



People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
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Department of Electronics and Telecommunications



Academic Master's thesis

Domain: Science and technology

Sector: Telecommunications

Option: Telecommunications System

Topic:

Ensuring The Performance of NTN-NR 5G Communications

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Academic Year: 2024/2025

إلى الذين حملوا دفاترهم في طريق الشهادة،
ورسموا بدمائهم معادلات العزة على جدران الحصار،
إلى شهداء غزة، وجرحاها، ومقاومياها،
إلى القائد الصامد "يحيى السنوار"، رمز الكبرياء في زمن الانحناء،

نهدي هذا العمل المتواضع،
وفاءً لمن علمونا أن العلم والمقاومة وجهان لنفس الطريق.



Acknowledgments

First, we thank *Dr.SAYAH MOAD* and *Prof.BOUNEGAB ABDALHAMID* for allowing us to develop and research this thesis under their supervision and acknowledging all the guidance, orientation, experience, patience, and constant knowledge sharing that contributed to shaping our thesis work and immensely to our personal and professional development. It has been a true pleasure.

We also want to thank *Mr. NECIRI SAID* from MOBILIS for his contribution to this work, for always being available to answer any questions, providing crucial suggestions and a better understanding of the reality of telecommunications, and especially for the support throughout the thesis.

We are grateful to be part of *the University of KASDI MERBAH OUARGLA*, where everyone can actively help each other. Therefore, we want to give special thanks to all *the professors* who contributed to our academic and practical achievements during this educational period and to the administrative staff who ensured and contributed to the organization and coordination of this trip.

We want to express our gratitude to all *our colleagues* and *friends* for all the moments throughout our academic lives, the study nights, the trips, the get-togethers, and the experiences overall. It has, without a doubt, made us the people we are today. I thank them all sincerely.

I am deeply grateful to all *our families*, particularly *our fathers*, who have provided unwavering support throughout our lives, despite the occasional nagging. They've always given us support, strength, and insight, and I owe our current opportunities to them.

Abstract

The performance of 5G Non-Terrestrial Networks (NTN) combined with Low Earth Orbit (LEO) satellite constellations is evaluated in this thesis. The key performance indicators (KPIs), throughput, latency, coverage, and power efficiency are estimated across several scenarios where different subcarrier spacing (SCS), modulation schemes, and altitude are tested. The research emphasizes NTN's contribution in balancing coverage, capacity, adaptive SCS selection, altitude deployment and hybrid designs. Difficulties in HARQ adaptation, interference control, and Doppler shift point out areas of future study direction.

Keywords: 5G Non-Terrestrial Networks (NTN), LEO Satellite, KPIs, throughput, latency, coverage, subcarrier spacing (SCS).

ملخص:

يتم في هذه الأطروحة تقييم أداء شبكات الجيل الخامس غير الأرضية (NTN) جنبا إلى جنب مع مجموعات الأقمار الصناعية ذات المدار الأرضي المنخفض (LEO). يتم تقدير مؤشرات الأداء الرئيسية، (KPIs) و الإنتاجية، و الزمن الكامن، و التغطية، و كفاءة الطاقة عبر العديد من السيناريوهات حيث يتم اختبار مسافات متلفة بين الموجات الحاملة الفرعية (SCS)، و مخططات التعديل، و الارتفاع. يؤكد البحث على مساهمة NTN في تحقيق التوازن بين التغطية و القدرة و اختيار SCS التكميني و نشر الارتفاع و التصميمات الهجينة. تشير الصعوبات في التكيف مع HARQ، و التحكم في التداخل، و تحول دوبلر إلى مجالات اتجاه الدراسة المستقبلية.

الكلمات المفتاحية:

شبكات الجيل الخامس غير الأرضية (NTN)، القمر الصناعي LEO، مؤشرات الأداء الرئيسية، الإنتاجية، زمن الوصول، التغطية، تباعد الموجات الحاملة الفرعية (SCS).

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List of Acronymes

Acronym	Explanation	Acronym	Explanation	Acronym	Explanation
5G	Fifth Generation	IoT	Internet of Things	LEO	Low Earth Orbit
NR	New Radio	URLLC	Ultra-Reliable Low-Latency Communication	UAS	Unmanned Aircraft System
ITU	International Telecommunication Union	3GPP	3rd Generation Partnership Project	HAPS	High-Altitude Platform Stations
eMBB	Enhanced Mobile Broadband	KPIs	Key Performance Indicators	UAV	Unmanned Aerial Vehicle
mMTC	Massive Machine-Type Communication	RAN	Radio Access Network	NGSO	Non-Geostationary Orbit
UE	User Equipment	NG-RAN	Next-Generation Radio Access Network	RF	Radio Frequency
5GC	5G Core Network	USIM	Universal Subscriber Identity Module	SRI	Satellite Radio Interface
gNB	5G NodeB	ng-eNB	next-generation eNodeB	ISL	Inter-Satellite Links

LTE	Long-Term Evolution	gNB-CU-CP	gNB-CU Control Plane	GPS	Global Positioning System
RRM	Radio Resource Management	gNB-CU-UP	gNB-CU User Plane	DTH	Direct-to-Home
QoS	Quality of Service	gNB-DUs	gNB Distributed Units	RREL	Release
DU	Distributed Unit	SBA	Service-Based Architecture	FUL	Frequency Uplink Low
RU	Radio Unit	NFs	Network Functions	FDL	Frequency Downlink High
gNB-CU	gNB Centralized Unit	APIs	Application Programming Interfaces	LS-band	L and S band
CP	Control Plane	AMF	Access and Mobility Management Function	MBS	Multicast-Broadcast Services
UP	User Plane	SMF	Session Management Function	SNR	Signal-to-noise ratio
UPF	User Plane Function	NEF	Network Exposure Function	CDL	Clustered Delay Line
PCF	Policy Control Function	NR-DC	NR-NR Dual Connectivity	TDL	Tapped Delay Line
NSSF	Network Slice Selection Function	MN	Master Node	ARFCN	Absolute Radio Frequency Channel Number

UDM	Unified Data Management	SN	Secondary Node	OFDMA	Orthogonal Frequency Division Multiple Access
HSS	Home Subscriber Server	NSA	Non-Standalone	SC-FDMA	Single-Carrier Frequency Division Multiple Access
AUSF	Authentication Server Function	SA	Standalone	PAPR	Peak-to-Average Power Ratio
NRF	NF Repository Function	DL	Downlink	LDPC	Low-Density Parity-Check
NEF	Network Exposure Function	OFDM	Orthogonal Frequency Division Multiplexing	VSAT	Very Small Aperture Terminal
DC	Dual Connectivity	CP	Cyclic Prefix	QoS	Quality of Service
EN-DC	E-UTRA-NR Dual Connectivity	UL	Uplink	MIMO	Multiple Input Multiple Output
DFT-s-OFDM	Discrete Fourier Transform-spread OFDM	MIMO	Multiple-Input Multiple-Output	PAPR	Peak-to-Average Power Ratio

TDD	Time Division Duplex	FR	Frequency Range	NTN	Non-Terrestrial Network
FDD	Frequency Division Duplex	QAM	Quadrature Amplitude Modulation	OFDMA	Orthogonal Frequency Division Multiple Access
SatCom	Satellite Communication	SC-FDMA	Single-Carrier Frequency Division Multiple Access	GEO	Geostationary Earth Orbit
LDPC	Low-Density Parity-Check	MMEO	Medium Earth Orbit		

List of Symbols

Symbole	Description
$\mathbf{v}_{\text{Layers}}^{(j)}$	Facteur de pondération pour le niveau de couche j
$Q_m^{(j)}$	Nombre de bits par symbole pour la modulation j
$f^{(j)}$	Facteur d'efficacité du codage pour la couche j
R_{max}	Débit de transmission maximal
$N_{\text{PRB}}^{\text{BW}(j),\mu}$	Nombre de blocs de ressources (PRB)
T_s^μ	Durée d'un symbole OFDM pour μ donné
$OH^{(j)}$	Overhead (surplus) pour la couche j
δ_{prop}	Délai de propagation
d	Distance de propagation
\mathbf{v}	Vitesse de propagation
δ_{Trans}	Délai de transmission
D_{serv}	Taille des données à transmettre
R	Débit de transmission
F_{REF}	Fréquence de référence actuelle
$F_{\text{REF-offs}}$	Fréquence de référence d'origine
ΔF_{Global}	Écart de fréquence global
N_{REF}	Indice de la fréquence de référence actuelle
$N_{\text{REF-Offs}}$	Indice de fréquence de référence d'origine
R_E	Rayon de la Terre
α	Angle d'élévation
h_0	Hauteur du satellite ou station
P_{RX}	Puissance reçue
P_{TX}	Puissance transmise
G_{RX}	Gain de l'antenne de réception

λ	Longueur d'onde du signal
PL	Perte totale de liaison
PLO	Perte de base
PL _g	Perte due à la géométrie
PL _s	Perte due à la scintillation
PL _e	Perte due aux erreurs environnementales
f_c	Fréquence porteuse
FSPL	Free Space Path Loss
NF	Facteur de bruit
SNR _i	Rapport signal/bruit avec facteur de bruit
SNR ₀	Rapport signal/bruit sans facteur de bruit
T	Température du bruit ajouté
T_0	Température de référence
Δf	Décalage Doppler instantané
θ	Angle du mouvement par rapport au signal
c	Vitesse de la lumière
$f_{d,shift}$	Fréquence de décalage Doppler satellite
\mathbf{v}_{sat}	Vitesse du satellite
H	Hauteur orbitale du satellite

List of software

MATLAB	Numerical and Simulation Computing Software
ATOLL	5G NR Planning
Microsoft Excel	Spreadsheet Application
Microsoft Word	Text Editor Software
ChatGPT	Artificial Intelligence Technology

General Introduction

Overview and Motivation

Mobile communications services are continuously advancing along with application demands. As the world shifts toward a fully interconnected and digitalized society, expectations are rising, including the need for greater data capacity, lower latency, real-time data reliability, and seamless global connectivity.

The Fifth Generation (5G) New Radio (NR) wireless system is a cutting-edge technology designed to meet the increasing mobile market demands. The fifth-generation (5G) mobile communications system, represented by Release 15 of the 3rd Generation Partnership Project (3GPP), combines New Radio (NR), a novel radio access technique. 5G NR introduces higher data speeds, lower latency, greater capacity, spectrum flexibility, forward compatibility, and innovative antenna technologies [1].

It is the foundation for new services, ecosystems, and economic growth, transforming industries like healthcare, manufacturing, and smart cities.

The evolution of telecommunication technologies and the increasing demand for new services, combined with the exponential growth of smart devices, has led to the development of non-terrestrial network (NTN) systems as a powerful way to supplement terrestrial networks in providing services to uncovered or underserved geographic areas. According to the definition of the 3rd Generation Partnership Project (3GPP) [2], NTN is a classification of networks that use airborne (i.e., UAS and HAPS) or spaceborne payload for communication. Examples of spaceborne platforms include low-Earth orbiting (LEO) satellites, medium-Earth orbiting (MEO) satellites, and geosynchronous Earth orbiting (GEO) satellites. The non-terrestrial satellite access ecosystem has traditionally struggled with interoperability [3].

5G-NTN synergy can bridge connectivity gaps in remote and underserved areas, ensuring global coverage. Figure 1.

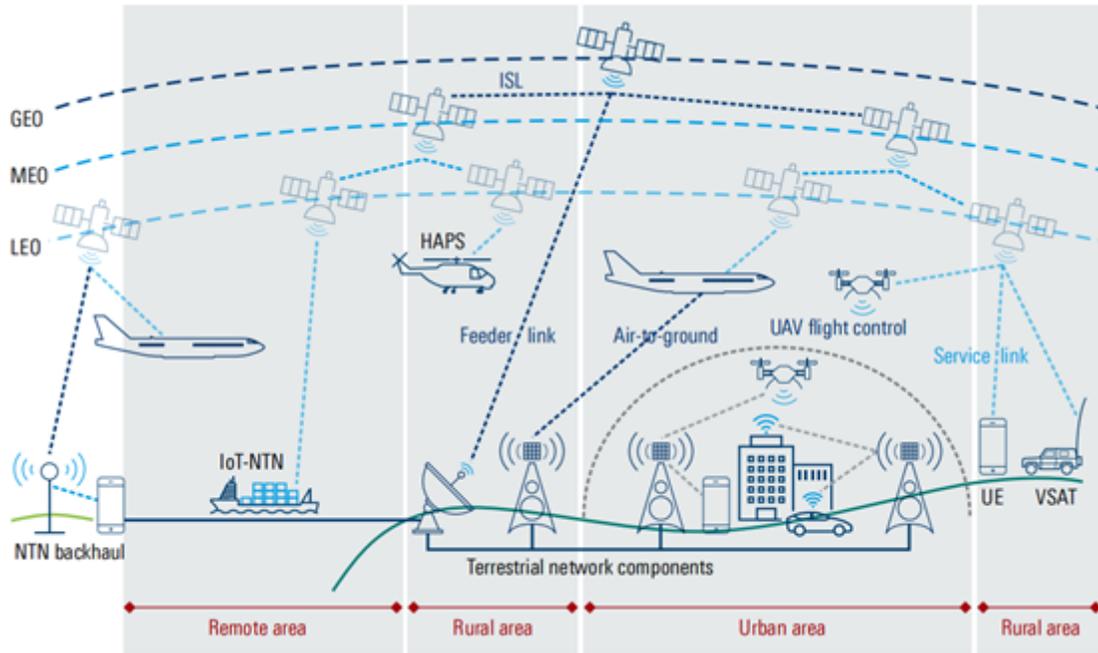


Figure 1: General connectivity overview of NTN (extracted from [44]).

Objective and Contents

The primary objective of this research is to evaluate the performance of Non-Terrestrial Networks (NTN) in the context of 5G communications, with a specific focus on Key Performance Indicators (KPIs) that can assess the effectiveness and efficiency of NTN solutions in meeting the requirements of 5G networks the research aims to achieve the following objectives:

Analyse the Impact of NTN on 5G Performance

The initial goal is to evaluate how NTN, particularly satellite communication systems, can contribute to the overall performance of 5G networks. This includes examining their role in improving network coverage, capacity, latency, and reliability, especially in remote, rural, and underserved regions where terrestrial networks are limited.

Define and Measure KPIs for NTN in 5G

Key Performance Indicators (KPIs) are essential for evaluating the success of any network. This research will focus on identifying and defining the most relevant KPIs for NTN in 5G, such as data rate, latency, coverage, reliability, energy efficiency, and security. These KPIs will assess NTN's performance and compare its capabilities with those of traditional terrestrial networks.

This thesis consists of three chapters:

First Introduction and overview of the problem and what is being analysed in this thesis. In the end, the objective behind this work is presented

Chapter 1: 5G and Non-Terrestrial Networks This chapter will provide an overview of NTN and its role in 5G communications. It will explore satellite communication systems, different orbital layers (LEO, MEO, GEO), and the evolution of NTN. It will also cover key use cases and the architecture of NTN in 5G.

Chapter 2: Theoretical Background of the Practical Work This chapter will outline the simulation tools and software used in the research, including MATLAB and ATOLL. It will describe how these tools are implemented for NTN 5G performance analysis, geographical data processing, and coverage estimation.

Chapter 3: Simulation Results This chapter will present the simulation results for NTN networks in MATLAB, focusing on key Performance indicators like throughput, latency, and coverage. It will compare NTN performance with traditional terrestrial 5G networks, evaluating their effectiveness through the KPIs defined earlier. It will include challenges faced during the simulation and solutions implemented.

Finally, the conclusion presents the key findings of this study and offers concluding remarks on potential future research to conclude the thesis.

Fundamental Concepts

This chapter offers an overview of 5G, primarily emphasizing its architecture. It addresses the 5G Access Network (NG-RAN) and 5G Core Network Dual Connectivity (DC). It explores the 5G Access Network (NG-RAN) and Dual Connectivity (DC) in the 5G Core Network. It also analyzes the radio interface and the classification of 5G use cases. The chapter concludes by examining non-terrestrial networks, covering their architecture, frequency bands, mobility, and applications with a particular focus on satellite-based systems. These elements serve as key enablers for integrating 5G with NTN.

1.1 Evolution of Mobile Communications Systems Before 5G

Our lives have undergone significant changes due to mobile communication technology. They remove the restrictions on time and location that come with moving information from one location to another. This enables anyone to access or trade information at any time, from any location. Today, mobile communication devices are an integral part of our daily lives [1].

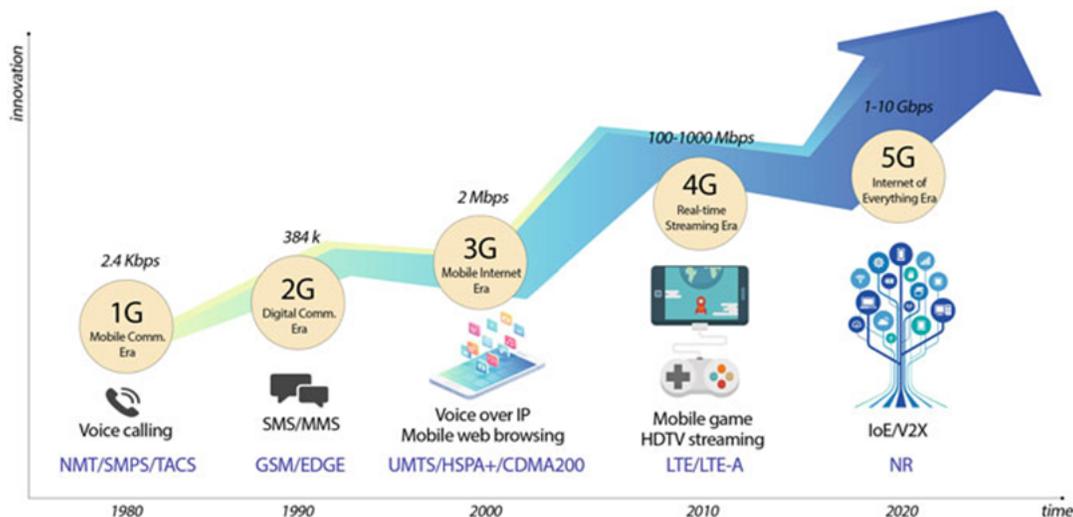


Figure 1.1: Evolution of mobile communication systems (extracted from [1])

1G: The Birth of Mobile Communication

1G revolutionized mobile communication. The cellular system was first presented by Bell Labs in 1947. NTT commercialized this idea in 1979. In the early 1980s, Motorola introduced the first mobile phone, “DynaTAC,” offering 1G mobile connectivity. Numerous countries established their own 1G standards, such as NMT in Eastern Europe and Russia, AMPS in North America, TACS in the UK, and TZ-801/2/3 in Japan. 1G used analog communication methods with 150 MHz carrier frequencies, focusing solely on voice conversations. Although the 1G revolutionized personal communication by eliminating space constraints, it had significant drawbacks. Low communication quality and security resulted from the limitations of analog communication technology. There was no compatibility between mobile communication systems, as each country established its system.

2G: The Advent of Digital Communication

2G launched digital mobile communication. The key change from 1G was the shift from analog to digital communication technology. The power of digital technology has dramatically enhanced communication quality and security. 2G offered more than just

a voice connection. The system enabled the transfer of encrypted messages, including voice, text, pictures, and multimedia messages. Mobile communication systems gained popularity due to the variety of message kinds, which increased commercial potential. In 1991, the Global System for Mobile Communications (GSM) became the first 2G standard. With a data rate of 9.6 kbit/s, GSM evolved into GPRS and EDGE, which offered maximum transmission speeds of 40 and 384 kbit/s, respectively. The 2G GSM standard uses time division multiple access (TDMA).

3G: The Era of Mobile Internet

3G-enabled mobile Internet. A key advance in 3G was the introduction of data packet-based communication technology. Packet-switched communication technologies enabled mobile Internet access to the World Wide Web. From anywhere using mobile communication systems. The highest data rate of 3G was estimated at 2 Mbps, four times quicker than 2G. The increased data rate enabled new services, such as Skype, fast online browsing, and video streaming and conferencing. This era saw the introduction of smartphones, including the Blackberry in 2002 and the iPhone in 2007. This device further enhanced mobile communication system services. The 3G technology was developed to meet IMT-2000 criteria. In 2001, NTT DoCoMo introduced the first 3G service based on the 3GPP-standardized Universal Mobile Telecommunications System (UMTS). This system progressed to HSPA+, achieving peak uplink and downlink data rates of 28 and 56 Mbit/s, respectively. In North America and South Korea, the successful 3G standard was Code Division Multiple Access (CDMA) 2000, standardized by 3GPP2. The subsequent EVDO Rev B standard increased peak downlink data speeds to 14.7 Mbit/s.

4G: The Rise of Mobile Broadband

4G launched real-time streaming. The main difference between 3G and 4G is the enhancement of data rates to hundreds of megabits per second. Enhanced data rates enabled new mobile services, including real-time gaming and high-definition television (HDTV). Improved data rates were achieved by a new multiple access technique called orthogonal frequency division multiple access (OFDMA). Additionally, MIMO communications technologies enhanced data rates by an order of magnitude. Two key breakthroughs transformed cellular system design to combat channel fading and interference in wireless environments.

The commercial 4G LTE service began in Sweden in 2009 and expanded globally. For instance, South Korea and the UK introduced LTE services in 2011 and 2012. Maximum downlink and uplink data speeds for LTE systems are 100 and 50 Mbit/s, respectively,

using a 20 MHz channel. This LTE system was upgraded to LTE Advanced (LTE-A). LTE-A was standardized in 2010 as part of 3GPP Release 10. More spectrums and antennas were utilized to boost data rates. LTE-A offers data rates of up to 1000 and 500 Mbit/s in downlink and uplink, respectively. To increase system capacity, coordinated multipoint transmission and carrier aggregation technologies were essential.

1.2 5G Overview

The 5G New Radio (NR) wireless system, featuring the New Radio (NR) air interface [4], is the leading next-generation solution designed to meet the growing demands of the mobile market. 5G NR supports diverse services, each with unique requirements.

The International Telecommunication Union (ITU) [5] defines three primary use case categories: Enhanced Mobile Broadband (eMBB) delivers high data rates for applications like Massive Machine-Type Communications (mMTC), which connects massive IoT devices that feature low power consumption, long battery life, and low cost (e.g., smart cities, sensors), and Ultra-Reliable Low-Latency Communication (URLLC) enables mission-critical applications (e.g., autonomous vehicles, industrial automation) with sub-1ms latency and 99.999% reliability.

To achieve these capabilities, the 3rd Generation Partnership Project (3GPP) has redefined multiple aspects of wireless technology for 5G NR, including Key Performance Indicators (KPIs), Higher speeds, lower latency, global coverage, Network Architecture, Radio Access Network (RAN) Enhancements, beamforming [6],

Through these innovations, 5G NR delivers transformative benefits such as multi-Gbps data speeds, sub-millisecond latency, support for massive device connectivity, and the ability to create dedicated network slices tailored to specific service requirements—collectively enabling a new era of mobile connectivity.

1.3 5G Architecture

1.3.1 5G NR Overall Architecture

The 5G system architecture maintains fundamental components similar to previous cellular generations while introducing significant technological advancements. The system comprises three primary elements: User Equipment (UE), the Next-Generation Radio Access Network (NG-RAN), and the 5G Core Network (5GC), illustrated in Figure 1.2 The UE comprises two key subcomponents - a Mobile Station that handles radio communication and a Universal Subscriber Identity Module (USIM) for authentication and subscriber identification. This structural

continuity with earlier systems ensures backward compatibility while enabling revolutionary 5G capabilities through the advanced NG-RAN and cloud-native 5GC components. The accompanying diagram illustrates this fundamental architecture, showing how these elements interconnect to form the complete 5G system. This evolutionary approach allows for a smooth transition from 4G networks while providing the foundation for 5G's enhanced performance characteristics and service capabilities.



Figure 1.2: 5G overall architecture (extracted from [7]).

1.4 5G Access Network (NG-RAN)

The NG-RAN is the radio access part of 5G, connecting user devices (UEs) to the 5G Core (5GC).

It replaces the 4G E-UTRAN and comprises two key node types: the gNB (5G NodeB) for native 5G New Radio (NR) connections and the ng-eNB (next-generation eNodeB) for LTE compatibility, both connecting to the 5G Core (5GC) through the NG interface [8].

Both nodes collectively manage essential radio functions, including Radio Resource Management (RRM), connection admission control, and Quality of Service QoS flow management. The architecture features a sophisticated interface system, with the NG interface linking both node types to the 5G Core. In contrast, the Xn interface enables direct gNB-to-gNB communication for coordinated operations.

NG-RAN architecture is composed of multiple gNBs (5G base stations) interconnected to form the radio access network illustrated in Figure 1.3, splitting base station functionality into three logical units - the Centralized Unit (CU) for control functions and higher layer processing, the Distributed Unit (DU) for real-time scheduling and lower layer protocols, and the Radio Unit (RU) for physical signal transmission and reception, separating the Central Unit (gNB-CU) into distinct Control Plane (gNB-CU-CP) and User Plane (gNB-CU-UP) components. This separation, facilitated through F1-C and F1-U interfaces, enables more flexible network scaling and resource allocation. The gNB-CU-CP maintains control over multiple User Plane

instances and Distributed Units (gNB-DUs), connected through the E1 interface for internal coordination, illustrated in Figure 1.4. This structure supports advanced capabilities, including network slicing, efficient management of inactive mode UE, and seamless mobility between LTE and NR networks through direct and core network-assisted handovers [9].

Network scaling and resource allocation. The gNB-CU-CP maintains control over multiple User Plane instances.

And Distributed Units (gNB-DUs), connected through the E1 interface for internal coordination illustrated in (Fig.1.4) [8]. This structure supports advanced capabilities, including network slicing, efficient management of inactive mode UE, and seamless mobility between LTE and NR networks through both direct and core network-assisted handovers [9].

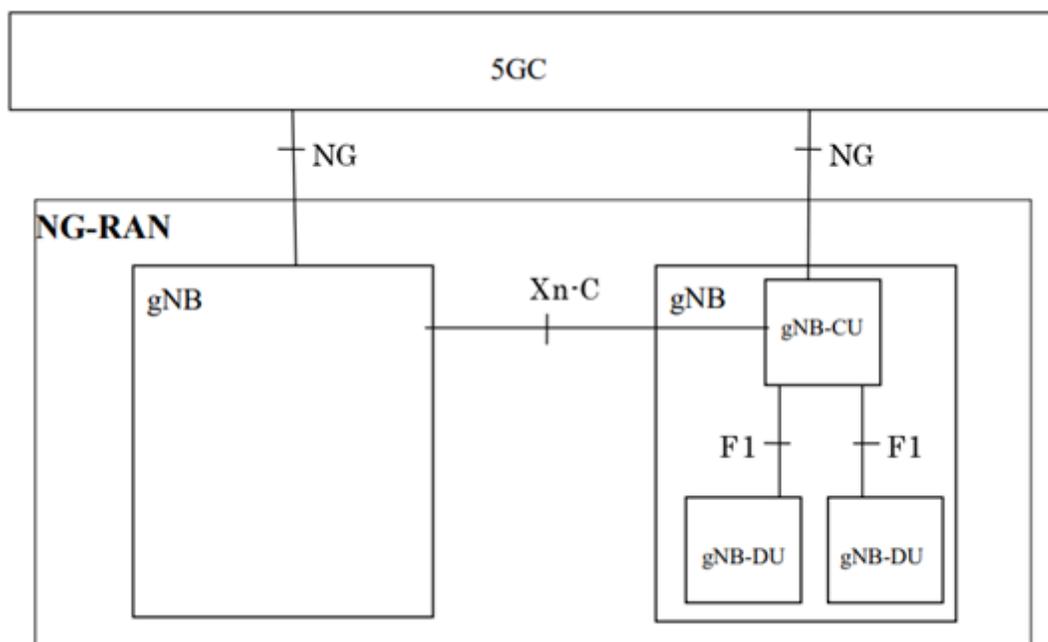


Figure 1.3: The NG-RAN logical architecture (From [8]).

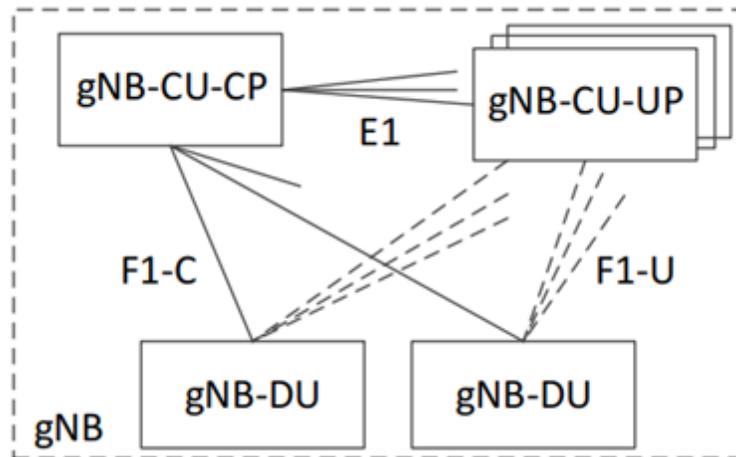


Figure 1.4: gNB architecture with separation of gNB-CU-CP and gNB-CU-UP. (From [8])

1.5 5G Core Network

Unlike the 4G EPC (Evolved Packet Core), 5GC is designed for flexibility, automation, and support for diverse 5G use cases (eMBB, URLLC, mMTC). The 5G Core (5GC) represents a complete transformation from previous generations, introducing a cloud-native, service-based architecture (SBA) that enables network slicing, ultra-low latency, and massive scalability.

The 5G Core (5GC) consists of modular Network Functions (NFs) that communicate via standardized Application Programming Interfaces (APIs).

The main functions are shown in Figure 1.5 and include:

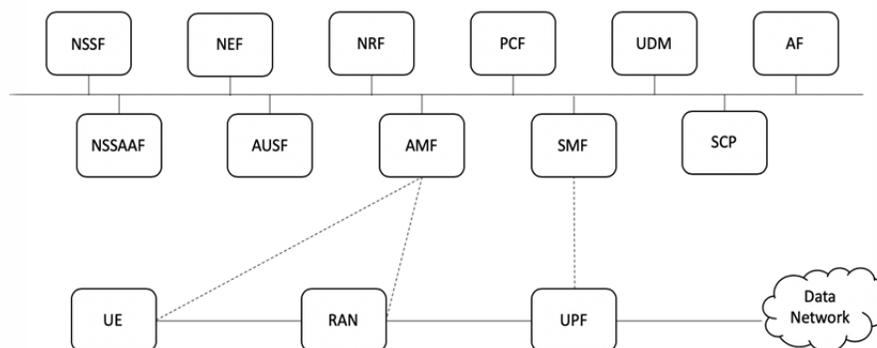


Figure 1.5: High-level representation of the 5G Core Network. (adapted from [10]).

The 5GC adopts a modular SBA where network functions communicate through standardized APIs. This revolutionary approach enables unprecedented flexibility, allowing

operators to scale services and deploy innovative features like network slicing dynamically.

The 5GC decomposes traditional network elements into specialized functions, including [10]:

- The Access and Mobility Management Function (AMF) for connection handling.
- Session Management Function (SMF) for session control.
- User Plane Function (UPF) for data routing.
- Policy Control Function (PCF) is used to manage the quality of service and network policies.
- Network Slice Selection Function (NSSF) for assigning network slices to users.
- Unified Data Management (UDM) for Stores subscriber data (like HSS in 4G).
- Authentication Server Function (AUSF) for handling security & authentication.
- The NF Repository Function (NRF) helps Network Functions (NFs) discover each other.
- Network Exposure Function (NEF) allows 3rd-party apps to access network APIs.

1.6 Dual Connectivity (DC)

There are two types of Dual Connectivity E-UTRA-NR Dual Connectivity (EN-DC) for 4G/5G interworking and NR-NR Dual Connectivity (NR-DC) for pure 5G deployments. Enables user equipment (UE) to simultaneously utilize radio resources from at least two distinct base stations, a Master Node (MN) and a Secondary Node (SN), with a Master Node (MN) handling critical control plane functions and a Secondary Node (SN) providing additional user plane resources. EN-DC, commonly deployed in Non-Standalone (NSA) 5G networks, utilizes an LTE eNB as the anchor for control signaling while incorporating a 5G gNB to boost data throughput, creating an efficient migration path for operators. NR-DC, designed for standalone (SA) networks, combines multiple 5G connections to maximize capacity, which is particularly effective when aggregating different frequency bands like sub-6 GHz and millimeter waves. Figure 1.6 comprehensively overviews all possible standalone and non-standalone architectural configurations [11].

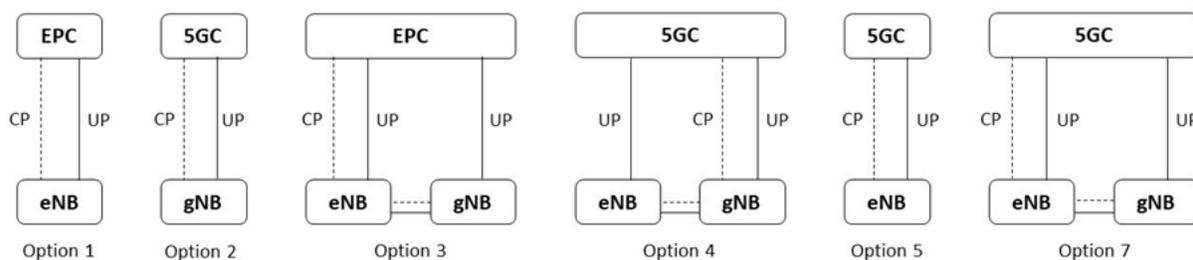


Figure 1.6: LTE-NR architecture options (adapted from [11]).

1.7 5G Radio Interface

The 5G radio access technology, New Radio (NR), is standardized in 3GPP [7]. For physical layer 1, DL uses OFDM with Cyclic Prefix (CP), similar to LTE. For UL supports both OFDM and DFT-s-OFDM (Discrete Fourier Transform-spread OFDM), DFT-s-OFDM improves uplink coverage with a lower Peak-to-Average Power Ratio (PAPR) but is limited to single-layer transmission.

5G deployment offers two architectural approaches: Non-Standalone (NSA) and Standalone (SA shown in Figure 1.7).

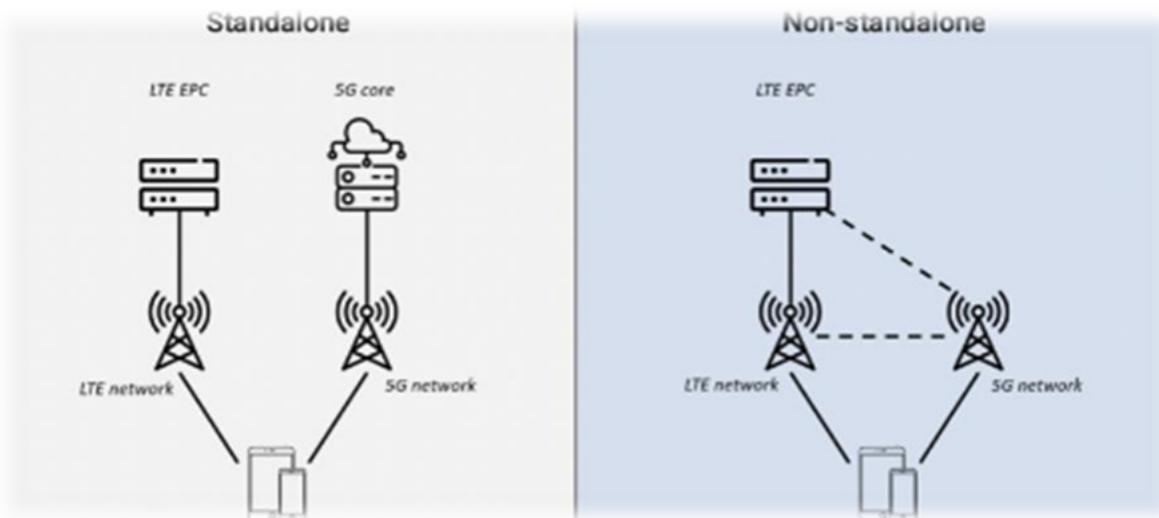


Figure 1.7: Standalone and non-standalone versions (extracted from [30])

The NSA architecture, or E-UTRA-NR Dual Connectivity (EN-DC) or "Option 3", represents a transitional solution integrating 5G NR radio access with existing 4G LTE core infrastructure. In this configuration, the LTE eNB serves as the Master Node for control functions (controls signaling), while the NR gNB acts as a Secondary Node to provide additional capacity.

The SA architecture constitutes a complete 5G system with NR radio access connected to a native 5G core network, enabling full realization of 5G capabilities. These deployment options provide operators with flexibility in their migration path from 4G to comprehensive 5G networks.

The NR air interface operates across two distinct frequency ranges, which are represented in Table 1.1.

Table 1.1: NR channel bandwidth

Frequency range designation	Frequency range [MHz]	Supported channel bandwidth [MHz]
FR1	410 – 7 125	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, 100
FR2	24 250 - 52 600	50, 100, 200, 400

NR supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD), Table 1.2

Table 1.2: NR bands and duplexing schemes

NR Band [MHz]	Duplex scheme	Frequencies [MHz]		Total Bandwidth [MHz]
		Downlink	Uplink	
700	FDD	703–733	758–788	60
3600	TDD	3400–3800		400

NR's multiple access scheme lies in Orthogonal Frequency Division Multiple Access (OFDMA) for downlink and Single-Carrier Frequency Division Multiple Access (SC-FDMA) for uplink, enhanced through an innovative flexible numerology system ($\mu = 0 - 4$) that dynamically adjusts subcarrier spacing from 15kHz to 240kHz . Depending on the configured numerology, this adaptability directly impacts the physical layer frame structure, where each $10 - \text{ms}$ frame contains between 10 and 160 slots.

The system employs advanced modulation schemes up to 256 QAM and low-density parity-check (LDPC) channel coding to maximize spectral efficiency.

Spatial processing capabilities have been significantly upgraded through massive MIMO configurations (up to 128 antennas) and sophisticated beamforming techniques, with digital beamforming predominating in FR1 and hybrid approaches in FR2.

These radio interface advancements collectively enable 5G NR to simultaneously support enhanced mobile broadband through wide bandwidth carriers, ultra-reliable low-latency communications via mini-slot transmissions, and massive machine-type communications through optimized signaling protocols, all while maintaining forward compatibility for future enhancements.

5G NR frame structure [14] is represented in Figure 1.8

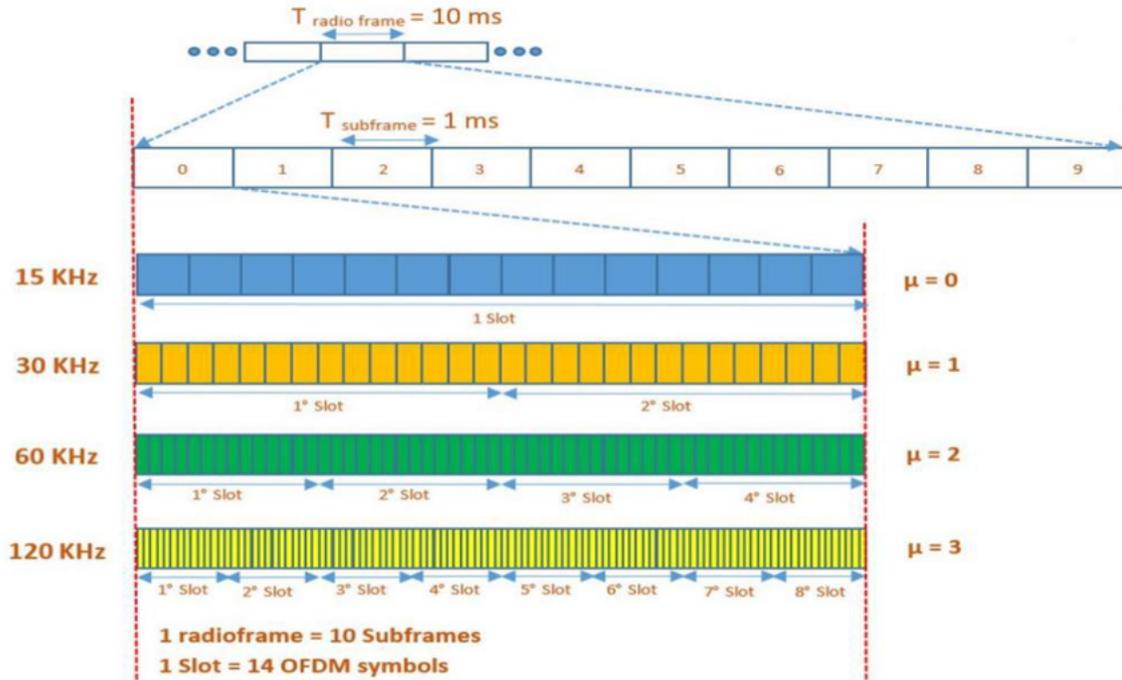


Figure 1.8: 5G NR frame structure (adapted from [14])

1.8 Classification of 5G Use Cases

5G is designed to meet diverse service requirements. The International Telecommunication Union (ITU) has categorized 5G use cases into three main groups [15], shown in Figure 1.9:

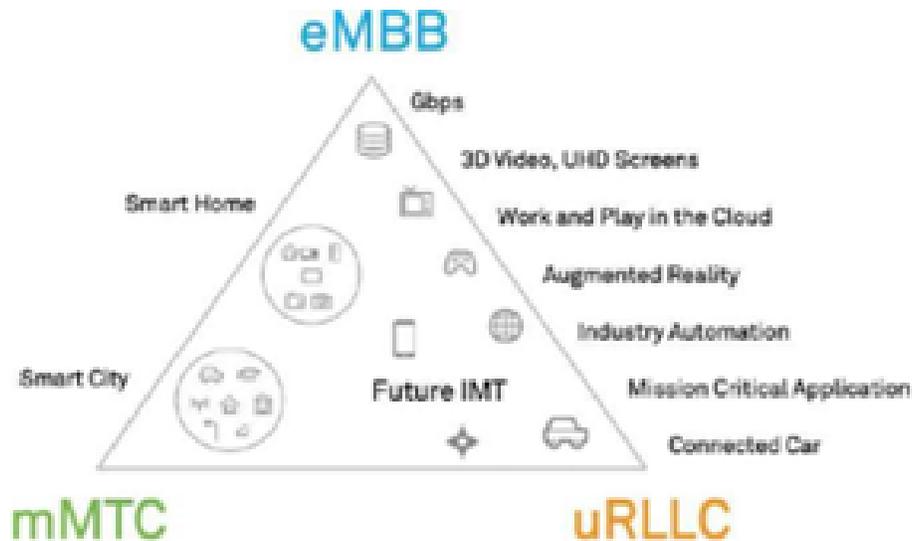


Figure 1.9: Three types of 5G application scenarios [16]

Mobile Broadband (eMBB): Deliver high-speed internet for bandwidth-intensive applications, targeting peak data rates of 20 *Gbps* downlink and 10 *Gbps* uplink with latencies of less than 10 *ms*, enabling applications such as 4K/8K video streaming, augmented reality, and cloud gaming.

Ultra-Reliable Low-Latency Communications (URLLC): Enable mission-critical applications requiring instant response like autonomous vehicles and industrial automation through exceptional reliability (99.9999%) and ultra-low latency (sub-1 ms)

Massive Machine-Type Communications (mMTC): Support large-scale IoT with connection densities reaching 1 *million* devices per square kilometer and extended battery life exceeding 10 *years* for sensors and innovative city applications.

Network Slicing: allows multiple virtual networks to operate over a shared physical infrastructure, enabling telecom operators to deliver customized services for different industries. According to 3GPP and NGMN, this feature supports various applications with varying latency, reliability, capacity, and coverage requirements. Service Requirements include **identifying devices/users per slice, creating a Dynamic slice for diverse market needs, and delivering Dedicated service** from specific slices. 5G enhances traditional mobile services and introduces new use cases tailored to emerging market needs, including advanced mobility, policy control, security, and ultra-low latency [29].

5G introduces network slicing technology that creates multiple virtual networks on shared physical infrastructure, each optimized for specific service characteristics: high-bandwidth slices for media delivery, ultra-reliable slices for industrial control systems, and low-power slices for IoT devices. The flexible 5G framework meets current connectivity demands. It provides a future-proof foundation for emerging applications across industries, from precision agriculture to remote healthcare, while maintaining backward compatibility with existing networks through sophisticated interworking functions [17].

1.9 Non-Terrestrial Networks

NTN expands 5G's reach to air, sea, and space to complement traditional terrestrial cellular systems by integrating satellite communication (SatCom) or spaceborne (i.e., GEO, MEO, LEO), airborne (i.e., UAS and HAPS), and drone-based platforms to provide ubiquitous, reliable, and resilient connectivity. The 3GPP's Release 17 standardization enables three primary NTN

architectures: Geostationary Earth Orbit (GEO) and Low Earth Orbit (LEO) satellite systems, High-Altitude Platform Stations (HAPS), and Unmanned Aerial Vehicle (UAV) networks, each addressing distinct coverage and latency requirements.

NTN platforms are classified into two **spaceborne** and **airborne** systems (Figure 1.10). Spaceborne platforms are categorized based on three key parameters: **Altitude**, **Beam Footprint Size**, and **Orbit Type**, listed in Table 1.3

Table 1.3: Types of NTN Platforms [2].

Platforms	Altitude Range	Orbit	Beam Footprint Size
GEO satellite	35786 km	Fixed position in terms of elevation/azimuth w.r.t. a given point on Earth	200 – 3500 km
MEO satellite	7000 – 25000 km	Circular around Earth	100 – 1000 km
LEO satellite	300 – 1500 km	Circular around Earth	100 – 1000 km
UAS platform (including HAPS)	8 – 50 km (20 km for HAPS)	Fixed position in terms of elevation/azimuth w.r.t. a given point on Earth	5 – 200 km

These three key parameters distinguish different types of spaceborne platforms, including: With an orbital altitude of 35,786 km, GEO satellites provide continental-scale coverage with approximately 500 ms latency, offering fixed wide-area coverage (continental) for backhaul, maritime, and rural broadband applications.

The Medium Earth Orbit (MEO) satellites have a circular orbit around the Earth at an altitude varying from 7,000 to 25,000 km and approximately 150 to 300 ms latency. They are used for Navigation (GPS) and global IoT.

LEO satellite constellations like Starlink achieve near-fiber latency of 20- 50ms through orbital altitudes of 300-1,500km, and they are used for High-speed internet (Starlink, OneWeb) and disaster recovery. Intermediate solutions include HAPS platforms operating at 20-50km altitude for regional coverage and UAVs for localized, mobile deployments.

Low-Earth orbit (LEO) and Medium-Earth Orbit (MEO) are classified as Non-Geostationary Orbit (NGSO) systems. NGSO systems refer to any Earth-centered orbital path where a satellite’s revolution period differs from Earth’s 24-hour rotational cycle, unlike geostationary

satellites, which maintain fixed positions relative to Earth's surface.

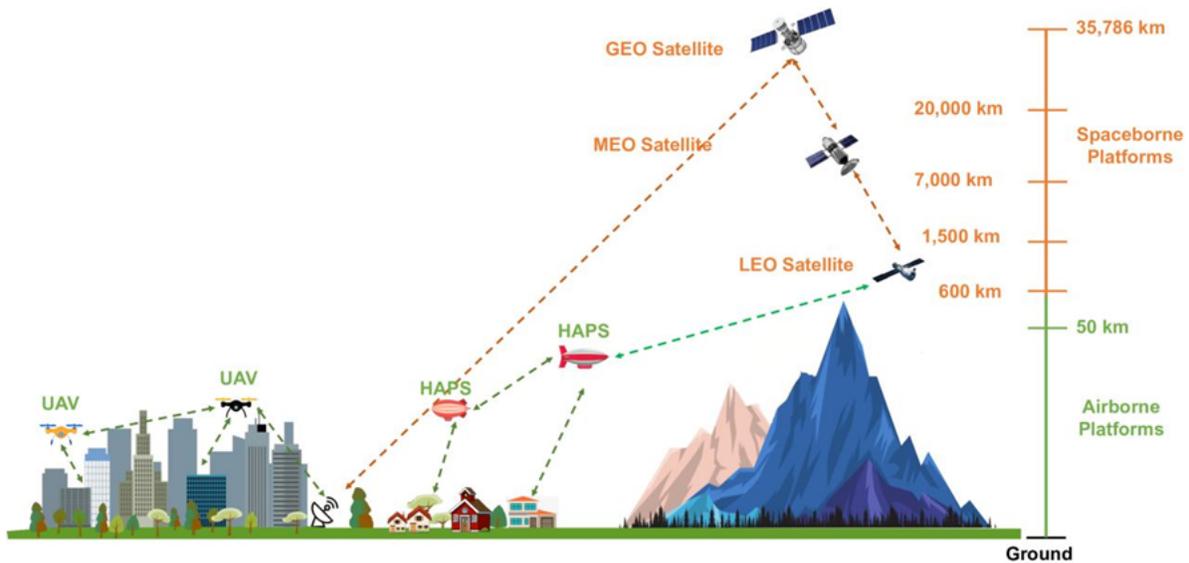


Figure 1.10: Illustration of the classes of orbits of satellites [18]

1.10 NTN Architecture

Satellite communication systems are structured around three fundamental segments from [19],[20], [21], and [22]:

- **Space Segment(satellite):** consisting of a space station
- **Ground Segment:** Consisting of gateway, terrestrial baseband functions (gNB), and core network(5GC).
- **User Segment:** User equipment and terminals

The satellite access network architecture incorporates several critical components as illustrated in Figure 1.11:

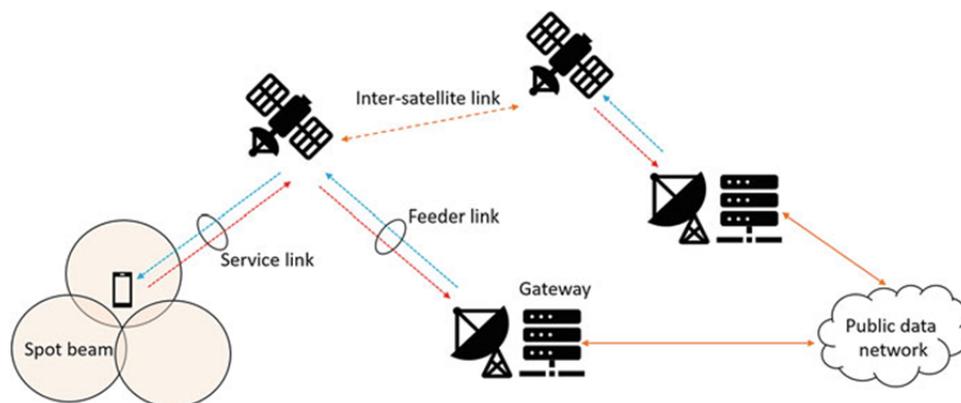


Figure 1.11: An illustration of satellite communications system architecture [23]

- **NTN Terminal:** UE or specialized satellite communication devices when direct UE connectivity isn't supported
- **Service Link:** The radio frequency connection between user terminals and the satellite platform
- **Space Platform Payloads:** Configuration of space platform carrying a payload [23][24] illustrated in Figure 1.12 and Figure 1.13
 - **Non-regenerative Payload (Bentpipe payload / Transparent mode):** Functions as an analog RF repeater in space and provides basic signal processing, including RF filtering (signal conditioning), frequency conversion (shifting uplink signals to downlink bands), and amplification (signal boosting), and amplifies the signal without digital processing.
 - **Regenerative Payload (Non-Transparent Mode):** Incorporates digital processing capabilities beyond basic RF functions, demodulation, decoding, switching, and re-modulation functions, effectively embedding base station intelligence within the satellite.

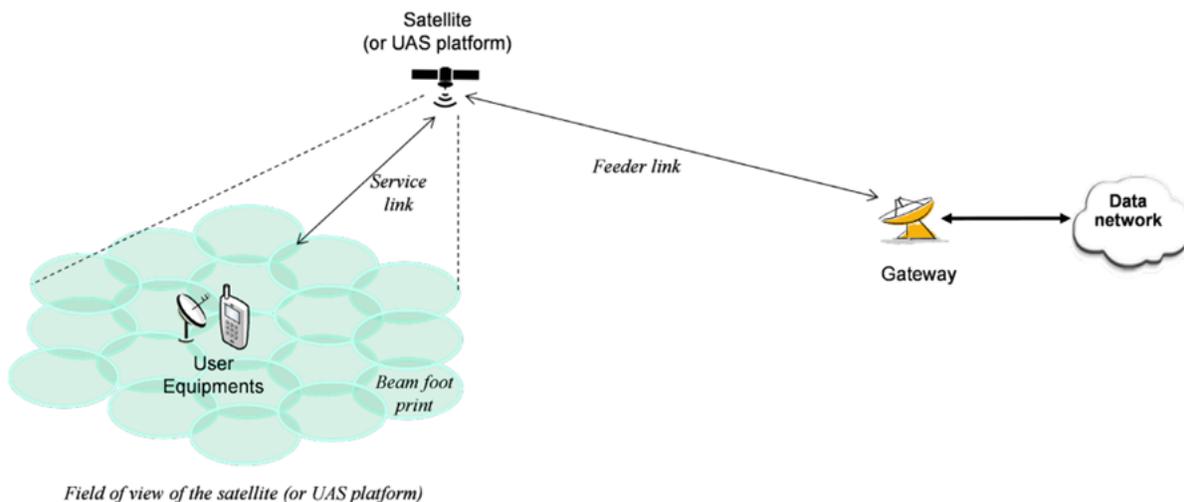


Figure 1.12: Satellite NTN typical scenario based on transparent payload [24]

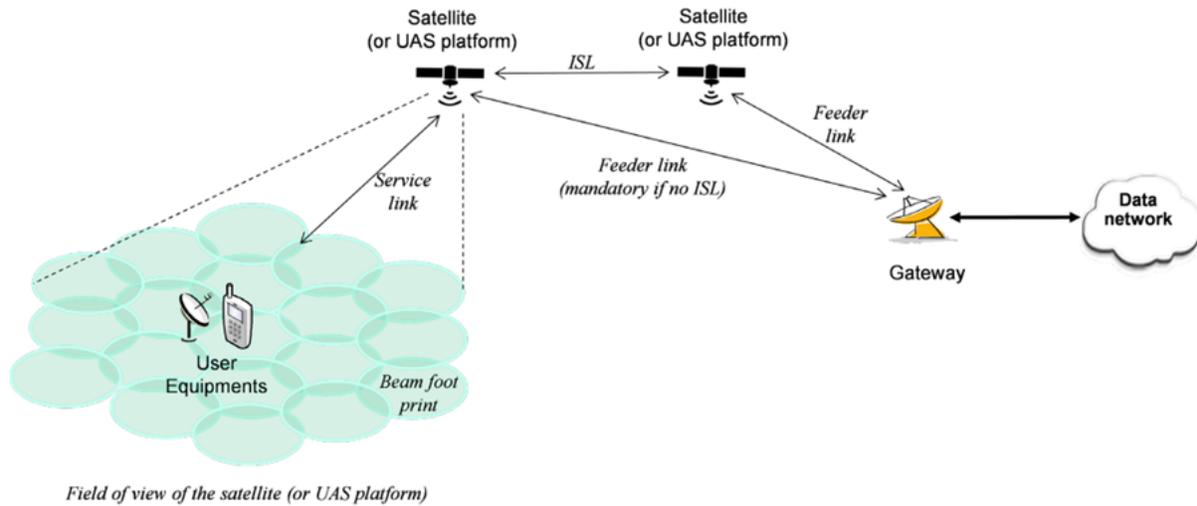


Figure 1.13: Satellite-based NTN typical scenario based on regenerative payload [24]

- **Inter-Satellite Links (ISL):** Requires regenerative payload to enable direct satellite-to-satellite communication, using either RF or optical technologies.
- **Gateways are logical nodes (Earth stations):** connecting the NTN platform (satellite network) with the 5G core infrastructure.
- **Feeder Links (Satellite Radio Interface SRI):** The communication channels and the radio link between the NTN gateway and the satellite platform.

1.11 NTN frequency bands:

Satellite communication systems operate across various frequency bands from L-band to Ka-band [25].

- **L-band (1-2 GHz):** This band is characterized by long-distance coverage with minimal atmospheric attenuation, making it ideal for voice, data, and video transmission and maritime and aeronautical communications.
- **S-band (2-4 GHz):** Offers balanced performance, moderate range, and serves critical applications, including Satellite navigation (GPS), weather monitoring, and mobile satellite services.
- **C-band (4-8 GHz):** This band provides reliable performance for television/radio broadcasting and telephony and is excellently resistant to weather interference.
- **Ku-band (12-18 GHz):** This extremely high bandwidth enables high-throughput satellite (HTS) services like direct-to-home (DTH) television, though it is susceptible to rain fade.

- **K-band (18–27 GHz):** Experiences significant water vapor absorption at 22 GHz, limiting its primary use to military and scientific applications.
- **Ka-band (26.5–40 GHz):** Supports advanced broadband services despite substantial weather-related signal degradation. Used for High-speed internet, 5G backhaul, and next-generation satellite broadband (Starlink)

In 3GPP, the NR bands [19] in Table 1.5 are defined for the UE’s NTN communication with the satellite.

Table 1.4: NR NTN satellite bands defined in 3GPP [19]

REL	NR Band	Uplink (UL) operating band Satellite Access Node receive / UE transmit FUL -low - FDL-high	Downlink (DL) operating band Satellite Access Node transmit / UE receive FUL -low - FDL-high	Remarks
REL-17	n256	1980–2010 MHz	2170–2200 MHz	FR1, FDD, S-band
REL-17	n255	1626.5–1660.5 MHz	1525–1559 MHz	FR1, FDD, L-band
REL-18	n254	1610–1626 MHz	2483.5–2500 MHz	FR1, FDD, LS-band
REL-18	n512 n511 n510	27.5–30.0 GHz 28.35–30.0 GHz 27.5–28.35 GHz	17.3 – 20.2 GHz 17.3 – 20.2 GHz 17.3 – 20.2 GHz	FR2, FDD, Ka-band

Non-Geostationary Orbit (NGSO) satellites offer significant advantages over GEO systems through reduced propagation delays and enhanced data rates, making them valuable complements to terrestrial 5G networks. However, their orbital motion introduces unique mobility challenges that require sophisticated handover management strategies. The dynamic nature of NGSO networks stems from the constant movement of satellites relative to Earth’s surface and the mobility of user equipment (UE) within coverage areas. This dual mobility scenario creates a time-varying channel environment that significantly impacts network operations, particularly in handover and paging procedures. NGSO systems employ three primary handover categories to maintain service continuity, as shown in Figure 1.14

- **Intra-Satellite Handover:** Triggered by movement between different beams of the same satellite, these transitions occur frequently in NGSO systems due to the rapid ground track

velocity of satellite footprints (particularly pronounced in LEO constellations).

- **Inter-Satellite Handover** occurs when a UE transitions between different satellites in the constellation. This results from the limited individual coverage area of each NGSO platform as it traverses its orbits.
- **Inter-access network handover (vertical handover)**: Occurs when satellites from different operator networks switch between satellite and terrestrial gNodeB connections in hybrid network architectures.

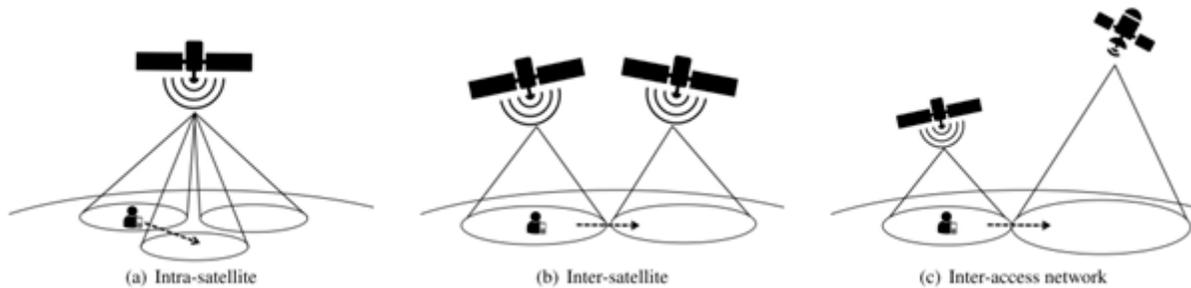


Figure 1.14: Type of handover [26]

1.12 NTN use cases

Non-terrestrial network (NTN) technology offers a wide range of applications; One key use case involves leveraging. Low Earth Orbit (LEO) satellites can provide backhaul connectivity to cell towers in remote or rural areas where fiber or terrestrial microwave links are unavailable, enabling standard 4G/5G services in underserved areas. Additionally, NTN can extend coverage to sensors, actuators, and IoT devices in areas without terrestrial networks. The most advanced NTN proposals aim for global, low-latency, direct-to-device satellite communication links with data rates exceeding 2 Mbps. 3GPP has identified several primary NTN use cases [27], including:

- **Multi-connectivity (Terrestrial + Satellite)**: where Devices connect simultaneously to both terrestrial and satellite networks to prioritize low-latency traffic while offloading less critical data.
- **Fixed cell connectivity**: Provides 5G access in geographically isolated areas such as ships at sea or offshore oil, rural areas, and underserved regions.
- **Mobile cell connectivity**: enables seamless, uninterrupted handovers between terrestrial and satellite networks and supports high-mobility scenarios like aircraft (in-flight connectivity) and high-speed trains (continuous coverage).

- **Enhanced Network Resiliency & Backup:** enhancing network resiliency by serving as a backup during outages and aggregating connections to prevent disruptions. Bridging 5G Coverage Gaps: Helps mobile operators extend 5G coverage to unconnected or sparsely populated areas.
- **Satellite-Based Broadcast & Multicast Services:** These deliver TV and multimedia content via 5G Multicast-Broadcast Services (MBS), improving efficiency for large-scale media distribution. NTN is anticipated to play a crucial role in 5G and future communication systems by supporting various sectors, such as transportation, eHealth, energy, automotive, public safety, and more. Figure 1.15 The use cases for 5G NTNs can be categorized into three main areas:
 - **Service Continuity:** Providing NTN connectivity in regions with inaccessible or impractical terrestrial networks.
 - **Service Ubiquity:** Enhancing network availability during emergencies, such as natural disasters, which may disrupt or damage terrestrial infrastructure.
 - **Service Scalability:** Offloading traffic from terrestrial networks, particularly during peak usage times, to improve overall efficiency [28].

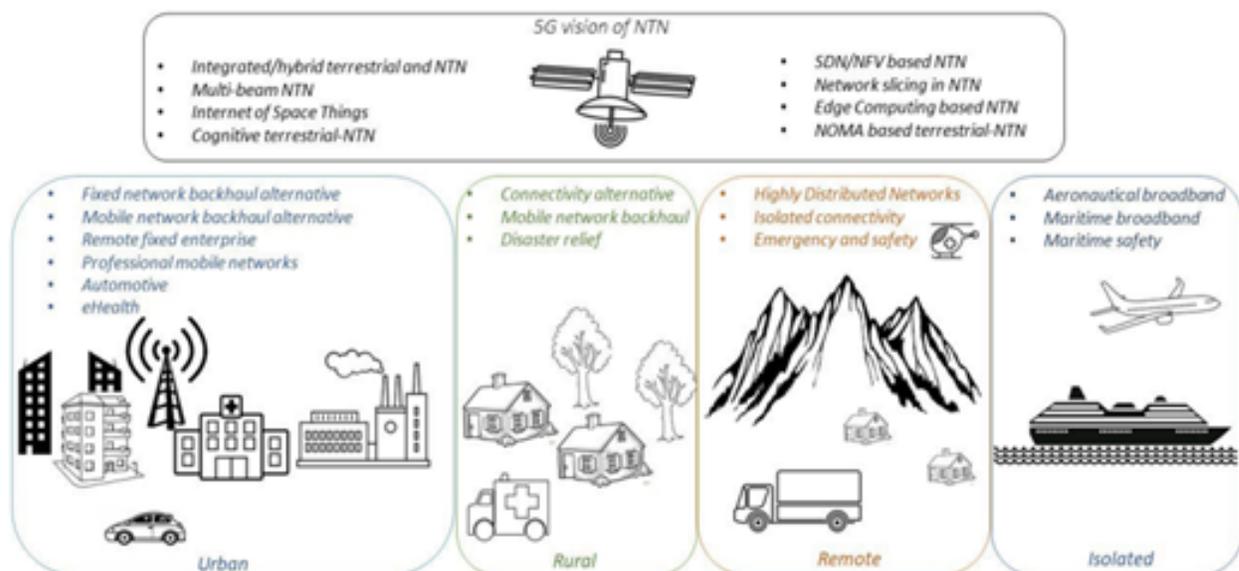


Figure 1.15: 5G NTN use cases [28].

This chapter presents the model's development, key methodologies, and findings. First, it provides an overview of the software model. Next, it discusses the key performance indicators (KPIs) for 5G NR NTN deployments, including latency, coverage, and capacity, as well as the Radio Network Planning Tool and its implementation.

2.1 Overview of the Model and Satellite Network Requirements:

This thesis employs MATLAB with 5G Toolbox and Satellite Communications Toolbox to model and evaluate the performance of 5G NR NTN in LEO satellite constellations, focusing on Starlink and OneWeb deployments. The simulation framework integrates 3GPP-compliant 5G NR waveforms, LEO satellite channel modelling, and end-to-end link simulations to assess key performance indicators (KPIs) (Figure 2.1), latency, coverage, and capacity.

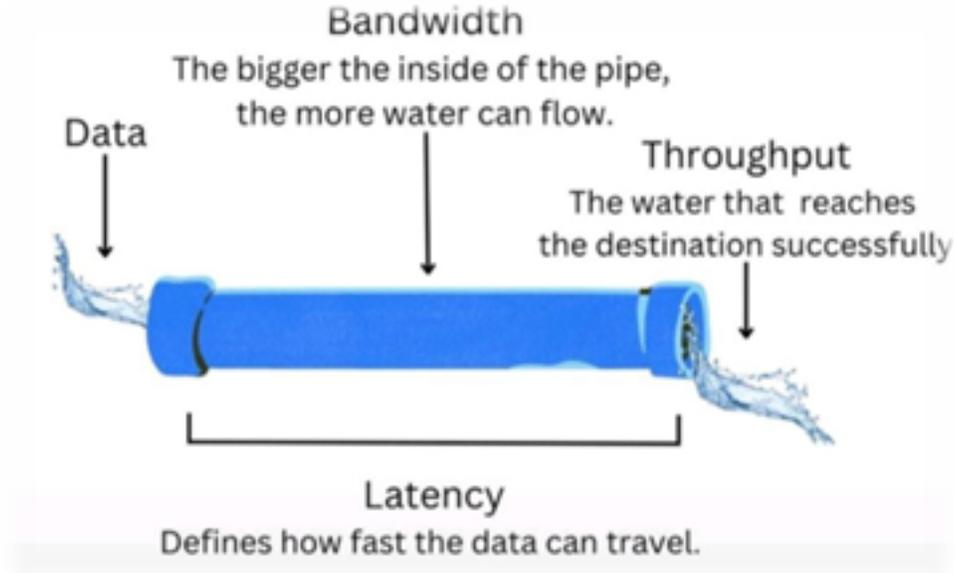


Figure 2.1: Key Performance Indicators (KPIs)

2.2 Throughput

Throughput in communication networks is the actual and successful data transfer rate over a specified communication channel within a designated time frame. It demonstrates the network's capability to transmit data effectively. The formula for calculating data rate in 5G NR calculator allows calculating the maximum throughput of the 5G NR network for the user (depending on their mobile device UE) or cell. The estimated data transmission rate of 5G NR can be determined using the following formula [31]:

$$\text{data rate (in Mbps)} = 10^{-6} \cdot \sum_{j=1}^j \left(v_{Lavers}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R_{max} \cdot \frac{N_{PRB}^{BW(j),\mu} \cdot 12}{T_s^\mu} \cdot (1 - OH^{(j)}) \right) \quad (2.1)$$

Where the main issue of NTN-NR 5G communication effectiveness is achieving optimal throughput, the network's ability to support advanced applications in areas with limited

coverage and mobility is essential. Achieving high throughput presents unique challenges related to the NTN channel, including delay, Doppler effects, and signal variability. It requires specialized solutions for effective radio resource management, the use of advanced MIMO techniques, and the reduction of protocol overhead.

2.3 Latency

In a network, there are four sources of latency: propagation, transmission, queuing, and processing. Processing and queuing latencies transpire within the nodes, transmission latency arises from the node to the link, and propagation latency occurs within the link [32].

Concerning propagation latency, the signal traverses a link, which will be considered free space. The formula is presented as follows:

$$\delta_{prop[s]} = \frac{d_{[m]}}{\mathbf{v}_{[m/s]}} \quad (2.2)$$

Where:

- d : Distance of the link.
- \mathbf{v} : Velocity of the signal in the link (3×10^8 m/s).

Transmission latency refers to the duration required for a signal to convey bits across a link. It is contingent upon the data rate and the volume of data to be transferred and can be expressed as:

$$\delta_{Trans[ms]} = \frac{8D_{serv[Bytes]}}{R_{[Gbits/s]}} 10^{-6} \quad (2.3)$$

Where:

- D : Packet size in bytes.
- R : Data rate provided by the link.

The subsequent tables provide standard NR-ARFCN (Absolute Radio Frequency Channel Number) values and their associated frequency ranges and bandwidths to analyze the variation of transmission delay with frequency and bandwidth. These characteristics are essential for determining the data rate directly influencing transmission latency (this section based on [33]).

The formula for 5G NR ARFCN is described in:

$$F_{REF} = F_{REF-off} + \Delta F_{Global} (N_{REF} - N_{REF-off}) \quad (2.4)$$

Table 2.1 defines how 5G NR ARFCN (N_{REF}) values map to actual frequencies based on different frequency ranges.

Table 2.1: 5G NR ARFCN Frequency Ranges and Parameters

Frequency range (MHz)	ΔF_{Global} (kHz)	$F_{REF-Offs}$ (MHz)	$N_{REF-Offs}$	Range of N_{REF} (NR-ARFCN)
0 – 3000	5	0	0	0 – 599999
3000 – 24250	15	3000	600000	600000 – 2016666
24250 – 100000	60	24250.08	2016667	2016667 – 3279165

The 5G NR standard organizes its spectrum into two central frequency ranges (FR1 and FR2) as defined in Table 2.2

Table 2.2: 5G NR Frequency Range Designations (FR1 & FR2)

Frequency range designation		Corresponding frequency range
FR1		410 MHz – 7125 MHz
FR2	FR2-1	24250 MHz – 52600 MHz
	FR2-2	52600 MHz – 71000 MHz

Table A.1 and Table 2, which define the 5G NR operating bands in FR1 (sub-6 GHz) and 5G NR FR2 (mmWave) bands:

Table 2.3: Modulation Schemes and code rate (adapted from [45])

SCS [kHz]	Modulation Scheme	Code Rate R_{\max}
15	QPSK	78/1024
	16-QAM	378/1024
	64-QAM	466/1024
30	QPSK	193/1024
	16-QAM	490/1024
	64-QAM	567/1024
60	QPSK	449/1024
	16-QAM	616/1024
	64-QAM	666/1024

Table 2.4: Number of maximum RBs in the respective bandwidth [3GPP23e].

Number of maximum RBs				
SCS [kHz]	Bandwidth [MHz]			
	5	10	15	20
15	25	52	79	106
30	11	24	38	51
60	-	11	18	24

2.4 Coverage

Coverage is a significant performance metric in satellite-based networks. It delineates the maximum geographical extent within which a terminal can establish a link with a satellite. According to [23] and [14], the satellite can only service customers within a particular elevation range, with the minimum elevation angle commonly set to 10° .

The maximum distance d between the user terminal and the satellite can be determined using the following equation:

$$d_{[km]} = \sqrt{R_{E[km]}^2 \sin^2 \alpha_{[^\circ]} + h_{0[km]}^2 + 2h_{0[km]}R_{E[km]} - R_{E[km]} \sin \alpha_{[^\circ]}} \quad (2.5)$$

where:

- d : Distance from the terminal to the satellite.
- $R_{E[km]}^2$ Earth radius (6371 km).
- $h_{0[km]}^2$: Satellite altitude.
- α Elevation angle.

With a constant radius R_E of 6371 km, the Earth is considered a perfect sphere in this computation. This part references [44]

2.4.1 Starlink SpaceX

The US aerospace corporation SpaceX runs the Starlink satellite network, providing internet connectivity to land users. According to the FCC notice, Starlink can launch around 11927 low-Earth orbit (LEO) satellites. Up to 30,000 satellites are anticipated in the long run [34]. The satellites, which range in height from 540 km to 1300 km, are placed in several orbital planes. Although the terrestrial coverage region in the northern hemisphere does not surpass 60° latitude, Starlink's first testing achieved data throughputs of up to 93 Mbps for individual users, around 16 Gbps capacity per satellite, with latency values of 31ms. Future goals include internet speeds up to 300 Mbps and terrestrial coverage beyond those latitudes. Starlink offers a stationary VSAT with a phased-array antenna of around 60 cm as a user terminal. Ku-band frequencies used by SpaceX Starlink are 10.7 GHz to 12.7 GHz for downlink and 14 GHz to 14.5 GHz for uplink.

2.4.2 OneWeb

A British business, OneWeb, intends to put up to 650 satellites in orbit [36]. OneWeb was saved from bankruptcy with investments made by the Indian business Bharti Global and the British government [35]. Unlike Starlink and Kuiper, OneWeb employs a height of around 1207 km, and its orbital planes also span the polar regions. OneWeb's constellation design results in elliptical beam footprints that are low in height and have a broad inner axis, whereas Starlink's elliptical footprints are more circular.

Other satellites include Telesat (Lightspeed), Amazon (Kuiper), AST & Science, Iridium, and China (SatNet).

2.4.3 Link-Level Simulations

Tapped Delay Line (TDL) and Clustered Delay Line (CDL) are related concepts. The TDL models for NTN are derived from the CDL models, with an added Doppler shift resulting from satellite movement. Factors affecting this Doppler shift include satellite velocity, elevation angle, and carrier frequency.

2.4.4 Beamforming and MIMO

Beamforming and MIMO techniques enhance user experience, capacity, and coverage cost-effectively. Beamforming focuses antenna radiation on a specific receiving device. Constructive interference can be achieved by adjusting the phase and amplitude of transmitted signals. This constructive interference can amplify the received signal strength and user throughput [37]. It's essential for the user equipment (UE) to accurately capture the signal as the beams adapt to

their environment due to multi-path fading. There are two main approaches to beamforming: digital and analog. Analog beamforming employs phase shifters in the RF domain to transmit the same signal at different phases, using less power than digital beamforming [38]. In contrast, digital beamforming pre-codes the transmitted signal's amplitude and phase before RF emission, allowing for increased flexibility and the implementation of efficient algorithms, thus enhancing cell capacity by sending data for multiple users through the same physical resource blocks. However, digital beamforming requires a separate RF chain for each antenna element, which leads to complex designs and higher power consumption. The beam pattern of a mobile communication base station is crucial to cellular network efficiency. Classic beamforming directs radio energy in one direction, while MIMO techniques utilize the spatial diversity of the radio channel. Nonetheless, these techniques only operate on the horizontal antenna pattern, leaving the vertical pattern unchanged [40]. Emerging flexible antenna technologies, which enable the adaptation of both vertical and horizontal patterns, offer dynamic control of antenna configurations in three dimensions, improving spectral efficiency and making 3D beamforming feasible. MIMO's capacity to exploit spatial diversity could enhance signal quality and user capacity. The uplink procedure is different, and 3GPP introduces the concept of beam correspondence.

Massive MIMO offers huge increases in spectrum effectiveness for cellular systems, as illustrated by [41], where spectral efficiency increased almost linearly with antenna number.

2.4.5 Physical layer

Long delays, Doppler shift, severe path attenuation, and polarisation rotation are thought to be the main effects of NTN on the physical layer, as previously mentioned. The physical waveform doesn't need a special modification since NTN balances timeliness, intricacy, and viability. Because OFDMA is in 5G NR and also for NTN connections, 3GPP has chosen to keep it as the principal waveform. There were debates and protests because OFDMA has a high peak-to-average-power ratio (PAPR), and certain satellite communications companies have already chosen not to utilise OFDM. The susceptibility of OFDMA to Doppler shifts is another difficult characteristic; hence, a carrier frequency correction and pre-adjustment are required. However, as the effect is minimal, repurposing OFDM for satellite-based connection will benefit system impact and potential future dual connectivity scenarios between terrestrial and non-terrestrial.

The 5G system can accommodate new frequency bands, and minor adjustments like increased transmit power, the introduction of circular polarisation, or advanced beamforming techniques don't need a thorough revision of the specifications. 5G NTN will reuse the current physical channel topology and reference signals.

Adaptive modulation and coding are already used in 5G NR and will continue to be used

in NTN with preferred phase-shift key modulation techniques up to a value of 16. The UE and satellite support QPSK and 16QAM; 64QAM is optional. The free space path loss (FSPL), estimated from the constellation geometry, is the most significant SNR degradation with NTN. The longer RTT causes potential link quality feedback to the gNB scheduler later. A more robust MCS technique is chosen based on the QOS profile since the route loss may vary at high satellite velocities and longer packet lengths.

It is anticipated that NTN MIMO will be left for future advancements since spectral efficiency gains based on multiple antenna technologies (MIMO) suffer from the dominating LOS and long distance, which results in delayed rank indication feedback. The fading of all the channels between the satellite and UE is often spatially linked when no scatterers are close to the satellite antenna.

2.4.6 Hybrid Automatic Repeat Request (HARQ)

With incremental redundancy techniques like adaptation of the redundancy version, Hybrid Automatic Repeat Request (HARQ), which was introduced in Release 6 (the launch of HSDPA), facilitates a dependable connection based on quick acknowledgements and retransmissions. The disadvantage of such a HARQ procedure is its stop-and-wait feature. A retransmission happens unless the transmitter receives a positive acknowledgement before sending the subsequent data packet [42]. Multiple HARQ processes run in multi-tasking mode to get around stalling. Up to 16 HARQ processes may run concurrently per UE in 5G NR Release 15, and several timers regulate behaviour like the intervals between RX and acknowledgement and retransmissions.

Since NTN results in much longer delays, the present HARQ techniques must be modified. 3GPP addresses three potential modifications:

- Increasing the current HARQ process count to 32 processes.
- Switching the retransmission to higher layers, such as RLC AM, and turning off HARQ feedback.
- Automatic retransmission configuration, such as TTI bundling characteristics.

Because of memory constraints and the maximum number of parallel channels that may be used, a straightforward linear increase in HARQ processes is not practicable. For instance, several HARQ processes would be needed for a GEO constellation with a 544 ms RTT. Depending on the UE capabilities, 3GPP decided to raise the total number of HARQ processes for a LEO constellation to 32. This means changing the DCI HARQ ID field in the scheduling message to a 5-bit size. The RRC parameter HARQ-Process Number Size DCI, which is optional, specifies whether the DCI field's HARQ process number is increased to five bits. 3GPP decided

to allow the disabling of HARQ feedback, which can be configured via the RRC parameter HARQ-feedback, enabling or disabling per HARQ process for each HARQ process, to facilitate NTN without imposing undue demands on processing capacity and UE memory. As a result, the transmitter may send data successively using the HARQ method without waiting for a response, which might result in a stall. To increase the connection's dependability, the RRC may optionally allow PDUs to be automatically retransmitted. Similar to features like TTI bundling currently allowed in legacy wireless communications, this blind retransmission is unrelated to any input.

The network has three scheduling choices: Disable, which excludes HARQ retransmissions; Blind retransmissions, or Extended HARQ feedback. Such automated retransmissions are only permitted within a specific interval after the first transmission of a PDSCH PDU to prevent the UE from excessively monitoring the PDSCH.

Path loss: The link budget is affected by a few factors, mainly the well-known free space path loss (FSPL) equation.

$$P_{RX} = P_{TX} G_{RX} \left(\frac{\lambda^2}{4\pi} \right) \left(\frac{1}{4\pi d^2} \right) \quad (2.6)$$

This formula shows that the wavelength λ , the distance between the TX and RX antennas d , the transmit power P_{TX} , the transmit antenna gain G_{TX} , and the receive antenna gain G_{RX} . The exponent γ , representing the medium loss between the antennas, affects the reception power P_{RX} . The number $\gamma = 2$, representing solely air as the medium, is used for simplicity's sake [43]. Basic path loss PL_0 , which corresponds to plain air FSPL, attenuation due to atmospheric gases PL_g , attenuation due to atmospheric scintillation PL_s , and a building entrance path loss PL_e are the components that 3GPP uses to assume the composite path loss during the research phase.

$$PL = PL_0 + PL_g + PL_s + PL_e \quad (2.7)$$

The FSPL is described in [23] as a function of the carrier frequency fc and the distance d between the UE and the satellite to enable quick and easy computation:

$$FSPL_{d,fc} = 32.45 + 20 \log_{10} fc + 20 \log_{10} d \quad (2.8)$$

Along with the FSPL, the connection simulations consider shadow fading (SF), a zero-mean normal distribution with a standard deviation, and clutter loss (CL) caused by nearby structures and ground-based objects.

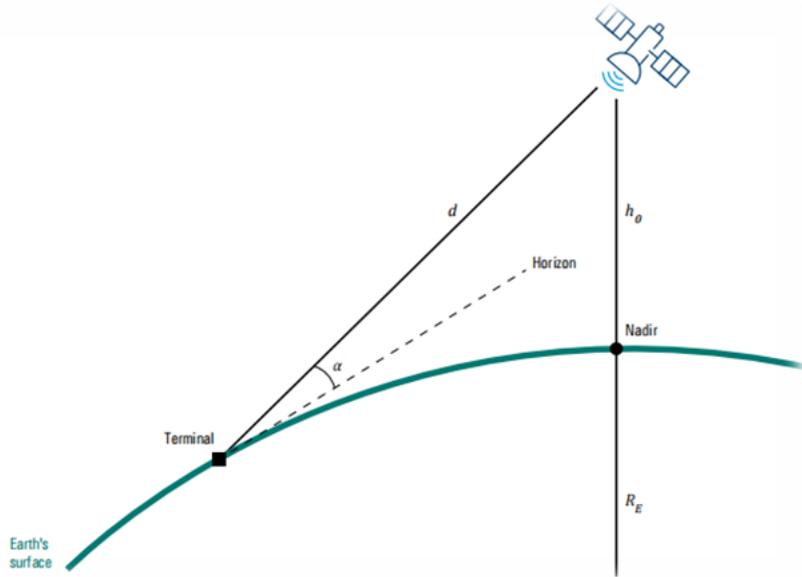


Figure 2.2: Distance d between UE and satellite as a function of the elevation angle and the orbit altitude [44]

2.4.7 Noise figure

Recall that the noise figure (NF) measures the SNR deterioration brought on by the RF chain's entities. For illustration, we use the generic word T to refer to the antenna temperature and think of the RF chain as the reception chain. We can assume an ideal receiver has two ports: input and output. In this case, the SNR at the input and the output would be identical. Regretfully, internal noise artefacts produced by a genuine receiver make the SNR at the receiver's output seem lower than the SNR at its input.

The NF describes the extra noise the receiver adds to the noise from the source. It is a performance parameter calculated by dividing the SNR at the input by the SNR at the output in decibels. Assuming an ambient temperature of $T_0 = 290\text{ K}$ and a receiver noise temperature of T , another viewpoint views the NF as the rise in noise power, referring to the receiver noise caused by the receiver chain components.

$$NF = 10 \cdot \log_{10} \left(\frac{SNR_i}{SNR_o} \right) = 10 \cdot \log_{10} \left(1 + \frac{T}{T_0} \right) \quad (2.9)$$

Table 2.5: Link budget results

Transmission mode	DL	UL
Frequency	2 GHz	2 GHz
TX: EIRP	78.8 dBm	23 dBm
RX: G/T	-31.6 dB · K ⁻¹	1.1 dB · K ⁻¹
Bandwidth	30 MHz	0.4 MHz
Free space path loss	159.1 dB	159.1 dB
Atmospheric loss	0.1 dB	0.1 dB
Shadow fading margin	3 dB	3 dB
Scintillation loss	2.2 dB	2.2 dB
Polarization loss	0 dB	0 dB
Additional losses	0 dB	0 dB
CNR	6.6 dB	2.8 dB

2.4.8 The Doppler shift

Either the Doppler shift at the satellite as receiver or the Doppler at the UE as receiver would need to be considered in a more general reflection. Furthermore [23], such as constellations of GEO or LEO satellites and static UE or UE moving at greater velocities, such as aeroplanes or generic aerial vehicles (UAVs). It is often believed that the velocity v (the relative velocity between the UE and the satellite), the carrier frequency c , and the angle θ between the velocity vector and the signal's direction of propagation are used to compute the Doppler shift that occurs.

$$\Delta f = f c \cdot v \cdot \cos(\theta) / c \quad (2.10)$$

When the transmitter travels away from the receiver, the Doppler shift Δf is negative; when the transmitter goes in the other direction, it is positive.

Table 2.6: Link budget results

Frequency	2 GHz	20 GHz	30 GHz
Doppler shift	± 48 kHz	± 480 kHz	± 720 kHz
Doppler variation	544 Hz/s	5.4 kHz/s	8.1 kHz/s

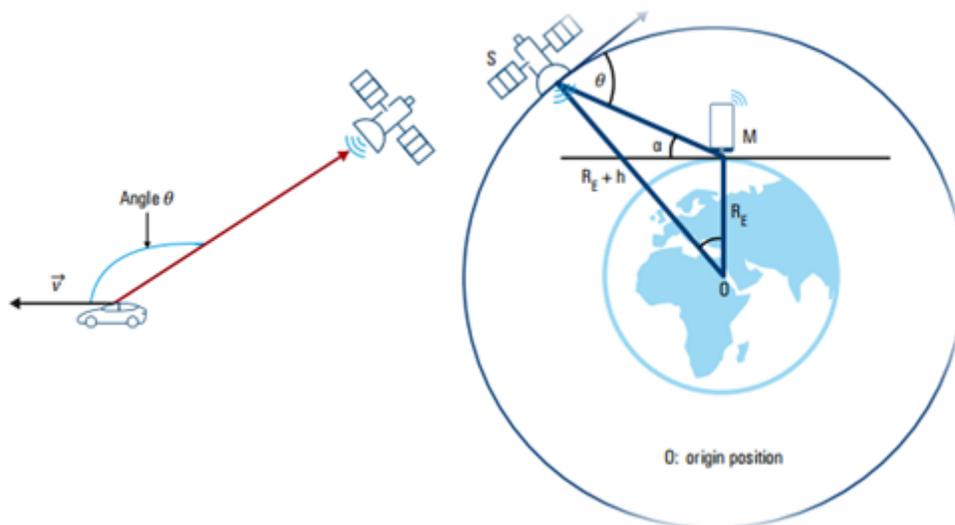


Figure 2.3: Doppler shift [44]

The general Doppler shift characteristics are shown in the outline in Figure 2.3. Doppler is explained in terms of the angle θ on the left. Since the two UE and satellite velocities are thought to be relative to the Earth in our consideration, they may be added together. The system geometry is depicted on the right side of the figure: the earth centre is at origin position O , the UE at position M is on the circular orbit defined as the earth's surface with an overall constant earth radius R_E , and the satellite S is assumed to travel on a circular orbit with altitude h . To keep things simple, we believe that the UE is stationary. However, if necessary, any UE motions may add to the satellite velocity to provide an updated VSAT. To calculate the Doppler shift concerning the elevation angle α , we rewrite the formula as follows:

$$f_{d,shift} = \left(\frac{v_{sat}}{c} \right) \cdot \left(\frac{R_E}{R_E + h} \cos \alpha \right) \cdot f_c \quad (2.11)$$

The elevation angle α is fixed at 50° in the channel models outlined in [23]. The Doppler shift often varies with the channel's temporal evolution. It is related to the elevation or direction difference between TX and RX, and the total velocity vectors of the UE and satellite. The phase rotation brought on by the Doppler shift is computed about a reference phase at time t_0 .

In NTN, we must consider both the Doppler rate and the variation in Doppler shift, as the Doppler shift may change throughout the duration of the connection. Additionally, the Doppler shift indicates the carrier frequency deviation that occurs at a specific point in time. In a LEO constellation, the satellite's relative velocity with the UE varies during the connection period, as does the elevation angle α . This situation is illustrated in Figure 2.4, where the UE acquires the LEO satellite when it exceeds the minimum elevation angle at connection ingress and loses it when it falls below the minimum elevation angle at connection egress.

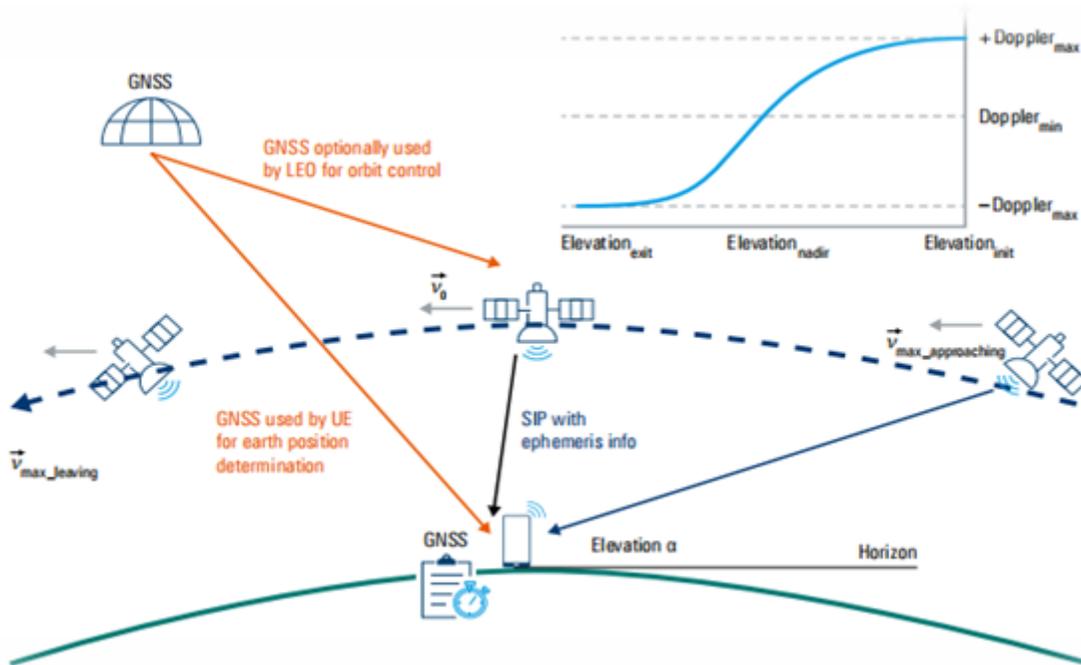


Figure 2.4: Doppler shift rate in a LEO scenario [44]

2.4.9 Radio Network Planning Tool

Atoll by Forsk is a leading radio planning and optimization tool for 5G NR network design. It enables operators to maximize coverage, capacity, Service Areas, and DL/UL quality while minimizing interference and costs. Figure 2.5 shows the OUARGLA City maps.

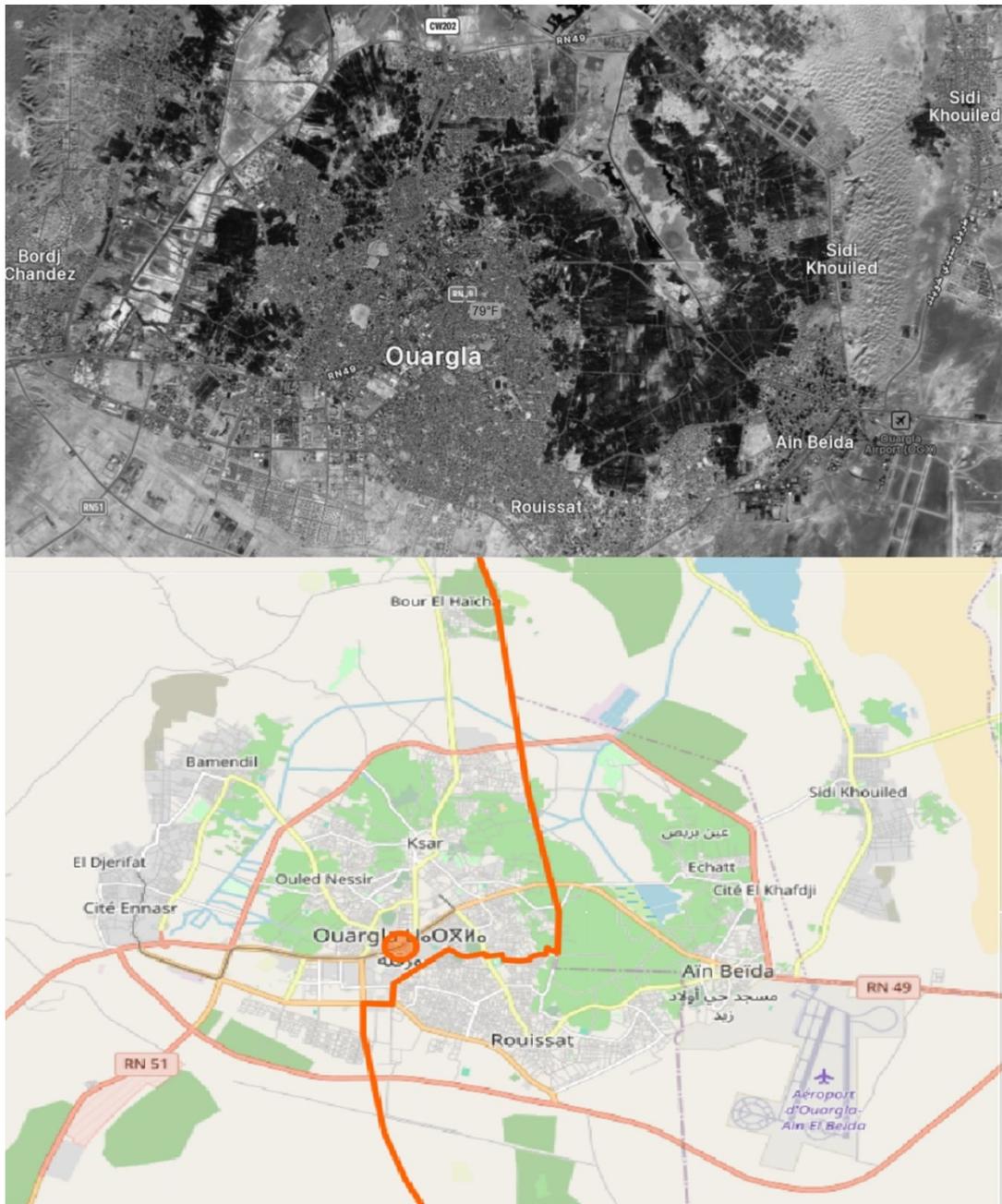


Figure 2.5: OUARGLA City, from satellite and standard image maps

This study is made through capacity (Throughput), coverage, and quality prediction calculation for NR. The network must be created before predicting. Fill in propagation model, sites, cells, transmitters, clutter, heights, and vector by these steps, as shown in the following figures:

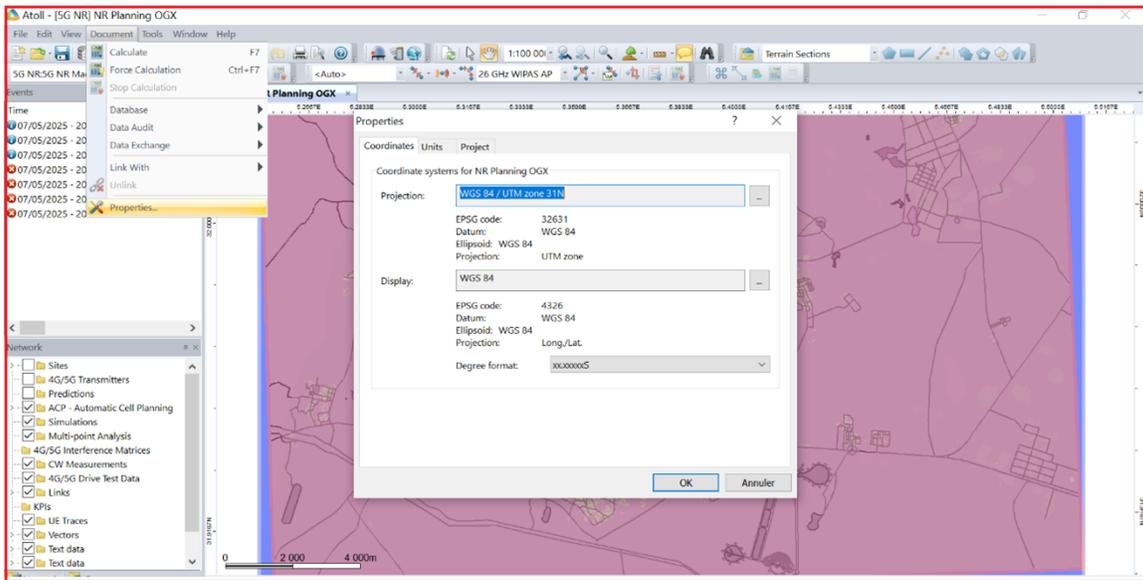


Figure 2.6: Setting Coordinate System

Improved cartographic data management, including digital elevation models, clutter, height, and vector data. Integrated GIS tools and Google Earth.

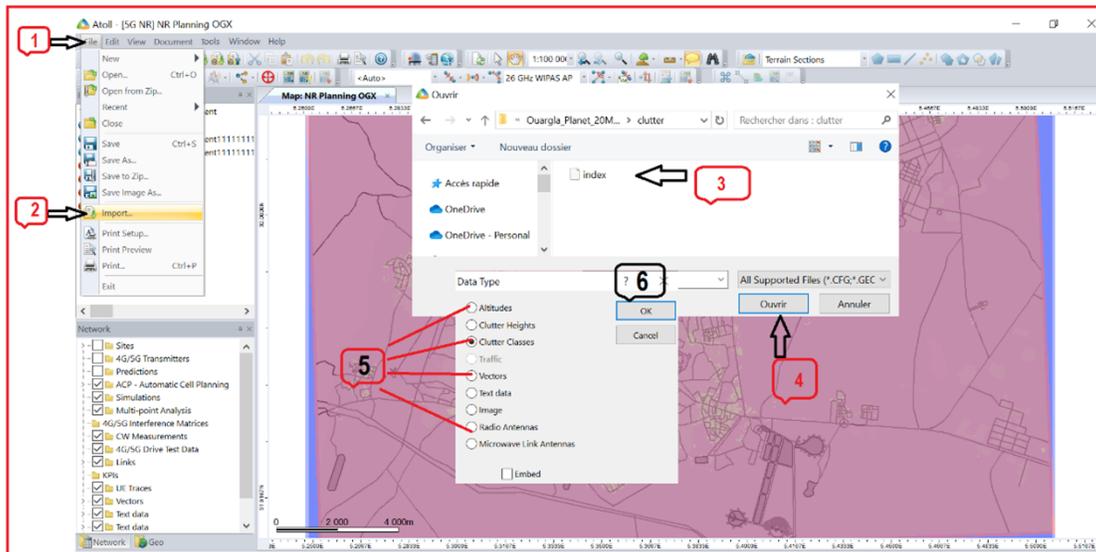


Figure 2.7: Importing GIS Map Data

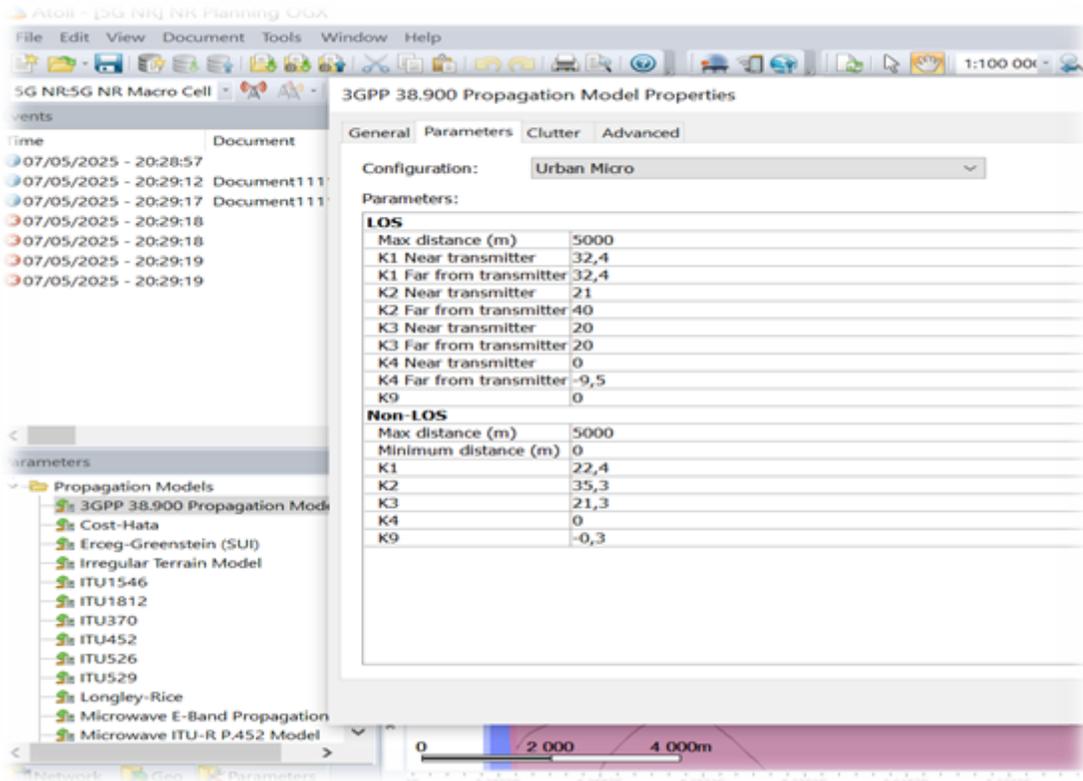


Figure 2.8: Setting Propagation Model

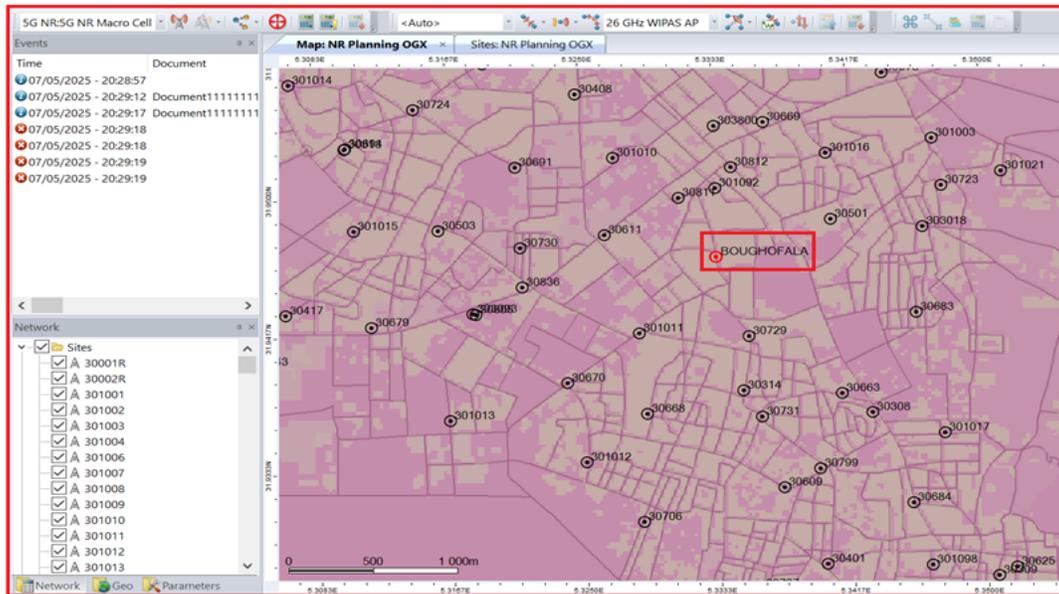


Figure 2.9: Site, Transmitter, and Cell Creation

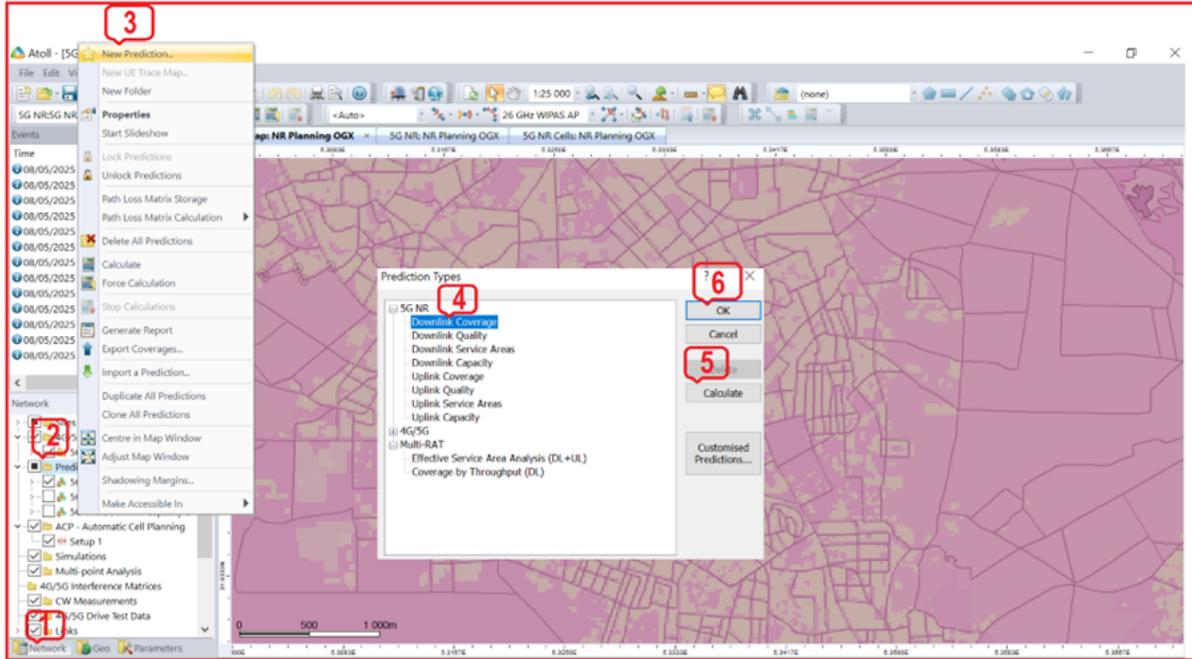


Figure 2.10: Running Prediction:

This chapter describes the reference scenario, all its in-depth modifications, and the radio network design tool's prediction results for the area under investigation. After thoroughly examining the many scenario variants, the model's output is finally shown.

3.1 Scenarios Description and Results

Table 3.1: Different Scenarios

Scenarios	LEO Satellite	Band (GHz)	Channel	MCS
1	Starlink	Ku	TDL-A	16-QAM
2	Starlink	Ku	Narrowband	16-QAM
3	Oneweb	Ku	TDL-A	16-QAM
4	Oneweb	Ku	Narrowband	16-QAM

1st Scenario LEO Satellite (Starlink-like) at 550km in Ku Band (15GHz):

The simulation results demonstrate the performance of a 5G NR NTN using a Starlink (LEO) satellite at 550 km altitude operating in the Ku band (15 GHz) with a TDL-A channel model.

Table 3.2: 1st Scenario with different Subcarrier spacings

SCS (kHz)	Max Throughput (Mbps)	Min Viable Power (dBm)	SNR Threshold (dB)
15	2.86	75 (6.12dB SNR)	24.12
30	5.89	78 (6.05dB SNR)	22.05
60	11.79	81 (5.97dB SNR)	16.97
120	23.74	86 (8.13dB SNR)	12.13
240	47.49	86 (6.71dB SNR)	17.71

Table 3.2 illustrates that the system achieves a maximum throughput of 2.86 Mbps (100% efficiency) at a transmit power of 93 dBm or higher in SCS 15 kHz, corresponding to an SNR of 24.12 dB or higher. Below this threshold, throughput scales with transmit power, starting at 0.84 Mbps (29.4% efficiency) at 75 dBm (6.12 dB SNR) and progressively improving to 2.69 Mbps (94.1% efficiency) at 88 dBm (19.12 dB SNR). The results indicate that the system reaches a saturation point at a power level of 93 dBm or higher, where additional power yields no further gains.

Figure 3.1 and **Figure 3.2** show that at 15 kHz SCS, the system demonstrates excellent power efficiency, achieving a maximum throughput of 2.86 Mbps at 93 dBm with relatively low SNR requirements of 24.12dB, making it ideal for wide coverage and IoT applications.

The 30 kHz configuration shows an improved throughput of 5.89 Mbps but requires a higher minimum power, 78 dBm, representing a good balance for urban mobile broadband. Higher SCS values of 60 kHz, 120 kHz, and 240 kHz deliver substantially greater maximum throughputs of 11.79 Mbps, 23.74 Mbps, and 47.49 Mbps, respectively, but with increasingly stringent power and SNR requirements, making them better suited for high-capacity fixed links

and backhaul applications. The 60 kHz SCS offers a desirable compromise for high-speed video services, providing over 4x the throughput of 15 kHz while maintaining reasonable power demands. The analysis shows the fundamental trade-off in NTN system design: lower SCS values favor coverage and power efficiency. In comparison, higher SCS values enable greater capacity at the expense of increased power requirements and reduced operational range. For a Starlink-like constellation, a mixed approach using 30 kHz for general user access and 60-120 kHz for gateway links would likely provide the optimal balance between coverage and capacity. The results also highlight the importance of adaptive SCS selection and advanced power amplification techniques to maximize system efficiency across different service scenarios.

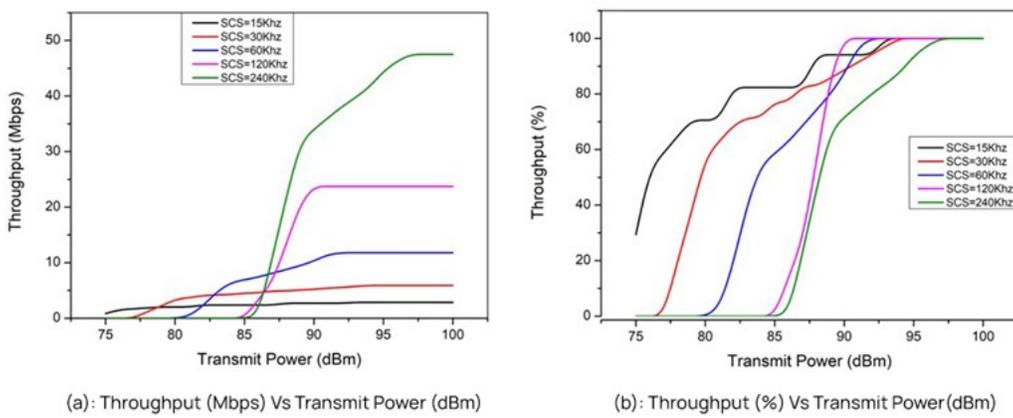


Figure 3.1: Throughput Vs Transmit Power with different SCS Scenario 1

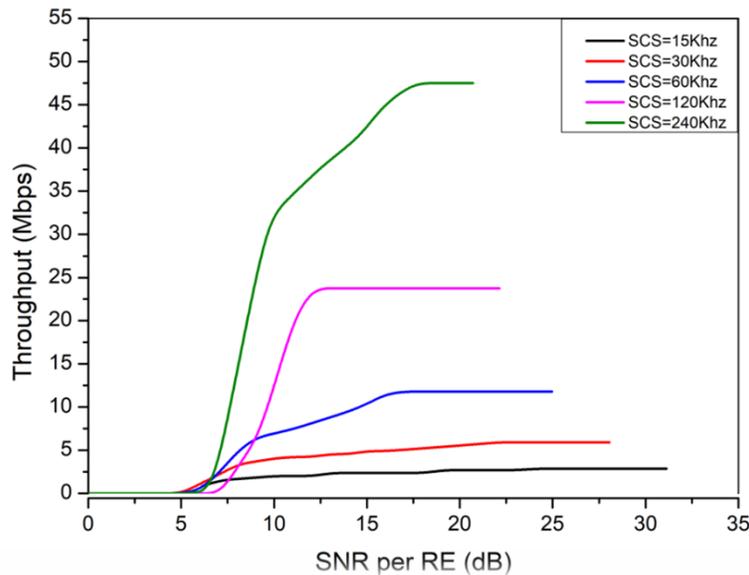


Figure 3.2: Throughput (Mbps) with SNR per RE (dB) with different SCS Scenario 1

2nd Scenario LEO Satellite (Starlink-like) at 550km in Ku Band (15GHz):

This analysis examines the performance characteristics of a Starlink-like LEO satellite operating in Ku-band 15 GHz at 550km altitude.

Table 3.3: 2nd Scenario with different Subcarrier spacings

SCS (kHz)	Max Throughput (Mbps)	Min Viable Power (dBm)	SNR Threshold (dB)
15	2.86	76 (7.72dB SNR)	8.72
30	5.89	79 (7.70dB SNR)	8.70
60	11.79	81 (6.68dB SNR)	8.68
120	23.74	85 (7.67dB SNR)	8.67
240	47.49	87 (6.65dB SNR)	8.65

Table 3.3, Figure 3.3, and Figure 3.4 show that the 15 kHz configuration demonstrates superior power efficiency, achieving a full throughput of 2.86 Mbps at just 77 dBm with an SNR of 8.72dB, making it ideal for wide-area coverage and power-constrained applications. In contrast, higher SCS values show progressively steeper power requirements - the 30kHz system reaches maximum throughput (5.89Mbps) at 80dBm, 8.70dB SNR, while 60kHz requires 83dBm, 8.68dB SNR for 11.79Mbps. The most demanding configurations, 120kHz and 240kHz, deliver substantially higher peak throughputs, 23.74 Mbps and 47.49 Mbps, respectively, but require significantly greater power, 86 dBm and 89 dBm, and present much higher activation thresholds, with no throughput below 85 dBm for 120kHz and 87 dBm for 240kHz. These results illustrate a clear performance continuum where lower SCS values, 15-30 kHz, favor broad coverage and power efficiency, while higher SCS values, 60-240 kHz, enable greater capacity at the cost of increased power demands and reduced operational range. The 15 kHz configuration is promising for IoT and rural broadband applications due to its early activation at low power levels. At the same time, the 60 kHz option presents an attractive middle ground for urban mobile broadband, offering 4x the throughput of 15 kHz with reasonable power requirements. Extremely high-throughput configurations, 120-240 kHz.

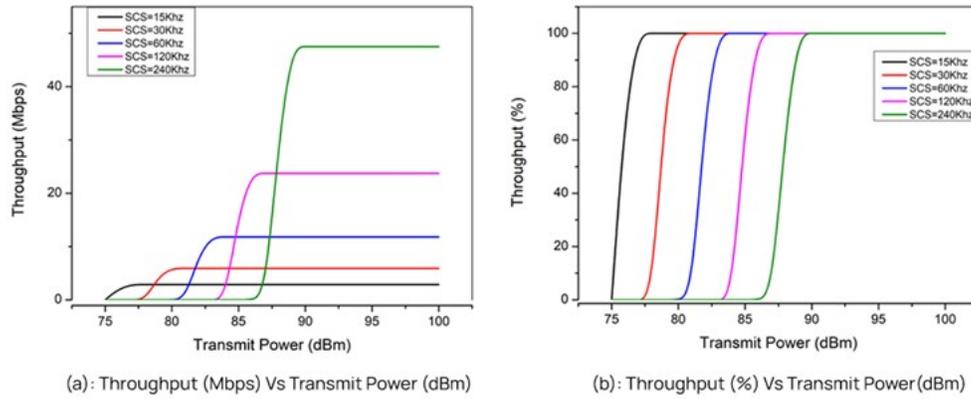


Figure 3.3: Throughput Vs Transmit Power with different SCS Scenario 2

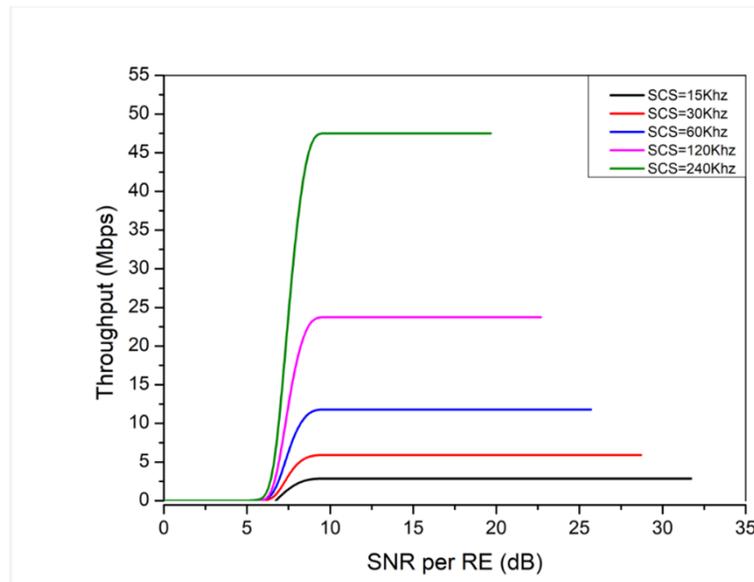


Figure 3.4: Throughput (Mbps) with SNR per RE (dB) with different SCS Scenario 2

3rd Scenario LEO Satellite (One web) at 1200km in Ku Band (15GHz) TDL-A channel:

The performance analysis of a OneWeb-like LEO satellite operating at 1200km altitude in Ku-band (15 GHz) reveals significant differences across SCS configurations that profoundly impact system design considerations.

Table 3.4: 3rd Scenario with different Subcarrier spacings

SCS (kHz)	Max Throughput (Mbps)	Min Viable Power (dBm)	SNR Threshold (dB)
15	2.53	81 (4.63dB SNR)	23.63
30	5.05	84 (4.59dB SNR)	20.59
60	10.10	88 (5.63dB SNR)	15.63
120	20.20	92 (7.07dB SNR)	12.07
240	40.24	93 (6.91dB SNR)	12.91

Table 3.4, Figure 3.5, and Figure 3.6. At the 15 kHz SCS, achieving initial throughput at 81 dBm, 4.63dB SNR, and reaching a maximum throughput of 2.53 Mbps at 100 dBm, making it the most suitable choice for power-efficient user terminals and coverage-oriented applications. In contrast, the 30 kHz SCS shows a steeper performance curve, requiring 84 dBm for initial operation but delivering 5.05 Mbps maximum throughput, representing a balanced option for fixed terminals with adequate power capabilities. The higher SCS configurations 60kHz, 120kHz, and 240kHz exhibit progressively more challenging power requirements, with 60kHz needing 88 dBm just for initial operation and 98 dBm to achieve its 10.10 Mbps maximum capacity. These configurations become viable only for specialized high-capacity gateway links with less critical power constraints. Particularly noteworthy is how the 1200km altitude fundamentally alters the performance landscape compared to lower orbital systems, with all configurations requiring 10-15dB more transmit power and showing much more distinct performance thresholds between SCS options.

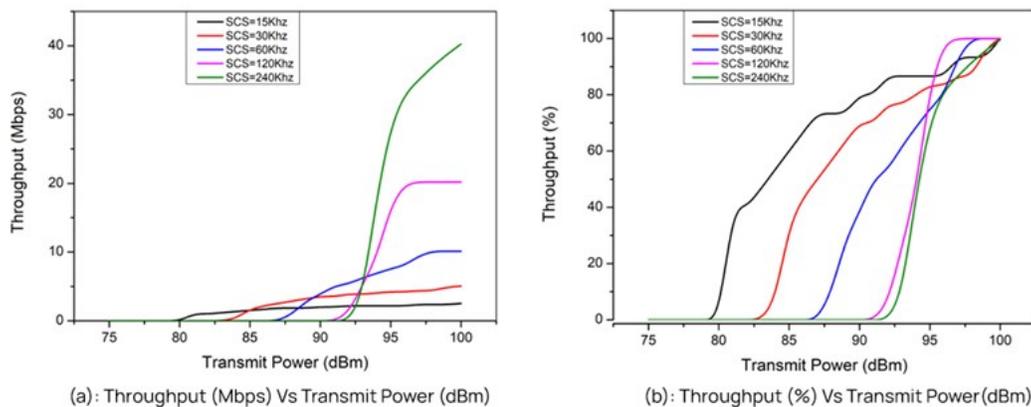


Figure 3.5: Throughput Vs Transmit Power with different SCS Scenario 3

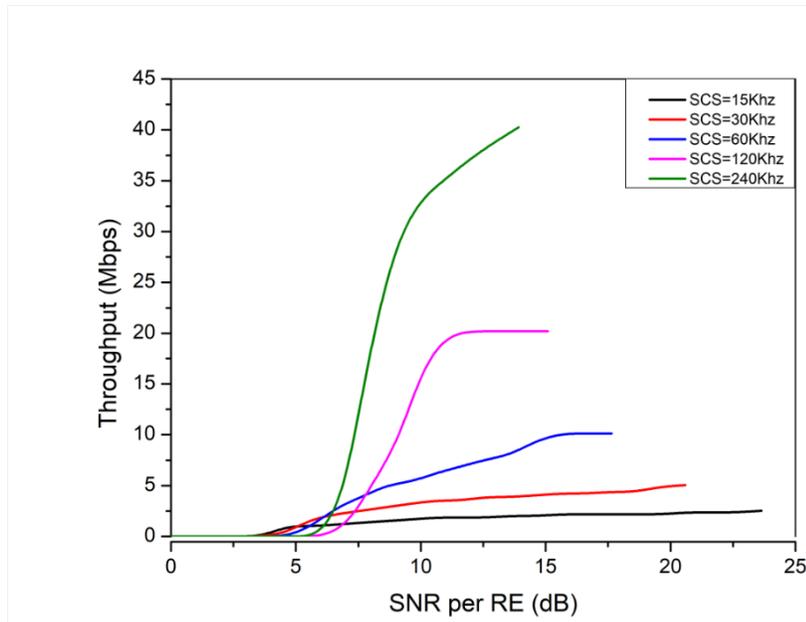


Figure 3.6: Throughput (Mbps) with SNR per RE (dB) with different SCS Scenario 3

4th Scenario LEO Satellite (Oneweb) at 1200km in Ku Band (15GHz) Narrowband channel:

This analysis examines the performance of a OneWeb LEO satellite operating at 1200km altitude in Ku-band (15 GHz) across five different SCS configurations, 15 kHz to 240 kHz, illustrated in [Table 3.5](#), [Figure 3.7](#), and [Figure 3.8](#).

Table 3.5: 4th Scenario with different Subcarrier spacings

SCS (kHz)	Max Throughput (Mbps)	Min Viable Power (dBm)	SNR Threshold (dB)
15	2.53	82 (6.44dB SNR)	8.44
30	5.05	85 (6.44dB SNR)	8.44
60	10.10	88 (6.43dB SNR)	8.43
120	20.20	91 (6.42dB SNR)	8.42
240	40.42	94 (6.39dB SNR)	8.39

The 15 kHz SCS achieves an initial throughput of 82 dBm (6.44dB SNR) and reaches a maximum throughput of 2.53 Mbps at 84 dBm (8.44dB SNR). This configuration maintains a stable 100% throughput across a wide power range (84-100 dBm), making it ideal for power-efficient user terminals and coverage-oriented applications. The 30 kHz SCS shows a steeper performance curve, requiring 87 dBm (8.44dB SNR) to reach its maximum throughput of 5.05 Mbps, representing a balanced option for fixed terminals with adequate power capabilities. Higher SCS configurations exhibit progressively more demanding requirements. The 60 kHz SCS achieves 10.10 Mbps maximum throughput but only at 90 dBm (8.43dB SNR), while the 120

kHz configuration delivers 20.21 Mbps at 93 dBm (8.42dB SNR). The most demanding 240 kHz SCS reaches 40.42 Mbps at 96 dBm (8.40dB SNR), making it suitable only for specialized high-capacity gateway links where power constraints are less critical. The higher SCS options provide greater throughput capacity but require significantly higher transmit power and exhibit more abrupt performance transitions. The 15 kHz configuration's ability to maintain full throughput across a wide power range (16dB) contrasts sharply with higher SCS options that show narrow operational windows.

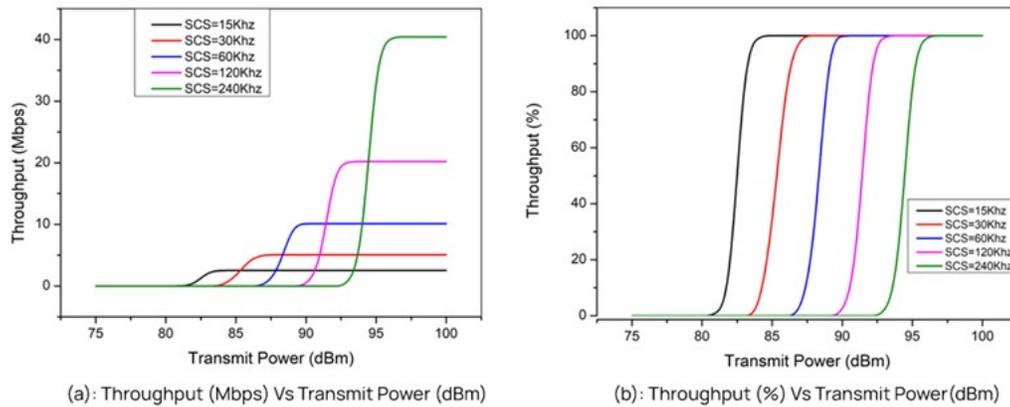


Figure 3.7: Throughput Vs Transmit Power with different SCS Scenario 4

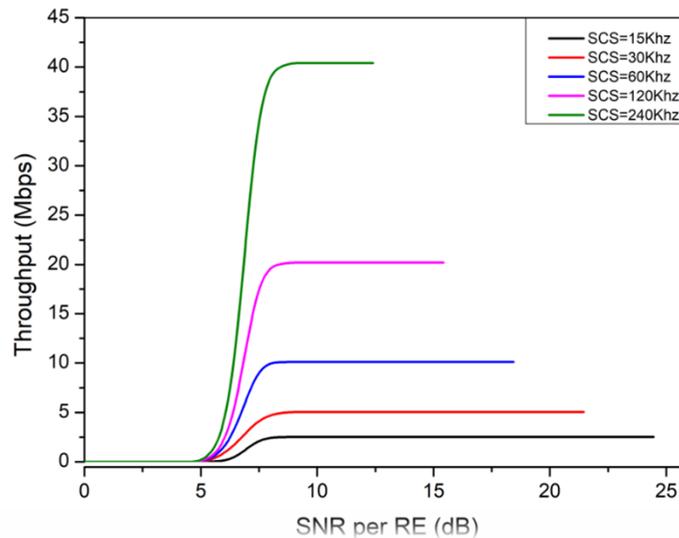


Figure 3.8: Throughput (Mbps) with SNR per RE (dB) with different SCS Scenario 4

These four scenarios, Starlink TDL-A, Starlink Narrowband, OneWeb TDL-A, and OneWeb Narrowband, reveal critical insights about 5G NTN performance in LEO satellite networks. Across all scenarios, we observe consistent trade-offs between SCS configurations, with

lower SCS 15-30 kHz demonstrating superior coverage and power efficiency, while higher SCS 60-240 kHz enables greater capacity at the cost of significantly increased power requirements. The Starlink scenarios at 550 km altitude consistently outperform their OneWeb counterparts at 1200 km in terms of power efficiency, requiring 10-15dB less transmit power for comparable performance levels due to the reduced path loss at lower altitudes. The Narrowband configurations show more abrupt performance transitions than TDL-A channels, particularly noticeable in their "all-or-nothing" throughput characteristics at higher SCS values. Interestingly, the 15 kHz SCS maintains its advantage across all scenarios for coverage-oriented applications. At the same time, 60 kHz emerges as a practical upper limit for most user terminal applications, with 120 kHz and 240 kHz only becoming viable for specialized gateway links with substantial power resources.

The Starlink TDL-A scenario demonstrates the effective overall characteristics, with 15 kHz SCS achieving 2.86 Mbps at 93 dBm and 60 kHz delivering 11.79 Mbps at 92 dBm. The Starlink Narrowband variant shows similar trends but with slightly steeper performance curves. In contrast, the OneWeb scenarios require substantially higher power levels, with the TDL-A configuration needing 84 dBm for 2.53 Mbps at 15 kHz and 90 dBm for 10.10 Mbps at 60 kHz. The OneWeb Narrowband scenario exhibits the most challenging requirements, particularly at higher SCS values, where a 240 kHz configuration demands 96 dBm to achieve 40.42 Mbps. All scenarios show that higher SCS configurations become increasingly impractical for user terminals, with their benefits only realizable in gateway applications where power constraints are relaxed. The Narrowband scenarios consistently show more abrupt performance transitions than their TDL-A counterparts.

3.2 Optimizing Scenarios

5G NTN LEO satellite configurations reveal distinct performance characteristics across different operational scenarios, shown in [Table 3.6](#), [Table 3.7](#), and [Table 3.8](#).

Table 3.6: Optimizing Scenario 1 (Starlink, 16-QAM, TDL-A)

SCS (kHz)	Max Throughput (Mbps)	Min Viable Power (dBm)	SNR Threshold (dB)
15	5.55	81 (8.99dB SNR)	20.89
30	11.42	84 (8.82dB SNR)	21.87

Table 3.7: Optimizing Scenario 2 (LEO 300 km, 64-QAM, TDL-A)

SCS (kHz)	Max Throughput (Mbps)	Min Viable Power (dBm)	SNR Threshold (dB)
15	39.18	86 (15.69dB SNR)	27.69

Table 3.8: Optimizing Scenario 3 (Starlink, 64-QAM, TDL-A)

SCS (kHz)	Max Throughput (Mbps)	Min Viable Power (dBm)	SNR Threshold (dB)
15	27.66	92 (16.24dB SNR)	23.24

For the Starlink 550km configuration using 16-QAM, the 30 kHz SCS demonstrates superior spectral efficiency, delivering 11.42 Mbps throughput at 84 dBm, nearly double the 15 kHz configuration's capacity while maintaining comparable SNR requirements. The lower 300km altitude scenario with 64-QAM achieves a remarkable throughput of 39.18 Mbps at 15 kHz, showcasing how reduced path loss at lower altitudes enables significantly higher data rates and lower latency. However, this comes with increased power demands of 86 dBm and SNR requirements of 27.69 dB, making it most suitable for high-capacity applications. The 550km 64-QAM configuration shows a 30% throughput reduction compared to 300km, requiring 92 dBm transmit power to achieve 27.66 Mbps, highlighting the substantial impact of altitude on system performance. Across all scenarios, the implementation of 2x2 MIMO with HARQ retransmissions proves crucial for maintaining reliable communications, particularly in challenging NTN environments. These results suggest that optimal system design should carefully balance altitude considerations with SCS selection and modulation schemes, with lower SCS 15 and 30 kHz preferable for coverage-oriented deployments and higher SCS configurations potentially viable only for gateway links where power constraints are relaxed. While technological enhancements like MIMO and advanced modulation can improve throughput, the fundamental constraints of orbital altitude and propagation physics remain dominant factors in LEO satellite network design.

Table 3.9 shows the site parameters of the chosen reference site, "Bougoufala", and Table 3.10 shows the Transmitter parameters.

Table 3.9: Site parameters configured

Name	Longitude	Latitude	Support Height (m)
BOUGHOFALA	5.33337	31.94615	50

Table 3.10: Transmitter parameters

Main Propagation Model	3GPP 38.900 Propagation Model
Radius	10 000
Main Resolution	5
Antenna Height	30
Frequency Band	n257 (see Table A.1)
Carrier Bandwidth	50 MHz - NR-ARFCN 2054583
Layer	Macro
Noise Figure	5 dB
MIMO Type	SU-MIMO; MU-MIMO
Maximum Traffic Load (DL/UL)	100%
Radio Equipment	5G NR Radio Equipment
Number of Antennas TX/RX	128
Mechanical DownTilt	60 degree

3.3 Prediction Results and Their Analyses

We utilize coverage, capacity, and quality predictions to evaluate signal levels, quality, and throughput. This coverage prediction presented in Figure 3.9 is calculated using PDSCH Signal Level (DL) (dBm):

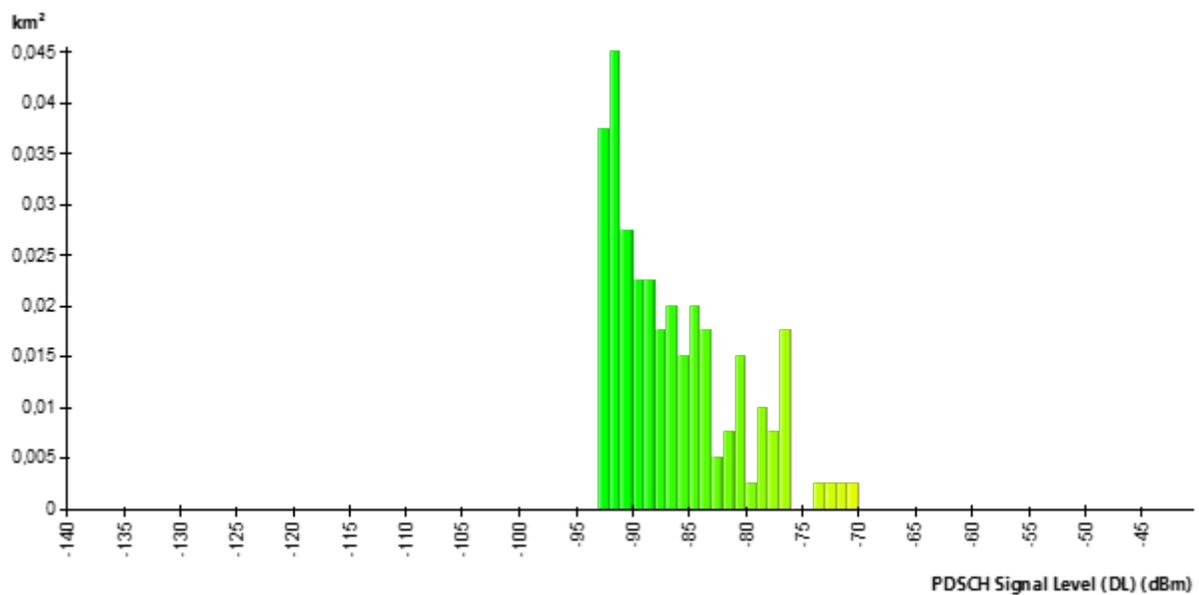


Figure 3.9: Histogram Coverage

The given data shows that with only 0.938% coverage at this threshold, the data reveals that observable signal coverage starts at -71 dBm, suggesting extremely poor beginning signal intensity. Coverage significantly increases between -80 dBm and -90 dBm, increasing from 14.7% to 65.6%. This indicates considerable signal improvement in this region, most likely owing to lower route loss, beamforming gains, or closeness to the cell site. At -93 dBm, peak coverage of 100% is attained; this stays constant down to -140 dBm, The abrupt variations in coverage percentages that is, from 3.1% at -76 dBm to 8.8% at -77 dBm may point to topography impacts or changes in antenna layout good coverage is achieved below -90 dBm, but weak signal issues exist above -70 dBm. Overall, we obtain a robust coverage at low signal levels.

Figure 3.10 shows the Histogram of the capacity prediction, With only a nominal 3.75% degradation at the maximum tested rate of 50,000 kbps (50,000 kbps), the data indicates that 100% of the simulated region meets a minimum peak RLC channel throughput of 48,000 kbps (48 Mbps). With almost no throughput constraints in the simulated environment, this constant performance at throughput levels from 48 Mbps to 0 kbps suggests strong network capacity. The modest performance fall at the 50 Mbps threshold points to this, perhaps limited by base station processing capacity, modulation scheme limits, or available spectrum bandwidth. This may represent the realistic upper limit of the network's current setup. The ideal 100% coverage for all lower throughput needs guarantees that the network architecture effectively satisfies standard 5G performance standards, which usually span 20–50 Mbps for improved mobile broadband applications.

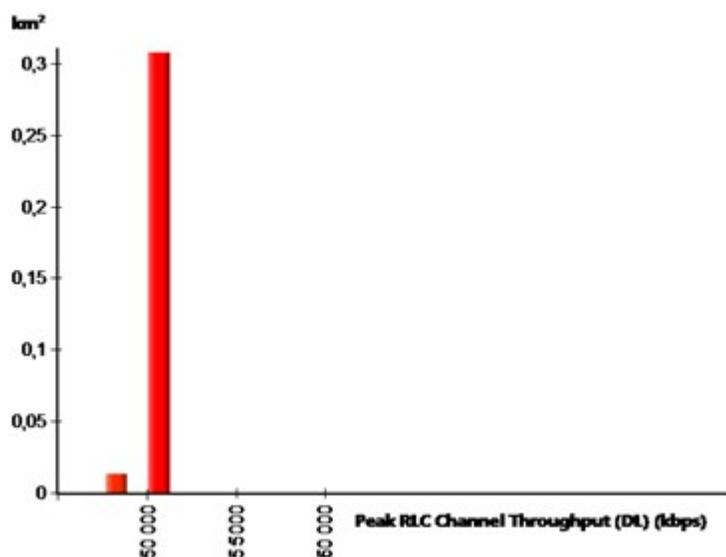


Figure 3.10: Histogram Capacity

An essential understanding of the signal-to-interference-plus-noise ratio (SINR) performance

of the network is revealed by the 5G NR downlink quality prediction (Figure 3.11). The result indicates that no coverage (0%) is attained for PDSCH C/(I+N) values over 22 dB, showing these are very unusual in the simulated environment circumstances of high quality. With only 1.56% probability, the first significant coverage is shown at 22 dB, indicating that this constitutes the highest possible signal quality in this network design. As the quality threshold lowers, coverage increases gradually; at 15 dB it reaches 50% probability, and at 11 dB it exceeds 90%. From 1.56% to 50%, the change in coverage probability from 22 dB to 15 dB demonstrates the most notable improvement, reflecting the network's best working range for balancing coverage and quality. At 6 dB and below, complete 100% coverage is often attained; this indicates that while the network provides universal connectivity at these lower quality levels, better quality connections (above 15 dB) are only attainable under more favorable situations.

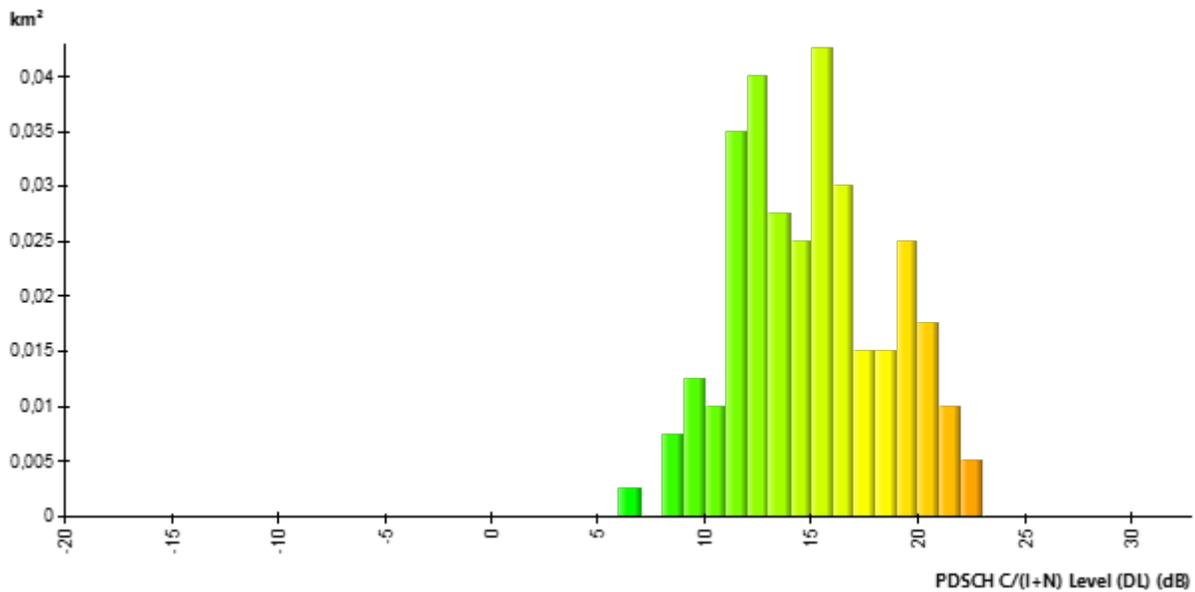


Figure 3.11: Histogram Quality

The findings imply that, in line with many 5G installations, the network is built to prioritize extensive coverage above always good signal quality. While situations beyond 15 dB would be confined to areas near cell sites or with extraordinary radio conditions, the quality criteria between 6 and 15 dB probably reflect the actual working range where most users would have satisfactory performance. This trend suggests possible optimization chances, especially regarding signal quality enhancement in regions that now meet the minimal standards. The strong quality-to-coverage link between 22 dB and 15 dB implies that even modest signal strength or interference control changes might significantly enhance the availability of better-quality connections.

3.4 General Analysis

The simulation findings throughout the four scenarios comparing Starlink-like (550 km) and OneWeb-like (1200 km) networks show a critical understanding of the trade-offs between subcarrier spacing (SCS), power efficiency, and throughput in 5G non-terrestrial networks (NTN).

Ku-band (15 GHz) is Ideal for IoT, rural internet, and mobile apps, and lower SCS settings (15–30 kHz) often show better power efficiency and broader reach. For example, Starlink’s 15 kHz SCS achieves 2.86 Mbps at under 75 dBm, but OneWeb’s equivalent needs more power (81 dBm) because of its higher altitude and more route loss.

Higher SCS values (60–240 kHz) offer much faster throughput (up to 47.49 Mbps for Starlink at 240 kHz), but need much more transmit power (86–96 dBm) and display steeper SNR thresholds, therefore restricting their applicability to high-capacity gateways or fixed connections.

Height affects performance; Starlink’s 550 km orbit beats OneWeb’s 1200km system by 10–15 dB in power efficiency for the same throughput. Furthermore, channel models are essential: While narrowband systems demonstrate sudden, “all-or-nothing” performance shifts, necessitating exact power management, TDL-A channels show slow throughput scaling with power. Although they increase throughput, e.g., 39.18 Mbps at 300km altitude, optimization techniques such as adaptive SCS selection and MIMO-enhanced 64-QAM compromise SNR and battery consumption, LEO satellite access with up to 35 ms end-to-end latency, with an additional 5 ms network latency.

Coverage and quality studies underline the design goals of the network even more. Although the system achieves almost global coverage below -93 dBm, signal quality (SNR) is somewhat variable; only 50% of regions surpass 15 dB SNR, indicating a concentration on ubiquitous connection over always good performance. Though slight deterioration at 50 Mbps implies hardware or spectrum limits, capacity forecasts reveal strong throughput (48 Mbps with 100% coverage). These results highlight scenario-specific designs’ requirement to balance altitude, SCS, and modulation to maximize coverage, capacity, and power economy in 5G NTN implementations.

General Conclusion

This thesis systematically assesses the performance of 5G Non-Terrestrial Networks (NTN) in Low-Earth Orbit (LEO) satellite constellations. Through simulations and analysis of key performance indicators (KPIs), including throughput, latency, coverage, and power efficiency, several important conclusions have been obtained.

Introduction, The fundamental background for combining NTN with 5G technologies to meet the rising need for ubiquitous, high-speed connections is established in this chapter. Outlining the transforming power of 5G technologies, enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications highlights the need for NTN systems, such as LEO satellites and airborne platforms, to close coverage gaps in remote and underdeveloped areas. Emphasizing the importance that 3GPP standardization plays in allowing seamless integration, the chapter notes significant hurdles in NTN implementation, including interoperability concerns, technological limits (e.g., latency, Doppler effects), and regulatory complexity. Evaluating NTN's influence on 5G performance, establishing pertinent KPIs, determining cost-effectiveness, and tackling scalability and technological constraints top the study goals. This chapter prepares the ground for further technical studies, simulations, and assessments by offering a disciplined road map for the thesis, therefore helping to promote the implementation of NTN as a complementary solution to terrestrial 5G networks in reaching worldwide connectivity objectives.

Chapter 1, Emphasizing their transforming power via the Next-Generation Radio Access Network (NG-RAN) and cloud-native 5G Core (5GC), this chapter methodically describes the fundamental architecture and technological advancements of 5G networks. Using dual connection (EN-DC/NR-DC), the NG-RAN's separated architecture, consisting of Centralized, Distributed, and Radio Units, allows flexible resource management and easy interaction with older LTE systems. To enable dynamic network slicing, ultra-low latency, and scalability across several use cases (eMBB, URLLC, mMTC), the 5GC's service-based architecture (SBA) modularizes network services (AMF, SMF, UPF). Using Ku/Ka-bands for high-throughput connectivity and regenerative payloads for onboard processing, Non-Terrestrial Networks (NTN) increase the reach of 5G via spaceborne (LEO, MEO, GEO satellites) and aerial (HAPS,

UAV) platforms, complementing terrestrial infrastructure. Emphasizing NTN's contribution in bridging coverage gaps and improving robustness, we tackled critical difficulties such as Doppler shift mitigation, handover management in NGSO constellations, and hybrid terrestrial-NTN designs. This chapter builds the technical framework for assessing NTN performance in the following simulations by specifying 5G NTN synergies in frequency allocation, beamforming, and use cases (e.g., rural back haul, in-flight connectivity), to underline its critical role in attaining global, ubiquitous 5G connectivity.

Chapter 2 presents the methodology framework for assessing 5G NTN performance through MATLAB-based simulations and Atoll radio network design. Analyzing important KPIs like throughput, latency, and coverage, the model combines 3GPP-compliant waveforms, LEO satellite channel characteristics, and dynamic link-level parameters using the 5G and Satellite Communications Toolbox. Free-space channel loss, Doppler shift (up to ± 720 kHz at 30 GHz), and adaptive HARQ retransmission systems suited for extended propagation delays are among NTN-specific difficulties the modeling methodology addresses. Using Atoll's propagation models and GIS tools, a reference network in Ouargla City was designed for terrestrial-satellite integration with features like 128-antenna MIMO, 50 MHz capacity in the n257 mmWave band, and 3GPP 38.900 route loss models. Significant results include the determination of NTN coverage thresholds (e.g., 100% coverage below -93 dBm) and the effect of subcarrier spacing (15–240 kHz) on throughput-power trade-offs. This thorough methodology offers a basis for evaluating NTN installations in Chapter 4, combining theoretical models with pragmatic network design issues to handle actual restrictions in 5G satellite integration.

Chapter 3, Comprehensive examination of 5G NTN LEO satellite performance across four scenarios in this chapter exposes necessary trade-offs between subcarrier spacing (SCS), altitude, and channel models. With Starlink's 15 kHz attaining 2.86 Mbps at 75 dBm, suited for IoT and rural broadband, lower SCS configurations (15–30 kHz) show improved power efficiency and coverage. Higher SCS (60–240 kHz), on the other hand, allowed for significant throughput increases (up to 47.49 Mbps at 240 kHz) but required much more power (86–96 dBm), fit for gateway connections. Reduced route loss allowed Starlink's 550km altitude to exceed OneWeb's 1200km system by 10–15 dB in power efficiency; meanwhile, Narrowband channels showed rapid performance changes compared to TDL-A's slow scaling. Though signal quality (SNR >15 dB) was restricted to 50% of locations, stressing ubiquity above consistency, coverage projections showed a strong connection below -93 dBm. Although optimisations with 64-QAM and MIMO increased throughput (e.g., 39.18 Mbps at 300km), they needed greater SNR (27.69 dB). Underlining NTN's potential to complement terrestrial 5G, these results support adaptive SCS selection, altitude-aware deployment, and hybrid architectures to balance coverage, capacity, and power constraints, thus stressing challenges in Doppler management

and interference control for future refinement.

This study focused on throughput and coverage; latency in LEO-NTN is primarily driven by altitude-derived propagation delay. Our SCS and HARQ configurations implicitly support 3GPP's URLLC-NTN targets (<50 ms for LEO).

Finally, 5G NTN closes the digital gap and marks a radical turn in world connectedness. Although technological challenges still exist, the ideas in this thesis provide a road map for maximizing NTN installations, thus guaranteeing scalable, effective, high-performance satellite-integrated 5G networks. In the 6G era, further developments in antenna technology, AI-driven resource management, and uniform regulatory frameworks will release NTN's potential even more. This study provides the groundwork for further studies on NTN's involvement in 6G, including artificial intelligence-powered network orchestration, quantum communications, and inter-satellite connectivity. The combination of NTN with developing technology seems to alter concepts of global connectivity.

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Annexe

Table A.1: 5G NR operating bands in Frequency Range 1 FR1 (sub-6 GHz)

NR Operating Band	Uplink MHz / NR-ARFCN (First – <Step size> – Last)	Downlink MHz / NR-ARFCN (First – <Step size> – Last)	Duplex Mode
n1	1920 – 1980 384000 – <20> – 396000	2110 – 2170 422000 – <20> – 434000	FDD
n2	1850 – 1910 370000 – <20> – 382000	1930 – 1990 386000 – <20> – 398000	FDD
n3	1710 – 1785 342000 – <20> – 357000	1805 – 1880 361000 – <20> – 376000	FDD
n5	824 – 849 164800 – <20> – 169800	869 – 894 173800 – <20> – 178800	FDD
n7	2500 – 2570 500000 – <20> – 514000	2620 – 2690 524000 – <20> – 538000	FDD
n8	880 – 915 176000 – <20> – 183000	925 – 960 185000 – <20> – 192000	FDD
n12	699 – 716 139800 – <20> – 143200	729 – 746 145800 – <20> – 149200	FDD

n13	777 – 787 155400 – <20> – 157400	746 – 756 149200 – <20> – 151200	FDD
n14	788 – 798 157600 – <20> – 159600	758 – 768 151600 – <20> – 153600	FDD
n18	815 – 830 163000 – <20> – 166000	860 – 875 172000 – <20> – 175000	FDD
n20	832 – 862 166400 – <20> – 172400	791 – 821 158200 – <20> – 164200	FDD
n24	1626.5 – 1660.5 325300 – <20> – 332100	1525 – 1559 305000 – <20> – 311800	FDD
n25	1850 – 1915 370000 – <20> – 383000	1930 – 1995 386000 – <20> – 399000	FDD
n26	814 – 849 162800 – <20> – 169800	859 – 894 171800 – <20> – 178800	FDD
n28	703 – 748 140600 – <20> – 149600 1446084	758 – 803 151600 – <20> – 160600 1556084	FDD
n29	N/A N/A	717 – 728 143400 – <20> – 145600	SDL
n30	2305 – 2315 461000 – <20> – 463000	2350 – 2360 470000 – <20> – 472000	FDD
n31	452.5 – 457.5 90500 – <20> – 91500	462.5 – 467.5 92500 – <20> – 93500	FDD
n34	2010 – 2025 402000 – <20> – 405000	2010 – 2025 402000 – <20> – 405000	TDD
n38	2570 – 2620 514000 – <20> – 524000	2570 – 2620 514000 – <20> – 524000	TDD
n39	1880 – 1920 376000 – <20> – 384000	1880 – 1920 376000 – <20> – 384000	TDD

n40	2300 – 2400 460000 – <20> – 480000	2300 – 2400 460000 – <20> – 480000	TDD
n41	2496 – 2690 499200 – <3> – 537999 499200 – <6> – 537996	2496 – 2690 499200 – <3> – 537999 499200 – <6> – 537996	TDD
n46	5150 – 5925 743334 – <1> – 795000	5150 – 5925 743334 – <1> – 795000	TDD
n48	3550 – 3700 636667 – <1> – 646666 636668 – <2> – 646666	3550 – 3700 636667 – <1> – 646666 636668 – <2> – 646666	TDD
n50	1432 – 1517 286400 – <20> – 303400	1432 – 1517 286400 – <20> – 303400	TDD
n51	1427 – 1432 285400 – <20> – 286400	1427 – 1432 285400 – <20> – 286400	TDD
n53	2483.5 – 2495 496700 – <20> – 499000	2483.5 – 2495 496700 – <20> – 499000	TDD
n54	1670 – 1675 334000 – <20> – 335000	1670 – 1675 334000 – <20> – 335000	TDD
n65	1920 – 2010 384000 – <20> – 402000	2110 – 2200 422000 – <20> – 440000	FDD
n66	1710 – 1780 342000 – <20> – 356000	2110 – 2200 422000 – <20> – 440000	FDD
n67	N/A N/A	738 – 758 147600 – <20> – 151600	SDL
n70	1695 – 1710 339000 – <20> – 342000	1995 – 2020 399000 – <20> – 404000	FDD

n71	663 – 698 132600 – <20> – 139600	617 – 652 123400 – <20> – 130400	FDD
n72	451 – 456 90200 – <20> – 91200	461 – 466 92200 – <20> – 93200	FDD
n74	1427 – 1470 285400 – <20> – 294000	1475 – 1518 295000 – <20> – 303600	FDD
n75	N/A N/A	1432 – 1517 286400 – <20> – 303400	SDL
n76	N/A N/A	1427 – 1432 285400 – <20> – 286400	SDL
n77	3300 – 4200 620000 – <1> – 680000 620000 – <2> – 680000	3300 – 4200 620000 – <1> – 680000 620000 – <2> – 680000	TDD
n78	3300 – 3800 620000 – <1> – 653333 620000 – <2> – 653332	3300 – 3800 620000 – <1> – 653333 620000 – <2> – 653332	TDD
n79	4400 – 5000 693334 – <1> – 733333 693334 – <2> – 733332	4400 – 5000 693334 – <1> – 733333 693334 – <2> – 733332	TDD
n80	1710 – 1785 342000 – <20> – 357000	N/A N/A	SUL
n81	880 – 915 176000 – <20> – 183000	N/A N/A	SUL
n82	832 – 862 166400 – <20> – 172400	N/A N/A	SUL

n83	703 – 748 140600 – <20> – 149600	N/A N/A	SUL
n84	1920 – 1980 384000 – <20> – 396000	N/A N/A	SUL
n85	698 – 716 139600 – <20> – 143200	728 – 746 145600 – <20> – 149200	FDD
n86	1710 – 1780 342000 – <20> – 356000	N/A N/A	SUL
n89	824 – 849 164800 – <20> – 169800	N/A N/A	SUL
n91	832 – 862 166400 – <20> – 172400	1427 – 1432 285400 – <20> – 286400	FDD
n92	832 – 862 166400 – <20> – 172400	1432 – 1517 286400 – <20> – 303400	FDD
n93	880 – 915 176000 – <20> – 183000	1427 – 1432 285400 – <20> – 286400	FDD
n94	880 – 915 176000 – <20> – 183000	1432 – 1517 286400 – <20> – 303400	FDD
n95	2010 – 2025 402000 – <20> – 405000	N/A N/A	SUL
n96	5925 – 7125 795000 – <1> – 875000	5925 – 7125 795000 – <1> – 875000	TDD
n97	2300 – 2400 460000 – <20> – 480000	N/A N/A	SUL
n98	1880 – 1920 376000 – <20> – 384000	N/A N/A	SUL

n99	1626.5 – 1660.5 325300 – <20> – 332100	N/A N/A	SUL
n100	874.4 – 880 174880 – <20> – 176000	919.4 – 925 183880 – <20> – 185000	FDD
n101	1900 – 1910 380000 – <20> – 382000	1900 – 1910 380000 – <20> – 382000	TDD
n102	5925 – 6425 796334 – <1> – 828333	5925 – 6425 796334 – <1> – 828333	TDD
n104	6425 – 7125 828334 – <1> – 875000 828334 – <2> – 875000	6425 – 7125 828334 – <1> – 875000 828334 – <2> – 875000	TDD
n105	663 – 703 132600 – <20> – 140600	612 – 652 122400 – <20> – 130400	FDD
n106	896 – 901 179200 – <20> – 180200	935 – 940 187000 – <20> – 188000	FDD
n109	703 – 733 140600 – <20> – 146600	1432 – 1517 286400 – <20> – 303400	FDD

Table 2: 5G NR FR2 (mmWave) bands

NR Operating Band	Uplink and Downlink MHz / NR-ARFCN (First – <Step size> – Last)	Duplex Mode
n257	26500 – 29500 MHz 2054166 – <1> – 2104165	TDD
	26500 – 29500 MHz 2054167 – <2> – 2104165	TDD
n258	24250 – 27500 MHz 2016667 – <1> – 2070832	TDD
	24250 – 27500 MHz 2016667 – <2> – 2070831	TDD
n259	39500 – 43500 MHz 2270832 – <1> – 2337499	TDD
	39500 – 43500 MHz 2270832 – <2> – 2337499	TDD
n260	37000 – 40000 MHz 2229166 – <1> – 2279165	TDD
	37000 MHz – 40000 MHz 2229167 – < 2 > – 2279165	TDD
n261	27500 MHz – 28350 MHz 2070833 – < 1 > – 2084999	TDD
	27500 MHz – 28350 MHz 2070833 – < 2 > – 2084999	TDD

n262	47200 MHz – 48200 MHz 2399166 –< 1 >- 2415832	TDD
	47200 MHz – 48200 MHz 2399167 –< 2 >- 2415831	TDD
n263	57000 MHz – 71000 MHz 2562499 –< 1 >- 2795832	TDD