Analysis of the Inclusion of the Non-Terrestrial Component in 5G Networks

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

To everyone that knows me

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Abstract

The main objective of this thesis is the study and analysis of the inclusion of non-terrestrial components in 5G networks, namely satellites. To achieve this goal, fundamental concepts of the 5G system have been introduced, focusing specifically on developing and analysing models of coverage, capacity, and latency. Through the model and various simulations, several satellite architectures and scenarios are explored, evaluating the impact on key performance indicators for different cases. The results obtained show the importance of parameter exchange for coverage extension, the influence on capacity increase, and the impact on latency, providing valuable insights into the implementation of this network. This model serves as a tool for network optimisation and resource allocation, as well as identifying limitations. Regarding LEO satellites, a percentage of 2% of served users is achieved for the most demanding service. This thesis demonstrates the potential of satellite networks for extending 5G coverage to rural or underserved areas, along with the associated challenges.

Keywords

Non-Terrestrial Networks, 5G, Satellites, Coverage, Capacity, Latency.

Resumo

O objetivo principal desta tese é o estudo e análise da inclusão de componentes não-terrestres em redes 5G, nomeadamente satélites. Para alcançar este objetivo foram introduzidos conceitos fundamentais do sistema 5G, e foca-se nomeadamente em desenvolver e analisar modelos de cobertura, capacidade e latência. Através do modelo e de várias simulações, são exploradas várias arquiteturas de satélites e cenários, avaliando o impacto nos indicadores-chave de desempenho para casos diferentes. Os resultados obtidos mostram a importância de troca de parâmetros para a extensão de cobertura, a influência no aumento de capacidade, e o impacto na latência, providenciando conhecimento valioso na implementação desta rede. Este modelo serve como ferramenta para otimização da rede e alocação de recursos, bem como limitações. Relativamente a satélites LEO para o serviço mais exigente é obtido uma percentagem de 2% para o número de utilizadores servidos. Esta tese, mostra o potencial de redes de satélite para a extensão de rede 5G para áreas rurais, ou áreas não servidas, e os desafios para tal.

Palavras-Chave

Redes Não-Terrestres, 5G, Satélites, Cobertura, Capacidade, Latência.

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List of Acronyms

5G	5th Generation of Mobile Network Technology
5GC	5G Core
AF	Application Function
AMF	Access and Mobility Management Function
AR/VR	Augmented Reality and Virtual Reality
AUSF	Authentication Server Function
BBU	Base-Band Unit
BS	Base Station
CN	Core Network
C-RAN	Cloud/Centralised Radio Access Network
CU	Centralised Unit
DL	Downlink
DN	Data Network
DU	Distributed Unit
E2E	End to End
EASDF	Edge Application Server Discovery Function
eMBB	Enhanced Mobile Broadband
EMS	Element Management System
F-AP	Fog Access Point
FDD	Frequency Division Duplex
FEC	Forwarded Error Correction
F-RAN	Fog RAN

FSO	Free Space Optics
F-UE	Fog User Equipment
GEO	Geostationary Earth Orbit
gNB	Fifth Generation Node B
HAPS	High-Altitude Platform Systems
H-CRAN	Heterogeneous C-RAN
HPN	High Power Nodes
IaaS	Infrastructure as a service
IoT	Internet of Things
ISL	Inter Satellite/Aerial links
LDPC	Low-Density Parity-Check Coding
LEO	Low Earth Orbit
LoS	Line-of-Sight
MAC	Media Access Control
MCC	Mobile Cloud Computing
MEC	Multi-access Edge Computing
MEO	Medium Earth Orbit
MIMO	Multiple Input Multiple Output
MMTC	Massive Machine Type Communication
NEF	Network Exposure Function
NF	Network Functions
NFV	Network Function Virtualisation
NFVI	Network Function Virtualisation Infrastructure
NFV-MANO	Network Functions Virtualisation Management and Orchestration
NG	New Generation
NR	New Radio

NRF	Network repository function
NSA	Non-Standalone
NSACF	Network Slice Admission Control Function
NSSAAF	Network Slice Selection Authentication and Authorisation Function
NSSF	Network Slice Selection Function
NTN	Non-Terrestrial Network
OFDMA	Orthogonal Frequency Division Multiple Access
OSS/BSS	Operations and Business Support System
PaaS	Platform as a Service
PCF	Policy control function
QoS	Quality of Service
RAN	Radio Access Network
RB	Resource Block
RF	Radio Frequency
RRH	Remote Radio Heads
SA	Standalone
SaaS	Software as a Service
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SCP	Service communication proxy
SCS	Subcarrier Spacing
SDN	Software-Defined Networking
SNR	Signal-to-noise Ratio
SMF	Session Management Function
TDD	Time Division Duplex
TN	Terrestrial Network
UAV	Unmanned Aerial Vehicles

UDM	Unified Data Management
UE	User Equipment
UL	Uplink
UPF	User plane function
URLLC	Ultra-Reliable and Low-Latency Communications
VNF	Virtualisation Network Functions

List of Symbols

α	Elevation angle
Δf	Bandwidth
Δf_{RB}	Bandwidth per RB
δ_{5GC_DN}	Propagation latency from 5GC to DN
δ_{5GC_Proc}	5GC processing latency
δ_{5GC_RX}	Latency of the 5GC node on the receiver side
δ_{5GC_Trans}	5GC transmission latency
δ_{5GC_Tx}	Latency of the 5GC node on the transmitter side
δ_{CU_5GC}	Propagation latency from CU to 5GC
δ_{CU_Proc}	CU processing latency
δ_{CU_Queue}	CU queuing latency
δ_{CU_RX}	Latency of the CU node on the receiver side
δ_{CU_Trans}	CU transmission latency
δ_{CU_TX}	Latency of the CU node on the transmitter side
δ_{DN}	Latency of the DN node
δ_{DN_Proc}	DN processing latency
δ_{DN_Trans}	DN transmission latency
δ_{DU_CU}	Propagation latency from DU to CU
δ_{DU_Proc}	DU processing latency
δ_{DU_Queue}	DU queuing latency
δ_{DU_RX}	Latency of the DU node on the receiver side

δ_{DU_Trans}	DU transmission latency
δ_{DU_TX}	Latency of the DU node on the transmitter side
δ_{Edge}	Latency of the Edge node
δ_{Edge_5GC}	Propagation latency from Edge to 5GC
δ_{Edge_Proc}	Edge processing latency
δ_{Edge_Trans}	Edge transmission latency
δ_{gNB_5GC}	Propagation latency from gNB to 5GC
δ_{gNB_Edge}	Propagation latency from gNB to Edge
δ_{gNB_Proc}	gNB processing latency
δ_{gNB_Queue}	gNB queuing latency
δ_{gNB_RX}	Latency of the gNB node on the receiver side
δ_{gNB_Trans}	gNB transmission latency
δ_{gNB_TX}	Latency of the gNB node on the transmitter side
$\delta_{gNB-5GC\_DN}$	Propagation latency from gNB to 5GC-DN
$\delta_{gNB-5GC\_RX}$	Latency of the gNB-5GC node on the receiver side
$\delta_{gNB-5GC\_Trans}$	gNB-5GC transmission latency
$\delta_{gNB-5GC\_TX}$	Latency of the gNB-5GC node on the transmitter side
$\delta_{gNB-Edge\_5GC}$	Propagation latency from gNB to Edge-5GC
$\delta_{gNB-Edge\_RX}$	Latency of the gNB-Edge node on the receiver side
$\delta_{gNB-Edge\_Trans}$	gNB-Edge transmission latency
$\delta_{gNB-Edge\_TX}$	Latency of the gNB-Edge node on the transmitter side
δ_{Prop}	Propagation latency
δ_{Relay_SAT}	Propagation latency from Relay to SAT
δ_{SAT_gNB}	Propagation latency from SAT to gNB
δ_{SAT_RX}	Latency of the SAT node on the receiver side

δ_{SAT_Trans}	SAT transmission latency
δ_{SAT_TX}	Latency of the SAT node on the transmitter side
δ_{Total_node}	Total Node latency
δ_{Trans}	Transmission latency
δ_{UE_TX}	Latency of the UE node on the transmitter side
δ_{UE_DU}	Propagation latency from UE to DU
δ_{UE_gNB}	Propagation latency from UE to gNB
$\delta_{UE\_gNB-5GC}$	Propagation latency from UE to gNB-5GC
$\delta_{UE\_gNB-Edge}$	Propagation latency from UE to gNB-Edge
δ_{UE_Proc}	UE processing latency
δ_{UE_Relay}	Propagation latency from UE to Relay
δ_{UE_RX}	Latency of the UE node on the receiver side
δ_{UE_SAT}	Propagation latency from UE to SAT
δ_{UE_Trans}	UE transmission latency
δ_{Prop}	Propagation latency
ρ_{CU}	Ratio of functionalities assigned to the CU
ρ_{DU}	Ratio of functionalities assigned to the DU
ρ_{N}	Signal-to-noise ratio
ρ_{UE}	UE Processing Delay Ratio
$\theta_{3\mathrm{dB}}$	Half-power beamwidth
λ	Satellite carrier wavelength
μ	Numerology
v	Velocity of the signal in the link
A_{cover}	Area of Satellite coverage
A_{f}	Activity factor

d	Distance of the link
d_{cover}	Satellite diameter covered
d_{max}	Maximum distance of the link
$d_{terminal}$	Distance from the terminal to the satellite
D_{serv}	Packet size in bytes for a specific service
D	Antenna diameter
F	Noise Figure
f_{sf}	Scaling factor
G_{RX}	Receiver antenna gain
G_{TX}	Transmitter antenna gain
h_0	Satellite altitude
L_0	Free space propagation
L_p	Total path loss
L_{pb}	Basic path loss
L_{pg}	Attenuation due to atmospheric gases
L_u	Losses due to user
M_{SF}	Shadow fading
$N_{PRB}^{BW,\mu}$	Number of Resource Blocks according to numerology
$N_{Active,s}$	Number of users actively using a service
N_P	Number of users connected to the node
N_s	Overall user density for a specific service
$N_{s,cell}$	Number of users for a specific service per area covered
$N_{Users\ possible,s}$	Number of users possible to use a service
O_H	Overhead
$P_{Served\ users}$	Percentage of served users

P_{EIRP}	Effective isotropic radiated power
$P_{EIRP,density}$	Effective isotropic radiated power density
P_{RX_min}	Receiver sensitivity
Q_m	Modulation Order
R	Data rate provided by the link
$R_{Active\ needed}$	Throughput needed for active users
R_{Cap}	Throughput offered
R_E	Earth radius
R_{max}	Maximum Code Rate
R_{RB}	Data rate per Resource Block
R_s	Data rate of a specific service
T_s^{μ}	Average symbol duration
v_{Layers}	Number of layers of MIMO

List of Software

MATLAB	Numerical and Simulation Computing software
Microsoft Excel	Spreadsheet Application
Microsoft PowerPoint	Presentation and Slide Program
Microsoft Word	Text Editor Software
ChatGPT	Artificial Intelligence Chatbot Technology

Chapter 1

Introduction

This chapter introduces the thesis. It provides a brief description of the new technologies that come with 5G and a small introduction to non-terrestrial networks, complementing each other. It is followed by some challenges in the implementation of 5G non-terrestrial networks. Lastly, the objective behind this work is presented and it ends with the content of the thesis.

1.1 Overview and Motivation

Mobile users and services, as well as application requirements, are constantly evolving. The world is transitioning into a fully connected and digitalised society, and this results in higher requirements, such as more data, less latency, reliability of live data and full connectivity.

The fifth generation of mobile network technology (5G) supports much higher data rates, reduced latency, and increased capacity. 5G technologies include advanced antenna systems, multiple-input multiple-output, beamforming, software-defined networks, network function virtualisation and cloud/edge computing. All these technologies make 5G well-suited for a wide range of applications. Despite everything, the major problem of 5G is the implementation of infrastructures everywhere and the cost of it.

Non-terrestrial networks (NTN) refer to communication networks that use non-land-based infrastructure to transmit and receive communication signals. Some examples of non-terrestrial networks include satellite and airborne networks (e.g., airships or drones). The most noteworthy advantage of these types of networks is that they can provide connectivity in areas where it is difficult or even impossible to build terrestrial networks, such as in remote or rural areas and in disasters or emergencies, or even provide connectivity in the middle of the ocean or the air. It can also provide additional capacity and support to existing terrestrial networks.

Combining 5G with non-terrestrial networks holds great promise, particularly regarding connectivity to non or under-served areas, for a fully connected world, Figure 1.1.

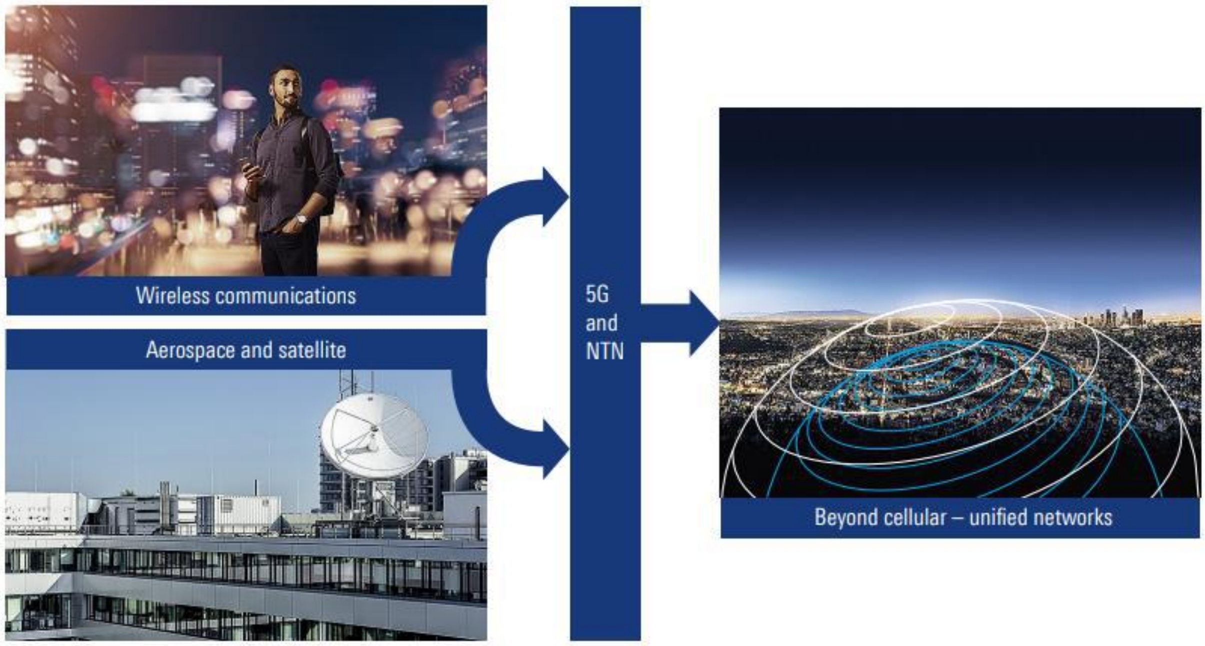

Figure 1-1 Combination of 5G and an NTN (extracted from [R&SC22]).

Several critical satellite communication technologies require further analysis and further development to effectively deliver this combined solution:

- **Antenna Design:** Beamforming plays a significant role in satellite communication and must deal with the improvement of antenna gain, also leverage coverage, addressability aspects, and interference reduction. The technology aims to achieve multi-beam, agile and scalable phased array antennas.
- **Inter-satellite link:** The focus is that it must have a way of supporting satellite constellations, in case of a multi-hop scenario, and interaction between satellites, normally satellites use radio frequency or free space optical link.
- **Routing, scheduling, and networking:** Important issues, especially with Low Earth Orbit (LEO) satellites, where the satellite is in movement relative to the Earth, the coverage and capacity dynamically change. Effective routing, scheduling, and network management are essential.
- **Automation and Satellite constellation management:** There is a permanent need for maintenance and control of the flight path, and interference management regarding frequency channels.
- **Radio Interface:** Concerns regarding spectrum allocation, managing time delays and accounting for Doppler shift effects.
- **Power Management:** Satellites have limited power budgets, requiring efficient communication protocols and energy harvesting technologies.
- **Propagation Modelling:** Accurately predicting signal propagation considering atmospheric conditions, terrain variations, and obstructions is crucial for optimising network performance and reliability. Additionally, incorporating real-time data, leveraging machine learning, and adopting hybrid approaches can further enhance model accuracy and adaptability.

In 1945, Arthur C. Clarke proposed that with the use of only three geostationary orbit satellites, it was possible to provide almost worldwide radio coverage. Due to the high costs and the rapid improvements in terrestrial communications, satellite networks were not the most appropriate system at the time.

Much later, with stricter requirements and less costly, the importance of the Low Earth Orbit satellite has increased again. Several Low Earth Orbit constellations have appeared, such as Starlink and OneWeb. Figure 1.2 displays the annual number of objects (satellites, probes, and space station flight components) launched into orbit. There has been an increase recently, primarily because of SpaceX's Low Earth Orbit constellation (Starlink) that came to reduce the cost of launching satellites.

Figure 1-3 shows a signal coverage comparison, where part (A), a traditional terrestrial scenario, where the signal originates from a base station, and as the distance increases, the receive signal strength hugely diminishes, limiting the area of coverage. In contrast, part (B), depicts a satellite system aiding in signal distribution, as the source, where the signal strength remains less variable across a larger distance.

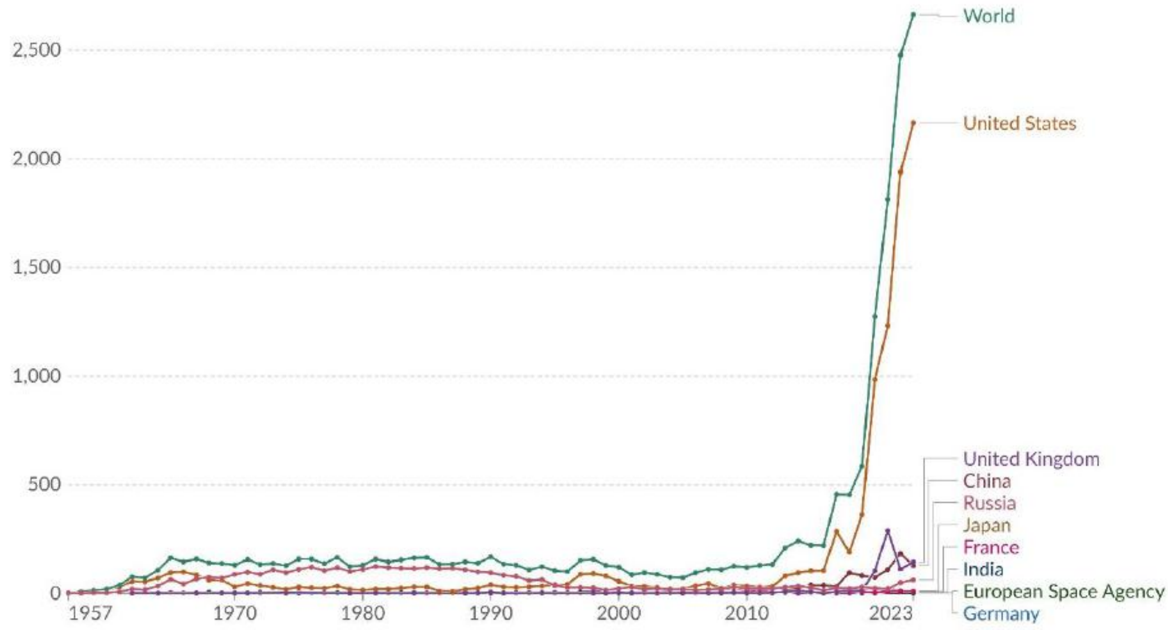

Figure 1-2 Annual number of objects launched into space (extracted from [UNOO24]).

The integration of non-terrestrial components in 5G networks is beneficial to a fully connected world. The thesis was developed in collaboration with the Portuguese operator NOS with the very aim of including non-terrestrial components in 5G networks.

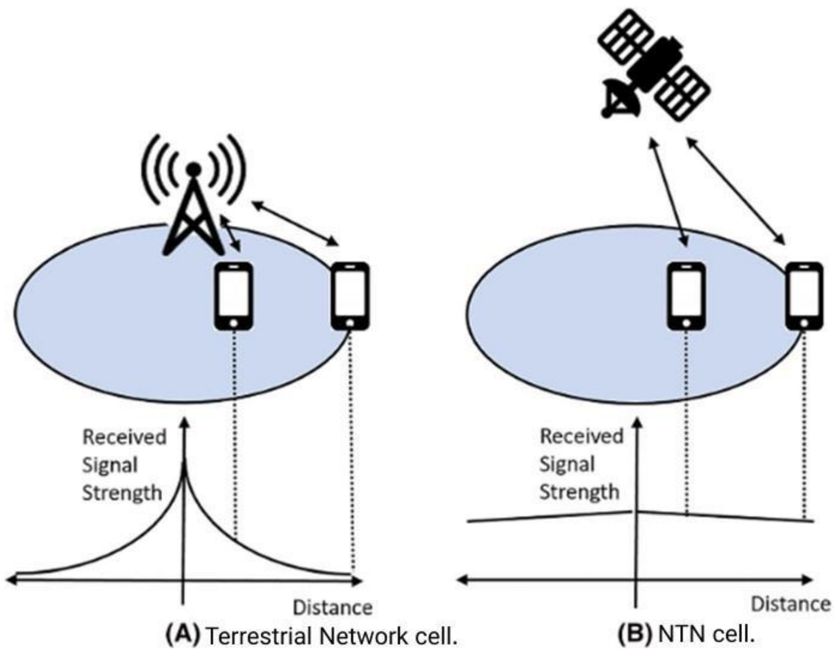

Figure 1-3 Received signal strength in a terrestrial network cell (A) and in a NTN cell (B) (extracted from [MSPK22]).

1.2 Objective and Contents

This thesis's principal objective is to analyse the already existing terrestrial networks and how they can be complemented with non-terrestrial ones, namely, drones, high altitude platforms systems, and principally satellites, for different purposes, i.e., ranging from the provision of capacity for occasional events to the extension of coverage in rural areas. In this thesis, many aspects will be analysed, e.g., frequency bands, links among network nodes, targeted usage, the autonomy of non-terrestrial components, implementation regarding coverage, capacity, as well as latency. With this analysis, a model was developed for the inclusion of the non-terrestrial component with 5G networks.

This thesis consists of five chapters:

- Chapter 1: The current one, introduces an overview of the problem and what is being analysed in this thesis.
- Chapter 2: Introduces fundamental concepts related to 5G networks, the Radio Interface and Services and Applications requirements. Proceeds to analyse the specific topic of Non-Terrestrial Networks, and an additional study on satellite-based networks, followed by the state-of-the-art
- Chapter 3: Provides an overview of the model and the service requirements for the required services, followed by the dimensioning of the three main parts of the model, coverage, capacity, and latency. The third part contains the model implementation with the flow diagrams for each specific model and the overall model, clearly explained, and finally the model’s assessment.
- Chapter 4: Presents the several scenarios developed and analysed. Each scenario suffers some variations that intend to further evaluate the model and reach an appropriate conclusion of the suitable services and satellite system.
- Chapter 5: Concludes the thesis by summarising the main conclusions of the work and final remarks regarding possible future work are discussed.

Chapter 2

Fundamental Concepts and State of the Art

This chapter provides an overview of 5G, mainly focusing on the network. It addresses the network architecture, network virtualisation and slicing, cloud network technology as well as edge computing. The analyses of the Radio Interface and its services and applications are also given. All these are key enabling technologies for the integration of 5G and Non-Terrestrial Networks. It closes with the study of Non-Terrestrial Networks and a more focused approach on satellite-based ones.

2.1 5G Network

2.1.1 Network Architecture

A characteristic of 5G (NR) is that the Access Network can connect not only to a new 5G Core (5GC) network but also to the 4G (LTE) Core network. These deployment options are known as the Non-Standalone (NSA) and Standalone (SA), shown in Figure 2.1. This chapter is based on [3GPP22a].

- **NSA architecture**: The 5G architecture is used in conjunction with the existing 4G infrastructure, enabling the NR technology without network replacement, making use of the capacities offered by 5G NR (lower latency and bigger capacity) even though only 4G services are supported.
- **SA architecture**: In this version, it is not built upon a 4G infrastructure, but the 5G NR is connected to the 5G Core Network, enabling the full set of 5G services, such as network-slicing and cloud-native core availability.

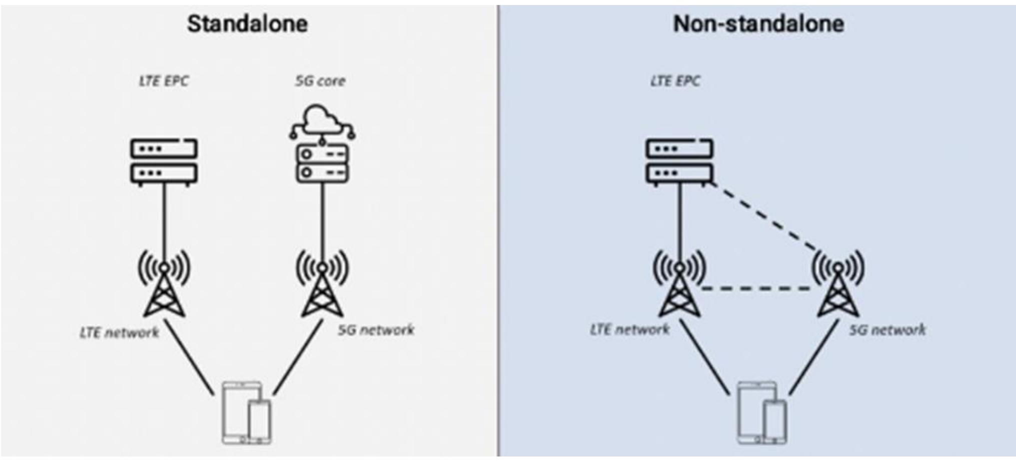

Figure 2-1 Standalone and Non-Standalone versions (adapted from [STLP22]).

Each architecture has its advantages, being up to the operator to decide which one is better in the specific environment and needs of the users, for instance, the kind of population and zone where the service will be delivered in terms of speed connectivity, or more futuristic services.

Taking [3GPP22a] as a reference, which contains the 5G Network Architecture, defining the core architecture, functional elements and the high-level interfaces between them, the interaction between network functions (NFs) can be represented in two ways, service-based and reference point representations. The focus is on the service-based one: NFs within the control panel enable other authorised NFs to access their services, also including point-to-point reference points where necessary, providing a way of ensuring that all 5G functional and service requirements are satisfied.

The non-roaming architecture is shown in Figure 2.2, where service-based interfaces are used within the Control Plane. By utilising software-defined networking and network function virtualisation, this model seeks to maximise the modularity, reusability, and self-containment of network services as well as to encourage the ability to grow flexibly.

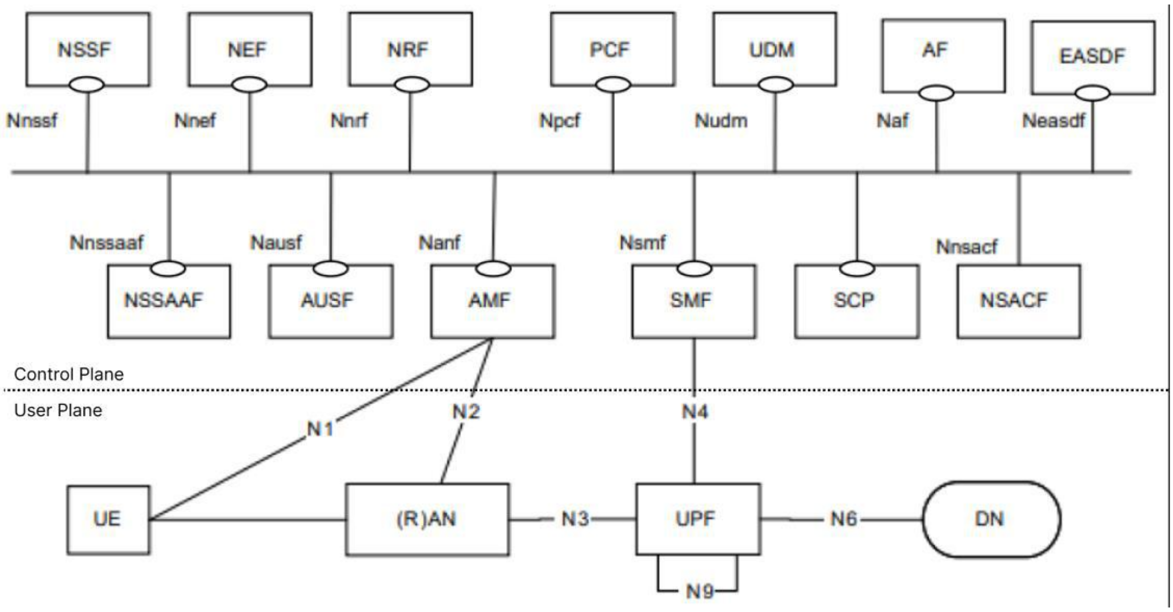

Figure 2-2 Non-Roaming 5G Service-Based Architecture (SBA) (adapted from [3GPP22a]).

The SBA consists of several modules and network functions that are listed below:

- **User equipment (UE):** Any device that gives an end-user access to network services.
- **Data network (DN):** Represents the connection to other services (e.g., internet access)
- **Radio access network (RAN):** Enables access to a 5G core network.
- **Access and mobility management function (AMF):** This module receives all access information and is responsible for the management of the access control and mobility tasks.
- **Authentication server function (AUSF):** Performs authentication between the User equipment and the network.
- **Session management function (SMF):** Sets up and manages sessions between a UE and a data network.
- **User plane function (UPF):** Responsible for packet routing and forwarding, inspection, QoS handling, and many other configurations according to the service type. It works as the anchor point for Intra/Inter Radio Access Technology in the 5G Architecture.
- **Policy control function (PCF):** Provides a policy framework incorporating network slicing, roaming and mobility management. Also enables end-to-end QoS enforcement with QoS parameters.
- **Unified data management (UDM):** Handles access authorisation and subscription

management of the user.

- **Network repository function (NRF):** Bestows registration and discovery functionalities so that NFs can discover each other and communicate with each other inside an operators' network.
- **Network exposure function (NEF):** Allows the use of an interface for external users, enabling the control of network-related information (monitoring, provisioning, policy/charging, and analytics reporting capability).
- **Network slice selection function (NSSF):** Selects the set of network slice instances to satisfy the service request from a UE and determines a list of appropriate network slice instances for the needs of the UE.
- **Network slice selection authentication and authorisation function (NSSAAF):** Performs authentication and authorisation specific to a slice.
- **Application function (AF):** Interacts with the network influencing session management and with application services that require dynamic policy control.
- **Service communication proxy (SCP):** Grants NFs and NF services the ability to communicate with each other and with other user plane entities. Providing routing control, resiliency, and observability to the core network.
- **Network slice admission control function (NSACF):** Regulates the number of UEs and several PDU sessions (connectivity between the UE and a specific DN) per network slice.
- **Edge application server discovery function (EASDF):** Procedure by which a UE finds the IP address of an appropriate Edge Application Server.

2.1.2 Network Virtualisation and Slicing

The 5G network architecture has been designed in a way to support fast and reliable connectivity using new concepts, such as network function virtualisation (NFV), software-defined networking (SDN) and network slicing. The 5G architecture leverages the structural separation of hardware and software, as well as the programmability offered by SDN and NFV. The combination of these two enables a dynamic and flexible deployment, i.e., this technology permits the integration of non-terrestrial networks with terrestrial ones and on-demand scaling of NFs. This chapter is based on [Ahma19], [LYHu17], [NGMN15] and [5GPP20].

Another innovative concept that has been incorporated into the design of next-generation networks is the separation between user- and control-plane functions; this separation reduces latency on application service by selecting user-plane nodes that are closer to the RAN or more appropriate for the intended UE usage type without increasing the number of control plane nodes, efficient for high-bandwidth applications.

The NFV is fundamentally the replacement of network appliance hardware by a virtual level, allowing the separation of communication services from dedicated hardware, which means network operations can provide new services dynamically and without installing new hardware. The fundamental architecture of NFV is represented in Figure 2.3.

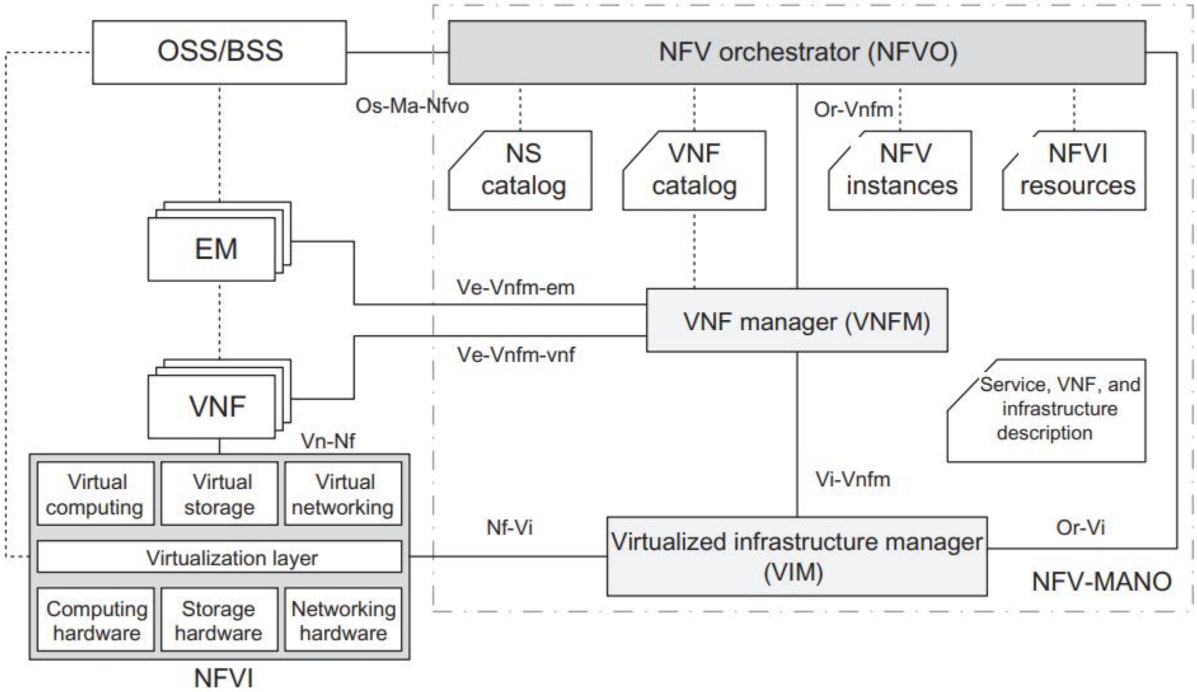

Figure 2-3 NFV architecture (extracted from [Ahma19]).

The NFV architecture consists of major components, such as Virtualisation Network functions (VNFs), Network functions virtualisation management and orchestration (NFV-MANO), and Network Function Virtualisation Infrastructure (NFVI) that work with traditional components like Operations and Business Support System (OSS/BSS).

- **VNF:** These are software implementations of network functions that can be deployed on a NFVI. Different VNFs can be linked together, like service chaining. It can help increase network scalability and agility while using the network infrastructure resources more efficiently.
- **Element management system (EMS):** Joint system of EMS, it performs the typical management functionality for one or several VNFs.
- **NFVI:** Represents the totality of all hardware and software resources in which VNF are deployed, managed, and executed. In other words, it creates the virtualisation layer on top of the hardware and abstracts the hardware resources. Consists of three distinct layers: Physical infrastructure, virtualisation layer and virtual infrastructure.
- **NFV-MANO:** Comprises three major functional blocks: VIM, VNF manager, and NFVO. The VIM handles the control and management of NFVI computing, storage, and network resources. Regarding the VNF manager, it is responsible for the VNF lifecycle management including installation, updates, and event reporting between NFVI and EMs. The NFVO is a key component since it provides key access to resources, as well as manages new network services and life cycles.

- **OSS/BSS:** Deal with applications and services, taking care of overall management of operations and businesses.

Focusing now on SDN, it is a network architecture approach that enables the network to be controlled by software applications, highly dynamic, manageable, and adaptable, complementing the NFV approach in network management. The splitting of the control and data forwarding functions is the main reason why this approach works, and as a consequence, it represents a key aspect in virtualisation and network slicing. It consists of 3 main layers, which are illustrated in Figure 2.4.

- **Infrastructure layer:** Consists of networking devices that control the forwarding and data processing capabilities of the network and represent the physical network infrastructure.
- **Control layer:** Maintains the link between the application layer and the infrastructure layer, is responsible for policies and traffic flows throughout the network, i.e., acts as the brain of the network.
- **Application layer:** This layer is designed mainly to fulfil user requirements and contains the end-user applications that utilise the network services and resources, controlling the network, such as network visualisation, dynamic access control, security, mobility, cloud computing, and load balancing.

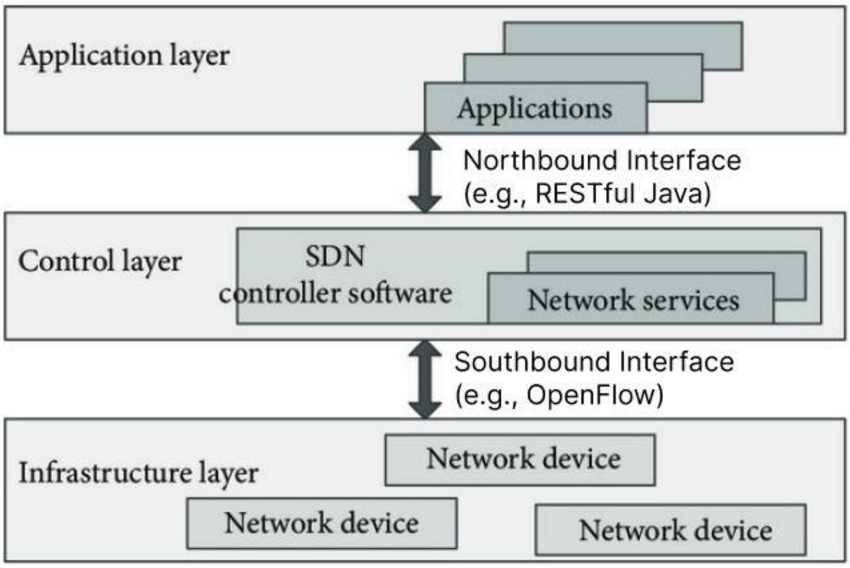

Figure 2-4 SDN illustration of layers (extracted from [LYHu17]).

The combination of these two technologies enables a key concept, network slicing. This concept consists of dividing the network into slices, providing multiple independent virtual networks dedicated to each service or customer, i.e., providing a different quantity of resources to different traffic types, using the same physical infrastructure.

The network slicing architecture contains access slices, core network (CN) slices and the selection function that connects these slices, where each CN slice is built from a set of NFs. A network slice will last throughout the intended service lifetime and will provide full network function support to the devices connected with the network slice. Figure 2.5 illustrates multiple 5G network slices being operated at the same time on the same infrastructure, slicing for different devices different NFs distributed across the network.

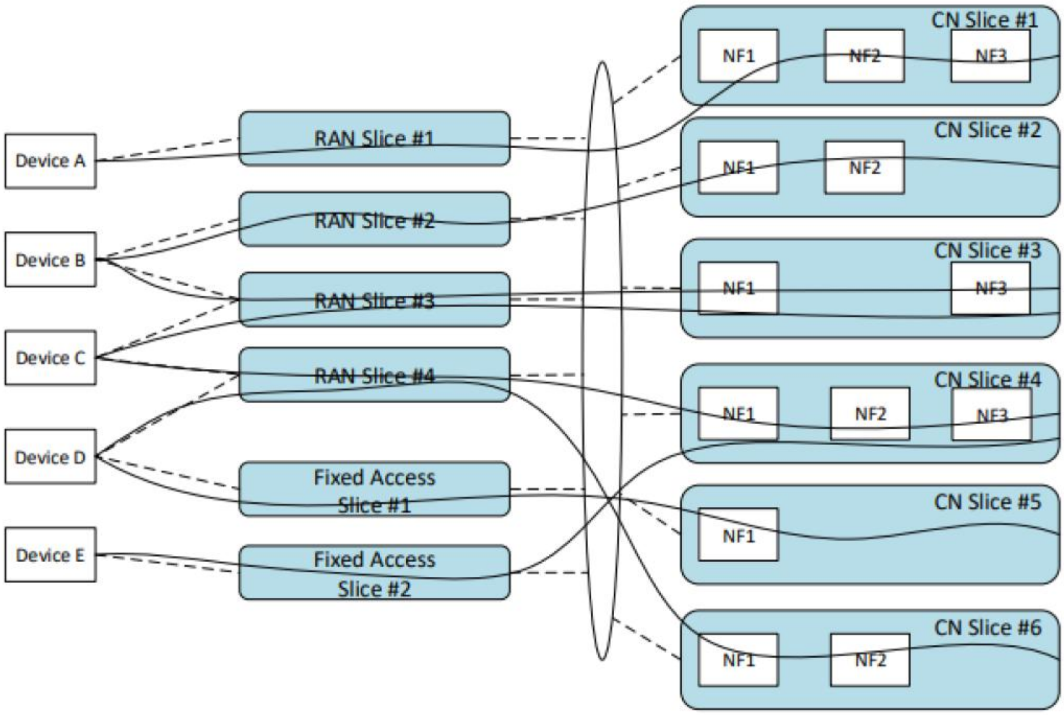

Figure 2-5 UE connection with the network slices (extracted from [NGMN15).

It is relevant to notice that with this concept the objective intended is that provides the minimum required resources for each given use case, where there is a possibility of having fixed slices reserved for special cases (e.g., SOS services).

2.1.3 Cloud and Edge Networking

With the coming of virtualisation, it opened the doors to many other technologies in 5G, such as Cloud Computing and Edge Computing. This chapter is based on [GuHa17], [HNHS19], [LHWe18], and [CCYS15].

Cloud Computing is a way of delivering computing services, including servers, storage, databases, networks, applications, and intelligence, over the cloud ("the Internet") allowing higher flexibility and efficiency. It has three main service models: Infrastructure as a service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS).

The Cloud/Centralised Radio Access Network (C-RAN) is a cloud computing architecture, represented in Figure 2.6, that provides a sophisticated level of cooperation and communication between base stations (BSs). It is composed of Base-Band Units (BBUs) pool, a combination of all BSs computational resources into a central pool which is responsible for the generation and processing of digitalised baseband signals providing high computational capabilities, and Remote Radio Heads (RRHs), responsible for the reception of radio signals, filtering, amplification, and transmission of these signals to the cloud platform through the fronthaul, usually optical transmissions networks that provide high capacity and high bandwidth.

This architecture has some challenges such as high bandwidth requirements between RRH and BBU, therefore the reason for it being usually fibre optics, resulting in considerable transport resources costs. As a solution to this comes the partially centralised C-RAN architecture.

The C-RAN can be divided into 3 types:

- **Fully Centralised**: All physical (radio functions), media access control (MAC) and network layer (routing functions) functionalities to the BBU. As a result, this structure can benefit from effortless operation and maintenance significantly, but at the cost of high bandwidth requirements being limited to Fronthaul capabilities.
- **Partially Centralised**: The physical layer functions are done at RRH while MAC and network layer functions are performed at the BBUs. It adds complexity to the RRH, resource sharing becomes reduced and advanced features cannot be effectively supported. The major advantage is that it reduces the requirement of bandwidth on the links.
- **Hybrid Centralised**: Some physical layer functions are done in RRHs, taking the responsibility of users or cell-specific functions that are mainly concerned with signal processing, while others are done in BBU. This type of structure can be very flexible in resource sharing, as well as, reducing energy consumption and communication overhead in BBUs.

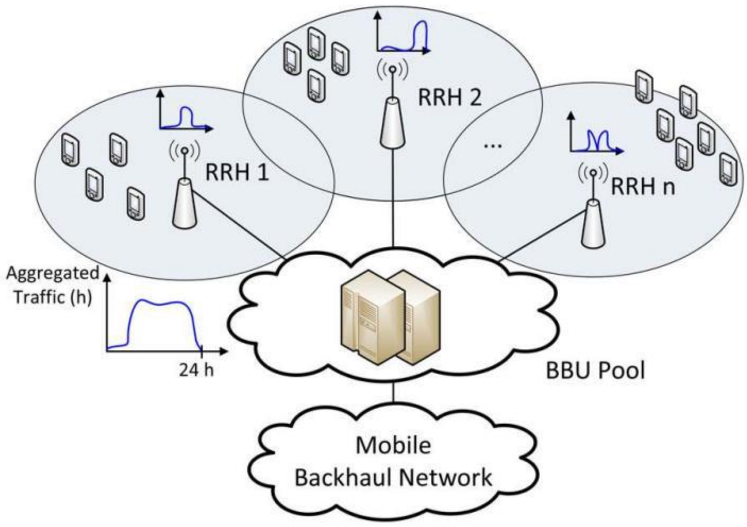

Figure 2-6 Representation of a C-RAN architecture (extracted from [CCYS15]).

Multi-access Edge Computing (MEC) is a technology that provides cloud-based network resources and services, at the edge of the network, i.e., closer to users, resulting in a significant reduction of the end-to-end latency. By having this edge node closer to the users performing analytics or caching content, the volume of data transmitted to the core network is reduced, thus having a more efficient use of existing network bandwidth, establishing a low-latency environment capable of meeting much more heavy requirements from services. The benefits of MEC are a reduction of network loads, increased security, and decreased latency.

It is possible to notice that the combination of both these technologies, Figure 2.7, can bring a lot of advantages. MEC can be used as a tool to handle offloading tasks by shifting time-sensitive BS functions to the Edge nodes, and the BBU pools, however other tasks that require more computing capability need to be addressed by the cloud since it has much more powerful computing capacities than the MEC entity. Therefore, it is possible to conclude that MEC and mobile cloud computing (MCC) complement each other.

An innovative technology, Fog computing, has emerged that might seem like a combination of MCC and MEC. Fog computing introduces a layer between edge devices and the cloud, relying on small computing servers near the edge devices that are all connected enabling a much more intelligent flow of information. This technology will be helpful for the Internet of Things.

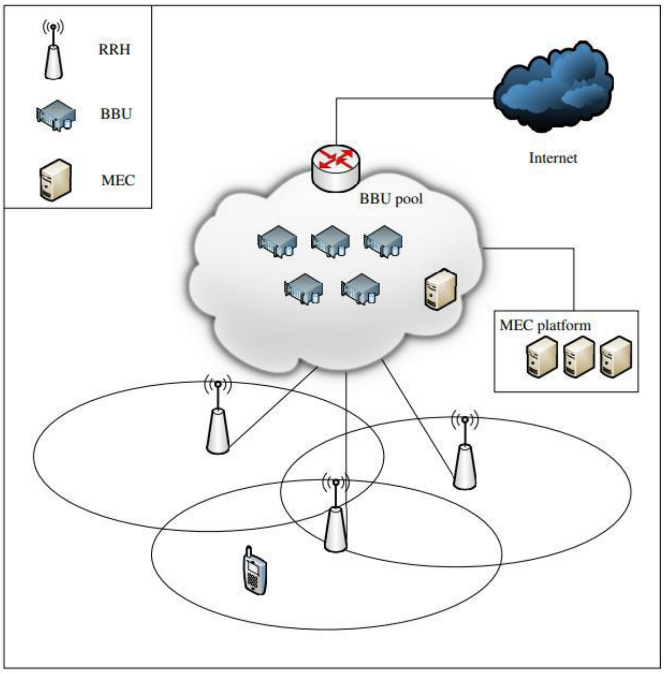

Figure 2-7 C-RAN and MEC system combination architecture (extracted from [LHWe18]).

Even though C-RAN has many advantages, it has its limitations, and with this comes different architectures to make up for these restrictions, such as Heterogeneous C-RAN (H-CRAN) and Fog RAN (F-RAN). While the first is adopted to enable dense heterogeneous networks, the second uses fog computing to extend cloud capabilities to the edge.

The H-CRAN architecture, which is virtually identical to the C-RAN, has been proposed to alleviate the burden on the fronthaul by decoupling both control and user planes. The control functions are now in the macro-BSs, denoted High Power Nodes (HPNs), instead of the BBU pool.

Regarding the F-RAN architecture, it is implemented based on the H-CRAN architecture and other specific components: Fog Access Point (F-AP), RRHS with capabilities related to caching, signal processing and management of radio resources; and Fog User Equipment (F-UE), Smart User Terminals dotted with the same capabilities as the F-AP, allowing direct communication between each other or relay communication of other F-UEs. Some relevant characteristics worth analysing among the different architectures are described below with a simplified visualisation, Figure.2.8 and Table 2.1:

- Level of Heterogeneity: It has a direct influence on capacity, energy consumption and spectrum efficiency. Increased heterogeneity causes several interferences that restrict performance gains and commercial deployments.
- Decoupling of the Control Plane from the User Plane: This separation improves network architecture flexibility, enhances the performance of the network, and is a must in network slicing.
- Execution of Network Functions: Functions such as storage, caching, control, communication, and management, might be centralised or distributed.
- Transmission Delay.
- Data Processing.
- Latency.
- Reliability.
- Burden on the Fronthaul.

Table 2-1 Qualitative comparison of C-RAN, H-CRAN and F-RAN in 5G mobile networks (adapted from [HNHS19]).

Characteristics	C-RAN	H-CRAN	F-RAN
Execution of NFs	Centralised	Centralised	Centralised and Distributed
Decoupling of Control/User planes	No	Yes	Yes
Level of Heterogeneity	Medium	Very High	High
Transmission Delay	Long	Long	Low
Data Processing	Cloud Data Centre	Cloud Data Centre	Near to Device
Latency	High	High	Low
Reliability	Medium	Very High	High
Burden on the Fronthaul	High	Medium	Low

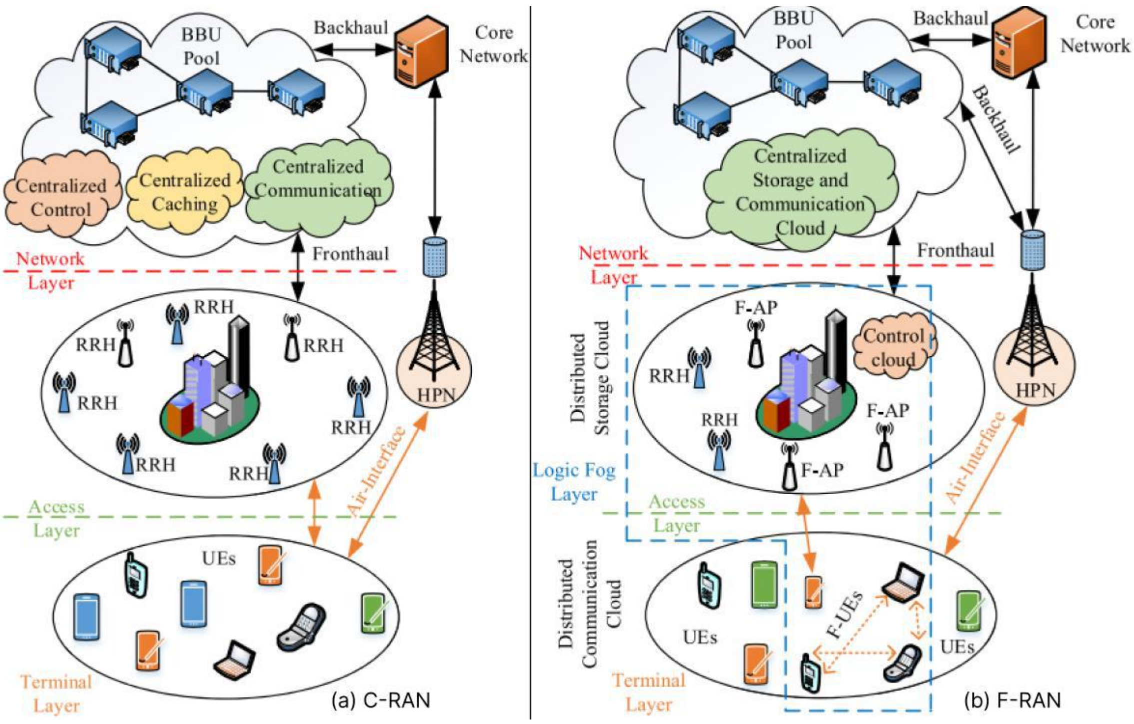

Figure 2-8 System Architecture in 5G mobile networks (adapted from [HNHS19]).

2.2 Radio Interface

In this section the important interface of 5G NR is addressed, being based on [ROSC16], [3GPP19a], [3GP22b], [Corr22] and [Enes20]. NR is the new radio air interface developed for 5G. NR compromises of different enabling technologies, which are shown in Figure 2.9, such as fundamental spectrum, multiple access schemes, coding, and modulation, among others.

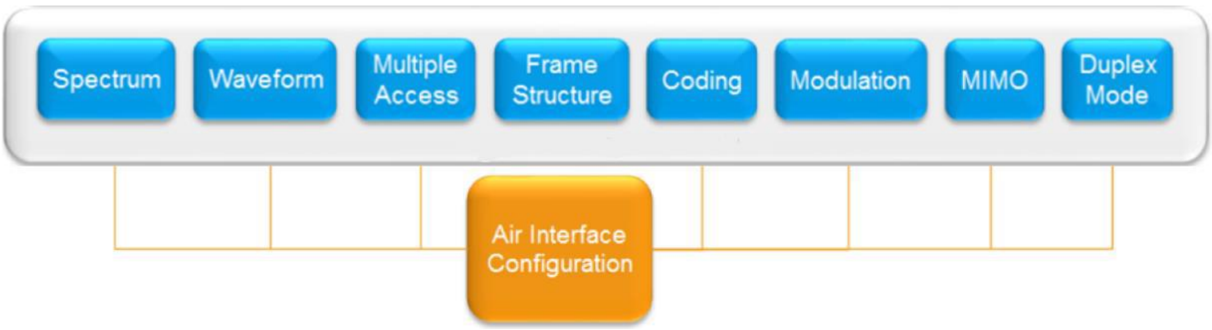

Figure 2-9 Radio Interface configuration of NR (adapted from [ROSC16]).

The 5G spectrum divides into two ranges, FR1, which beholds Sub-6 GHz frequencies, whereas FR2 defines bands in the mm wave spectrum, frequencies of 24 GHz and higher, as it is shown in Table 2.2.

Table 2-2 NR channel bandwidth (extracted from [3GPP19a])

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

Regarding the duplex scheme in 5G NR, concerning Uplink (UL) and Downlink (DL) data transmission, it supports Frequency Division Duplex (FDD) and Time Division Duplex (TDD). Table 2.3 represents the frequencies used in Portugal as well as the duplex scheme used for each band.

Table 2-3 NR bands used in Portugal (based on [Corr22]).

NR Band [MHZ]	Duplex scheme	Frequencies [MHz]		Total Bandwidth [MHz]
		Downlink	Uplink	
700	FDD	703-733	758 - 788	60
3 600	TDD	3 400 – 3 800		400

5G NR multiple access schemes consist of Orthogonal Frequency Division Multiple Access (OFDMA) for DL and Single-Carrier Frequency Division Multiple Access (SC-FDMA) for UL. This OFDM scheme has a flexible numerology, μ, that can be adapted to different scenarios and requirements and provides better spectral efficiency, since subcarriers have different bandwidths depending on the numerology. Table 2.4 show the relationship between the numerology, subcarrier spacing (SCS) and radio frame structure.

In Figure 2.10, the impact of numerology on Resource Block (RB) is shown. A resource block is a block of 12 subcarriers over which the transmission, of 14 OFDM symbols, is scheduled.

In terms of 5G NR adaptive modulation and coding, i.e., the number of useful bits that can be transmitted by a symbol, NR supports QPSK, 16 QAM, 64 QAM and 256 QAM as well as low-density parity-check coding (LDPC) when comes to codification.

5G NR also uses Multiple Input Multiple Output (MIMO), which results in transmission diversity, and spatial multiplexing and can also be complemented with beamforming. This results in less fading, a better signal-to-noise ratio and higher data rates. On the other hand, it also introduces interference.

Table 2-4 Supported Transmission Numerologies and Frame Structure (based on [Corr22]).

μ	**SCS = 2^{μ} x 15 [kHz]**	**Number of slots per frame (10 ms)**	**Number of slots per subframe (1 ms)**
0	15	10	1
1	30	20	2
2	60	40	4
3	120	80	8
4	240	160	16

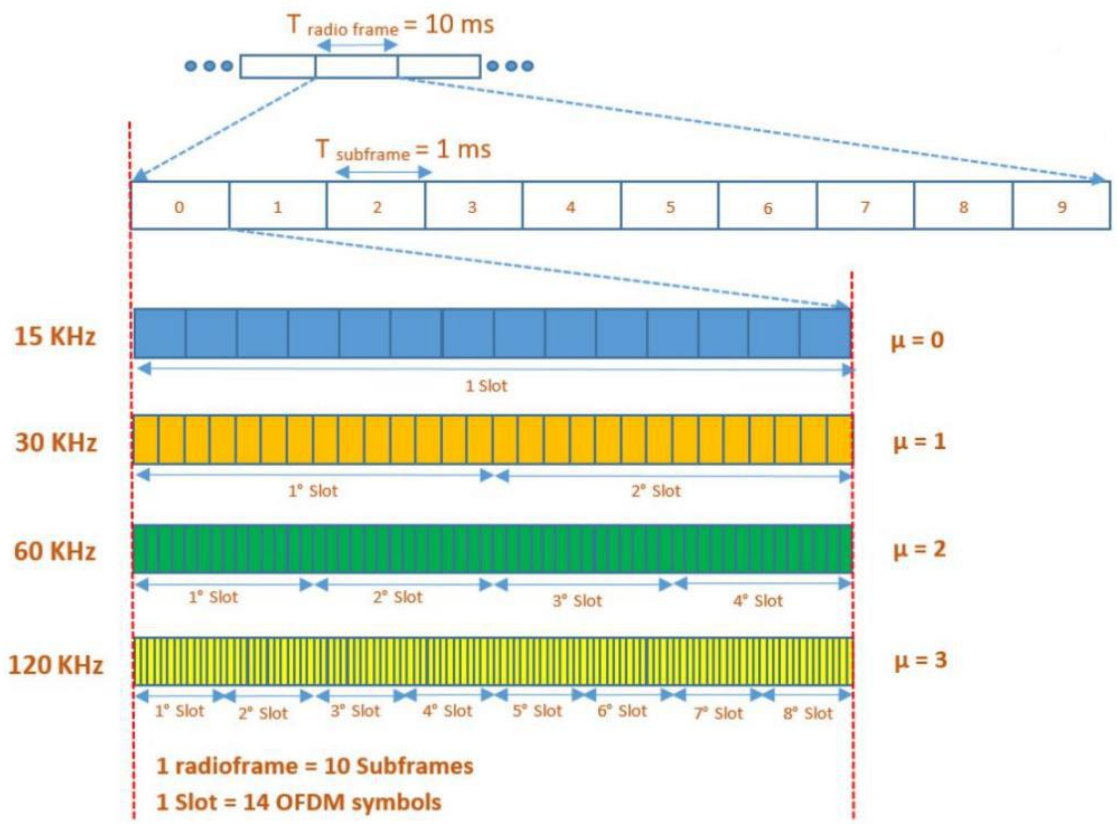

Figure 2-10 NR frame structure (extracted from [Corr22]).

The 5G NR beamforming, a core physical layer technology, resolves this issue, since it can improve system coverage performance and reliability by focusing the transmitted energy toward the intended user and also increasing system capacity through spatial multiplexing. That is, the digital beamforming transmits a superposition of signals, each with a separate directivity and power, allowing for greater flexibility. This is the solution used in the FR1 range where each antenna in the BS has a Radio Frequency (RF) chain circuit that does the amplification, attenuation, detections, filtration, and mixing.

2.3 Services and Applications Requirements

This section is based on [NRSA20], [TPUH16], and [EFSZ16]. The development of 5G follows the need for different service and application requirements in terms of capacity, latency, reliability, security or coverage. The main objective of this section is to analyse these requirements in the context of 5G use cases. In Table 2.5 typical use case requirements are shown and in Figure 2.11 the importance of key capabilities in each scenario is represented. These scenarios can be divided into three main types:

- **Enhanced Mobile Broadband (eMBB):** Requires high data rates, low latency and reliable broadband access over large coverage areas. Includes services such as Ultra High Definition, 3D, and augmented reality displays, among others.
- **Ultra-Reliable and Low-Latency Communications (URLLC):** Addresses the need for ultra-reliability and low-latency services, like industrial automation, remote medical surgery, or other information-critical applications.
- **Massive Machine Type Communication (MMTC):** Requires massive connectivity between devices that typically transmit small packets of information with low data rates (e.g., Smart Cities, Domotics and Smart Grid).

Table 2-5 Typical Use Cases Requirements (adapted from [PRGS18]).

Service type	Use Case	Latency [ms]	Data rate [Mbps]
eMBB	Virtual Reality	1	1000
eMBB	Education and Culture	5-10	1000
URLLC	Factory Automation	0.25-10	1
URLLC	Health Care	1	100
MMTC	Smart Grid	1-20	0.01-1.5

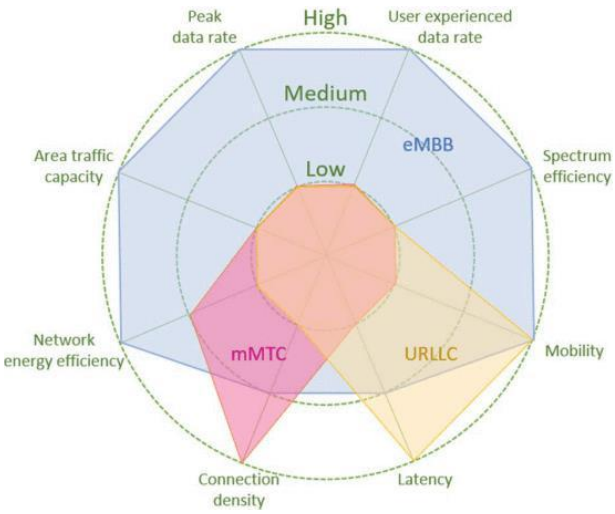

Figure 2-11 The importance of key capabilities in different usage scenarios (extracted from [NRSA20]).

These service categories can be divided into four different classes, regarding Quality of Service (QoS):

- **Conversation Class:** Characterised by real-time conversation services between end-users, it is the most delay-sensitive service due to real-time bidirectional data flow.
- **Streaming Class:** Real-time unidirectional data flow that can support a small delay variation since it is not limited to human sensory perception.
- **Interactive Class:** Distinguished by a request-response pattern of the end user, the round-trip delays are the most important attribute of this class.
- **Background Class:** A service class in which the applications run in the background, that is, the destination is not expecting the data within a certain time. Is the least delay sensitive however it is important that the data is delivered with a low error rate.

A simplified comparison between these services is seen in Table 2-6 and in Table 2-7, the specific service requirements are shown.

Table 2-6 Service Class Summary (extracted from [Corr22]).

Service Class	**Conversational**	**Streaming**	**Interactive**	**Background**
Real-time	Yes	Yes	No	No
Symmetric	Yes	No	No	No
Guaranteed rate	Yes	Yes	No	No
Delay	Minimum Fixed	Minimum Variable	Moderate Variable	High Variable
Buffer	No	Yes	Yes	Yes
Bursty	No	No	Yes	Yes
Example	Voice	Video-clip	www	email

Table 2-7 Requirements for 5G services satellite-based services (extracted from [3GPP23c] and [Carv21]).

	Interactive data	Voice	IoT	Video	Emergency texting
Data Rate DL [Mbps]	2	0.128	0.002	0.5	0.100
Data Rate UL [Mbps]	0.250	0.064	0.010	3	0.050
Max latency supported [ms]	50	100	400	150	100

2.4 Non-Terrestrial Networks

Based on [3GPP20], [3GPP21], [R&SC22], and [DKYB22], this section addresses Non-Terrestrial Networks (NTN). First, the overall analysis of various NTNs and some of their features, secondly, the focus being on Satellite-based NTNs.

NTNs are communication networks that operate outside the Earth's surface, that is, any network that involves non-terrestrial flying objects. The NTN family includes satellite communication networks, high-altitude platform systems (HAPS), and air-to-ground networks (e.g., drones and planes). They can act as access nodes to augment the performance of existing terrestrial networks in terms of capacity, coverage and delay, and can also address the shortfalls of terrestrial infrastructure implementations in remote or hard-to-reach areas.

Spaceborne platforms such as Low Earth Orbit (LEO), at altitudes ranging from 300-2 000 km, Medium Earth Orbit (MEO), at altitudes ranging from 7 000-20 000 km, and Geostationary Earth Orbit (GEO), at altitudes of 36 000 km satellites are being used by satellite communications networks. The demand for broadband services offered by LEO NTNs with large satellite constellations has surged (e.g., SpaceX, OneWeb, and LeoSat).

HAPS are airborne platforms, like aircraft and balloons, which are built to fly at great heights, around 20-50 km, and hover for extended periods of time. As they may not require a ground-based infrastructure, HAPS have the potential to operate relatively cheaply while being able to cover a large region.

Another technology to consider is Unmanned Aerial Vehicles (UAVs), also known as drones. They often operate remotely, automatically, or autonomously, and can be used as relay stations at low altitudes, around 0.1-0.4 km. The use of UAVs can extend the coverage of a 5G network to areas that would otherwise be difficult to reach (e.g., rural, or remote areas where building traditional infrastructure would not be cost-effective). Figure 2.12 shows the different non-terrestrial components and some scenarios where they can be applied.

In general, UAVs are used for short-range missions and have a very limited operational duration, on the other hand, HAPS and satellites are used for longer-range missions and have longer operational duration. As the operational altitude increases the round-trip propagation delay will increase as well. Additionally, the frequency of the signal can also have many implications for propagation delay and path loss. There are a variety of factors that affect path loss, such as the medium the signal propagates, atmospheric attenuation, rain attenuation, and more.

Basing on [Varr18], [DKYB22], [3GPP22c] and [3GPP23a]. Being more specific regarding satellites, satellites system architectures consist of three segments, space segment, ground segment and user segment. In terms of the satellite access network architecture, it consists of the following system elements:

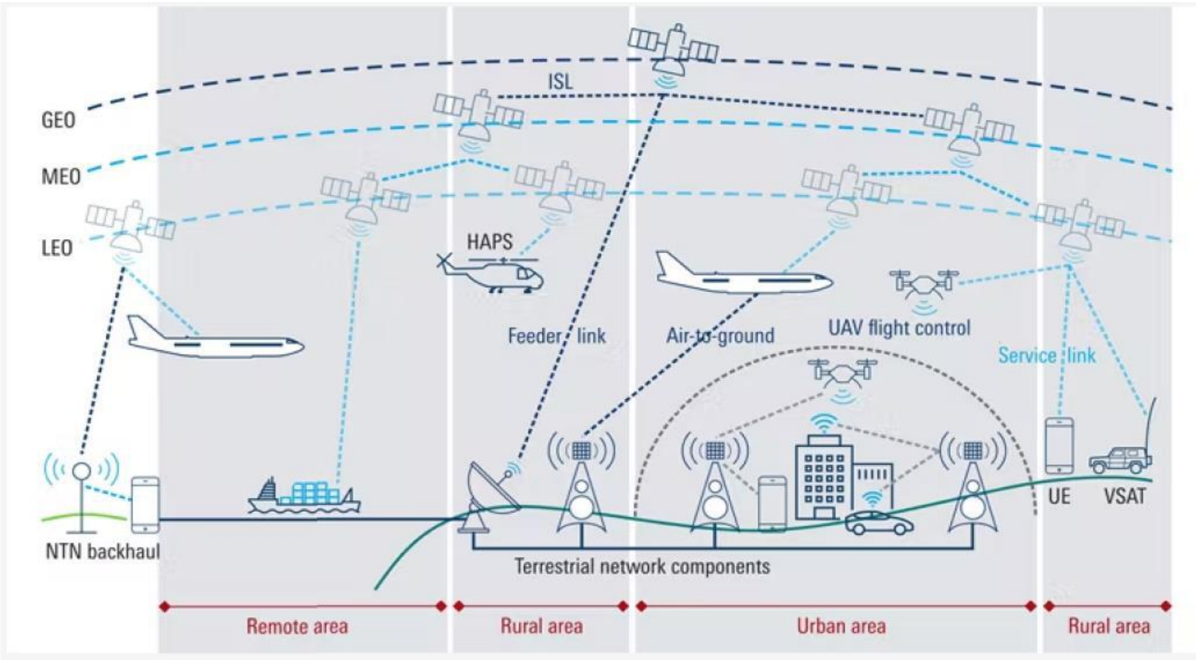

Figure 2-12 Different NTN and operable scenarios (extracted from [R&SC22]).

- **NTN Terminal:** UE or a specific terminal to the satellite network if the satellite does not directly serve UEs.
- **A service link**: Radio link between the UE and the space platform.
- **Configuration of space platform carrying a payload**:
    - **Transparent payload:** Performs Radio Frequency (RF) filtering, frequency conversion and amplification.
    - **Regenerative payload:** Carries out RF filtering, frequency conversion and amplification, as well as demodulation/decoding and other functions. It is equivalent to having the functions of a base station (e.g., evolve Node B (gNB)) on board.
- **Inter Satellite/Aerial links (ISL):** In case of regenerative payload. ISL represents the communication link between two or more satellites, allowing the share of information between satellites. Can operate in RF or an innovative technology regarding optical communications.
- **Gateways:** Connect the satellite to the 5G core network.
- **Feeder links:** Radio links between the Gateways and the NTN platforms.

A summary of the key features and their corresponding advantages and disadvantages for each satellite orbit type is provided in Table 2.8.

The uses cases foreseen for NTN services can be divided in three main categories; Figure 2.13 shows the different use cases:

- **Service Continuity:** Cases where 5G services cannot be provided over terrestrial networks (TNs) alone, how the combination of terrestrial and non-terrestrial networks can provide continuous access to services in such cases (e.g., maritime, or airborne platforms).

- **Service Ubiquity:** Use cases address potential users wishing to access 5G services in unserved or under-served areas, where TNs might not be available (e.g., agriculture and emergency networks).
- **Service Scalability:** Use cases that leverage the capabilities of satellites covering a large area, potentially directly to UEs, and use broadcasting similar content over a large area (e.g., Ultra High-Definition TV).

Table 2-8 Comparison of distinctive features of NTNs (adapted from [3GPP23a]).

Parameters	LEO	MEO	GEO
Operational altitude [km]	600 – 1 200	7 000 – 20 000	35 786
Cost	High	Moderate to High	Very High
Max propagation delay (UE to satellite) [ms]	15	43	140
Minimum constellation size (to cover Earth)	80	10	3
Lifespan [years]	5-10	7-15	15-20
Beam diameter [km]	50 - 500	100 – 500	200 – 2 000
Mobility	Fastest	Fast	Stationary

While traditionally cellular (TN) and satellite (NTN) frequencies have been distinct, future scenarios will require effective frequency-sharing mechanisms to manage potential interference.

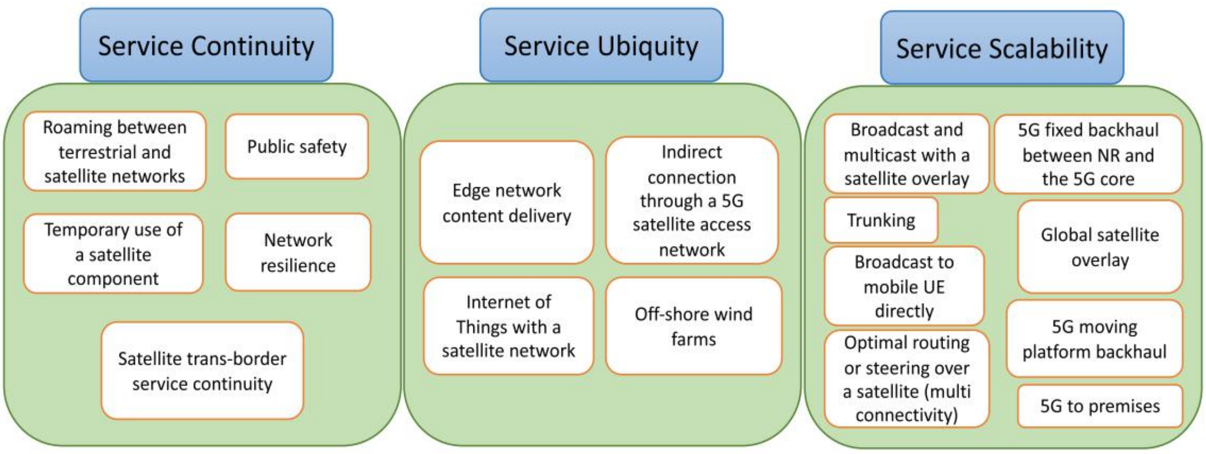

Figure 2-13 The three categories of satellite access use cases in 5G (extracted from [DKYB22]).

According to [ESAS09] the satellite frequency used consists of the bands shown in Figure 2.14, even higher frequencies than 40 GHz are being discussed nowadays since there is an increase in the demand for bandwidth. Each band has its characteristics and uses:

- **L-band:** Used for various satellite communication applications, including voice, data, and video transmission.
- **S-band:** For satellite communication systems that operate at shorter distances, such as satellite-based navigation and weather forecasting.
- **C-band:** Has a wide range of satellite communication applications, including television and radio broadcasting, telephony, and data transmission.
- **Ku-band:** For systems that operate at higher frequencies, used for high-bandwidth applications.
- **K-band:** Usually used for military purposes. At 22 GHz due to the water vapour absorption line, this band has increased atmospheric attenuation.
- **Ka-band:** Used for high-bandwidth applications, however, is more susceptible to attenuation from weather conditions, as frequency increases.

Higher frequency bands, or shorter wavelengths, are significant because they make it possible to build phased array antennas, which are composed of a computer-controlled array that produces a beam of radio waves that is electronically guided to a particular point, making the antenna adaptable, and offers an equivalent isotropic power that makes up for the propagation loss at higher frequencies, while planar antennas have fixed radiation patterns. Lower frequency bands, on the other hand, propagate farther since they experience less attenuation.

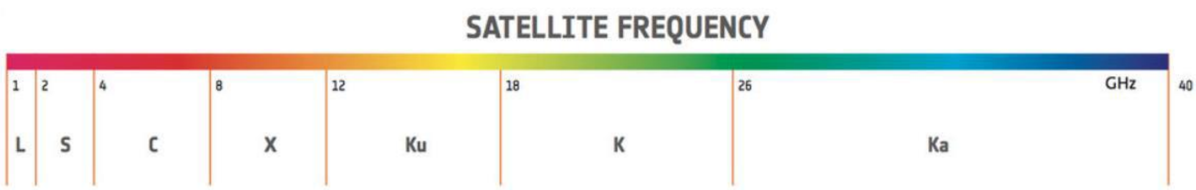

Figure 2-14 Satellite Frequency bands (extracted from [ESAS09]).

An important aspect of the radio interface of Satellites is that MIMO is more efficient when implemented using FDD instead of TDD, regarding latency, interference management and spectral efficiency since there are separate uplink and downlink range of frequencies and is particularly useful when leading with interference. The frequency bands first used and analysed in FR1, to begin with, are listed in Table 2.9.

Other topics are the effects of the elevation angle and the Doppler on propagation delay and loss. With respect to elevation angle, it is consistently argued that a satellite pointed directly downward offers significant advantages, especially in terms of path length and Line-of-Sight (LoS). On the other hand, for non-geostationary satellites, due to the relative motion on the receiver and/or transmitter side, the signals are received at different frequencies which is called Doppler shift, and it has to be compensated by advanced signal processing techniques.

Table 2-9 NTN satellite bands in FR1 (extracted from [3GPP22c]).

NTN Satellite Operating bang	Frequencies [MHz]		Duplex mode
	Uplink	Downlink	
s1 (S band) (n256)	1980 - 2010	2170 - 2200	FDD
s2 (L band)(n255)	1626.5 – 1660.5	1525 - 1559	FDD

One principal issue of the integration of NTN into the 5G systems is how to deal with mobility aspects like handover in connected mode or cell reselection in idle mode. In Figure 2.15 some mobility procedures that can be considered are shown.

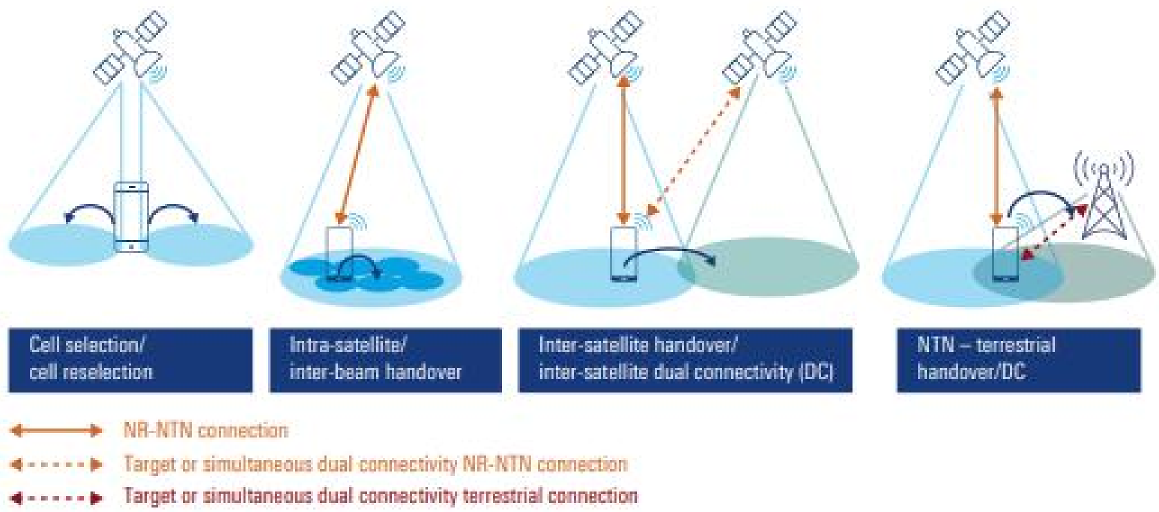

Figure 2-15 NTN mobility scenarios (extracted from [R&SC22]).

Satellite Architectures play a crucial role in enabling different services, therefore the choice of architecture is key when integrating satellite systems with 5G networks, to provide enhanced coverage, capacity, and overall quality of service for 5G. Figure 2-16 illustrates various scenarios for implementation for direct access, where the satellite segment is highlighted in green, complemented by [3GPP23b] and [LQRZ23].

The architectures that will be analysed are as follows:

- **Option S-gNB:** There is a direct access between the UE and the RAN via a transparent satellite.
- **Option S-DU/CU:** The RAN is split into two parts, the Distributed Unit (DU) on-board of the satellite and the Central Unit (CU) on the ground. This has the advantage of processing some functions in the satellite, resulting in benefits for the link budget and others in the ground station allowing a better resource management. One CU can be connected to DU on-board of different satellites.

- **Option S-Core:** In this option the whole gNB is on-board, increasing the complexity for the satellite payload, although it can also support more complex tasks as well.
- **Option S-Edge:** Part of the 5GC is also on-board of the satellite, this edge node enables even more low latency services that are crucial for satellite communications.
- **Option S-DN:** In this architecture the whole RAN and 5GC is incorporated in the satellite, with functions of 5GC these last two options can perform many more tasks and improve flexibility and coverage.
- **Option R-Sat:** There is a terrestrial gNB working as a relay node, therefore UE requires no adaptation. It works similarly as option A, where this time the signal comes from BS directly.

Regarding the integration of satellites into the backhaul, there is no adaptation required from the UE since the air interface between the UE and the BS is a ground station. This integration can highly impact the performance due to latency issues.

- **Option gNB-Core:** Makes the connection between the RAN and the 5GC, this architecture can introduce a lot of latency therefore it should be used as an emergency link or if there is no terrestrial connection in-between the RAN and the 5GC.
- **Option Core-DN:** Direct backhauling of a full standalone 5G network, simplest integration mechanism, can be helpful solving coverage issues.

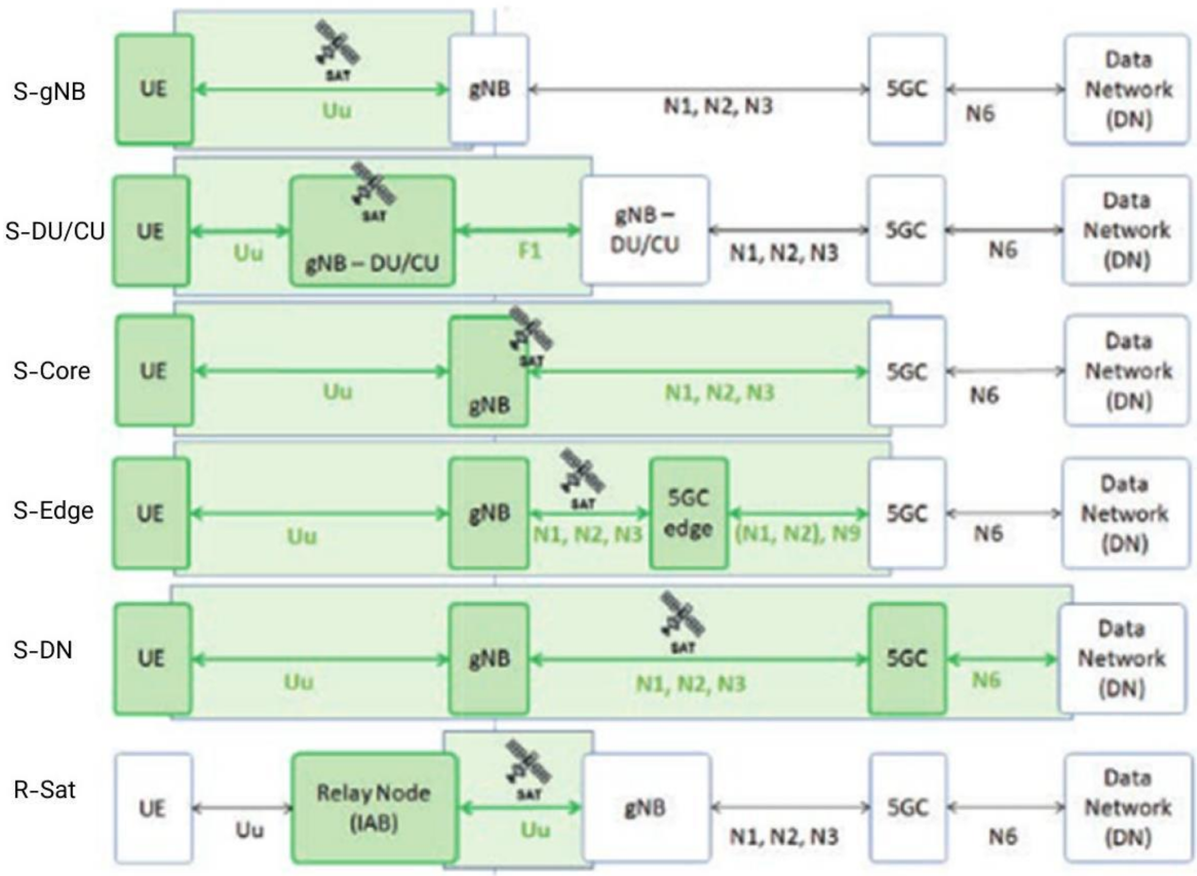

Figure 2-16 Possible Scenarios for direct access (extracted from [LQRZ23]).

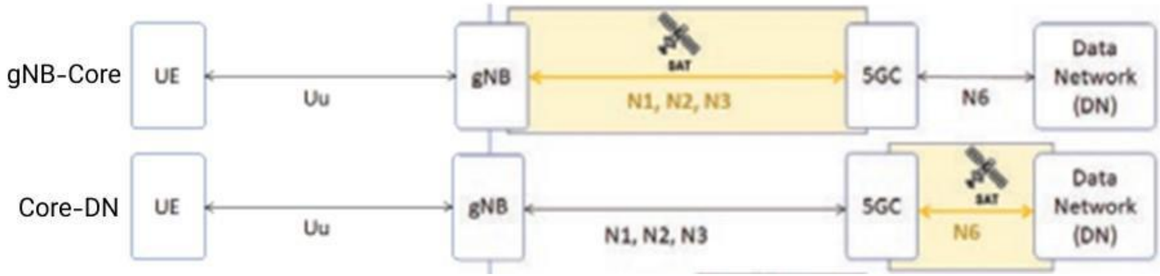

Figure 2-17 Possible Scenarios for backhaul access (extracted from [LQRZ23]).

2.5 State-of-the-Art

In this subsection, a view of recent and relevant research regarding the topic of the thesis is presented.

The main focus being a satellite-based network, there is a limitation on the possibilities that a satellite can bring. Space Operators came up with a significant development regarding this topic, more precisely, LEO mega-constellations shown in Figure 2.18, which consists of numerous satellites working together to provide a variety of services, in particular high-capacity, low-latency, and global coverage. Some network launching services are Starlink and OneWeb, [Hera21], and [R&SC22].

Figure 2-18 LEO mega constellation (extracted from [Hera21]).

Starlink is a satellite network that provides broadband internet access where it is not possible to install traditional wired infrastructure, such as fibre optic cables. So far it has deployed more than 1 500 satellites, and in the long term, up to 30 000 satellites are to be expected. The satellites are deployed in several orbital planes at altitudes varying from 540 – 1 300 km and use laser communication in the inter-satellite link. The User-Satellite communication uses Ku-band and achieves data throughputs up to

330 Mbps for an individual user, roughly 16 Gbps capacity per satellite with latency values of 31 ms. Ground-Satellite communication uses Ku-band for downlink and Ka-band for uplink. It uses phased-array technology for both the satellite and the UE to allow more easily handovers between different satellites.

Relatively to OneWeb, it follows the same plan as Starlink, but instead uses an altitude of about 1 200 km, resulting in more attenuation since the distance is greater. It has an estimation of being deployed 6 372 satellites eventually.

One CubeSat is a nanosatellite that is built to a standard size and form factor, measuring 10 by 10 by 10 cm^3. However, numerous CubeSats may be bolted together or may even dock together in orbit. One of the main advantages of CubeSats is their small size and low cost, making them an attractive option for a variety of users, and can also be used for a wide range of applications, such as Earth observation, space exploration, remote sensing, and telecommunications. Due to their low cost, they have also been used to test new systems, materials, and other technologies. This nanosatellite is well versatile and affordable, [PoGo17] and [Varr18].

These days there has been a lot of research, [ChYa21], if the ISL signal should be Free Space Optics (FSO) link instead of an RF, and they concluded that the benefits of an FSO link heavily outweigh the RF link. FSO has a much higher bandwidth, and small wavelength resulting in a smaller antenna size and high directivity. Also has fewer restrictions regarding spectrum allocation since it uses an unlicensed frequency range. The major drawback is that it deals very poorly with obstructions in the path and solar radiation.

In [CSMa17], the authors follow a deterministic approach to analyse problems regarding coverage area, capacity and inter-cell interference of base stations mounted on UAVs, by changing the threshold of received power, with this an optimal altitude and power consumption model for an aerial base station are also achieved. The results show that the maximum cell coverage increases with a lesser received power threshold at the edge of the cell. It is important to note that if the transmitted power increases the coverage also expands. Generally, if the received power threshold increases the capacity decreases and if the transmitted power increases the capacity increases as well. However, regarding the capacity analysis above a certain receiver threshold, for Urban scenarios, the percentage of receivers having capacity above the threshold does not change with respect to the height, while for Suburban scenarios if the receiver threshold increases the capacity decreases, it might be due to different fading environments.

Regarding non-terrestrial integrated networks, [ZZYA17], introduced the idea of space-air-ground integrated moving cells, which consist of the installation of BSs on non-terrestrial components. This solution can provide the required capacity extension by the increase of densification. This leads to several problems such as network management and interoperability.

Other work of [ZFZC18] might help with the previous problem of [ZZYA17], by utilising SDN, which can enable centralised network management and flexible resource use, however, it must be assessed if the scalability of the framework is practical in the network.

[ZJKG19] and [KCJZ17] proposed a cloud-based integrated terrestrial-satellite network architecture, where both satellite and terrestrial BSs are linked to a centralised baseband processing system. This enables cooperative transmission, resource management, and interference reduction. Although the system presumes that users have dual-mode terminals.

Due to the recent development of LEO satellites, space information networks [YMYZ16] recover focus. The space information networks are made of heterogeneous space network nodes such as satellites and HAPS. It can be divided into various layers, where each layer has an access and backbone network. Gateways and network nodes make up the backbone network and are connected to each other by laser links. Where access network enables users to access the space information network by microwave links. For the transfer of information to ground stations, the use of feeder links brings strong processing capability, and to overcome the limited resources in the space-based layer, the combination of a space-air layer is necessary.

Chapter 3

Models and Simulator Description

This chapter focuses on the development of the model and its main methodologies. Firstly, an overview of the model, service and constraints and its requirements. Secondly, a dimension process of the latency, coverage, and capacity models and how it is made its implementation, and finally, at the end of the chapter, a theoretical model assessment.

3.1 Model Overview and Requirements for Satellite Networks

One of the objectives of this thesis is to create a model that can simulate distinctive characteristics depending on the final goal, this section providing a description of the models.

The overview of this process consists of analysing the necessary input parameters to satisfy the requirements needed to provide a specific service with enough quality of service. This process both accomplishes this goal as well as optimise different parameters for the network in terms of cost and efficiency of resources.

The model can be divided into three planes: coverage, capacity, and latency planning. For each plane, the input parameters are of the utmost importance therefore the choice of the parameters will heavy influence the model. In Figure 3-1 a generic execution of the model is shown where the coverage planning consists in calculating the maximum coverage radius that the BS can link with the UE, determining the coverage area.

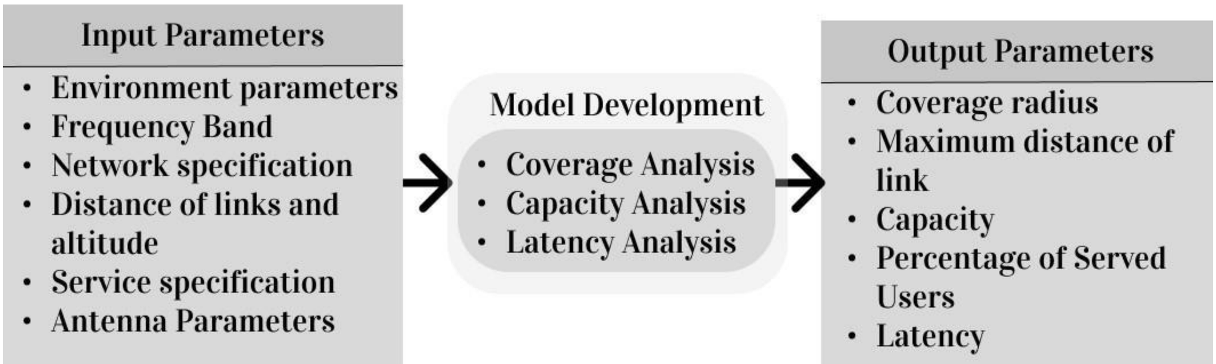

Figure 3-1 Model Configuration.

The capacity planning and latency, consists of determining the possibility of serving the desired services with the minimum requirements, for this the specific analysis of the latency and capacity is particularly important.

The input parameters of the dimensioning process are given by the user, scenario, and network. All inputs are correlated to each other, therefore, one parameter can impact the whole model.

Regarding the requirements and descriptions for some of the most important services that satellites can complement. In Table 3-1 some generic constraints regarding satellites in terms of distance and latency for the different type of satellite are shown. Table 3.2 presents the required data rate, latency, while also providing information about the overall scenario requirements.

Table 3-1 Constraints about different satellite architectures [3GPP23c].

Path		LEO		MEO	GEO	
		Regenerative Satellite	Transparent Satellite	Regenerative Satellite	Regenerative Satellite	Transparent Satellite
Distance Satellite-UE [km]	10º	1 932		14 018	40 586	
	90º	600		10 000	35 786	
Maximum latency one-way 10º [ms]		6	47	47	135	541
Minimum latency one-way 90º [ms]		2	33	33	120	477

Table 3-2 Requirements for 5G services satellite-based (adapted from [3GPP23c] and [Carv21]).

	Interactive data	Voice	IoT	Video Surveillance	Emergency texting
Data Rate DL [Mbps]	1	0.128	0.002	0.5	0.100
Data Rate UL [Mbps]	0.100	0.064	0.010	3	0.050
Max latency supported [ms]	50	100	400	150	100
Packet Size [Bytes]	1 000	218	300	800	170
Overall user density [per km²]	100	10	400	10	10
Activity factor [%]	1.5	20	1	20	1
UE-type	handheld	handheld	IoT	handheld	handheld
Reliability [%]	99.9	99.9	99.5	99.5	99.99
Availability [%]	99.99	99.99	99.99	99.90	99.99

In the case of a generic architecture overview of the satellite system, represented in Figure 3-2, where a simple architecture consisting of a Satellite connecting a UE to the gNB, the gNB connects via the NG (Next Generation) interface to the 5GC and in the end 5GC connects to the DN.

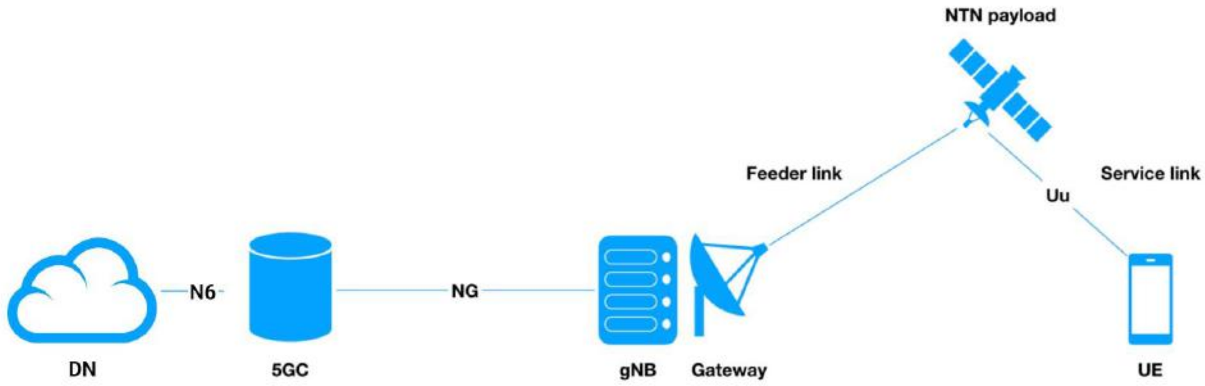

Figure 3-2 Satellite Architecture (adapted from [LREY21])

With both Table 3-1, Table 3-2, and Figure 3-2, it is possible to infer important information regarding each service operational requirements, and with this analyse the service and conditions of the network.

3.2 Dimensioning Process

3.2.1 Network Latency

In a network, there are 4 four sources of latency contributions: propagation, transmission, queuing, and processing. Processing and queuing latencies happen within the nodes, the transmission latency occurs from the node to the link, whereas the propagation latency occurs in the link. This subsection is mainly based on [Carv21].

Regarding the propagation latency, the signal goes through a link, the link will be assumed free space. The general expression is given by:

$$\delta_{Prop\ [\mathrm{s}]} = \frac{d_{[\mathrm{m}]}}{v_{[\mathrm{m/s}]}} \tag{3.1}$$

where:

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

The transmission latency is the time it takes for a signal to transmit the bits into a link, it depends on the data rate and the amount of data that needs to be transmitted, and can be given by:

$$\delta_{Trans}\,[\mathrm{ms}] = \frac{8\,D_{serv}\,[\mathrm{Bytes}]}{R_{[\mathrm{Gbits/s}]}} 10^{-6} \tag{3.2}$$

where:

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

In Figure 3-3 and 3-4, the different architectures and delays accumulated in the network nodes are represented, whereas the equations of the delays are represented below:

$$\delta_{UE\_TX}\,[\mathrm{ms}] = \delta_{UE\_Proc}\,[\mathrm{ms}] + \delta_{UE\_Trans}\,[\mathrm{ms}] \tag{3.3}$$

$$\delta_{UE\_RX}\,[\mathrm{ms}] = \delta_{UE\_Proc}\,[\mathrm{ms}] \tag{3.4}$$

$$\delta_{DU\_TX}\,[\mathrm{ms}] = \delta_{DU\_RX}\,[\mathrm{ms}] = \delta_{DU\_Proc}\,[\mathrm{ms}] + \delta_{DU\_Queue}\,[\mathrm{ms}] + \delta_{DU\_Trans}\,[\mathrm{ms}] \tag{3.5}$$

$$\delta_{CU\_TX}\,[\mathrm{ms}] = \delta_{CU\_RX}\,[\mathrm{ms}] = \delta_{CU\_Proc}\,[\mathrm{ms}] + \delta_{CU\_Queue}\,[\mathrm{ms}] + \delta_{CU\_Trans}\,[\mathrm{ms}] \tag{3.6}$$

$$\delta_{5GC\_Tx}\,[\mathrm{ms}] = \delta_{5GC\_RX}\,[\mathrm{ms}] = \delta_{5GC\_Proc}\,[\mathrm{ms}] + \delta_{5GC\_Trans}\,[\mathrm{ms}] \tag{3.7}$$

$$\delta_{DN}\,[\mathrm{ms}] = \delta_{DN\_Proc}\,[\mathrm{ms}] + \delta_{DN\_Trans}\,[\mathrm{ms}] \tag{3.8}$$

$$\delta_{Edge}\,[\mathrm{ms}] = \delta_{Edge\_Proc}\,[\mathrm{ms}] + \delta_{Edge\_Trans}\,[\mathrm{ms}] \tag{3.9}$$

$$\delta_{SAT\_TX}\,[\mathrm{ms}] = \delta_{SAT\_RX}\,[\mathrm{ms}] = \delta_{SAT\_Trans}\,[\mathrm{ms}] \tag{3.10}$$

$$\delta_{gNB\_TX}\,[\mathrm{ms}] = \delta_{gNB\_RX}\,[\mathrm{ms}] = \delta_{gNB\_Proc}\,[\mathrm{ms}] + \delta_{gNB\_Queue}\,[\mathrm{ms}] + \delta_{gNB\_Trans}\,[\mathrm{ms}] \tag{3.11}$$

$$\delta_{gNB-Edge\_TX}\,[\mathrm{ms}] = \delta_{gNB-Edge\_RX}\,[\mathrm{ms}] = \delta_{gNB\_Proc}\,[\mathrm{ms}] + \delta_{gNB\_Queue}\,[\mathrm{ms}] + \delta_{Edge\_Proc}\,[\mathrm{ms}] + \delta_{gNB-Edge\_Trans}\,[\mathrm{ms}] \tag{3.12}$$

$$\delta_{gNB-5GC\_TX}\,[\mathrm{ms}] = \delta_{gNB-5GC\_RX}\,[\mathrm{ms}] = \delta_{gNB\_Proc}\,[\mathrm{ms}] + \delta_{gNB\_Queue}\,[\mathrm{ms}] + \delta_{5GC\_Proc}\,[\mathrm{ms}] + \delta_{gNB-5GC\_Trans}\,[\mathrm{ms}] \tag{3.13}$$

where:

- $\delta_{UE/DU/CU/5GC/SAT/gNB/gNB-Edge/gNB-5GC\_TX}$: Accumulated latency on the transmitter side.
- $\delta_{UE/DU/CU/5GC/SAT/gNB/gNB-Edge/\,gNB-5GC\_RX}$: Accumulated latency on the receiver side.
- $\delta_{UE/DU/CU/5GC/DN/Edge/gNB\_Proc}$: Processing latency.
- $\delta_{DU/CU/gNB\_Queue}$: Queuing latency.

The processing latency refers to the time it takes for data to be handled, like routing it, checking for errors, or encrypting it. For the calculation of this delay in the UE it should be considered the processing delay ratio using the Table 3.2.

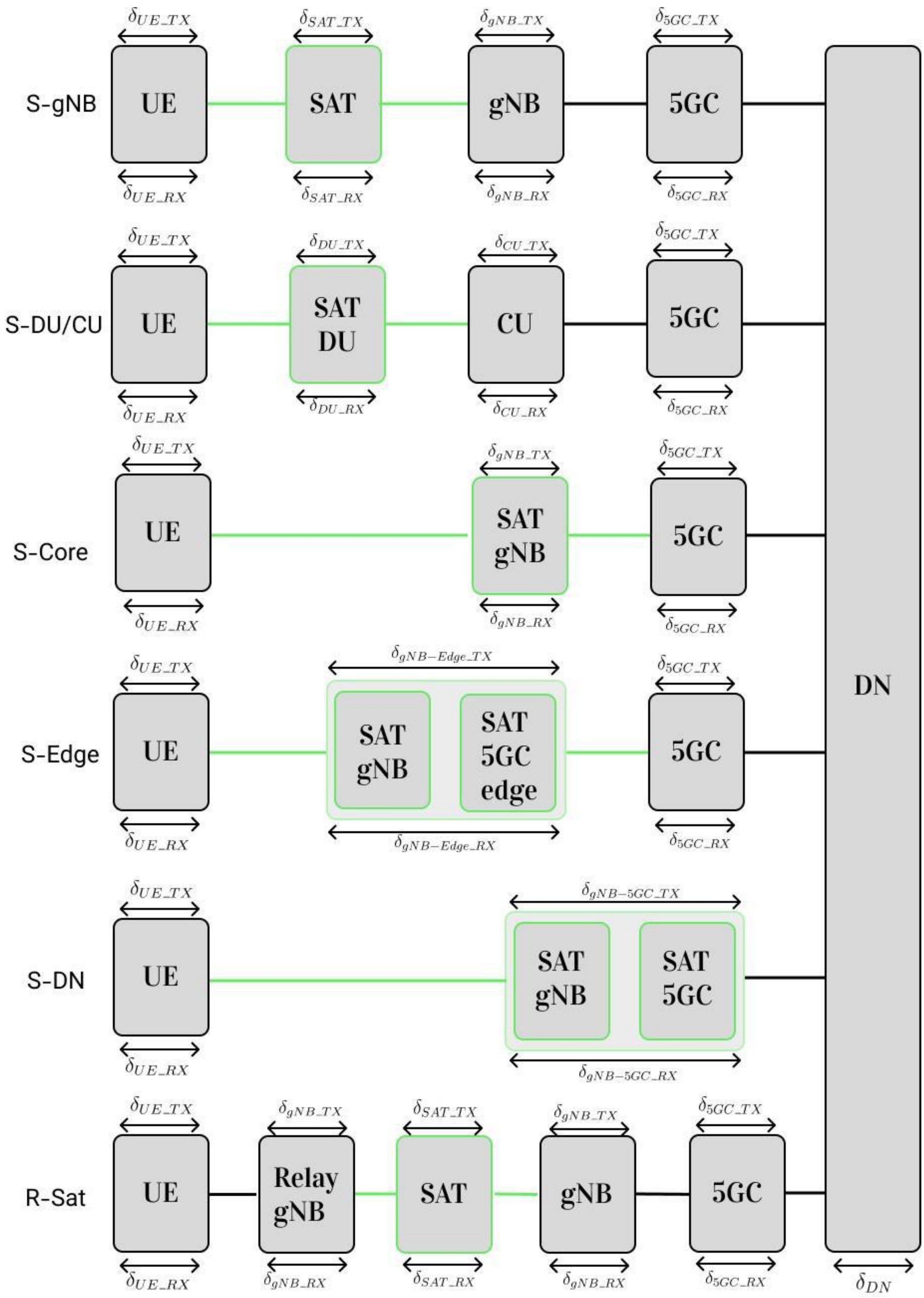

Figure 3-3 Different architectures for direct access with the delays imposed in the nodes (adapted from [LQRZ23] and [Carv21]).

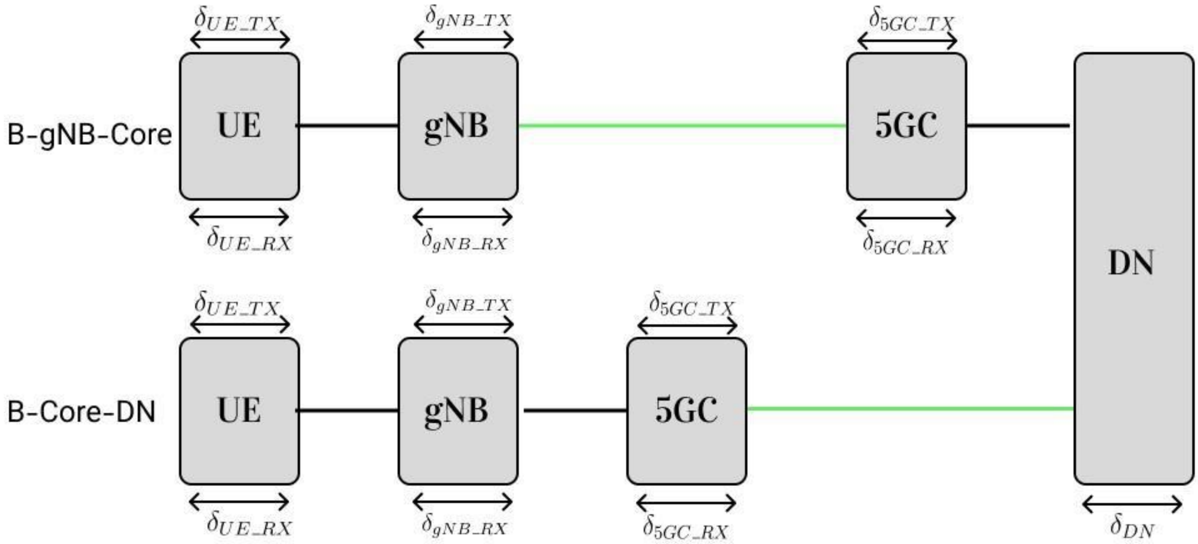

Figure 3-4 Different architectures for backhaul access with the delays imposed in the nodes (adapted from [LQRZ23] and [Carv21])).

Table 3-3 5G UE Processing Delay Ratio (adapted from [Carv21]).

Subcarrier Spacing (kHz)	15	30	60
ρ_{UE}	$\frac{2}{14}$		$\frac{3}{14}$

The processing delay in the UE is given by:

$$\delta_{UE\_Proc\,[\text{ms}]} = \delta_{UE\_Trans\,[\text{ms}]}\rho_{UE} \tag{3.13}$$

The processing delay in the distributed unit (DU) and centralised unit (CU) is given by:

$$\delta_{DU\_Proc\,[\text{ms}]} = \delta_{DU\_Trans\,[\text{ms}]}\rho_{DU} \tag{3.14}$$

$$\delta_{CU\_Proc\,[\text{ms}]} = \delta_{CU\_Trans\,[\text{ms}]}\rho_{CU} \tag{3.15}$$

$$\delta_{gNB\_Proc\,[\text{ms}]} = (\delta_{gNB\_Trans\,[\text{ms}]}) \cdot 9 \tag{3.16}$$

where:

- ρ_{DU}: Ratio of functionalities assigned to the DU (will take the value 7).
- ρ_{CU} : Ratio of functionalities assigned to the CU(will take the value 2).

The processing delay in the Core is given by:

$$\delta_{5GC\_Proc\,[\text{ms}]} = \frac{4}{2385} D_{[\text{Bytes}]} + \frac{469}{477} \tag{3.17}$$

To determine the Edge node and the DN processing delay, it is considered that the processing latency of the Edge node assumes a single functionality, and can be calculated by:

$$\delta_{Edge\_Proc\,[\text{ms}]} = (4 \cdot 10^{-5}) \cdot D_{[\text{Bytes}]} \tag{3.18}$$

$$\delta_{DN\_Proc\,[\text{ms}]} = (1.33 \cdot 10^{-5}) D_{[\text{Bytes}]} \tag{3.19}$$

The amount of time, data packets must wait before being processed is known as the queuing delay. This process can delay and influence the network performance by increasing latency, decreasing throughput and the occurrence of packet loss. An increase in queueing time may be caused by the size of the buffer and the complexity of the operation. This delay can be calculated by:

$$\delta_{Queue\,[\text{ms}]} = 10^3 \sum_{p=1}^{N_P} \frac{8D_{serv\,[\text{Bytes}]}}{R_{\max[\text{bps}]}} \tag{3.20}$$

where:

- D_{serv} : Packet size in bytes for a specific service.
- R_{max}: Maximum throughput offered by the link.
- N_P: Number of users connected to the node.

For the different scenarios of satellite architecture latency will highly vary, therefore depending on which scenario is used; the latency must be analysed, therefore the total node latency and total propagation delay regarding each type of scenario will be described. To take into account that the nodes and links in green are satellite dependent features, and the propagation delay link will be represented as δ_{X_Y}, where X is the origin and Y the destination.

For architecture option S-gNB, Figure 3.5, the total node latency and total propagation delay is described by (3.21) and (3.22), respectively:

$$\delta_{Total\_node\,[\text{ms}]} = \delta_{UE\_TX\,[\text{ms}]} + \delta_{SAT\_TX\,[\text{ms}]} + \delta_{gNB\_TX\,[\text{ms}]} + \delta_{5GC\_TX\,[\text{ms}]} + \delta_{DN\,[\text{ms}]} + \delta_{5GC\_RX\,[\text{ms}]} + \delta_{gNB\_RX\,[\text{ms}]} + \delta_{SAT\_RX\,[\text{ms}]} + \delta_{UE\_RX\,[\text{ms}]} \tag{3.21}$$

$$\delta_{Prop\,[\text{ms}]} = \delta_{UE\_SAT\,[\text{ms}]} + \delta_{SAT\_gNB\,[\text{ms}]} + \delta_{gNB\_5GC\,[\text{ms}]} + \delta_{5GC\_DN\,[\text{ms}]} + \delta_{UE\_SAT\,[\text{ms}]} + \delta_{SAT\_gNB\,[\text{ms}]} + \delta_{gNB\_5GC\,[\text{ms}]} + \delta_{5GC\_DN\,[\text{ms}]} \tag{3.22}$$

For architecture option S-DU/CU, Figure 3.6, the total node latency, and total propagation delay is described by:

$$\delta_{Total\_node\,[\text{ms}]} = \delta_{UE\_TX\,[\text{ms}]} + \delta_{DU\_TX\,[\text{ms}]} + \delta_{CU\_TX\,[\text{ms}]} + \delta_{5GC\_TX\,[\text{ms}]} + \delta_{DN[\text{ms}]} + \delta_{5GC\_RX\,[\text{ms}]} + \delta_{CU\_RX\,[\text{ms}]} + \delta_{DU\_RX\,[\text{ms}]} + \delta_{UE\_RX\,[\text{ms}]} \tag{3.23}$$

$$\delta_{Prop\,[\text{ms}]} = \delta_{UE\_DU\,[\text{ms}]} + \delta_{DU\_CU\,[\text{ms}]} + \delta_{CU\_5GC\,[\text{ms}]} + \delta_{5GC\_DN\,[\text{ms}]} + \delta_{UE\_DU\,[\text{ms}]} + \delta_{DU\_CU\,[\text{ms}]} + \delta_{CU\_5GC\,[\text{ms}]} + \delta_{5GC\_DN\,[\text{ms}]} \tag{3.24}$$

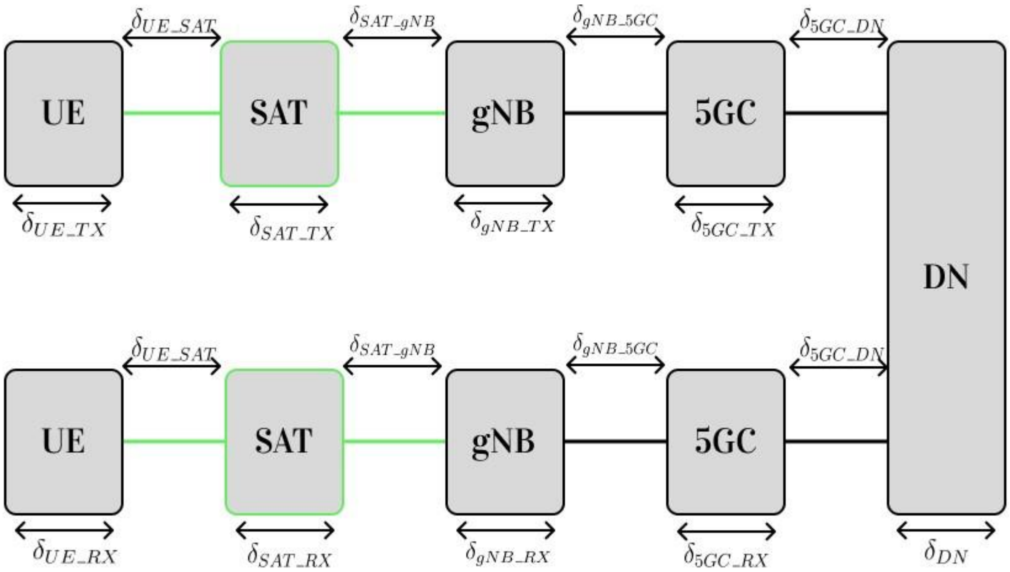

Figure 3-5 Latency contributions in scenario option S-gNB.

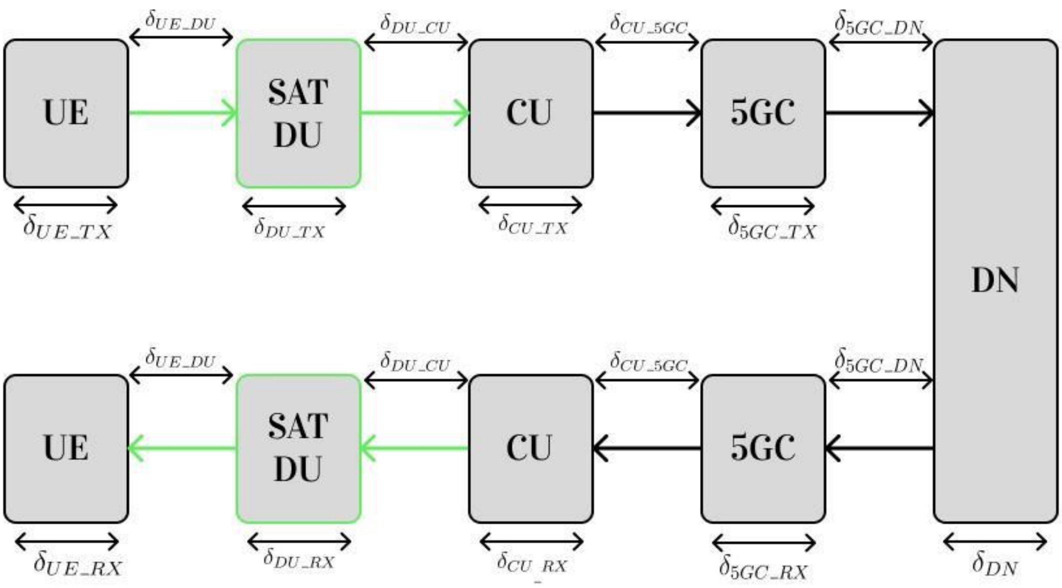

Figure 3-6 Latency contributions in scenario option S-DU/CU.

For architecture option S-Core, Figure 3.7, the total latency regarding node and propagation is described by:

$$\delta_{Total\_node}\ [\mathrm{ms}] = \delta_{UE\_TX}\,[\mathrm{ms}] + \delta_{gNB\_TX}\,[\mathrm{ms}] + \delta_{5GC\_TX}\,[\mathrm{ms}] + \delta_{DN}\,[\mathrm{ms}] + \delta_{5GC\_RX}\,[\mathrm{ms}] + \delta_{gNB\_RX}\,[\mathrm{ms}] + \delta_{UE\_RX}\,[\mathrm{ms}] \quad (3.25)$$

$$\delta_{Prop}\ [\mathrm{ms}] = \delta_{UE\_gNB}\,[\mathrm{ms}] + \delta_{gNB\_5GC}\,[\mathrm{ms}] + \delta_{5GC\_DN}\,[\mathrm{ms}] + \delta_{UE\_gNB}\,[\mathrm{ms}] + \delta_{gNB\_5GC}\,[\mathrm{ms}] + \delta_{5GC\_DN}\,[\mathrm{ms}] \quad (3.26)$$

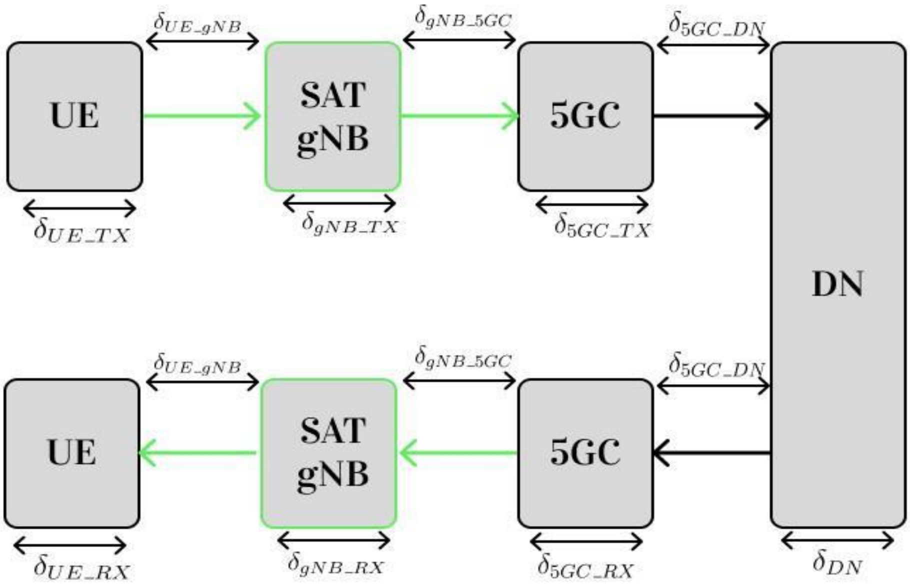

Figure 3-7 Latency contributions in scenario option S-Core.

The total node latency and total propagation delay of architecture option S-Edge, Figure 3.8, is described by:

$$\delta_{Total\_node}\ [\mathrm{ms}] = \delta_{UE\_TX}\,[\mathrm{ms}] + \delta_{gNB-Edge\_TX}\,[\mathrm{ms}] + \delta_{gNB-Edge\_RX}\,[\mathrm{ms}] + \delta_{UE\_RX}\,[\mathrm{ms}] \tag{3.27}$$

$$\delta_{Prop}\ [\mathrm{ms}] = \delta_{UE\_gNB-Edge}\,[\mathrm{ms}] + \delta_{gNB-Edge\_5GC}\,[\mathrm{ms}] + \delta_{5GC\_DN}\,[\mathrm{ms}] + \delta_{UE\_gNB-Edge}\,[\mathrm{ms}] + \delta_{gNB-Edge\_5GC}\,[\mathrm{ms}] + \delta_{5GC\_DN}\,[\mathrm{ms}] \tag{3.28}$$

For architecture option S-DN, Figure 3.9, the total node latency and total propagation delay is described by:

$$\delta_{Total\_node}\ [\mathrm{ms}] = \delta_{UE\_TX}\,[\mathrm{ms}] + \delta_{gNB-5GC\_TX}\,[\mathrm{ms}] + \delta_{DN}\,[\mathrm{ms}] + \delta_{gNB-5GC\_RX}\,[\mathrm{ms}] + \delta_{UE\_RX}\,[\mathrm{ms}] \tag{3.29}$$

$$\delta_{Prop}\ [\mathrm{ms}] = \delta_{UE\_gNB-5GC}\,[\mathrm{ms}] + \delta_{gNB-5GC\_DN}\,[\mathrm{ms}] + \delta_{UE\_gNB-5GC}\,[\mathrm{ms}] + \delta_{gNB-5GC\_DN}\,[\mathrm{ms}] \tag{3.30}$$

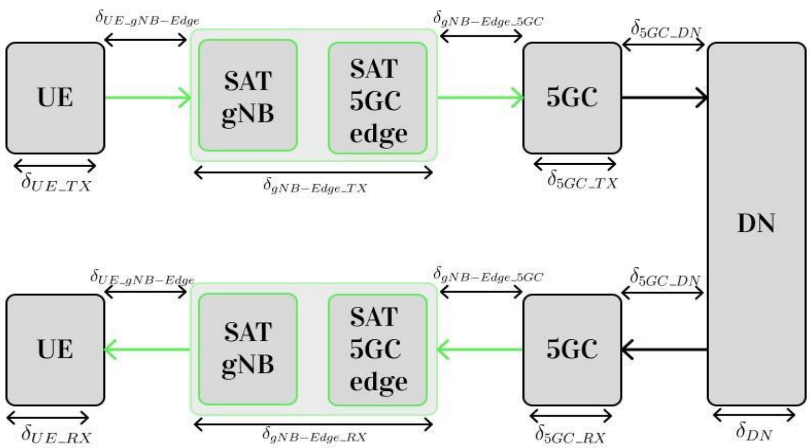

Figure 3-8 Latency contributions in scenario option S-Edge (where the Satellite takes functions of gNB and edge).

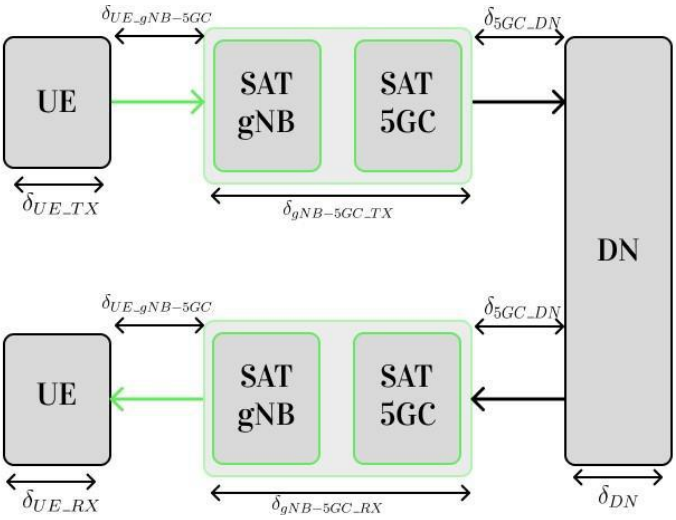

Figure 3-9 Latency contributions in scenario option S-DN.

For architecture option R-Sat, Figure 3.10, the total node latency, and total propagation delay is described by:

$$\delta_{Total\_node}\ [\mathrm{ms}] = \delta_{UE\_TX}\ [\mathrm{ms}] + \delta_{Relay\_TX}\ [\mathrm{ms}] + \delta_{SAT\_TX}\ [\mathrm{ms}] + \delta_{gNB\_TX}\ [\mathrm{ms}] + \delta_{5GC\_TX}\ [\mathrm{ms}]\ \text{-}$$
$$\delta_{DN}\ [\mathrm{ms}] + \delta_{5GC\_RX}\ [\mathrm{ms}] + +\delta_{gNB\_RX}\ [\mathrm{ms}] + \delta_{SAT\_RX}\ [\mathrm{ms}] + \delta_{Relay\_RX}\ [\mathrm{ms}] + \delta_{UE\_RX}\ [\mathrm{ms}] \quad (3.31)$$

$$\delta_{Prop}\ [\mathrm{ms}] = \delta_{UE\_Relay}\ [\mathrm{ms}] + \delta_{Relay\_SAT}\ [\mathrm{ms}] + \delta_{SAT\_gNB}\ [\mathrm{ms}] + \delta_{gNB\_5GC}\ [\mathrm{ms}] + \delta_{5GC\_DN}\ [\mathrm{ms}]$$
$$\delta_{UE\_Relay}\ [\mathrm{ms}] + \delta_{Relay\_SAT}\ [\mathrm{ms}] + \delta_{SAT\_gNB}\ [\mathrm{ms}] + \delta_{gNB\_5GC}\ [\mathrm{ms}] + \delta_{5GC\_DN}\ [\mathrm{ms}] \quad (3.32)$$

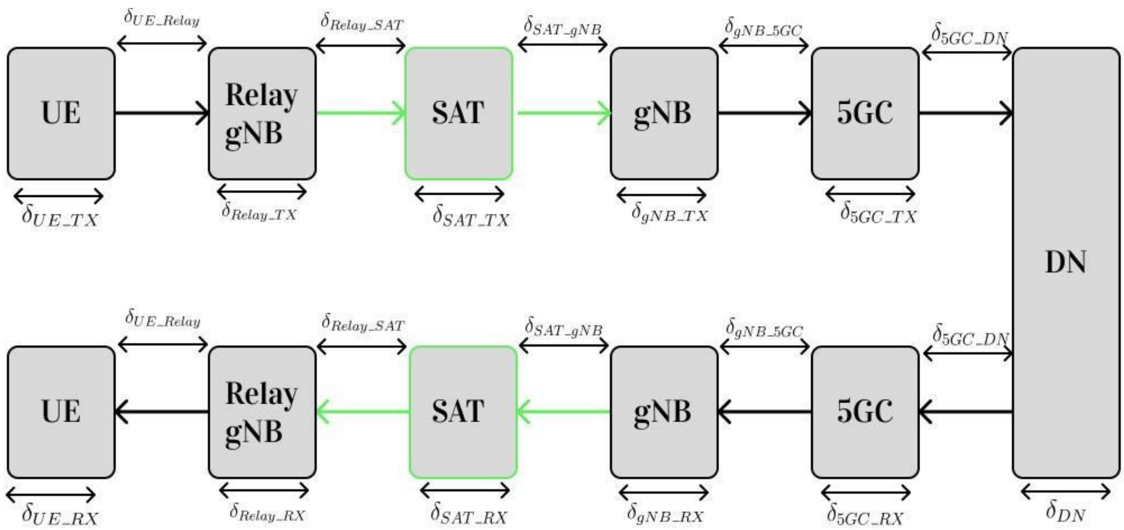

Figure 3-10 Latency contributions in scenario option R-Sat.

Regarding now scenarios related to backhaul access where the satellite only function is linking different nodes, in option B-gNB-Core, Figure 3.11, the total node latency, and total propagation delay is:

$$\delta_{Total\_node}\ [\text{ms}] = \delta_{UE\_TX}\ [\text{ms}] + \delta_{gNB\_TX}\ [\text{ms}] + \delta_{5GC\_TX}\ [\text{ms}] + \delta_{DN}\ [\text{ms}] + \delta_{5GC\_RX}\ [\text{ms}] + \delta_{gNB\_RX}\ [\text{ms}] + \delta_{UE\_RX}\ [\text{ms}] \quad (3.33)$$

$$\delta_{Prop}\ [\text{ms}] = \delta_{UE\_gNB}\ [\text{ms}] + \delta_{gNB\_5GC}\ [\text{ms}] + \delta_{5GC\_DN}\ [\text{ms}] + \delta_{UE\_gNB}\ [\text{ms}] + \delta_{gNB\_5GC}\ [\text{ms}] + \delta_{5GC\_DN}\ [\text{ms}] \quad (3.34)$$

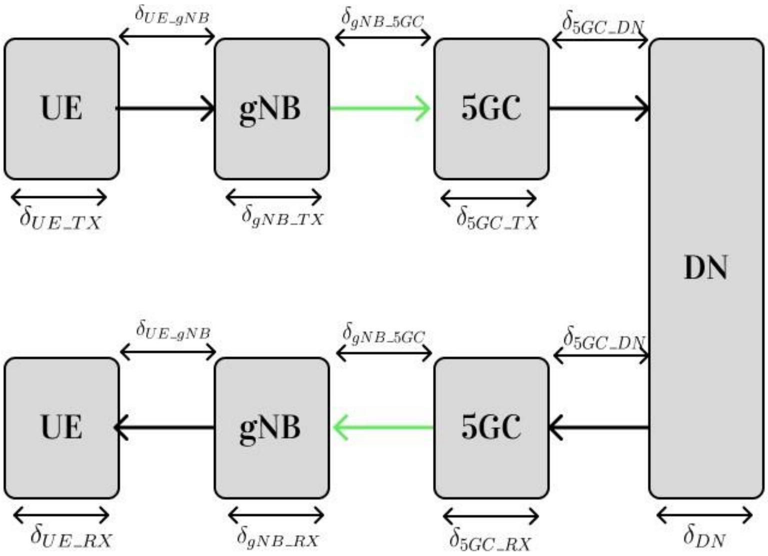

Figure 3-11 Latency contributions in scenario option B-gNB-Core (in green is the satellite link).

As for option B-Core-DN it is similar to option B-gNB-Core, only difference is that the satellite links 5GC and the DN instead of the gNB and 5GC, the equations relative to the latency are:

$$\delta_{Total\_node}\ [\text{ms}] = \delta_{UE\_TX}\ [\text{ms}] + \delta_{gNB\_TX}\ [\text{ms}] + \delta_{5GC\_TX}\ [\text{ms}] + \delta_{DN}\ [\text{ms}] + \delta_{5GC\_RX}\ [\text{ms}] + \delta_{gNB\_RX}\ [\text{ms}] + \delta_{UE\_RX}\ [\text{ms}] \quad (3.35)$$

$$\delta_{Prop}\ [\text{ms}] = \delta_{UE\_gNB}\ [\text{ms}] + \delta_{gNB\_5GC}\ [\text{ms}] + \delta_{5GC\_DN}\ [\text{ms}] + \delta_{UE\_gNB}\ [\text{ms}] + \delta_{gNB\_5GC}\ [\text{ms}] + \delta_{5GC\_DN}\ [\text{ms}] \quad (3.36)$$

The end to end (E2E) latency of each architecture is therefore calculated using the total propagation delay and total node latency of the respective architecture, where if the E2E latency is higher that the max latency supported for each service then it is impossible to deliver that service.

3.2.2 Coverage Analysis

The coverage analysis, based on [3GPP20] and [Corr22], gives an assessment of the maximum area covered by the satellite, setting the maximum distance for which a connection between the terminal and the satellite can be established, due to the fact that the minimum angle that the satellite can make a connection is 10º. As shown in Figure 3-12, the distance from the terminal to the satellite can be determined, using:

$$d_{[\text{km}]} = \sqrt{R_{E\,[\text{km}]}^2 \sin^2 \alpha_{[°]} + h_{0\,[\text{km}]}^2 + 2h_{0\,[\text{km}]} R_{E\,[\text{km}]}} - R_{E\,[\text{km}]} \sin \alpha_{[°]} \tag{3.39}$$

where:

- d: Distance from the terminal to the satellite.
- R_E : Earth radius (6371 km).
- h_0 : Satellite altitude.
- α : elevation angle.

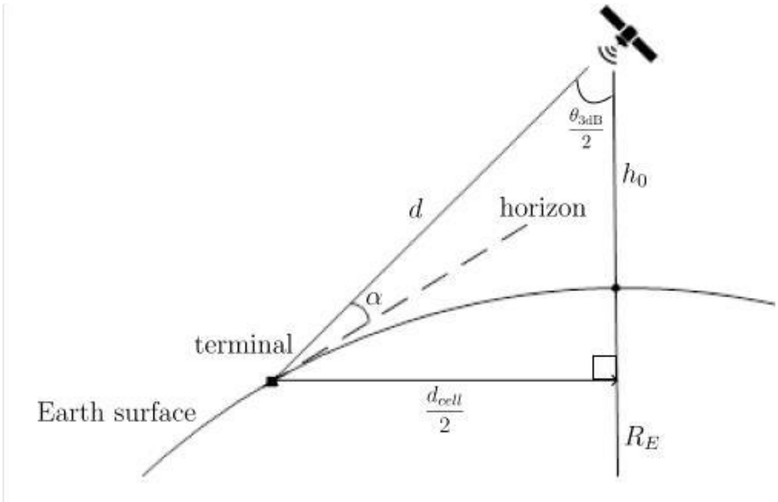

Figure 3-12 Representation of the geometry of a satellite (adapted from [3GPP20]).

Regarding the beam size computation, one satellite beam diameter has been derived from a typical approximation of a 3 dB beamwidth generated by a parabolic antenna, using [3GPP19b]:

$$\theta_{3\text{dB}\,[°]} = 70 \frac{\lambda_{[\text{m}]}}{D_{[\text{m}]}} \tag{3.40}$$

where:

- λ : Satellite carrier wavelength.
- D : Antenna diameter.

Using the half-power beamwidth the calculation for the diameter that the satellite can cover is:

$$d_{cover\,[\text{km}]} = 2 \cdot (h_{0\,[\text{km}]} \cdot \tan \frac{\theta_{3\text{dB}\,[°]}}{2}) \tag{3.41}$$

The area that a satellite can cover is given by:

$$A_{cover}[\text{km}^2] = \pi \, (\frac{d_{cover\,[\text{km}]}}{2})^2 \tag{3.42}$$

Another important concept is the path loss, which refers to the reduction of the signal strength as it passes through several stages of attenuation. The path loss for satellite is composed of the parameters as follows:

$$L_{p\ [\mathrm{dB}]} = L_{pb\ [\mathrm{dB}]} + L_{pg\ [\mathrm{dB}]} \tag{3.43}$$

where:

- L_p : Total path loss.
- L_{pb} : Basic path loss, accounts for free space propagation and shadow fading.
- L_{pg} : Attenuation due to atmospheric gases.

Regarding the basic path loss, it takes into consideration the free space loss that occurs naturally as a radio wave propagates through free space without any obstructions and shadow fading that occurs due to variations in the signal caused by obstacles; with these parameters the basic path loss can be determined by:

$$L_{pb\ [\mathrm{dB}]} = L_{0\ [\mathrm{dB}]} + M_{SF\ [\mathrm{dB}]} \tag{3.44}$$

where:

- L_0 : Free space propagation.
- M_{SF}: Shadow fading assumed 1.2 dB.

where the free space path loss is given by:

$$L_{0\ [\mathrm{dB}]} = 32.45 + 20\log_{10}(f_{[\mathrm{MHz}]}) + 20\log_{10}(d_{[\mathrm{km}]}) \tag{3.45}$$

Concerning the attenuation due to atmospheric gases (L_{pg}) that is caused by absorption, it depends mainly on frequency and elevation angle. At the S band the atmospheric gases can be considered being 0.2 dB.

Additionally, for the coverage planning, the maximum path loss, L_{p_max} , allowed by the equipment is given by:

$$L_{p\_max\ [\mathrm{dB}]} = P_{EIRP\ [\mathrm{dBm}]} + G_{RX\ [\mathrm{dBi}]} - P_{RX\_min\ [\mathrm{dBm}]} \tag{3.46}$$

where:

- P_{EIRP} : Effective isotropic radiated power.
- G_{RX} : Total receiver antenna gain.
- P_{RX_min} : Receiver sensitivity.

In case it is given the effective isotropic radiated power density, that is, the power per unit bandwidth, can be transformed to P_{EIRP} , using:

$$P_{EIRP\ [\mathrm{dBm}]} = P_{EIRP,density\ [\mathrm{dBW/MHz}]} + 10\log_{10}(\Delta f_{[\mathrm{MHz}]}) + G_{TX\ [\mathrm{dBi}]} + 30 - L_{u\ [\mathrm{dB}]} \tag{3.47}$$

where:

- $P_{EIRP,density}$: Effective isotropic radiated power density.
- Δf: Bandwidth.
- G_{TX} : Transmitter antenna gain.
- L_u : Losses due to user, 3 dB for voice, and 0 dB for data.

The receiver sensitivity power determines the minimum power that must reach the receiver to make a connection, [Corr22], which is given by:

$$P_{RX\_min\ [\text{dBm}]} = -174 + 10\log(\Delta f_{RB\ [\text{Hz}]}) + F_{[\text{dB}]} + \rho_{N\ [\text{dB}]} \tag{3.48}$$

where:

- Δf_{RB} : Bandwidth per RB, which depends on the numerology.
- F : Noise Figure usually varies between 5 to 8 dB.
- ρ_N : Signal-to-noise ratio (SNR) for a given throughput.

For a given throughput, there is a choice to be made regarding the SNR, depending on the modulation used. Expressions were obtained according to [IBel19], using a coding rate of 1/3 for QPSK, 1/2 for 16-QAM and 3/4 for 64-QAM all with MIMO 2x2. The throughput per RB and the corresponding SNR can be given by the following equations, as seen in Figure 3-13:

$$R_{RB\ [\text{Mbps}]} = \begin{cases} \frac{2.34201}{14.0051 + e^{-0.5779 \cdot \rho_{N\ [\text{dB}]}}}, \text{QPSK} \\ \frac{47613.1 \cdot 10^{-6}}{0.0926275 + e^{-0.2958 \cdot \rho_{N\ [\text{dB}]}}}, \text{16-QAM} \\ \frac{26405.8 \cdot 10^{-6}}{0.0220186 + e^{-0.2449 \cdot \rho_{N\ [\text{dB}]}}}, \text{64-QAM} \end{cases} \tag{3.49}$$

$$\rho_{N\ [\text{dB}]} = \begin{cases} \frac{1}{-0.5779} \cdot \ln\left(\frac{2.34201}{R_{RB\ [\text{Mbps}]}} - 14.0051\right), \text{QPSK} \\ \frac{1}{-0.2958} \cdot \ln\left(\frac{47613.1 \cdot 10^{-6}}{R_{RB\ [\text{Mbps}]}} - 0.0926725\right). \text{16-QAM} \\ \frac{1}{-0.2449} \cdot \ln\left(\frac{26405.8 \cdot 10^{-6}}{R_{RB\ [\text{Mbps}]}} - 0.0220186\right), \text{64-QAM} \end{cases} \tag{3.50}$$

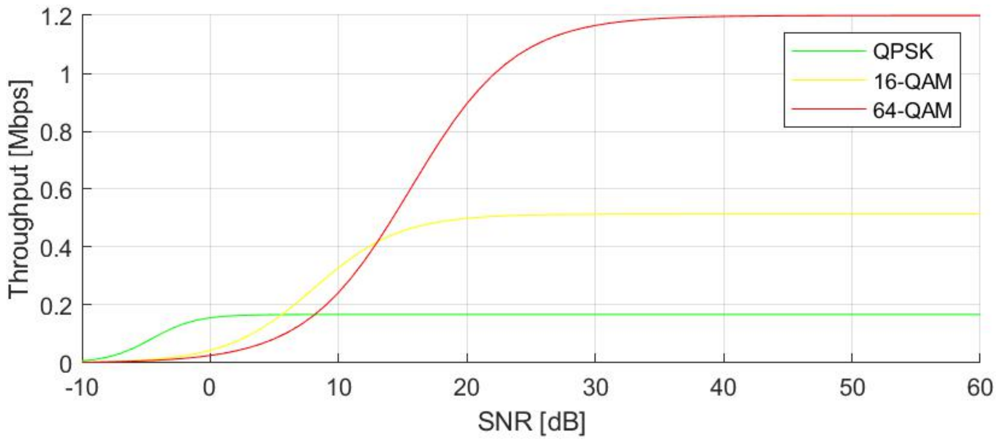

Figure 3-13 Throughput as a function of the SNR, considering MIMO 2x2.

Having all these values, it is possible to calculate the maximum distance that a link between the UE and the satellite can be established using the following formula:

$$d_{\max\ [\mathrm{km}]} = 10^{\left(\frac{L_{p\_max\ [\mathrm{dB}]} - L_{pg\ [\mathrm{dB}]} - M_{SF\ [\mathrm{dB}]} - 32.45 - 20\log_{10}(f_{[\mathrm{MHz}]})}{20}\right)} \quad (3.51)$$

3.2.3 Capacity Analysis

For the maximum throughput offered by a 5G radio link a specific equation is given by [3GPP23d], important to notice that the link must be in optimal conditions to achieve the maximum throughput.

$$R_{Cap\ [\mathrm{Mbps}]} = 10^{-6} \cdot \left(v_{Layers} \cdot Q_m \cdot f_{sf} \cdot R_{max} \cdot \frac{12 \cdot N_{PRB}^{BW,\mu}\ [\mathrm{symbol}]}{T_s^{\mu}\ [\mathrm{s}]} \cdot (1 - O_H)\right) \quad (3.52)$$

where:

- v_{Layers} : Number of layers dependent on the MIMO system implemented (maximum of 8 for the DL and maximum of 4 for UL, it will be used 2 in this case to be coherent with the throughput and SNR relation).
- Q_m : Supported modulation order (2 for QPSK, 4 for 16-QAM, 6 for 64-QAM).
- f_{sf} : Scaling factor (1, 0.8, 0.75, 0.4), relevant in situations of UE high or medium mobility, due to handover process, it will be assumed as 1 in this case.
- R_{max} : Constant dependent on the modulation order and determined by the Channel Quality Indicator, it is defined as the ratio between useful bits and total transmitted bits (useful plus redundant bits). The redundant bits are added for forwarded error correction (FEC). In Table 3-4 the different values for the code rate for each modulation and numerology is shown.
- $N_{PRB}^{BW,\mu}$: Number of RB allocated in the bandwidth given with numerology μ, being taken from Table 3-5.
- $T^{\mu}_{s\ [\mathrm{s}]}$. Average symbol duration in a subframe with numerology μ, it is defined in (3.53).
- O_H: Overhead for control channels is related to the bandwidth required to transmit the packet overhead (0.14 for DL and 0.08 for UL in FR1).

The average symbol duration in a subframe is given by:

$$T^{\mu}_{s\ [\mathrm{s}]} = \frac{10^{-3} \cdot}{14 \times 2^{\mu}} \quad (3.53)$$

One of the objectives is to calculate the traffic for each service and the number of users that is possible to offer the required data for each service. For this, firstly the number of users for a specific service per area covered is calculated by:

$$N_{s,cell} = N_{s\ [\mathrm{users/km^2}]} A_{cover\ [\mathrm{km^2}]} \quad (3.54)$$

where:

- N_s : Overall user density for a specific service, being taken from Table 3-1.

Table 3-4 Modulation Schemes and code rate (adapted from [Mari21]).

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 3-5 Number of maximum RBs in the respective bandwidth (extracted from [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

In each cell, there is an activity factor for the number of users actively using a specific service, $N_{Active,s}$, so an activity factor is important to consider:

$$N_{Active,s} = N_{s.cell} A_{f\ [\%]} \tag{3.55}$$

where:

- A_f : Activity factor, percentage of active users.

Using these parameters, it is possible to infer the needed throughput in the cell to allow all users to experiment the needed throughput for the wanted service.

$$R_{Active\ needed\ [\text{Mbps}]} = N_{Active,s} \cdot R_{s\ [\text{Mbps}]} \tag{3.56}$$

where:

- R_s : Data rate of a specific service from Table 3-2.

Having the throughput offered in a cell, and the throughput required for each service, the possible number of users that can use a service is calculated:

$$N_{Users\ possible,s} = \frac{R_{Cap\ [\text{Mbps}]}}{R_{s\ [\text{Mbps}]}} \tag{3.57}$$

Using the values obtained from (3.51) and (3.53) it is possible to calculate the percentage of users covered by the satellite, using:

$$P_{Served\ users\ [\%]} = \frac{N_{Users\ possible,s}}{N_{Active,s}} \cdot 100 \tag{3.58}$$

3.3 Model Implementation

This section describes the model implementation related to coverage, capacity and latency planning described in the previous sections, developed in MATLAB. The model is divided into three major parts, the latency, coverage, and capacity analysis, in Figure 3-14, the general mode workflow is described, where firstly the input parameters are introduced in the model and subsequently the choice of the service is made before analysing all other models, each model has its own workflow further down and will output specific parameters, needed for the study of this thesis.

Firstly regarding the coverage analysis part, that is illustrated by Figure 3-15 a), it gives an assessment of the area covered by a specific satellite and the steps necessary to calculate the maximum distance that a UE can connect to the satellite using as input parameters: frequency band, antenna diameter, altitude of the satellite, service specification, in terms of data rate required per service to choose wisely the modulation order and ρ_N ,also P_{EIRP} and antenna gain.

Starting by the calculation of the beam size computation using (3.40), (3.41) and (3.42), after the path loss propagation is calculated, using (3.43), within the obtained coverage radius. Following the previous calculation, it is now needed to calculate the SNR and receiver sensitivity depending on the service used, the choice of service influences the throughput needed therefore the SNR as well, using (3.49) and (3.50). Subsequently the P_{RX_min} is obtained from (3.48) and finally the maximum path loss allowed by the equipment in (3.46). Finalising. it is now possible to calculate the maximum distance, (3.51), that a connection between the UE and the satellite is ensured, this process must be done to the DL and UL.

In terms of the capacity analysis, Figure 3-15 b), the input parameters needed for this analysis are the service specification regarding throughput required by the service, the coverage radius obtained from the previous coverage analysis, the user density, numerology, bandwidth, modulation order and number of layers in MIMO.

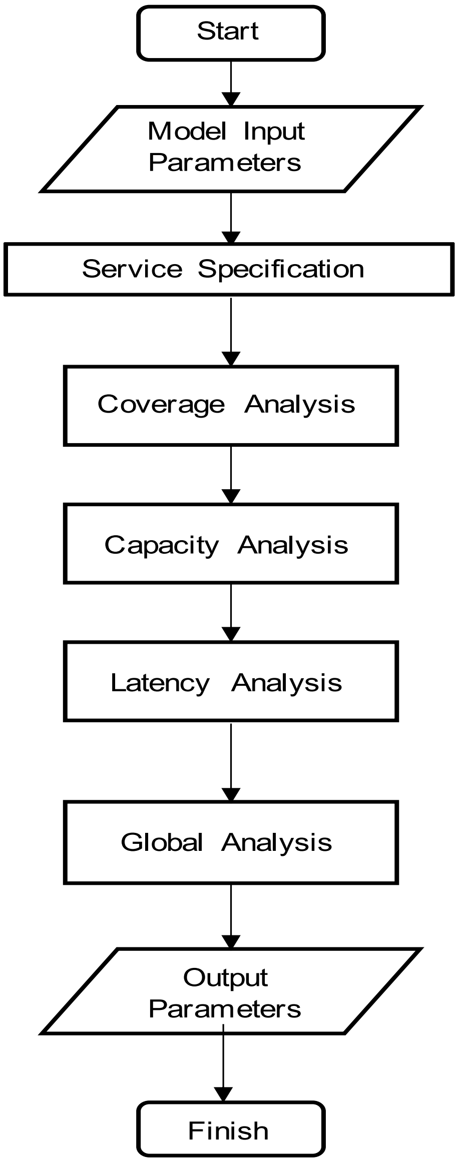

Figure 3-14 General Model flowchart.

This section of capacity analysis starts by computing the maximum cell capacity offered for the different input parameters using (3.52). Moreover, the service used by the user requires a minimum data rate for it to successfully work, with this information and the number of users actively using the service obtained in (3.55), it is possible to calculate the total throughput needed with (3.56). With the minimum data rate per service known and the maximum capacity of the cell, it allows the calculation of the possible number of users that is achievable to supply the service employing (3.57). Having the number of possible users served and the number of active users it is easily attained the percentage of users that are able to utilise the service successfully. Having as output parameters, the capacity needed and offered, the data rate of the link and the number of served users as well as the percentage of the served users.

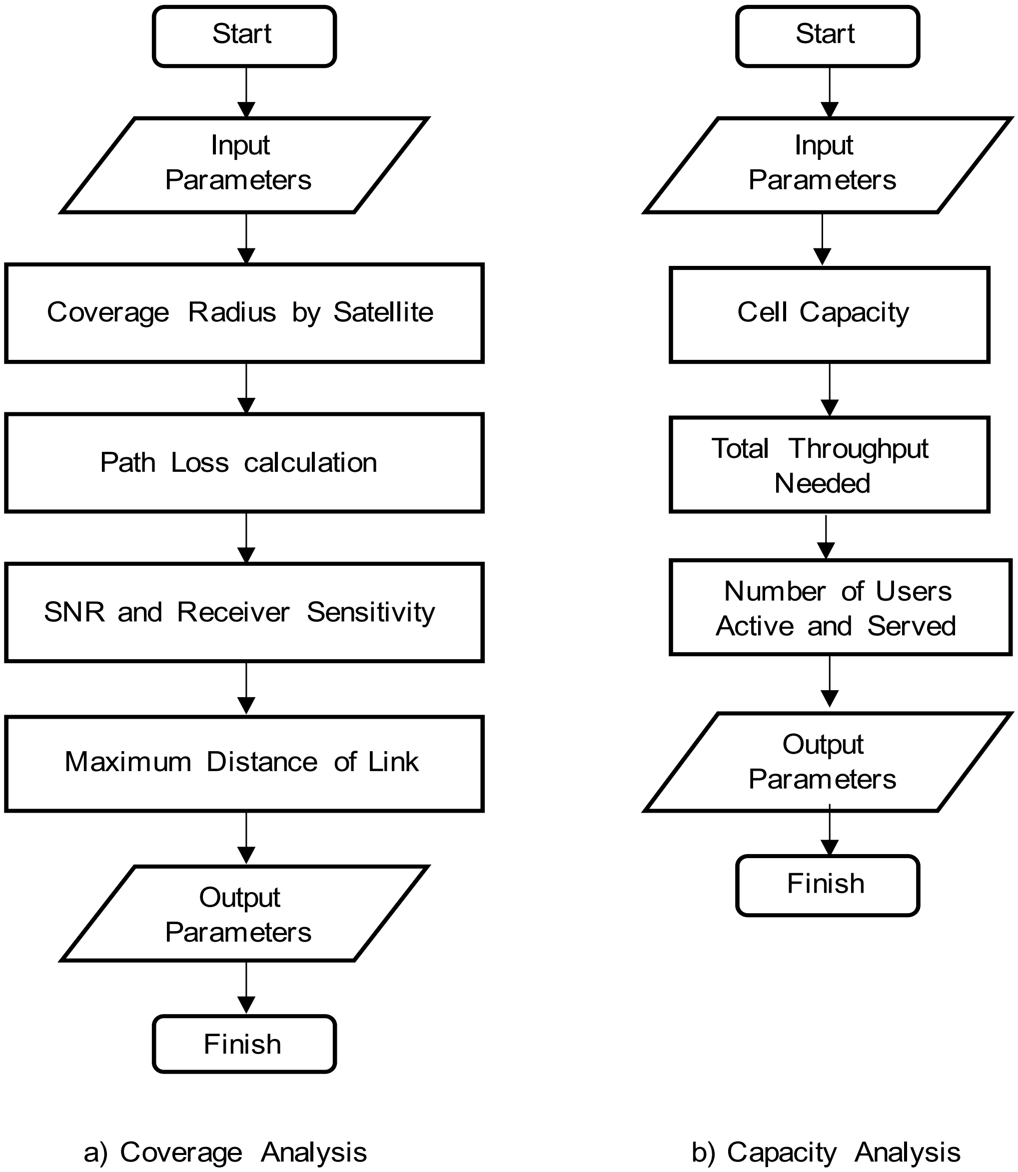

Figure 3-15 Model workflow of the coverage and capacity analysis.

As for the final part, illustrated by Figure 3-16, represents the flowchart of the latency analysis part, in which the programme starts by introducing the input parameters such as distances between links, service specification in terms of latency required and packet size of the service, numerology and data rate provided by the link. This initial parameter makes it possible to know the initial latency restrictions depending on the satellite orbit configuration, which is a restriction that highly affects the performance in terms of latency due to a high difference of distances, and the choice of which to use must be made for further analysis.

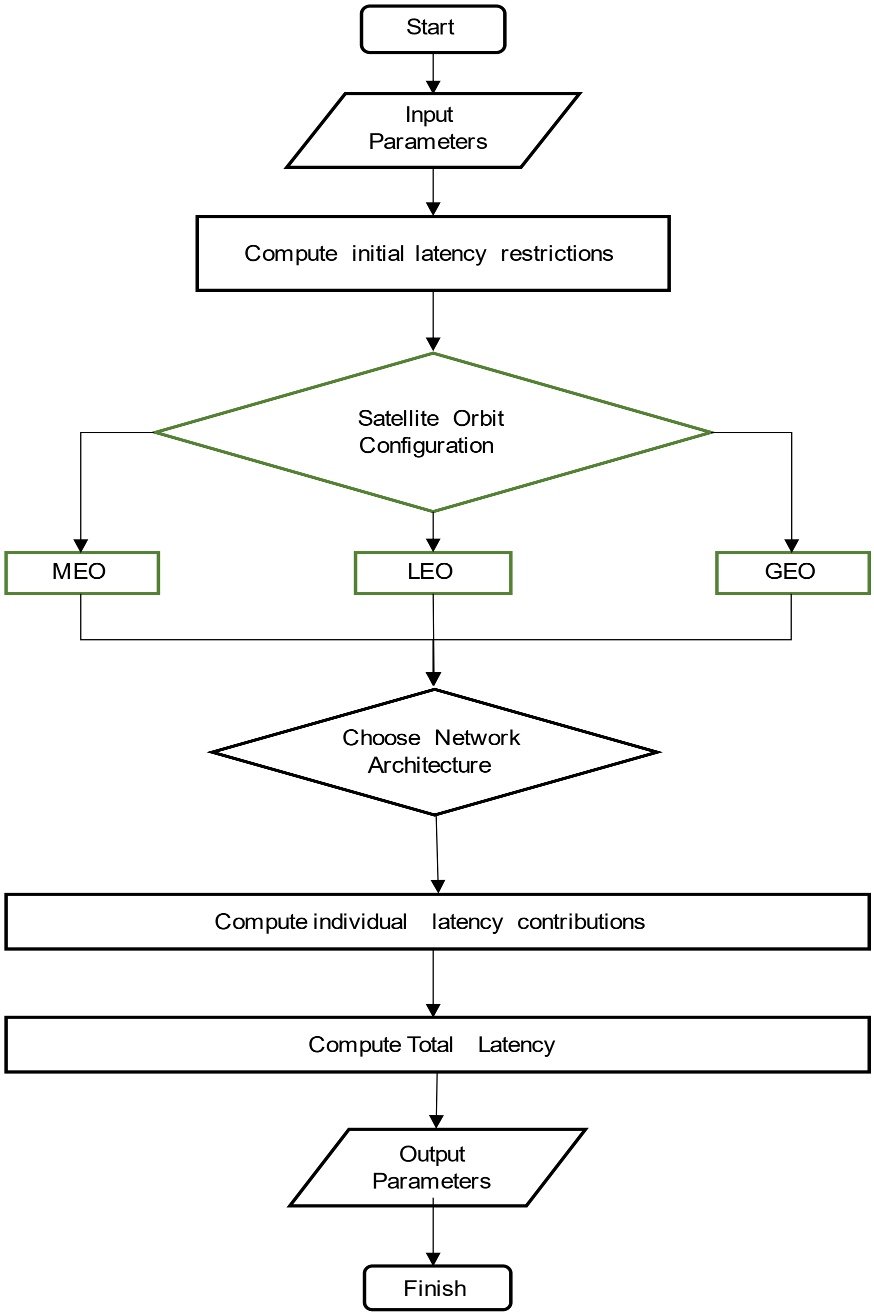

Figure 3-16 Latency Analysis model workflow.

After this decision of the satellite orbit to be used, it is possible to make a choice of analysing one or many network architectures; for this purpose, it should be calculated the latency contributions of each node and each link of an architecture. The node latency can be calculated from (3.3) to (3.13), where it is analysed for each node what affects it, in terms of processing, queuing and transmission. Additionally, the latency related to the propagation latency in the links is calculated using (3.1). With both these parameters it is then possible to obtain the total latency related to the respective architecture, which makes clear the choice of the architecture most suitable for the input parameters. It is important to refer that in the case of the architecture with a MEC node installed, it will be considered that data will not be forwarded further in the network, reducing massively the latency.

To end, the global analysis takes into consideration the coverage radius, the total latency, the data rate per service, capacity and served users to study the performance and limitations of the network.

3.4 Model Assessment

To assess the model described previously, this section applies some empirical tests to evaluate the implementation at the latency, coverage, and at the capacity level. It is also good practice to analyse if the input parameters are valid. This is a crucial phase that should be done with careful consideration off the plethora of parameters that influence the model, in order to check if the model is coherent and accurate with the theoretical view. In Table 3-6 the assessment tests made for this model is shown.

Table 3-6 Model Assessment Tests.

Test ID	Element Validation	Model
1	Verify the path loss according to distance from the Satellite to the UE (dependent on elevation angle and height of the satellite).	Coverage
2	Check if the area of coverage is increasing with the height of the satellite and confirm with public results.	
3	Validate if the calculations for maximum link distance are in line with input parameters (scientific calculator and MATLAB tests)	
4	Check the number of served users in function of user density for multiple services (dependent on capacity of the system and A_{cover})	Capacity
5	Check if the number of active users, possible users, and percentage of served users is coherent with the input parameters (scientific calculator and MATLAB tests).	
6	Validation of the transmission latency with different satellite orbits.	Latency
7	Validation of the latency contributions for distinct types of satellite architectures, distances of links and nodes (scientific calculator).	

Starting by the coverage model evaluation, it is assumed that the frequency is 2 GHz, and the antenna diameter is 2 m, and as it is predicted, in Figure 3-17 it is shown that the higher the distance the path loss will also increase. The UE is the farthest away in the case of 10º elevation angle of the link, and the closest when right on top of the UE, 90º, where the distance is the lowest. Inferring that the satellite orbit chosen highly affects the system, where the LEO is the orbit with less path loss since it is the closest to Earth, whereas the MEO and GEO, have increased path loss. This is also confirmed with public studies.

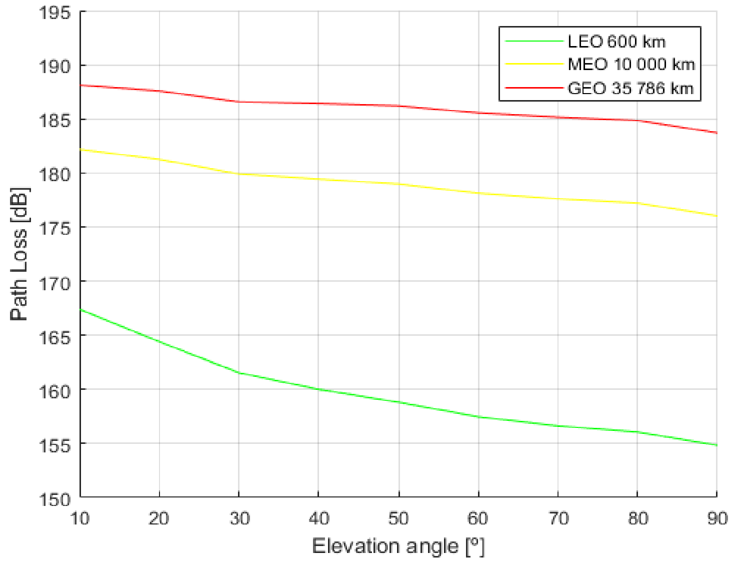

Figure 3-17 Path loss as a function of elevation angle, at 2GHz carrier.

In Figure 3-18 the relation between the altitude of the satellite and the area of coverage is shown, when the altitude increases the area of coverage also increases. With the increase of the coverage area the number of users present also increases and more loaded would be the system.

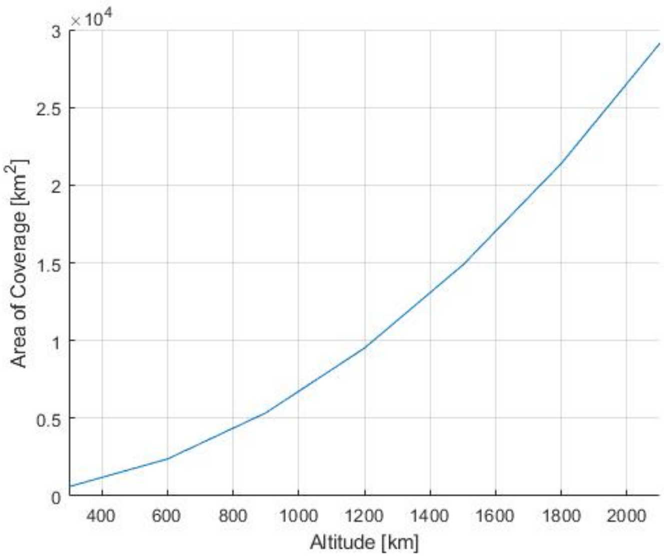

Figure 3-18 Area of coverage as a function of the altitude of the satellite, at 2GHz carrier.

Concerning the capacity model, a simple test of serving only one service per time, to verify the covered users depending on specific parameters was done, and as expected, the services that require less data rate and with less overall user density have a higher percentage of users covered as was intended.

Regarding the latency model, the delays were evaluated, and for increasing distances the propagation delay increased linearly as intended. Also, the contributions depending on if the service had higher packet size, then, as expected, the bigger the data information to be processed the slower it is transmitted, achieving a higher latency. The impact of having less or more nodes, increased or decreased the latency. Also, the use of the 5GC edge, where the data is only forwarded until it and sent back again to the UE, results in lower latencies and crucial for specific tasks.

Chapter 4

Results Assessment

This chapter details the description of the reference scenario and all variations made to it. Then it provides the results obtained by the developed model and a study of all these variations.

4.1 Scenarios Description and Output Parameters

The scenario, chosen to be the reference for the study, represents several instances of examination with various satellites. Each satellite is characterised in terms of mobile networks based on numerous factors, such as orbits, antenna specifications, frequency band, coverage area and link budget. In Table 4-1, one represents the final aim of the model, the output parameters, which will be the focus to concluding the best configuration, and in Table 4-2 the reference scenario that will be the main focus of the model for analysis.

Table 4-1 Output parameters of the model and respective equations.

Output Parameter	Equation
A_{cover}	(3.42)
d_{max}	(3.51)
R_{Cap}	(3.52)
$P_{Served\ users}$	(3.58)
$\delta_{\text{Total Latency}}$	(3.21) and (3.22)

The reference scenario intends to study the deployment scenario most used nowadays, LEO constellations, and assess the impact of changes in these parameters to better understand it.

One presents the scenarios of application of the developed model, the 5G services requirements and the specific input parameters variations that will influence the different scenarios, to understand the most suitable configuration for the system in study. Starting with the services requirements for the model evaluation, Table 4-3 describes the different parameters.

To do this analysis three satellite orbits will be considered. The geographical scenario is the rural settings and given the fact that from previous assessments it was concluded that the path loss was already overly high, for further analysis the UE will always be in LoS. The simulator takes several input parameters that are dependent on the configuration of the network, the device settings, the service scenario type in terms of users per service and more service-related parameters.

Table 4-2 Reference scenario parameters.

LEO_{06-2}	Altitude [km]	600
	Satellite antenna diameter [m]	2
	Satellite $P_{EIRP,density}$ [dBW/MHz]	34
	Satellite Antenna Gain, G [dBi]	30
	Frequency carrier [GHz]	2
	Bandwidth [MHz]	20
	SCS [kHz]	60
	Modulation	64-QAM
	Code Rate	666/1024

Table 4-3 Service requirements to evaluate the model.

	Interactive Data	Voice	IoT	Video Surveillance	Emergency texting
Data Rate DL [Mbps]	1	0.128	0.002	0.5	0.100
Data Rate UL [Mbps]	0.100	0.064	0.010	3	0.050
Max latency supported [ms]	50	100	400	150	100
Packet Size [Bytes]	1 000	218	300	800	170
Overall user density [per km²]	100	10	400	10	10
Activity factor [%]	1.5	20	1	20	1

Table 3-1 shows some reference values for the three orbits used for the scenarios, which will have a major influence on the analysis. Adding to it, Table 3-2 includes information regarding the specific requirements for each service, important for this study, which will give us the constraints to know if it is feasible or not to offer service through satellites.

The coverage inputs are represented in Table 4-4, where altitude varies relative to the corresponding satellite orbit, the antenna diameter increases with the height so the beam is more directed, and the power and the gain must also be higher to compensate for more losses due to increased height. Also, the bandwidth and the numerology depending on the spectrum possible to use are considered as input.

In Table 4-5 the set of satellite parameters that covers the distinct types of orbits that will be used for the analysis, according to Table 4-4, is represented. As for the UE, in Table 4-6, can be seen some parameters related to it that will influence the performance of the model.

Table 4-4 Input variations for coverage model (adapted from [3GPP23b]).

	LEO	MEO	GEO
Altitude [km]	{600,1200}	10 000	35 786
Satellite antenna diameter [m]	{1, 2}	6	{12, 22}
Satellite $P_{EIRP,density}$ [dBW/MHz]	{28, 34, 40}	46	{53, 59}
Satellite Antenna Gain, G [dBi]	{24, 30}	38	{45, 51}
Bandwidth [MHz]	{5, 10, 15, 20}		
SCS [kHz]	{15, 30, 60}		

Table 4-5 Set of satellite parameters for system simulation (adapted from [3GPP23b]).

	LEO_{06-2}	LEO_{06-1}	LEO_{12-2}	LEO_{12-1}	MEO_{10}	GEO_{36_22}	GEO_{36_12}
Altitude [km]	600	600	1 200	1 200	10 000	35 786	35 786
Satellite antenna diameter [m]	2	1	2	1	6	22	12
Satellite $P_{EIRP,density}$ [dBW/MHz]	34	28	40	34	46	59	53
Satellite Antenna Gain, G [dBi]	30	24	30	24	38	51	45

Table 4-6 Typical characteristics of UE in satellite networks (adapted from [3GPP23b]).

Characteristics	Handheld or IoT devices
Frequency band	S band (2 GHz)
Subcarrier Spacing [kHz]	15, 30, 60
Antenna type and configuration	omnidirectional antenna
P_{EIRP} [dBm]	23
Rx Antenna gain [dBi]	0
Noise figure [dB]	7

With these input parameters, the aim is to find the covered area of the satellite and the maximum distance of the link DL and UL, enabling a connection between the satellite and the UE.

The next set of variations is regarding the capacity model, where the input parameters are represented in Table 4-7. The bandwidth assumes four different values, due to the spectrum for the specific band used. The different values of the SCS will change the bandwidth used per RB, and the modulation will affect the number of bits transmitted per symbol, with the increase of the modulation more bits are transmitted, and the choice of modulation will depend on the requirements of the service data rate. As for the covered area, when the area covered is high then the number of users inside that area also increases, increasing the capacity needed to supply the services successfully.

Table 4-7 Input parameters variations for capacity model.

Bandwidth [MHz]	{5, 10, 15, 20}
Subcarrier Spacing [kHz]	{15, 30, 60}
Modulation	QPSK, 64-QAM
Code Rate	{78/1024, 193/1024, 449/1024. 466/1024, 567/1024, 666/1024}

The final objective of the capacity model is to calculate the percentage of users that can be successfully provided with these services.

For the last model, the latency analysis, the input parameters are the packet size of the service studied that is represented in Table 3-2, the data rate DL and UL obtained from the capacity model, and the distance of each link depending on the architecture. Having the final aim of seeing the minimum latency required for each architecture, and if it is coherent with the maximum latency to support a service.

For a simpler study of the architecture and its impact, instead of variating the links interconnecting each node, it will be assumed that any link that does not include the satellite will have a distance of 5 km.

4.2 Analysis of Coverage

This subsection aims to assess the influence of the satellite altitude, antenna specifications, radio specifications and also the service specification, on the covered area of the satellite and the maximum distance for a connection to be successful.

Starting with the analysis of the covered area influenced by the antenna diameter and altitude of the satellite, Table 4-8 is obtained. As expected, the increase in altitude also represents an increase in the covered area, while the increase of the antenna diameter decreases the area covered, which means the focus of energy is more directed, as seen in the half-power beamwidth, which is to expect that will give us better performance and better gain. This means, that depending on if the objective is to offer a larger coverage area or higher performance, there should be a trade-off.

Further analysis of each specific type of satellite and the specific service constraints is analysed the maximum distance of link that is possible to get with the specific input parameters, below will be shown various tables related to these services and satellites. For each maximum distance of link calculated, it was taken the value of ρ_N regarding the specific data rate pretended, and the corresponding most suited modulation.

Important to notice that as far as the AR/VR service is concerned, being the service with the highest requirements in terms of data rate, 1 000 Mbps for DL and 500 Mbps for UL, it is not provided even if only one UE uses all the resources. For this reason, it will be designed as not feasible.

Table 4-8 Covered area depending on the satellite altitude and antenna diameter.

	LEO_{06-2}	LEO_{06-1}	LEO_{12-2}	LEO_{12-1}	MEO_{10}	GEO_{36_22}	GEO_{36_12}
Maximum distance of possible physical link [km]	600.9	601.9	1 202	1 204	10 005	35 791	35 796
$\theta_{3\mathrm{dB}}$ [º]	6.6	9.3	6.6	9.3	3.8	1.9	2.7
A_{cover} [km^2]	3 735	7 487	14 941	29 948	345 350	1 205 500	2 210 500

The influence of the altitude in the maximum possible distance of link, it is expected that with higher altitude there will be other input parameters, described in Table 4-1, that will compensate for the increase of distance from the Earth to be possible a connection, the power transmitted and the antenna transmitter gain are two important parameters since the signal that reaches the UE must be good enough to perceive the information sent.

Figure 4-1 represents the maximum possible link distance DL, according to Table 4-5 parameters and with a bandwidth of 5 MHz and SCS 15 kHz, since these are the parameters that are possible to obtain the highest distance of the link, the narrow the bandwidth, requires less power to maintain signal quality, although it limits the data rate and overall capacity of the system, and with a narrow bandwidth, it introduces less noise in the system.

Inferring that with the increase of height the maximum distance of the link increases, and with less demanding services, this is, services that require less data rate, the distance of the link also increases, as it was expected. For the same calculations but for a bandwidth of 20MHz and SCS of 60 kHz, the lowest maximum distance of the link was obtained, the results obtained are not significantly different from Figure 4-1, with a minor decrease in the maximum distance of the link.

From Figure 4-1, one can visually see that reducing the antenna diameter, which consequently affects the transmitted power and antenna gain, decreases the maximum distance achievable by the link. Although the satellite covers more area, the reach of the signal decreases with the decrease of the antenna diameter.

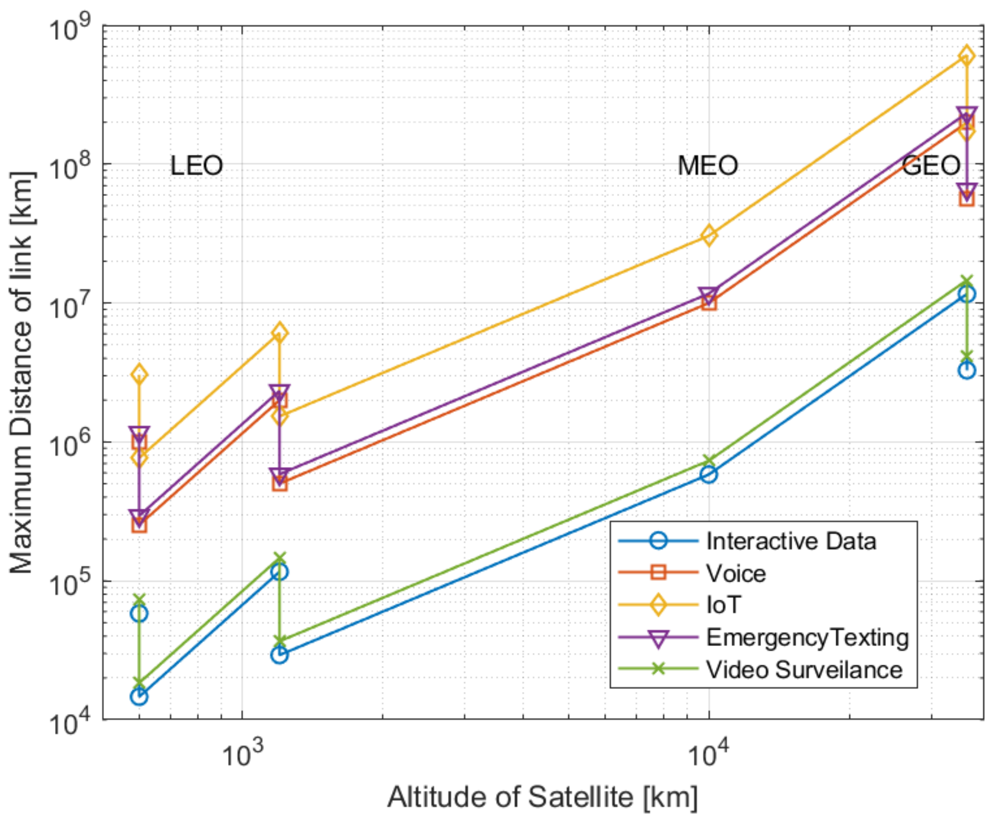

Figure 4-1 Maximum Distance of Link DL versus altitude, bandwidth 5 MHz and SCS 15 kHz.

One of the major concerns regarding NTN for mobile networks is the UL, the fact that UE has enormous constraints, especially regarding power and antenna characteristics that will affect the propagation path loss. For the UE to communicate with the satellite the signal must reach the latter, or else it will be only a one-directional communication, this is enough for the emergency texting. The following Tables 4-9, 4-10, 4-11 and 4-12 show the maximum distance of the link for each orbit and service. Where the UL is dependent on its own constraints given in Table 4-6, the gain of the antenna of the satellite, and the service data rate required that will affect the propagation, note that these values are theoretical and have the constraint of the physical link from Table 4-8, where the maximum distance of the link UL must be higher than the altitude of the satellite (minimum distance to be feasible a connection). This maximum distance is the distance where the power that reaches the receiver is higher than that obtained for each constraint.

Table 4-9 Maximum distance of link UL versus satellite for Interactive data.

Interactive data	UE UL					
P_{EIRP} [dBm]	SCS [kHz]	$\mathrm{LEO}_{06/12-2}$	$\mathrm{LEO}_{06/12-1}$	MEO_{10}	GEO_{36_22}	GEO_{36_12}
		d_{max} [km]				
23	15	4 708	2 359	11 826	52 825	28 044
	30	3 329	1 668	8 362	37 353	19 830
	60	2 354	1 179	5 913	26 412	14 022

As far as video surveillance service is concerned, it is impossible to provide the necessary data rate with only one RB, for that reason, it must be used more RBs to achieve the 3 Mbps needed for UL. Using 64-QAM, with 22 dB for SNR one needs to use at least 3 RB, and still then it is not possible to do a connection UL with any of the satellites. For that reason, the minimum RB possible was used for the video surveillance service, to be able to distribute more RBs to other users, while also achieving the 3 Mbps needed and the minimum distance for the link. After calculations, it is achieved for an SNR of 13 dB, where each RB has 0.41 Mbps, needing 8 RBs to provide the needed data rate for the service, and obtaining the maximum distance of the link for the LEO_{06-2} of 674 km, being the only condition where it is possible to establish a link between the UE and the satellite.

Table 4-10 Maximum distance of link UL versus satellite for Voice.

Voice	UE UL					
P_{EIRP} [dBm]	SCS [kHz]	$\mathrm{LEO}_{06/12-2}$	$\mathrm{LEO}_{06/12-1}$	MEO_{10}	GEO_{36_22}	GEO_{36_12}
		d_{max} [km]				
23	15	5 604	2 809	14 079	62 886	33 385
	30	3 963	1 986	9 955	44 467	23 607
	60	2 802	1 404	7 039	31 443	16 693

Table 4-11 Maximum distance of link UL versus satellite for IoT.

IoT	UE UL					
P_{EIRP} [dBm]	SCS [kHz]	$\mathrm{LEO}_{06/12-2}$	$\mathrm{LEO}_{06/12-1}$	MEO_{10}	GEO_{36_22}	GEO_{36_12}
		d_{max} [km]				
23	15	8 822	4 421	22 160	98 985	52 549
	30	6 238	3 126	15 669	69 993	37 158
	60	4 411	2 210	11 080	49 492	26 275

As expected, the more requirements of data rate there are and also with higher SCS affecting the ρ_N , the less the maximum distance of the link. Even with a high gain, it is not possible to compensate for all the losses of the signal, concluding, highlighted in red, the connections that are not possible to be made, being majorly the satellites with higher attitude.

Concluding the analysis of the coverage, Table 4-13 shows the services that are possible to be provided according to the satellite orbit and parameters, as inferred in the beginning the AR/VR for mobile is impossible to be provided no matter the satellite, and video surveillance being the most demanded uplink wise it is highly constrained by the UL making the only possible satellite being LEO_{06-2}. All other services are possible to be delivered to the UE except for the satellite GEO_{36_12}, which does not have enough antenna receiver gain to compensate for the UE UL signal. It is important to note that, as can be seen in Table 4-13, the IoT service can be provided with all different satellites, being one of the main focuses of nowadays telecommunications, for a fully connected world.

Table 4-12 Maximum distance of link UL versus satellite for Emergency Texting.

Emergency Texting	UE UL					
P_{EIRP} [dBm]	SCS [kHz]	$\mathrm{LEO}_{06/12-2}$	$\mathrm{LEO}_{06/12-1}$	MEO_{10}	GEO_{36_22}	GEO_{36_12}
		d_{max} [km]				
23	15	6 038	3 026	15 168	67 751	35 968
	30	4 269	2 140	10 725	47 908	25 433
	60	3 019	1 513	7 583	33 876	17 984

Table 4-13 Possible services to support by type of satellite, regarding coverage.

	LEO_{06-2}	LEO_{06-1}	LEO_{12-2}	LEO_{12-1}	MEO_{10}	GEO_{36_22}	GEO_{36_12}
Interactive data	V	V	V	V	V	V	X
Voice	V	V	V	V	V	V	X
IoT	V	V	V	V	V	V	V
AR/VR	X	X	X	X	X	X	X
Emergency Texting	V	V	V	V	V	V	X
Video Surveillance	V	X	X	X	X	X	X

4.3 Analysis of Capacity

This subsection intends to study the reference scenarios satellites and to make some variations to the capacity input parameters and the impact of it, more specifically the impact of the modulation, the bandwidth, the SCS and the impact of the satellite. Afterwards, the analysis of the traffic profiles according to the satellite and services, will be done, to measure the number of active users per service, the number of users that are possible to provide enough data rate to execute the service and also what would be the capacity needed to supply all active users in the service, and finally the percentage of active users.

The input parameters for the calculation of the capacity are given in Table 4-14, and the respective capacity offered by the cell is obtained. Analysing the capacity obtained, the higher the bandwidth and the higher the modulation used, the more capacity is offered by the system allowing more data rate or more users to use services.

Table 4-14 Calculation results of offered capacity DL.

Bandwidth [MHz]	SCS [kHz]	Modulation	Code Rate	R_{Cap} [Mbps]
5	15	QPSK	78/1024	1.10
		64-QAM	466/1024	19.75
	30	QPSK	193/1024	2.39
		64-QAM	567/1024	21.12
10	15	QPSK	78/1024	2.29
		64-QAM	466/1024	41.03
	30	QPSK	193/1024	5.23
		64-QAM	567/1024	46.08
	60	QPSK	449/1024	11.15
		64-QAM	666/1024	49.62
15	15	QPSK	78/1024	3.48
		64-QAM	466/1024	62.33
	30	QPSK	193/1024	8.28
		64-QAM	567/1024	72.96
	60	QPSK	449/1024	18.25
		64-QAM	666/1024	81.19
20	15	QPSK	78/1024	4.67
		64-QAM	466/1024	83.63
	30	QPSK	193/1024	11.11
		64-QAM	567/1024	92.92
	60	QPSK	449/1024	24.33
		64-QAM	666/1024	108.25

Considering now the values obtained for the covered area for the different satellites in Table 4-8, the model of capacity will be expressed for the different satellites to see the impact of the increase of the area covered relative to the users. In Table 4-15, one represents the reference scenario values obtained for the number of active users, depending on the activity factor of the service and the user density, the number of users possible to cover with the capacity of the system, conditional by the minimum data rate of the service and the total capacity offered, the total capacity needed if all users were to be able to utilise the service, and finally the percentage of served users.

As it is possible to infer from Table 4-15, the services that have less strict requirements in terms of data rate required are more well covered than the others, for example, voice has fewer users than IoT, yet the data requirements are higher, therefore the capacity needed to offer voice services is higher than offering IoT, with IoT having all the users covered, this is, provided with the minimum requirements to successfully utilise it.

Table 4-15 Analysis of the capacity model per service for satellite LEO06-2 with 108.25 Mbps DL.

LEO_{06-2}	$N_{Active,s}$	$N_{Users\ possible,s}$	$R_{Active\ needed}$ [Mbps]	$P_{Served\ users}$ [%]
Interactive data	5602	108	5602.9	1.9
Voice	7470	845	956.24	11.3
IoT	14941	54125	29.88	100.0
Emergency Texting	373	1082	37.35	100.0
Video Surveillance	7471	216	3735.3	2.89

In Figure 4-2, it can be seen that higher altitude and the bigger the covered area bring increasingly active users using the service, with more active users the capacity needed to provide them all with the minimum requirements to do the service also increases, which implicates that the percentage of served users tend to decrease with the increase of active user, as noticed in Figure 4-3, where it is possible to notice that the more demanding a service, the less the percentage of served users.

Analysing now the impact of using 5 MHz of bandwidth, 30 kHz as SCS, with 64-QAM modulation and code rate 567/1024, it gives us a total capacity offered by the system of 21.12 Mbps, in Table 4-16 one can see that having less capacity in the system, highly affects the percentage of served users by reducing a lot. No service is completely provided to all users, being the IoT the most served service. The capacity must be increased so this system can be used to fully provide IoT for all, so a fully connected world can be a possibility.

Finding now a mid-term between the 2 achievable capacities, using 10 MHz of bandwidth, 15 kHz as SCS, with 64-QAM modulation and code rate 466/1024, it obtained 41.03 Mbps of capacity. Doing the same analysis as before, Table 4-17 represents the values obtained. It shows that without pushing for much more capacity, it is possible to offer the total services for IoT and Emergency Texting, concluding that this approach of LEO satellites, might be a very feasible solution to provide these services.

From Figure 4-3, it was observed which services had a percentage of served users above 1% for each type of satellite, taking into consideration that the capacity was shared among all active users. For the number of possible users per service, using the minimum data rate required for each service, provided with the given capacity of 108.25Mbps. Analysing it, one can see in Table 4-18 the possible services that are provided per type of satellite.

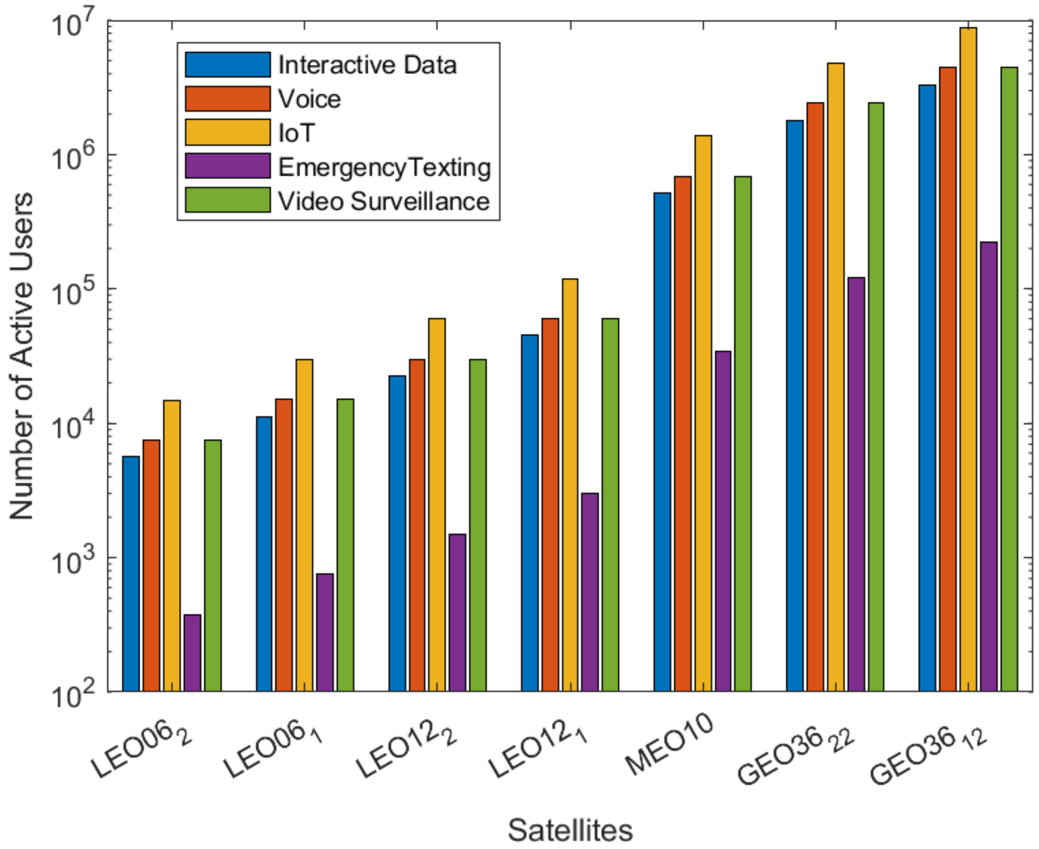

Figure 4-2 Number of active users for each service and satellite (108.25 Mbps DL).

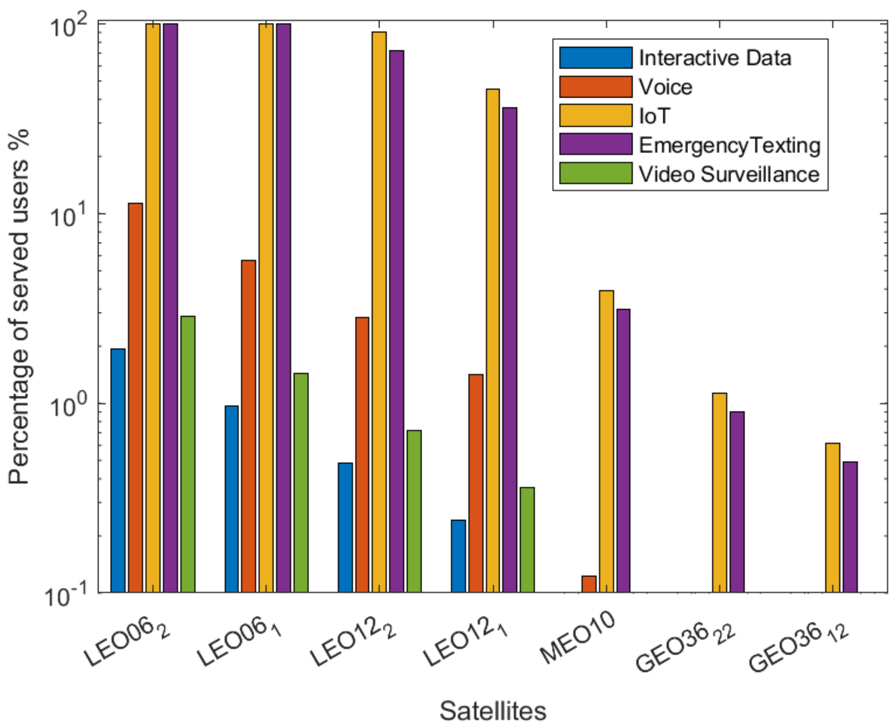

Figure 4-3 Percentage of served users for each service and satellite (108.25 Mbps DL).

Table 4-16 Analysis of the capacity model per service for satellite LEO06-2 with 21.12 Mbps DL.

LEO_{06-2}	$N_{Active,s}$	$N_{Users\ possible,s}$	$R_{Active\ needed}$ [Mbps]	$P_{Served\ users}$ [%]
Interactive data	5602	21	5602.9	0.4
Voice	7470	165	956.24	2.2
IoT	14941	10560	29.88	70.7
Emergency Texting	373	211	37.35	56.6
Video Surveillance	7471	42	3735.3	0.6

Table 4-17 Analysis of the capacity model per service for satellite LEO06-2 with 41.03 Mbps DL.

LEO_{06-2}	$N_{Active,s}$	$N_{Users\ possible,s}$	$R_{Active\ needed}$ [Mbps]	$P_{Served\ users}$ [%]
Interactive data	5602	41	5602.9	0.7
Voice	7470	321	956.24	4.28
IoT	14941	20515	29.88	100.0
Emergency Texting	373	410	37.35	100.0
Video Surveillance	7471	82	3735.3	1.1

Table 4-18 Possible services to support by type of satellite, regarding capacity.

	LEO_{06-2}	LEO_{06-1}	LEO_{12-2}	LEO_{12-1}	MEO_{10}	GEO_{36_22}	GEO_{36_12}
Interactive data	V	X	X	X	X	X	X
Voice	V	V	V	V	X	X	X
IoT	V	V	V	V	V	V	X
AR/VR	X	X	X	X	X	X	X
Emergency Texting	V	V	V	V	V	X	X
Video Surveillance	V	V	X	X	X	X	X

4.4 Analysis of Latency

The end part, the latency model, presents an analysis of the E2E latency and the impact of the satellite architecture on the latency, to guarantee that the maximum latency allowed for each service is not exceeded. This study is performed taking into account the reference scenario since this scenario is the more feasible to be practically implemented.

Regarding the input parameters, as previously said in Section 4.2, all links will be assumed to be 5 km, except the ones that connect to the satellite, the max data rate provided by the link DL and UL is obtained from the capacity model, where it is 108.25 Mbps DL and 13.012 Mbps for UL, and the packet size will be dictated by the service used.

One shows in Table 4-19 the values obtained for the total latency E2E, where it can be seen that the 3 services with lower packet size, voice, IoT and emergency texting, do not exceed the maximum latency allowed and have lower latency, whereas the interactive data and video surveillance have higher latency, this means that the bigger the packet size of the service, the higher the latency.

Table 4-19 Latency E2E regarding each service in function of the type of satellite architecture for satellite LEO06.

LEO_{06}	Total Latency E2E per service [ms]				
Type of architecture	Interactive data	Voice	IoT	Emergency texting	Video Surveillance
S-gNB	15.8	11.0	11.5	10.7	14.5
S-DU/CU	15.9	11.0	11.5	10.7	14.7
S-Core	15.1	10.8	11.2	10.5	14.0
S-Edge	6.4	4.5	4.7	4.4	5.9
S-DN	15.4	10.8	11.3	10.6	14.2
R-SAT	17.4	11.4	12.0	11.0	15.9
B-gNB-Core	15.8	11.0	11.5	10.7	14.5
B-Core-DN	15.8	11.0	11.5	10.7	14.5

By analysing further Table 4-19 in terms of the differences between satellite architectures, it can be seen that the more functionalities and flexibility there are in a satellite, which provides more functions, results in lower latency since the signal has to pass through fewer steps. Although there is an impact of latency, the latency difference is almost not impactful for the complete system, concluding that the propagation delay regarding the distance between the links, in this study between the node and the satellite, is the one that there is variation, might be the critical factor for this analysis.

Table 4-20 defines the total latency obtained, for the same parameters of the reference scenario except that the altitude is 1200 km, can be seen that the altitude particularly impacts the latency, although the conclusions taken from Table 4-19, regarding the services provided maintain the same.

Table 4-20 Latency E2E regarding each service in function of the type of satellite architecture for satellite LEO12.

LEO_{12}	Total Latency E2E per service [ms]				
Type of architecture	Interactive data	Voice	IoT	Emergency texting	Video Surveillance
S-gNB	23.8	19.0	19.5	18.7	22.6
S-DU/CU	23.9	19.0	19.5	18.7	22.7
S-Core	23.1	18.8	19.2	18.5	22.0
S-Edge	10.4	8.5	8.7	8.4	9.9
S-DN	23.4	18.8	19.3	18.6	22.3
R-SAT	25.4	19.4	20.0	19.0	23.9
B-gNB-Core	23.8	19.0	19.5	18.7	22.6
B-Core-DN	23.8	19.0	19.5	18.7	22.6

As far as it concerns MEO and GEO satellites, with a higher altitude the latency increases, therefore, in Table 4-21 and 4-22, these 2 satellite orbits due to the latency requirements are much more limited than LEO.

To be feasible to provide services that exceed the maximum allowed latency, it must use an MEC node, offloading computational tasks to this edge, eliminating the need for the data to travel back and forth between the UE and the DN, the drawback being that not all interactive data applications can use the MEC so even though there is this measure to be able to provide interactive data services, not all applications can be used.

In the theme of the MEC node, the voice service involves the exchange of information between UEs, however in this case the role of the MEC is not to replace end-to-end communication between UEs, but to optimise the process, by doing local processing of information that is not needed to go back and forth, this way reducing the latency processing information in nodes deeper in the network. Also, can support the deployment of applications with voice-driven functionalities, such as, virtual assistants.

Table 4-21 Latency E2E regarding each service in function of the type of satellite architecture for satellite MEO.

MEO_{10_6}	Total Latency E2E per service [ms]				
Type of architecture	Interactive data	Voice	IoT	Emergency texting	Video Surveillance
S-gNB	141.1	136.3	136.8	136.0	139.9
S-DU/CU	141.2	136.3	136.9	136.0	140.0
S-Core	140.4	136.1	136.6	135.9	139.4
S-Edge	69.1	67.2	67.4	67.0	68.6
S-DN	140.7	136.2	136.7	135.9	139.6
R-SAT	142.8	136.7	137.3	136.3	141.3
B-gNB-Core	141.1	136.3	136.8	136.0	139.9
B-Core-DN	141.1	136.3	136.8	136.0	139.9

Table 4-22 Latency E2E regarding each service in function of the type of satellite architecture for satellite GEO.

GEO_{36}	Total Latency E2E per service [ms]				
Type of architecture	Interactive data	Voice	IoT	Emergency texting	Video Surveillance
S-gNB	484.9	480.1	480.6	479.8	483.7
S-DU/CU	485.1	480.2	480.7	479.9	483.9
S-Core	484.2	479.9	480.4	479.7	483.2
S-Edge	241.0	239.1	239.3	238.9	240.5
S-DN	484.6	480.0	480.5	479.7	483.4
R-SAT	486.6	480.5	481.1	480.1	485.1
B-gNB-Core	484.9	480.1	480.6	479.8	483.7
B-Core-DN	484.9	480.1	480.6	479.8	483.7

Firstly, for the MEO satellites, one can see that due to the size of the processing needed for each service being different, the services with less packet size and where the latency is not as limiting, being these. IoT and Video surveillance, are the only 2 services that are able to be provided with all types of architecture. Regarding types of architecture, the S-Edge is without contest the architecture that enables more services in a MEO satellite. Regarding the GEO satellite orbit, one can see that it is impossible to provide any type of service, due to the very high latency obtained, with a uniquely exception, for the IoT service that can be provided with the Edge on the satellite, being the only available option in this case that is feasible this service regarding this satellite.

Table 4-23 shows the services that are able to be provided in terms of latency constraints.

Table 4-23 Possible services to support by type of satellite, regarding latency.

	LEO_{06-2}	LEO_{06-1}	LEO_{12-2}	LEO_{12-1}	MEO_{10}	GEO_{36_22}	GEO_{36_12}
Interactive data	V	V	V	V	X	X	X
Voice	V	V	V	V	V	X	X
IoT	V	V	V	V	V	V	V
AR/VR	X	X	X	X	X	X	X
Emergency Texting	V	V	V	V	V	X	X
Video Surveillance	V	V	V	V	V	X	X

4.5 General Analysis

Considering all the analysis carried out previously in terms of coverage, capacity and latency, it is possible to develop an analysis regarding the suitable satellites, on how the services can be provided.

Regarding the limitations noticed by this model, one can conclude that the possible services achieved with the configured parameters are given by Table 4-24 where it is achieved by the combination of all 3 models conclusion. It can be seen that the only satellite that is able to provide Interactive data and Video Surveillance is LEO_{06-2}, being the satellite of the reference scenario and also the most appropriate for high data services.

Nowadays, as said earlier in the thesis, the most appealing constellations of satellites are all using LEO satellites, and by the full analysis of this thesis, one can see that, in fact, these types of satellites are the most fulfilling in terms of provided services, although it would be needed much more satellites to cover the whole Earth, whereas 3 GEO satellites would suffice for full-coverage in terms of beamwidth, in fact the limitation in GEO satellites is, in fact, in the capacity and UL link constraint as seen from Table 4-13 and 4-18.

Table 4-24 General possible services to support by type of satellite.

	LEO_{06-2}	LEO_{06-1}	LEO_{12-2}	LEO_{12-1}	MEO_{10}	GEO_{36_22}	GEO_{36_12}
Interactive data	V	X	X	X	X	X	X
Voice	V	V	V	V	X	X	X
IoT	V	V	V	V	V	V	X
AR/VR	X	X	X	X	X	X	X
Emergency Texting	V	V	V	V	V	X	X
Video Surveillance	V	X	X	X	X	X	X

For GEO_{36_22} the capacity limitation, having 100 Mbps it can only achieve around 1% of served users for IoT, meaning that it would need one hundred times more capacity for it to cover 100% of the active users, that is, having 10 Gbps of capacity, thus enabling the use of this satellite for this type of service.

Doing this study for the other satellites, one can see that from LEO to GEO it is linearly descending regarding the percentage of served users, having each satellite with the same capacity offered depends only on the altitude of the satellite, which means, it depends on the area covered by the satellite resulting in more or less users to provide services.

Analysing further it is concluded that with these configurations the only services that are successfully provided with almost 100% of covered users and satisfactory performance are IoT and Emergency Texting, using LEO satellites. Checking the solutions to provide the full services using LEO_{06-2}, according to Table 4-15, it would be needed 50 LEO_{06-2} satellites with 108 Mbps each, or 1 LEO_{06-2} with a capacity of 5.4 Gbps, to provide the capacity needed to fully provide Voice.

Finally, it is possible to conclude that LEO satellites are in fact the most effective satellites for high-demanding services and the ones that can provide in theory all services, although with some adaptations and restrictions. Whereas the GEO satellites are extremely limited in what they can provide, the extremely high latency makes it impossible to provide any other service except for IoT, where it can provide it, with the exclusive use of the Edge in the satellite. The GEO satellites are also much more difficult to put in orbit, making it not the most appealing satellite for mobile communications services.

About MEO, one would expect that it would be an intermediate choice, facing advantages and disadvantages from both of the other satellites but in fact, MEO ends up having a lot more disadvantages than it is worthwhile. It has remarkably high latency and since the altitude is also much higher, the covered area increases by a lot, resulting in a high increase of capacity to provide the services.

In conclusion, LEO satellites might be the sweet spot for 5G satellite communications.

Chapter 5

Conclusions

This chapter finalises this work, summarising conclusions in each of the previous chapters.

The main objective of this thesis was to study the inclusion of Non-Terrestrial Components in the 5G Network. To assess the impact of Non-Terrestrial Network (NTN) elements on coverage, capacity, and latency in 5G NTN networks, a simulation model was developed. This model allows for the analysis of various scenarios by adjusting input parameters. Several simulations were made, to understand the impact and behaviour of the network, in terms of the type of architecture, altitude, antenna, and bandwidths, among others. The end reference scenario for the appropriate implementation was an LEO satellite, which contains several information worldwide according to numerous LEO constellations that can complement. Although it was analysed MEO and GEO satellites as well to see the behaviour of the Network.

Chapter 1, Introduction, briefly presents a summary of the current state of 5G Terrestrial Mobile Communications and a brief introduction to NTN, of what can it bring and also some limitations. Further in the chapter, the motivation behind the development of this thesis is established and to conclude the objective and content of this thesis is presented.

Chapter 2, Fundamental Concepts and State of the Art, presents the basic concepts regarding systems and mechanisms under study for 5G that are important to understand the context in which the model was developed. It starts by presenting the standalone and non-standalone versions of 5G, the network architecture and network functions. A subchapter featuring network virtualisation and slicing, explains that this feature reduces the physical network resources and helps in a more efficient use of the available network resources. The cloud and edge networking are useful technologies in terms of latency reduction since they move the resources closer to the end user. The radio interface is studied to better understand how the 5G is conducted, followed by the services and applications requirements in a 5G communication network. The fourth section goes into detail on the NTN networks, what they are, how they work, several types of components, some feature comparisons and use cases and goes into detail on the type of architectures has in terms of the complexity of the satellite in the network. To conclude, the state of the art is presented at the end of the chapter, summarising relevant information that goes into the study of this thesis.

Chapter 3, Models and Simulator Description, presents an overview of the model and its requirements, followed by a detailed description of the development of the model, namely its mathematical formulation to achieve the goals of this work, as well as in which sub-model they are framed, between latency, coverage and capacity. Subsequently, the description of the model implementation. With the assessment of the model at the end of the chapter.

For the latency sub-model, the satellite can be deployed using diverse types of architectures, depending on the complexity and functions of the satellite. The latency is further analysed from an individual viewpoint of links and nodes, in terms that it clearly explains each latency impact being calculated in the model, and how it all comes together to impact the E2E latency. Regarding the coverage sub-model, it is analysed the covered area regarding altitude and antenna, and also path loss and power that will affect the throughput, and the maximum distance of the link. Finally, the capacity sub-model is studied in order to understand its impact and limitations for the users. A sub-chapter explains the implementation of the model, using flowcharts to better understand the program workflow and to end the model assessment is performed, checking if the model is working as intended.

Chapter 4, Results Assessment, provides the analysis of the results obtained as the outputs of the model. It starts by describing the output parameters used for the end analysis, with the description of the scenarios parameters values, and input parameters for the different sub-models.

In Section 4.2, for the analysis of coverage, one can see the impact of the satellite altitude, antenna diameter, power transmitted, gain of receiver and transmitter and data rate required per service, in terms of area covered and maximum distance of the link, being clear that the higher the altitude the larger the area covered. As for the antenna diameter, the higher the diameter is, the more directed the signal is therefore the area covered is smaller and the maximum distance of the link is higher. Analysing further, it is possible to infer that the more data rate is required, depending on the service, the less the maximum distance of the link DL obtained, which is due to characteristics of the signal degradation. For the UL since the UE has more restrictive configurations, it can be concluded that the limitations for this system are in the UL, where there are cases in which it is impossible to make a UL connection. The results obtained in this section show at the end the possible services supported by each type of satellite.

In Section 4.3, in the analysis of the capacity, it can be studied the influence of the bandwidth, SCS, modulation and code rate, in the capacity offered for the system. Clearly, with higher bandwidth, higher SCS, and code rate, it can be seen that the capacity obtained increases, with the maximum capacity obtained being 108.25 Mbps The results obtained are presented in terms of the number of active users, number of possible users, the capacity needed in case of providing all users, and the percentage of users that are possible to provide the data rate required. Being IoT and Emergency Texting the less demanding services in terms of data rate, these services are also the most easily provided, with a close 100% success for LEO satellites using the reference scenario capacity parameters inputs. Whereas the more demanding services are not able to be provided. It is also shown that the higher the altitude, the less percentage of users are provided with services since the capacity does not increase.

For Section 4.4, regarding latency analysis, the study of the different impacts of the diverse types of architectures can be seen, where the LEO satellites for the 2 different altitudes are worth mentioning as suitable for all services in terms of latency restraints, and the choice of the architecture, in this case, must be done taking into account another criterion. For the MEO satellite orbit, the IoT service can be provided with all architectures, whereas Voice and Emergency Texting can only be provided by the edge in the satellite, S-Edge, being the only architecture that respects the minimum latency required to provide these services. For the extreme case, GEO satellites, being the most concerning regarding latency purposes due to being so far away, distance-wise, it is concluded that the only solution that can be used in GEO are IoT services and specifically using S-Edge architecture.

Finally, a last section where the conjunction of all other studies are carried out, and it shows the possible services per satellite, also adding some possible solutions to provide better performance.

While implementing a realistic mobile communication network with satellite integration presents significant complexity, the results of this study demonstrate, from the multitude of parameters that affect the overall network performance, that the choice of space and telecom architecture have a significant impact in the quality of service achievable. This is crucial because it directly affects the potential services offered and, consequently, the overall return on investments (Profit and Loss) for such projects.

While this thesis focused on the technical complexities of integrating satellites into mobile networks, the potential social impact is immense. Imagining the lives transformed where everyone gains access to education, healthcare, entertainment, and economic opportunities through reliable satellite communication. This research, by pinpointing the critical role of space and telecom architectures in achieving optimal service quality, paves the way for cost-effective and efficient NTN networks that can bridge the digital divide and empower these underserved communities worldwide.

For this reason, it is concluded that although satellite communications are a very interesting topic, with the high technology development regarding terrestrial networks, it would be most useful and effective to use satellite communications to provide services in remote areas with few users and where there are not terrestrial networks, or to help terrestrial networks when they are down.

Regarding future work, it would be interesting to analyse inter-link satellites and cloud-edge satellites in terms of NTN-only components in the network. Also, with the set of challenges and opportunities with the integration of NTN, as the boundaries of connectivity are pushed farther, managing the interference between TN and NTN systems becomes paramount and worth the study. The allocation of resources in heterogeneous networks requires innovative approaches, where artificial intelligence mechanisms can offer solutions for the management of this networks. Also, artificial intelligence can upscale and optimise the network when it comes to coverage, capacity, and routing across vast constellations of small satellites, bringing possibly a new era in communication, promising unparalleled access and efficiency in data transmission.

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