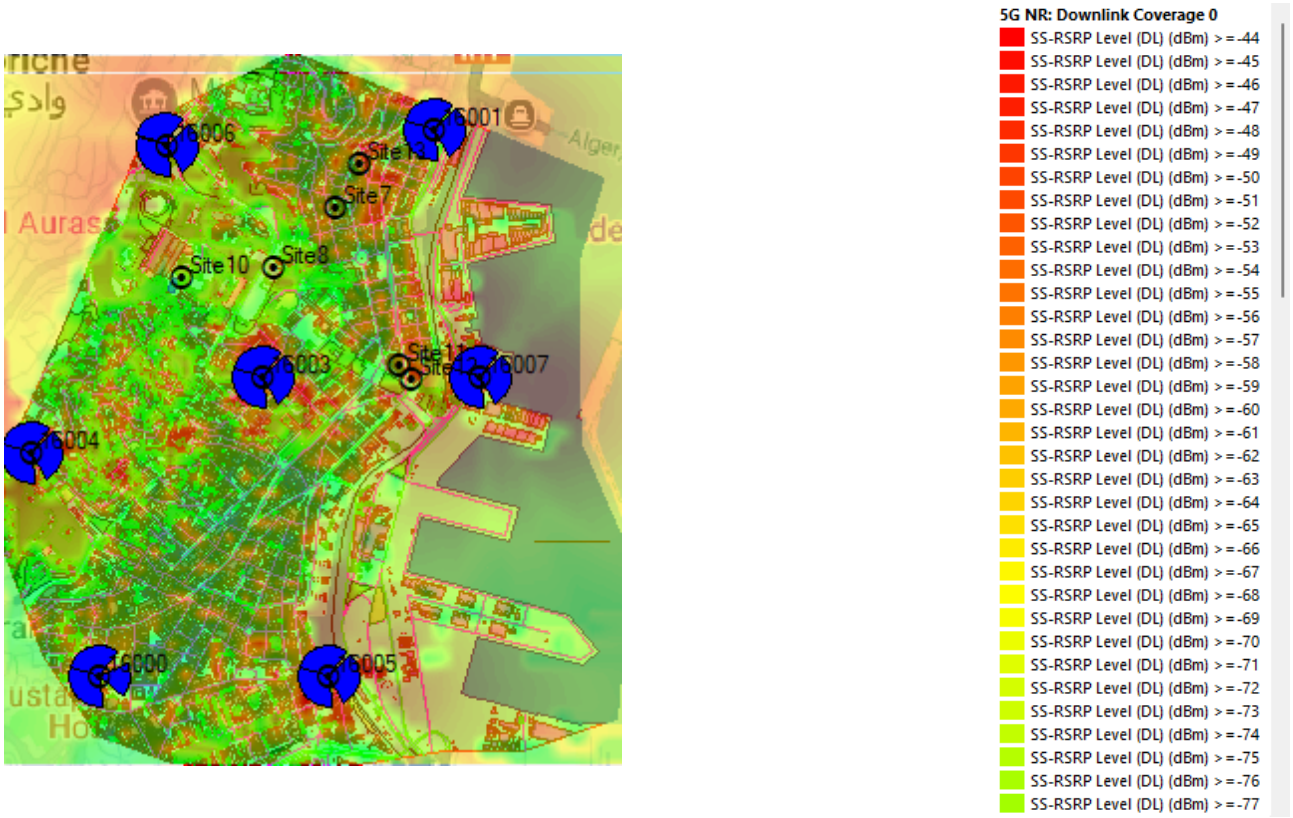


Figure V.15: Downlink Coverage prediction with 5G transmitters.

- **Small Cell Deployment (LTE & 5GNR)**: To address localized coverage deficiencies and accommodate areas with high user density, a targeted small cell deployment strategy was implemented. This densification step was based on observations made during the simulation and performance analysis phases, which identified signal weak spots and traffic hotspots, particularly in narrow streets, indoor zones, and pedestrian-dominated environments.

  A total of four small cells were integrated into the existing network: LTE small cells at Sites 10 and 13 and 5G NR small cells at Sites 7 and 8.

  The LTE small cells were configured with reduced transmit power and unique PCI values, specifically selected to limit interference with the surrounding macro LTE cells and to ensure smooth handover performance.

  For the 5G NR small cells, mid-band frequencies (3.5 GHz) were utilized. Configuration included optimized PRACH resources and appropriate numerology settings, facilitating fast access procedures and low-latency handovers in dense usage zones. PCI and PRACH values were initially auto-assigned using Atoll's integrated algorithms to minimize collisions and interference, followed by manual adjustment where needed to enhance mobility performance. As part of the small cell densification strategy, the following table V.3 presents PCI and PRACH configurations for the deployed LTE and 5G NR small cells.

Table V.3: Small Cell Configuration: PCI and PRACH Allocation

Site	Technology	Carrier	PCI	PRACH
10	LTE	10MHz EARFCN 6300	103	110–119
13	LTE	10MHz EARFCN 6400	104	240–249
7	5GNR	50MHz NR - ARFCN 623500	301	300–309
8	5GNR	50MHz NR - ARFCN 623500	302	390–399

This small cell layer significantly enhanced localized RSRP, SINR, and throughput, thereby validating the critical role of network densification in practical 4G /5G deployments. The effectiveness and positioning accuracy of these small cells are clearly illustrated in the network layout map (Figure V.16), which highlights their contribution to overall network performance. The LTE small cells deployed at Sites 10 and 13, as shown in the map, were strategically placed to address specific coverage gaps identified during the simulation phase. RSRP reflects down-

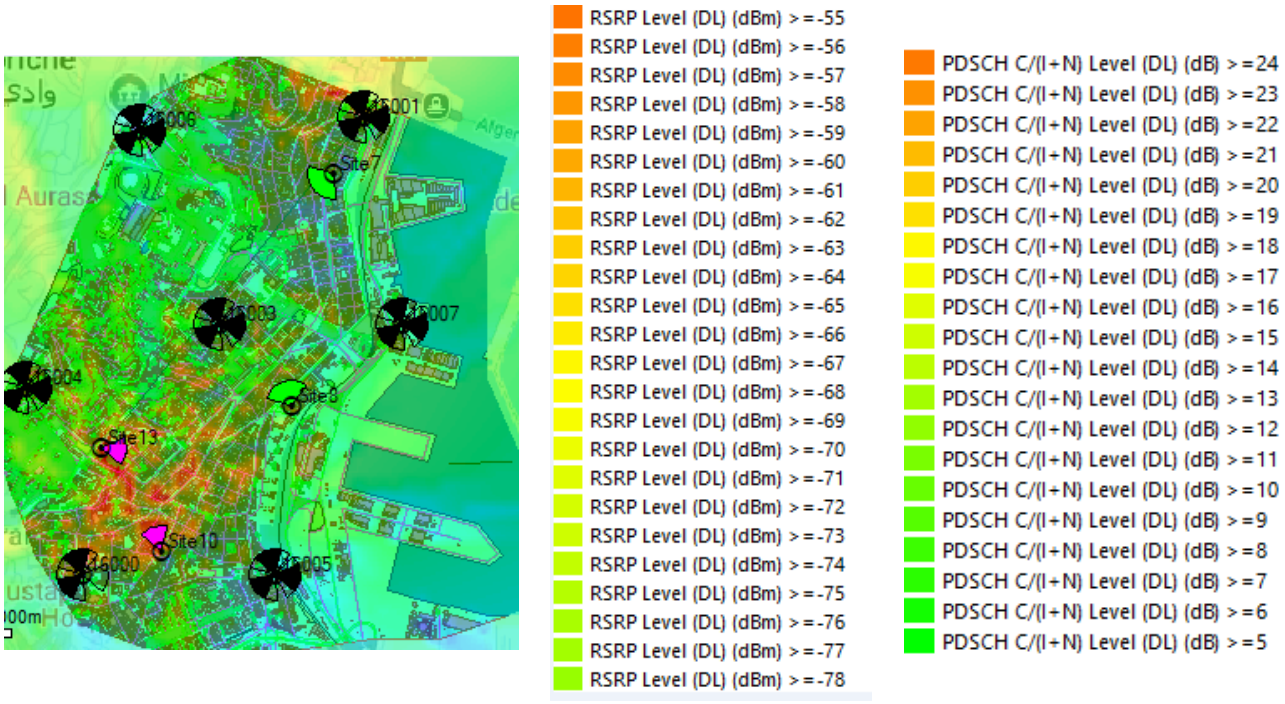


Figure V.16: small cell deployments LTE

link coverage, while SINR reflects the quality of that coverage.

- **LTE Downlink Coverage (DL RSRP)**:

  To assess the effectiveness of the LTE macro layer, a downlink RSRP simulation was conducted following the deployment phase. The prediction results revealed excellent signal coverage across the entire study area, with only minimal coverage gaps in isolated edge zones. The use of band 20 (800 MHz) played a pivotal role in achieving this outcome, thanks to its strong propagation characteristics and enhanced penetration through obstacles, particularly beneficial in rural and suburban environments.

These findings validate the LTE layer's function as a foundational coverage network, offering reliable support for voice services, mobility management, and moderate data throughput, forming a solid platform upon which more advanced technologies, such as 5G NR, can be built.

A comparative analysis between the initial and final LTE coverage maps (Figure V.17) highlights the improvements achieved through parameter tuning and antenna configuration. The final coverage map visually confirms a more uniform signal distribution and the LTE network's improved capability to provide stable service across the entire deployment area, especially along the edges where coverage gaps were previously observed.

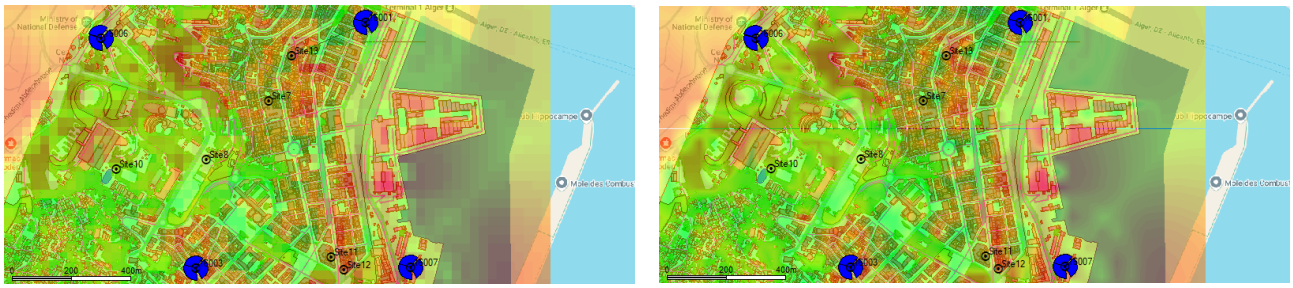


Figure V.17: LTE DL Coverage Before and After Optimization.

- **5GNR Downlink Coverage (High-Resolution Analysis)**:

  To precisely evaluate the downlink coverage performance of the deployed 5G NR layer, a high resolution simulation was conducted with a spatial granularity ranging from 10 to 50 meters. This approach was particularly effective in assessing signal behavior within dense urban environments, where coverage requirements are highly variable and user concentration is uneven.

  Operating in mid-band spectrum (3.3–3.8 GHz), 5G NR inherently faces more limited propagation range compared to lower-frequency LTE bands. However, by combining macro cell deployment with strategically placed small cells, the network achieved satisfactory coverage and signal strength in key user centric zones.

  Additionally, a detailed point analysis was performed in specific locations within the study area to validate the simulation results and assess signal quality at critical spots. This granular evaluation confirmed the robustness of coverage and the effective mitigation of coverage gaps in complex urban layouts.

  The simulation results (Figure V.18) demonstrated robust performance in critical service areas, confirming that the integration of small cells significantly improves both coverage depth and network capacity. This layer is particularly vital in meeting the stringent demands of enhanced Mobile Broadband (eMBB) use cases, ensuring high throughput, low latency, and service continuity in complex urban scenarios.

To validate the high-resolution 5G NR downlink coverage simulation, two specific zones within the study area were analyzed in detail, considering both user density and signal quality metrics.

Zone 1 (La Grande Poste): Figure V.19 presents a set of maps corresponding to the La Grande Poste area, selected for its high-density urban characteristics. These maps include analyses of 5G

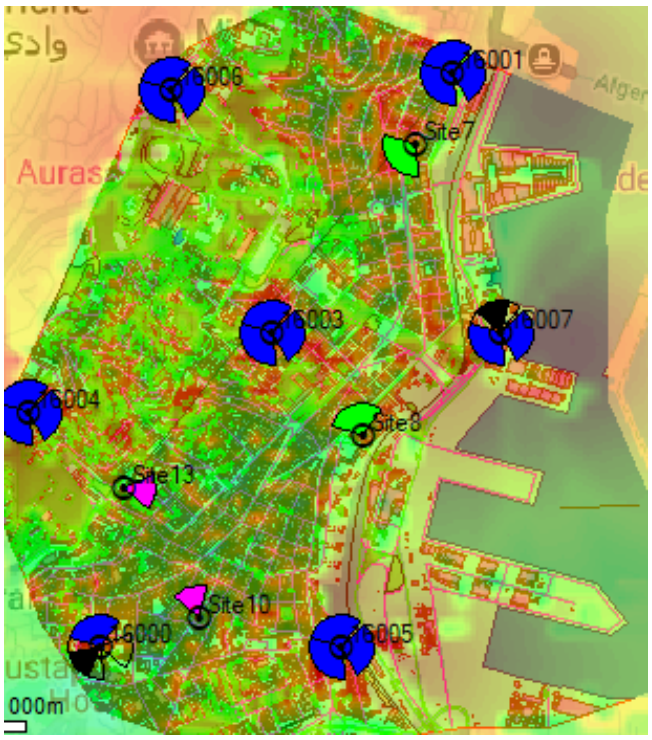


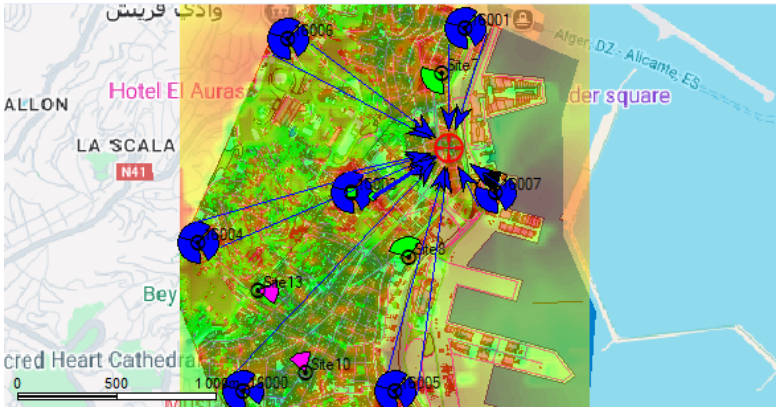
Figure V.18: 5G DL Coverage.

signal coverage, interference levels, and user distribution, offering a comprehensive view of the network's behavior in a real-world urban hotspot.

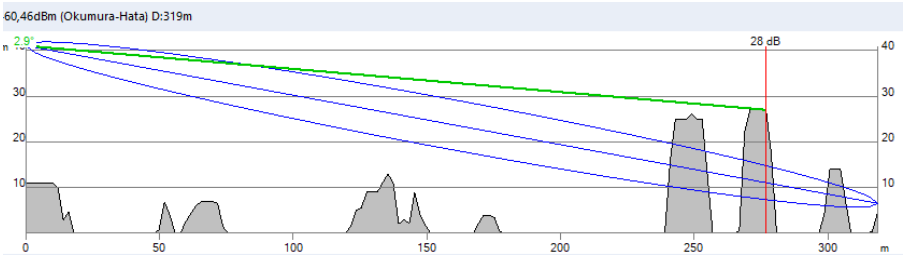
This area was selected due to its high user concentration, representing a typical dense urban hotspot. A point-by-point analysis evaluated the 5G reception quality, interference levels, and user profile distribution. The reception measurements confirmed strong signal presence with acceptable interference, supporting consistent connectivity for the large number of users in this zone. The 5G user profile showed a predominance of eMBB services, which require high throughput and low latency, both of which were effectively supported by the deployed network configuration.

Zone 2 (University of Algiers 1 – Rue Didouche Mourad): Figure V.20 presents a set of maps corresponding to the University of Algiers zone, which includes both indoor and outdoor environments with varying user densities. These maps illustrate 5G signal coverage, interference levels, and the spatial distribution of user services, offering a detailed understanding of network performance in a complex academic environment.

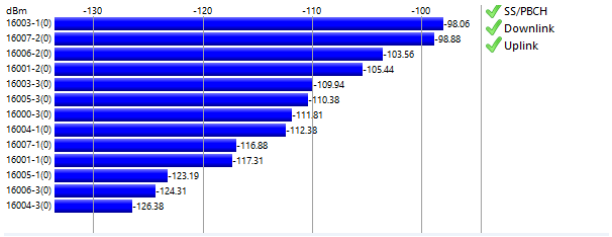
The second zone focused on the University campus area, which features mixed indoor and outdoor environments with variable user density. Similar to La Grande Poste, point analysis here examined reception quality and interference patterns alongside the user service profile. Results indicated that despite the complex urban layout and presence of buildings, the 5G NR layer maintained strong coverage and manageable interference. This ensured service continuity for a diverse range of user demands, from academic data usage to voice and video communications (See Figure V.20).



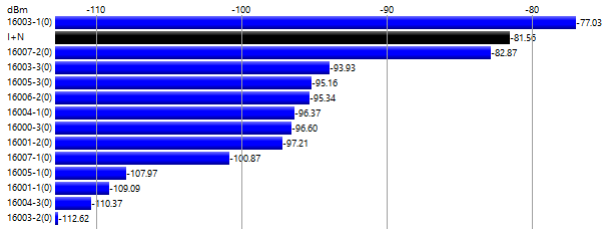
(a) Point analysis of Zone 1



(b) User profile



(c) 5G-NR reception



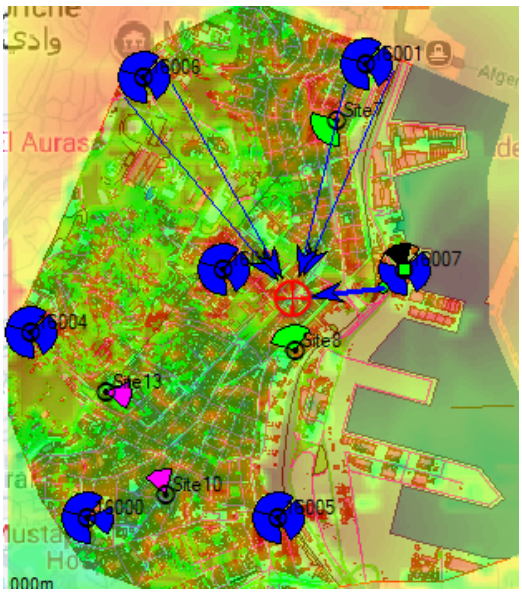
(d) 5G-NR interference

Figure V.19: Various maps for La Grande Poste zone analysis.

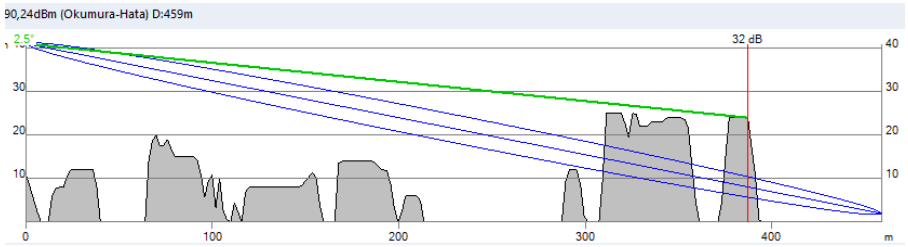
SINR Analysis: As part of the network optimization phase in the dense urban zone surrounding Site 8, a targeted antenna azimuth adjustment was performed for both LTE and 5G NR macro cells. The antennas were reoriented—for example, rotated from 340° to 270° to improve alignment with main traffic corridors, reduce inter cell interference, and enhance overall signal directivity.

The effect of this intervention was evaluated using a post optimization SINR simulation. The resulting map (Figure V.21) demonstrated substantial improvements, with SINR values increasing from baseline levels up to 27 dB in the most impacted areas. These gains were particularly noticeable at cell edges, leading to enhanced signal clarity and a smoother user experience.

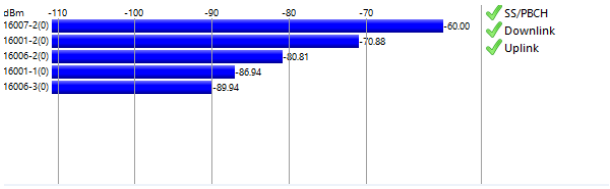
Simultaneously, PCI assignments were reconfigured to mitigate risks of PCI collisions and confusion, often encountered in dense deployment scenarios. This refined PCI plan contributed to more stable handovers and reinforced mobility robustness, thereby supporting consistent service quality throughout the area.



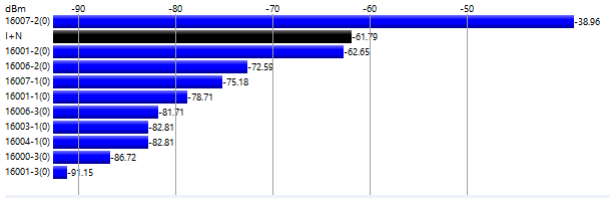
(a) Point Analysis of Zone 2



(b) User Profile



(c) 5G-NR reception



(d) 5G-NR interference

Figure V.20: Various maps for university of Algiers zone analysis.



Figure V.21: 5G DL quality before and after optimization.

V.1.7.3 Simulation Results

To assess the overall effectiveness of the deployed LTE and 5G NR network, a comprehensive traffic simulation and coverage analysis were performed within the same geographic zone illustrated in the global coverage map (Figure V.22). This zone, located in central Algiers, combines dense urban infrastructure with varying user concentrations, offering a realistic environment for performance validation.

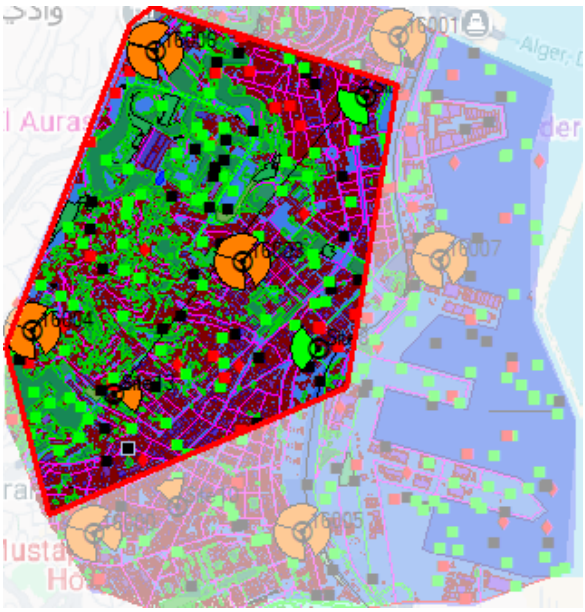


Figure V.22: Coverage map showing LTE and 5G NR deployment with macro and small cells in central Algiers.

The traffic simulation incorporated diverse service types Internet browsing, voice calls, and video communication based on predefined user profiles. The results confirmed the network's ability to support multi-service demands simultaneously, with Internet services achieving 22.67 Mbps out of the required 24 Mbps, and voice and video services maintaining stable uplink and downlink performance. These outcomes (Table V.4) indicate efficient resource scheduling, appropriate bandwidth allocation, and overall network robustness.

Table V.4: Comparison between demand and simulation results (Mbps)

Service	**Users**	**Max Demand DL**	**Max Demand UL**	**Peak RLC DL**	**Peak RLC UL**	**App. Throughput (DL / UL)**
Internet	17	24.00	2.50	24.00	2.50	22.67 / 2.34
Video Call	2	0.60	0.60	0.60	0.60	0.57 / 0.57
Voice Call	45	0.366	0.488	0.366	0.488	0.348 / 0.464

In parallel, the global coverage prediction highlighted seamless service continuity across urban and suburban sectors. The LTE layer (particularly using Band 20 at 800 MHz) provided extended reach and foundational coverage, while the 5G NR layer, operating in mid-band frequencies and reinforced by small cells, ensured high-capacity and low-latency support in user-dense areas.

The combined layout of macro and small cells contributed to optimized signal distribution and mobility handling.

V.2 Application in optimization in 5G network

V.2.1 iMANAGER MAE platforme interface

iMaster MAE is a centralized supervision platform that provides **Network Element Mediation (NEM)** capabilities. It enables the collection, analysis, and presentation of data from network equipment (gNB, eNodeB, etc.) to ensure full visibility into the network's status and quality. Figure V.23 presents the main interface of software, and the main features visible in the interface are:

- **KPI Analysis**: A module for analyzing KPIs, essential for real-time monitoring of radio performance.
- **Report Management**: Enables the generation and management of periodic or on-demand reports.
- **Object Group Management**: Structured management of network objects by logical groups (not directly visible but listed under recently used items).
- **Scheduled Report**: Allows the configuration and automatic scheduling of reports according to a defined timeline.
- **Common Tools**: Includes user settings, broadcast messages, and the information center.
- **Recently Used Panel**: A sidebar providing quick access to recently used tools.

This platform is particularly used by radio engineers for **diagnostics**, **4G/5G network optimization**, and the **continuous improvement of service quality**. With its intuitive interface and analytical modules, **Huawei iMaster MAE** is a key tool for the efficient management of modern mobile networks (see Figure V.23).

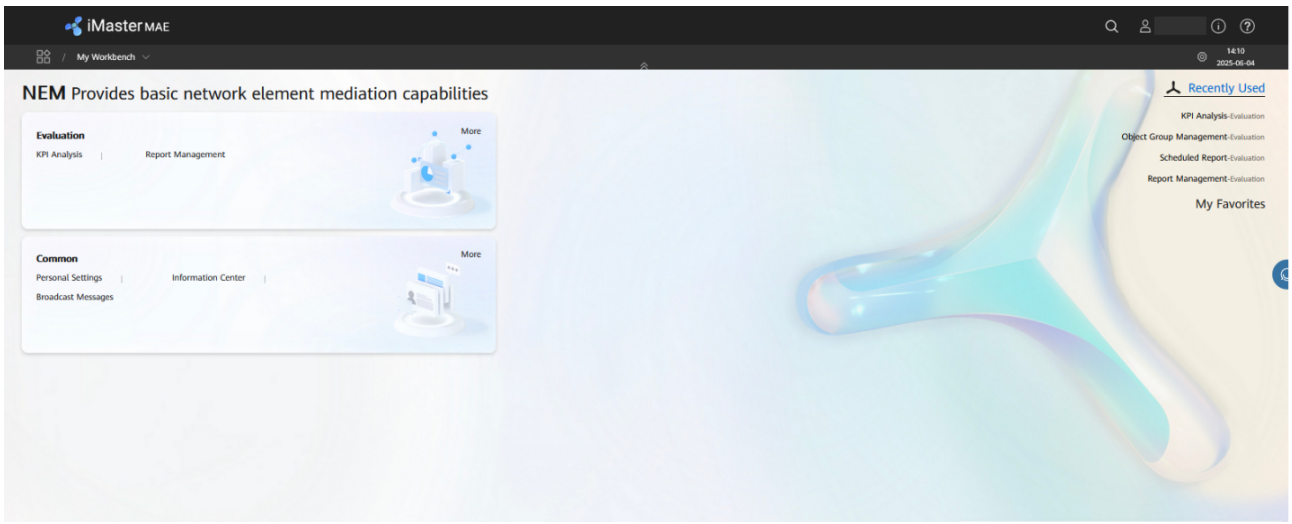


Figure V.23: iMANAGER MAE platform interface.

V.2.1.1 KPI Analysis

The interface consists of two main panels as shown in Figure V.24:

a. **Search criteria panel:** Contains the following functionalities:

- **Object dimension:** Includes *NE type*, *Object type*, and *Object group*. After selecting the group, one or more specific objects can be chosen.
- **Time dimension:** Allows the user to define the time range of the analysis (e.g., Hour, Day, Week, Month).
- **KPI Selection:**
  - **Report:** Selecting a report automatically includes all KPIs predefined in that report.
  - **KPI:** Alternatively, one or more specific KPIs can be selected manually for custom analysis.

b. **KPI results display panel:** This section shows the output of the KPI analysis in either tabular or graphical format. It includes data such as dates, object names, and associated KPI values, allowing users to interpret performance trends and identify anomalies in network behavior, as illustrated in Figure V.25.

V.2.1.2 MAE capacity visibility

This displays the MAE Capacity Visibility interface (see Figure V.26), highlighting network element connections, resource utilization status, and traffic KPIs across 5G, LTE, UMTS, and GSM technologies.

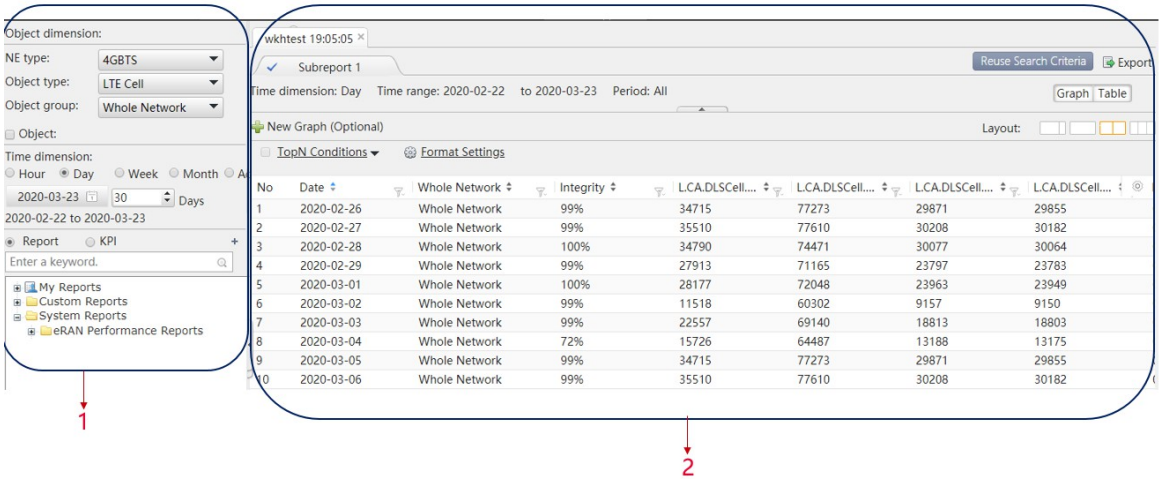


Figure V.24: KPI Analysis interface description.

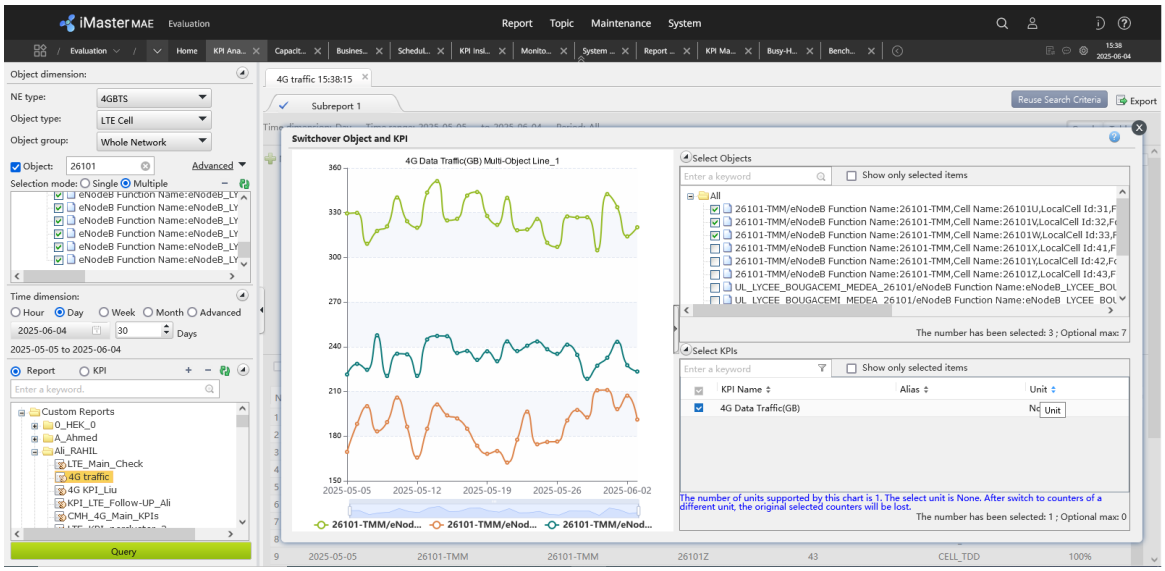


Figure V.25: KPI Results Display Panel Interface.

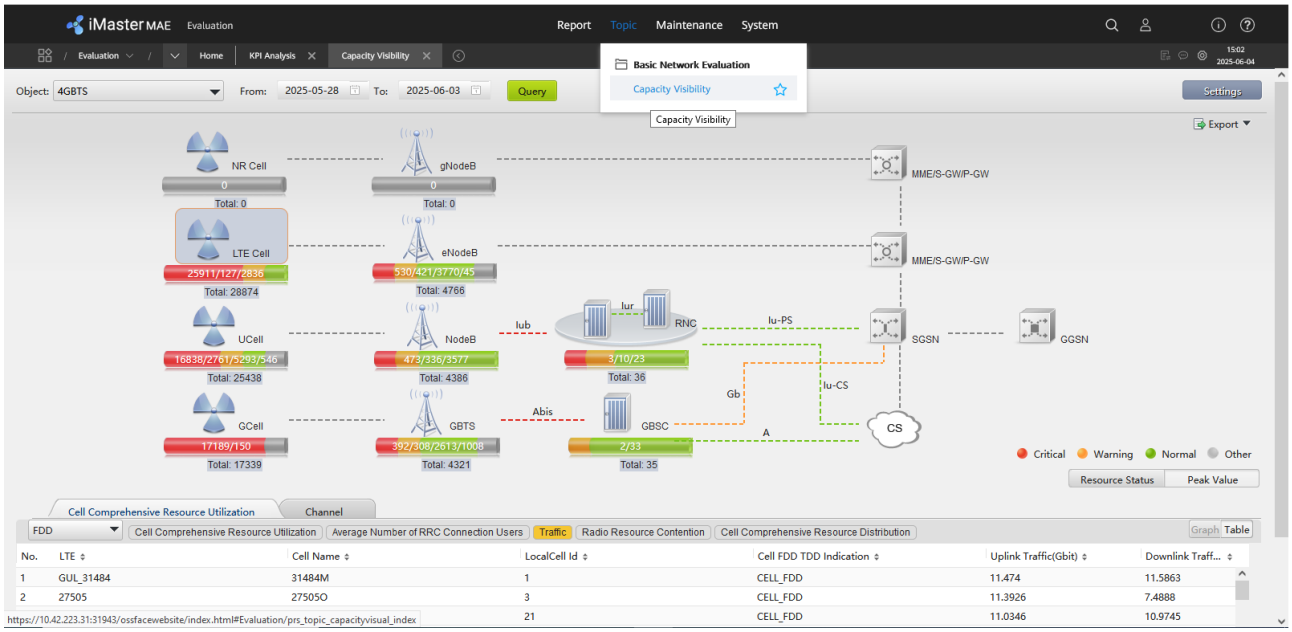


Figure V.26: MAE Capacity visibility interface.

V.2.1.3 Monitoring and KPI insight

MAE allows you to monitor network KPIs and traffic in real time by network region, helping you obtain information about network service quality and detect faults in a timely manner.

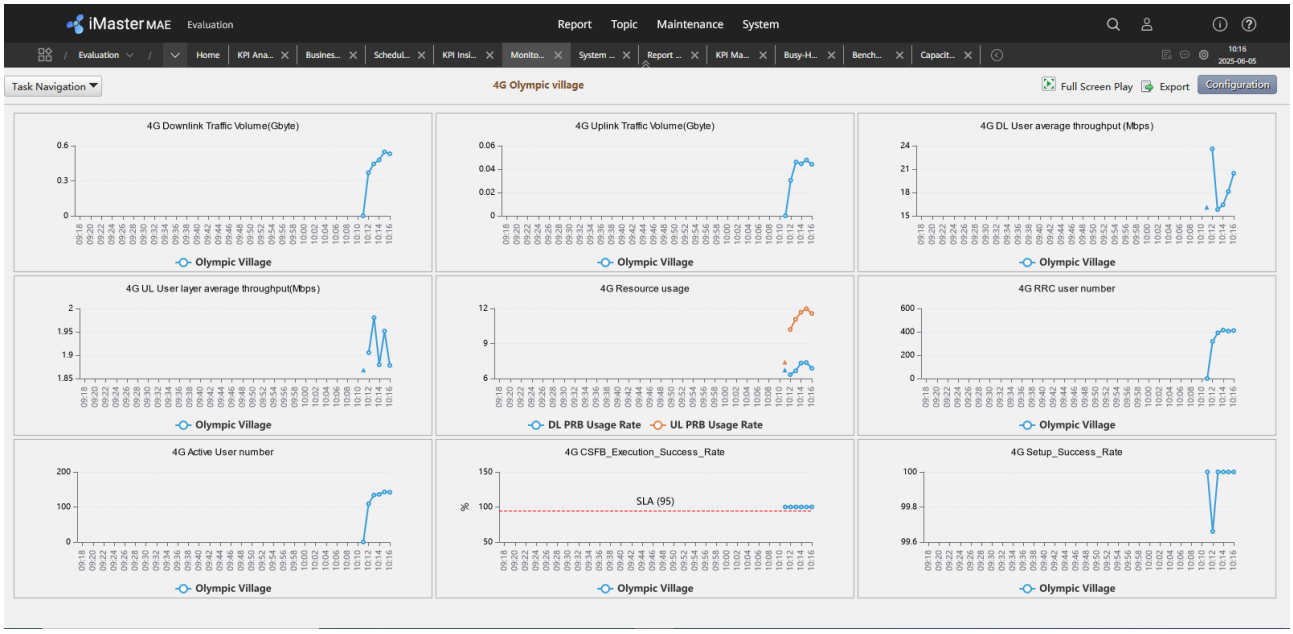


Figure V.27: Real time KPI monitoring interface.

Different from common KPI statistical tools (providing only reports), the system allows users to obtain the network performance data for monitoring network performance from each network object dimension by using one-click query, and displays network performance data in indicator charts, charts, and reports. The feature has integrated rich network optimization experience, which helps users perform network quality correlated analysis. KPI Insight supports the following object dimensions: whole network, BSC/RNC, and cell cluster.

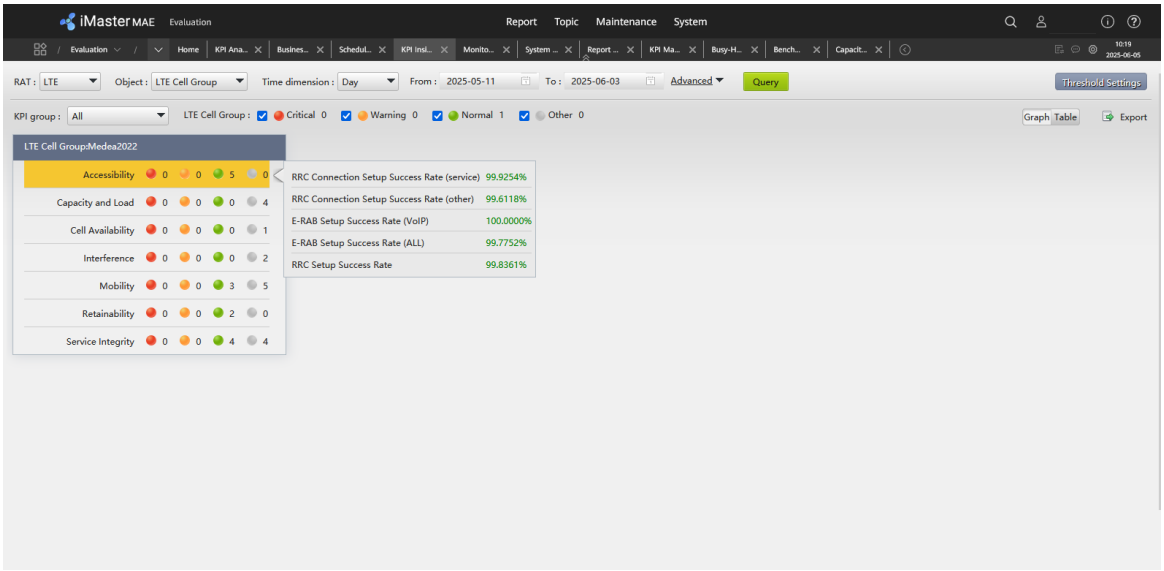


Figure V.28: KPI insight for performance monitoring.

V.2.2 Case Study: LTE Accessibility Analysis

V.2.2.1 Accessibility Issue Observed Under High Load

1) Problem Statement:

- The cell remains overloaded even after implementing tilt tuning and sharing traffic with neighboring cells.
- Affected cells: **261001Z** and **261001W**.
- These cells cover the **Medea supermarket** area.

2) Recommendations: Minimum Required Received Signal Level**(QRxLevMin)**defines the minimum signal level (in dBm) required for a cell to be considered eligible for reselection in LTE networks. A higher value makes cell reselection more stringent, enhancing signal quality but potentially limiting access. Conversely, a lower value facilitates access by broadening coverage. This parameter affects only idle mode. Proper configuration ensures selected cells meet the minimum service quality criteria. The default value of `qRxLevMin` is **-120 dBm**. It is recommended to change this value to **-114 dBm** to improve accessibility under high load conditions.

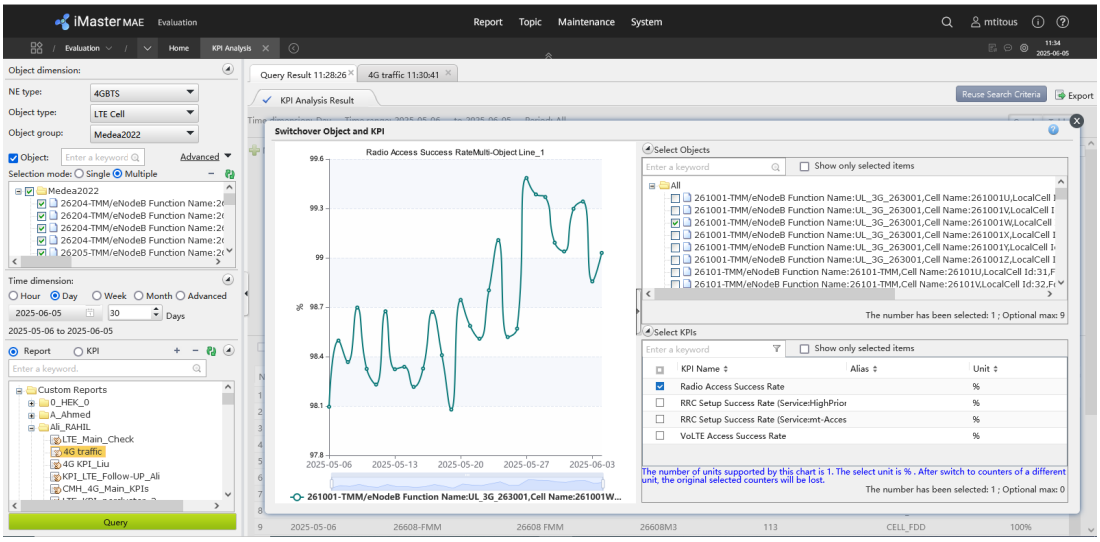


Figure V.29: Accessibility degradation in high load conditions.

3) Result: After tuning `qRxLevMin`, accessibility has improved. This improvement is clearly illustrated in Figures V.29 and V.30, where the overload symptoms are significantly reduced, and KPI values reflect better network access performance. The optimization allowed for more efficient signal acceptance and reduced call drops under congestion. In **cell 261001W**, as shown in Figure V.29, the accessibility ratio increased from **98.0782%** to **99.4849%**. Similarly, in **cell 261001Z**, illustrated in Figure V.30, the ratio improved from **98.742%** to **99.79%**.

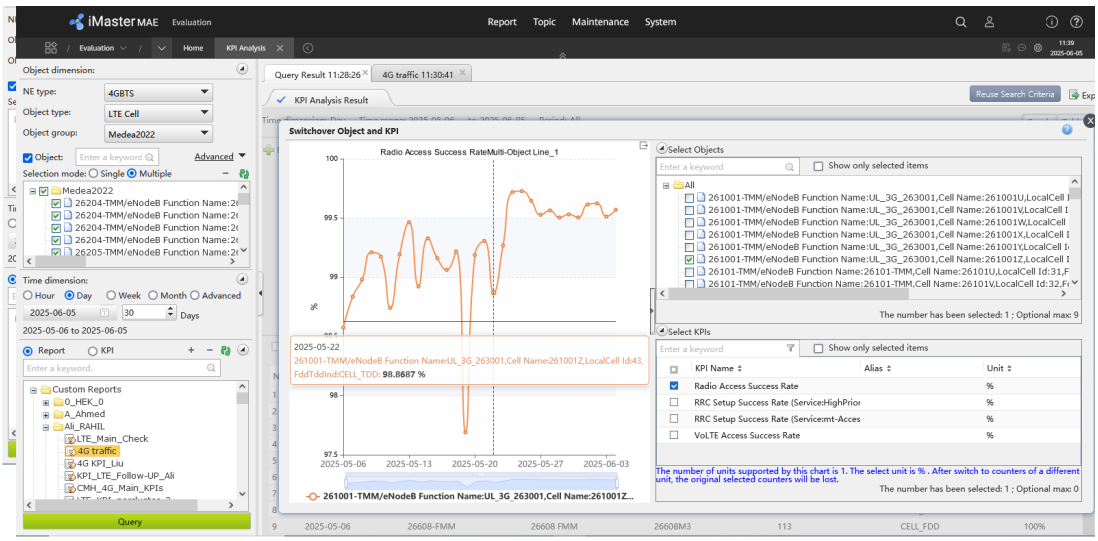


Figure V.30: Accessibility improvement after `qRxLevMin` tuning.

V.2.2.2 Retainability Analysis

1) Problem Statement: A high ERAB drop rate has been observed at cell **26622S1**. The eNodeB drop rate is also high, indicating issues with session retainability at both the radio and core network levels.

2) Recommendations

Maximum Number of RLC Retransmissions Allowed for User Equipment before Triggering RRC Reestablishment**(UeMaxRetxThreshold)**defines the maximum number of RLC retransmissions before triggering RRC reestablishment in LTE. A higher value increases reliability but adds delay; recommended for delay-insensitive services. It affects connected UEs only and doesn't interrupt idle mode.

a. **maxRetxThreshold parameter change:**

The `maxRetxThreshold` parameter value has been modified to improve radio link reliability:

- From **8 to 32** for **signaling radio bearers (SRB)**.
- From **8 to 16** for **data radio bearers (DRB)**.

b. **Parameter description:**

- `dlMaxRetxThreshold = 8 {1, 2, 3, 4, 6, 8, 16, 32}`
  Indicates the maximum number of RLC retransmissions in the downlink (DL) before stopping and reporting to the RRC that the threshold has been reached.
- `ulMaxRetxThreshold = 8 {1, 2, 3, 4, 6, 8, 16, 32}`
  Indicates the maximum number of RLC retransmissions in the uplink (UL) before stopping and reporting to the RRC.

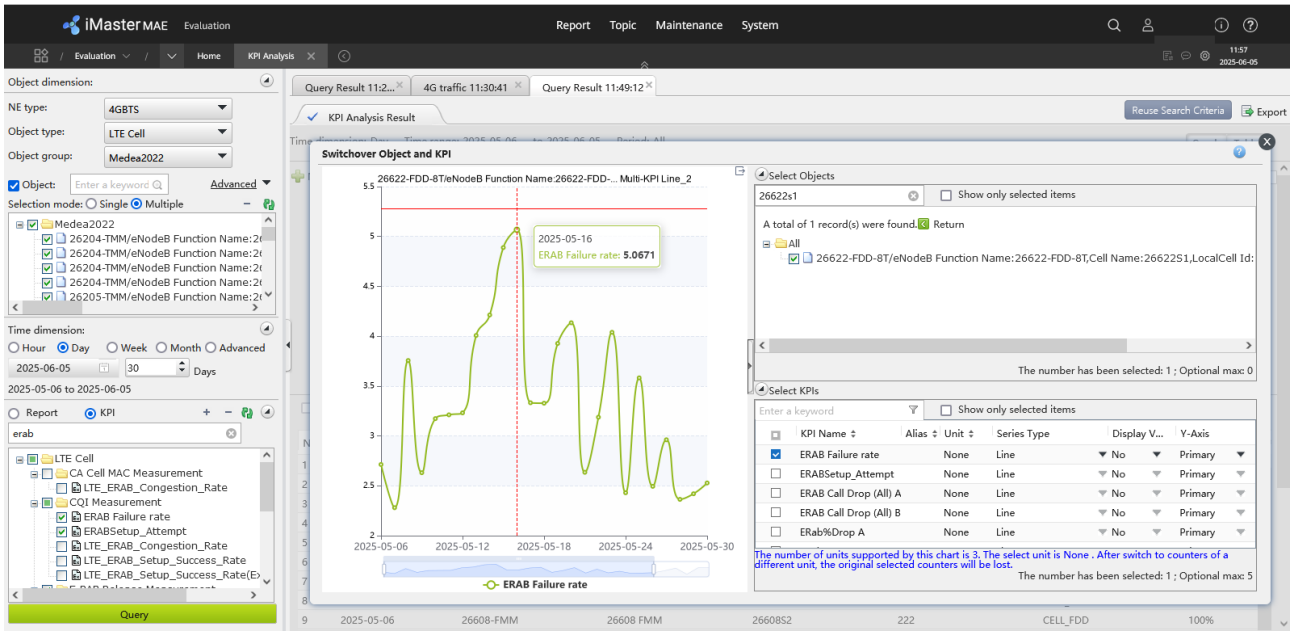


Figure V.31: ERAB drop rate root cause.

3) Result: After tuning the `MaxRetxThreshold` parameter values, the ERAB drop rate has significantly improved—from approximately **4%** to **1%**. This demonstrates a direct correlation between increased retransmission tolerance and improved retainability.

Figure V.31 illustrates the root causes of ERAB drops in the analyzed cell, emphasizing the importance of optimizing RLC layer behavior to sustain robust RRC connections. By increasing the retransmission threshold, transient radio conditions were better tolerated, thereby preventing premature session terminations.

V.2.2.3 Handover Success Rate Analysis

1) Problem Statement: The intra-frequency handover out success rate is significantly low.

2)Observation: Cell **261800M** exhibits a handover failure rate of **27%**, as shown in Figure V.32. The visualization reveals clusters of failures that may be attributed to degraded signal conditions in the target cells, misconfigured neighbor relations, or inappropriate mobility thresholds. These patterns indicate specific areas where handover performance tuning is required.

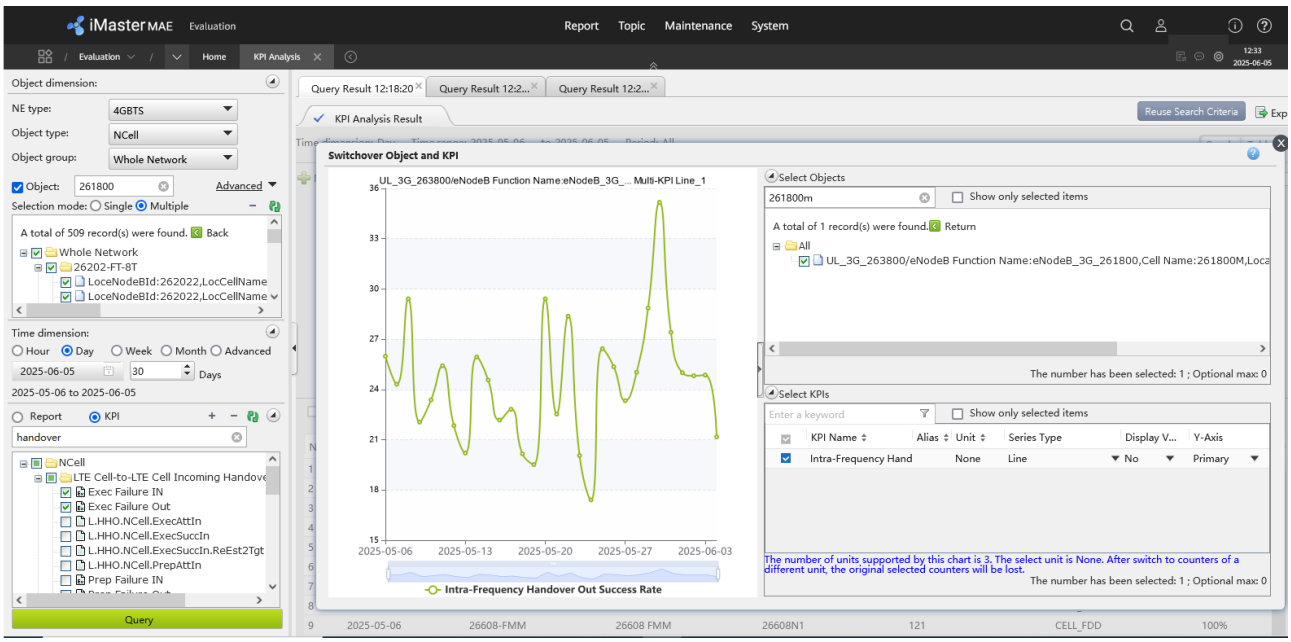


Figure V.32: Intra-frequency handover failure visualization.

Date	eNodeB Name	Local eNodeB identity	Local cell name	Target eNodeB ID	Target Cell Name	Exec Failure IN	Exec Failure Out
2025-06-04	UL_CAH_BOUGHAR_26204	26204	26204N1	261800	261800M	508	0
2025-06-03	UL_CAH_BOUGHAR_26204	26204	26204N1	261800	261800M	437	0
2025-06-01	UL_CAH_BOUGHAR_26204	26204	26204N1	261800	261800M	409	0
2025-06-02	UL_CAH_BOUGHAR_26204	26204	26204N1	261800	261800M	373	0
2025-06-01	26709-FDD-8T	267092	26709M1	261800	261800M	14	0
2025-06-03	26709-FDD-8T	267092	26709M1	261800	261800M	14	1
2025-06-02	26709-FDD-8T	267092	26709M1	261800	261800M	12	1
2025-06-04	26709-FDD-8T	267092	26709M1	261800	261800M	10	0
2025-06-02	26750	26750	26750M	261800	261800N	7	0
2025-06-03	26750	26750	26750M	261800	261800N	6	0
2025-06-03	UL_3G_263800	261800	261800M	261800	261800N	3	0
2025-06-04	UL_3G_263800	261800	261800N	261800	261800O	3	1
2025-06-04	UL_3G_263800	261800	261800M	261800	261800N	3	0

Figure V.33: Target cell radio deaf detection.

After checking all neighbor relations, it was observed that target cell **26204N1** appeared to be non-responsive potentially in a sleeping state or exhibiting *radio deafness*. This issue was confirmed through abnormal RSSI readings, as shown in Figure V.33.

3) Steps Taken: A hard reset was issued to cell **26204N1**, after which the cell returned to normal operational status.

4) Result

Following the reset, the target cell resumed proper functionality, leading to a **notable improvement** in the Intra-Frequency Handover Out Success Rate. Specifically, the handover failure rate for cell **261800M** decreased from **27%** to below **5%**, indicating a successful mitigation of the issue. Additionally, KPIs such as *handover attempt count*, *successful handovers*, and *radio link stability* improved. The area previously impacted by handover disruptions showed restored mobility

performance, and no further signs of *radio deafness* were observed in the target cell **26204N1** in subsequent monitoring cycles. This confirmed the positive and lasting impact of the corrective action.

V.2.3 Conclusion

This practical work demonstrated the end-to-end workflow of radio network planning using Atoll, from project initialization and parameter configuration to cell deployment and coverage simulation. By modeling LTE and 5G networks using the Okumura-Hata propagation model, we gained valuable insights into network performance and coverage behavior, highlighting Atoll's utility in designing efficient wireless systems.

Additionally, the integration of optimization tools such as the iManager MAE platform proved essential for monitoringKPIs and addressing real-world challenges related to accessibility, session retainability, and handover success. These tools enhance the ability to troubleshoot and optimize networks, thereby improving reliability and user experience in dynamic mobile environments.

CHAPTER VI

GENERAL CONCLUSION

VI.1 General Conclusion

The development of mobile communication has undergone a significant evolution, transitioning through multiple generations 2G, 3G , and 4 now arriving at 5G, which represents a paradigm shift in wireless communication. This thesis has addressed the essential aspects of 5G radio networks, focusing particularly on the implementation, planning, and optimization of Massive MIMO technology as a key enabler of 5G performance.

In the first stages of the work, the historical and technological evolution of mobile networks was explored. This established a contextual foundation for understanding how each generation introduced advancements in data rates, spectral efficiency, mobility support, and overall network capacity. Particular emphasis was placed on LTE and LTE-Advanced technologies, which paved the way for many of the concepts deployed in 5G.

The core of this study revolved around the detailed analysis of Massive MIMO systems, including their architecture, functionality, diversity strategies, spatial multiplexing, and beamforming techniques. By leveraging large-scale antenna arrays, Massive MIMO offers a powerful solution for increasing capacity and spectrum efficiency two fundamental requirements in modern wireless environments. Various beamforming methods (digital, analog, hybrid) and pre-coding schemes (such as SVD, ZF, and MMSE) were also examined to optimize signal transmission and reduce interference.

Complementary to the theoretical exploration, the thesis involved practical application and simulation of 5G network planning using Atoll, a professional planning tool. The project simulated deployment scenarios in a real urban environment, evaluating aspects such as signal coverage, SINR performance, and radio parameter configuration. The network planning was followed by performance optimization through KPI analysis using Huawei's iManager MAE platform, which enabled real-time diagnostics, fault detection, and system tuning. Performance indicators such as accessibility, retainability, mobility, and throughput were continuously monitored and improved

through parameter adjustment and troubleshooting strategies.

The case studies, particularly those involving accessibility improvement and handover optimization, demonstrated the tangible benefits of smart planning and real-time optimization in 5G networks. The observed improvements in ERAB drop rates, intra-frequency handover success, and service availability underscore the critical role of adaptive configuration and system monitoring in maintaining high service quality.

Overall, this research has shown that Massive MIMO, coupled with robust planning tools and intelligent optimization frameworks, holds immense potential to meet the growing demands of mobile broadband services. The results validate the technical and operational advantages of this approach, particularly in densely populated urban environments where spectral efficiency and user experience are paramount.

Looking forward, while this study has made significant contributions, several challenges remain—such as managing the complexity of channel estimation in high-mobility scenarios, mitigating interference, and ensuring secure communication. These areas represent fertile ground for future research, especially with the anticipated transition toward 6G networks, where AI-driven management, sub-THz bands, and intelligent surfaces will further redefine the landscape of wireless communication.

In conclusion, this thesis not only emphasizes the importance of planning and optimization in 5G networks, but also positions Massive MIMO as a cornerstone technology for the present and future of mobile communication. The synergy between theory, simulation, and practical application demonstrated throughout this project highlights the effectiveness of a well-rounded approach to designing high-performance, scalable, and intelligent mobile networks.

6G is expected to launch commercially by 2030. 6G early research and requirements gathering has started, and like with previous generations, will continue throughout its lifecycle. 6G specification development and standardization is slated for 2025-2029. First lab testing and pilots of 6G are expected to begin in 2028, preparing 6G for commercial release in or near 2030. Steps toward commercial readiness include the shift from 5G to 5G Advanced in 2024-2025. 5G Advanced is based on 3GPP's Release 18 specification, which is expected to get finalized in mid-2024. After 3GPP Release 18 is finalized, most expect 5G Advanced networks and devices to arrive commercially at some point in 2025. 3GPP Release 19 is expected to lay the groundwork for 6G, and it has an anticipated completion date in late 2025. Further 6G refinements would occur in future releases, including Releases 20-22. While the exact timelines for the subsequent releases aren't formally published at this time, previous release timelines indicate a development cycle, not including conceptualization or finalizations, of approximately 2 to 2.5 years. As a result, most anticipate the commercial release of 6G in or around 2030.

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