وزارة التعليـــم العــالي والبحــث العلمـــي وزارة البريد والمواصلات السلكية واللاسلكية

المدرسة الوطنية العليا للاتصـالات السلكية و اللاسلكية و تكنولوجيات الإعلام و الاتصـا ل -عبد الحفيظ بوصوف -

ÉCOLE NATIONALE SUPÉRIEURE DES TÉLÉCOMMUNICATIONS ET DES TECHNOLOGIES DE L'INFORMATION ET DE LA COMMUNICATION -Abdelhafid Boussouf-

Non-Terrestrial Networks (NTN) and future mobile networks.

Par Mwawasi Holliness Julai

IGE 44

Département des Enseignements en Spécialité, Post-Graduation et Recherche

Mémoire présenté
en vue de l'obtention du diplôme D'ingénieur d'État en télécommunications

Option : Systèmes de télécommunications

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Non-Terrestrial Networks (NTN) and future mobile networks.

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الملخص

ان القوة الدافعة الرئيسية التي كانت وراء تطور شبكات الاتصالات هي القدرة. مع اشتراك المزيد من المستخدمين في الشبكات الحالية ، يجب أن يتطوروا لتلبية هذه الحاجة. تطورت احتياجات المستهلكين على مر السنين وأصبحت أكثر تعقيدا ، لا يرغب الناس في التواصل فحسب ، بل يرغبون أيضا في الحصول على اتصال جيد النوعية. يمكن أن يكون الاتصال الجيد من حيث السرعة أو الموثوقية أو الراحة. يرغب المستهلكون في الوقت الحاضر في حمل أعمالهم المكتبية وألعاب الفيديو والتطبيقات الأخرى معهم أينما كانوا ، مما يؤدي إلى مفهوم النطاق العريض المتنقل. هذه الحاجة إلى الاتصال على الرغم من أن الموقع قد كشف عن قيود الشبكات الأرضية.
بقدر ما هو الحال مع أجيال شبكات الهاتف المحمول الحالية مثل معدلات البيانات العالية جدا G5 وسعة الشبكة التي تم تحقيقها ، فإنها تقتصر على المناطق التي يمكن فيها إعداد البنية التحتية للشبكة. هذا يجعل المناطق الجبلية والنائية بعيدة عن متناول تغطية الشبكة لأنه من المستحيل الاعداد ...
أدى هذا التطور الى تفضيلات المستهلكين في مفهوم وجود شبكات متصلة عالميا. بغض النظر عن موقع المستخدم سواء في الصحراء ، أو في إجازة في البحر حتى في الطائرة ، مع شبكة عالمية ، سيكونون دائما متصلين. ولما كانت السواتل بارزة لقدرتها على تغطية مناطق جغرافية واسعة ذات بنية تحتية أرضية محدودة ، فإنها أداة لا غنى عنها في إنشاء مثل هذه الشبكة.
بدأت الجهود المبذولة لدمج الأقمار الاصطناعية والأجهزة المحمولة جوا الأخرى في أواخر القرن العشرين وحدث أول إدراك لهذه الفكرة مع NTN G 5. بقدر ما سيمنح هذا العقد الحالي من الجيل الخامس المحمول تدريجيا المزيد من استخدام الأقمار الاصطناعية والأجهزة المحمولة جوا ، المتوقع أن يتم تحقيق شبكة موحدة بالكامل في G6. وهذا يعني أن مستقبل الاتصالات السلكية واللاسلكية وخاصة (شبكات الهاتف المحمول البرية العامة) PLMN سيشمل من NTN G5 من الآن فصاعدا الأجهزة الفضائية / المحمولة جوا ، مما يؤدي إلى ولادة تقنية جديدة مع تسمية الشبكات غير الأرضية (NTN).

الكلمات المفتاحية:
الشبكات غير الأرضية، الشبكات الأرضية، الشبكات المتنقلة، الأجهزة الفضائية / المحمولة جوا الساتلية، منصة NT

Summary.

The main driving force behind the evolution of telecommunication networks has been capacity.
As more users subscribe to existing networks, they must evolve to accommodate this need. Over the years consumer needs have evolved and become more complex, people no not only desire to communicate but also to have a good quality communication. A good quality communication can be in terms of speed, reliability or convenience. Presently consumers have the desire to carry with them their office work, video games and other applications wherever they are thus leading to the concept of mobile broadband. This need to be connected despite the location has exposed the limitations of terrestrial networks. As much as with current mobile network generations like the 5G very high data rates and network capacity have been achieved it is limited to areas where the network infrastructure can be set up. This makes mountainous and remote regions out of reach for network coverage as it is impossible to set up base stations in these areas.
This evolution in consumer preferences has led to the concept of having globally connected networks. No matter the position of a user whether in the desert, or on vacation in the sea even in an aircraft, with global network they will always be connected. Satellites being prominent for their ability to cover large geographical areas with limited ground infrastructure makes them an indispensable tool in the realization of such a network. Efforts to integrate satellite sand other airborne devices started in the 2000s and the first realization of this idea happened with the 5G NTN. As much as this current decade of the fifth-generation mobile will gradually accord more use of satellites and airborne devices, a fully unified network is expected to be achieved in the 6G. This means that the future of telecommunications and especially (Public Land Mobile networks) PLMN will from the 5G NTN henceforth include space/airborne devices, leading to the birth of a new technology with the appellation Non-terrestrial Networks (NTN).

Keywords: Non-terrestrial networks, terrestrial networks, mobile networks, satellites space/airborne devices, NT platform.

Résumé

La principale force motrice de l'évolution des réseaux de télécommunications a été la capacité. Au fur et à mesure que de plus en plus d'utilisateurs s'abonnent aux réseaux existants, ils doivent évoluer pour répondre à ce besoin. Au fil des ans, les besoins des consommateurs ont évolué et sont devenus plus complexes, les gens veulent non seulement communiquer mais aussi avoir une bonne communication de qualité. Une bonne communication de qualité peut être en termes de vitesse, de fiabilité ou de commodité. À l'heure actuelle, les consommateurs ont le désir de porter leur travail de bureau, leurs jeux vidéo et d'autres applications partout où ils mènent ainsi au concept de la large bande mobile. Ce besoin de connexion malgré l'emplacement qui a exposé les limites des réseaux terrestres. En ce qui concerne les générations actuelles de réseaux mobiles comme la 5G, les taux de données et la capacité de réseau très élevés ont été atteints, ceci est limité aux domaines où l'infrastructure de réseau peut être mise en place. Cela rend les régions montagneuses et éloignées hors de portée pour la couverture du réseau, car il est impossible de mettre en place des stations de base dans ces zones.

Cette évolution des préférences des consommateurs a conduit au concept d'avoir des réseaux connectés à l'échelle mondiale. Peu importe la position d'un utilisateur, que ce soit dans le désert, ou en vacances en mer, même dans un avion, avec le réseau mondial, ils seront toujours connectés. Les satellites étant importants pour leur capacité à couvrir de vastes zones géographiques avec des infrastructures terrestres limitées, ils constituent un outil indispensable dans la réalisation d'un tel réseau. Des efforts pour intégrer le sable satellite à d'autres appareils aériens ont commencé dans les années 2000 et la première réalisation de cette idée s'est produite avec le 5G NTN. Dans la mesure où cette décennie actuelle de la cinquième génération de téléphonie mobile accordera progressivement plus d'utilisation de satellites et de dispositifs aériens, un réseau totalement unifié devrait être atteint dans la 6G. Cela signifie que l'avenir des télécommunications et en particulier (réseaux publics terrestres mobiles) PLMN, à partir de la 5G NTN comprendra désormais des dispositifs spatiaux / aériens, conduisant à la naissance d'une nouvelle technologie avec l'appellation Réseaux non terrestre (NTN).

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List of abbreviations

The following is the list of acronyms as used in this document and their full meanings organized in alphabetic order.

1G: First Generation.

2G: Second Generation.

3G: Third Generation.

3GPP: 3rd Generation Partnership Project.

4G: Forth Generation.

5G: Fifth Generation.

5GC: Fifth Generation Core.

ACM: Adaptive Modulation and Coding.

AI: Artificial Intelligence.

BSC: Base Station Controller.

BSS: Broadcasting Satellite Services.

CDMA : Code Division Multiple Access.

CN: Core Network.

CSFB: Circuit Switched Fallback.

D-AMPS: Digital Advanced Mobile Phone System.

EDGE: Enhanced Data for Global Evolution.

eMBB: Enhanced Mobile Broadband.

EPC: Evolved Packet Core.

EPS: Evolved Packet System.

EUTRAN: Evolved UTRAN.

FDD: Frequency Division Duplexing.

FDMA: Frequency Division Multiple Access.

FM: Frequency Modulation.

FR 2: Frequency Range two.

FR: Frequency Range.

FR1: Frequency Range one.

FSS: Fixed Satellite Services.

GEO: Geostationary Earth Orbit.

GHz: Gigahertz.

GMR: GEO Mobile Radio.

GPRS: General Packet Radio Service.

GSM: Global System for Mobile Communications.

GSMA: GSM Association.

TDL: Tapped Delay Line.

HAPSs: High Altitude Platforms.

HARQ: Hybrid Automatic Repeat Request.

HDTV: High-Definition Television.

HetNet: Heterogeneous Network.

HLR: Home Location Register.

HSPA: High Speed Packet Access.

INMARSAT: International Maritime Satellite.

IoT: Internet of Things.

IP: Internet Protocol.

IS-95: Interim Standard 95.

ISL: Inter-Satellite Link.

ITU: International Telecommunication Union.

ITU: International Telecommunication Union.

Kbps: Kilobytes per second.

LEO: Low Earth Orbit.

LMDS Local Multipoint Distribution Systems.

LTE: Long-Term Evolution.

MBMS : Multimedia Broadcast Multicast Service.

Mbps: Megabytes per second.

MEO: Medium Earth Orbit.

MHz: Megahertz.

MIMO: Multiple Input Multiple Output.

ML: Machine Learning.

mMTC: Massive Machine Type Communications.

MNO: Mobile Network Operators.

MSC: Mobile Switching Center.

MSS: Mobile Satellite Services.

NFV: Network Function Virtualization.

NFV: Network Functions Virtualization (NFV).

NG-RAN: Next Generation Radio Access Network.

NGSO: Non-Geostationary Orbit.

NR :NR: New Radio.

NSA :NSA: Non-Standalone.

NTN: Non-Terrestrial Network.

OFDM: Orthogonal Frequency Division Multiplexing.

OFDMA: Orthogonal Frequency Division Multiple Access.

PAMR: Public Access Mobile Radio.

PLMN: Public Land Mobile Networks.

PMR: Private/Professional Mobile Radio.

QoS: Quality of Service.

RAT: Radio Access Technology.

SA : Standalone.

SAE: System Architecture Evolution.

SC-FDMA: Single Carrier FDMA.

SDMB: Satellite-Digital Multimedia Broadcasting.

SDN: Software Defined Network.

SDN: Software-Defined Networking.

SMS: Short Message Service.

SNR: Signal to Noise Ration.

SON: Self Organizing Network.

SRI: Satellite Radio Interface.

TDD: Time Division Duplexing.

TDMA: Time Division Multiple Access.

TN: Terrestrial Network.

UAV: Unmanned Aerial Vehicles.

UE: User Equipment.

UMTS: Universal Mobile Telecommunications Service.

URLLC: Ultra-Reliable Low Latency Communications.

UTRAN: UMTS Terrestrial Radio Access Network.

VoLTE: Voice Over LTE.

VSAT: Very Small Aperture Terminal.

WCDMA: Wideband CDMA.

WLL: Wireless Local Loop.

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General Introduction

The objective of this project is to expose the significant role that air/space-based platforms have in future telecommunication networks. Ubiquitous coverage is quickly becoming a priority for mobile subscribers and thus pushing mobile networks to evolve. Despite the monumental achievements that can be clearly noted in earth-based communication networks, they cannot evolve beyond their nature. Terrestrial networks are limited in terms of coverage and deployment of network infrastructure in areas that are geographically unreachable. Having a base station high above the ground increases the range of view allowing more subscribers to be covered by one base station. Outsourcing satellite networks, which are known for their high altitude, is an inevitable step in the quest to satisfy user needs. Satellite systems have limitations just like earth-based networks, but the two independent systems can be combined to form a hybrid network that will be able to meet consumer demands.

In 2019 the third-generation partnership project (3GPP) released a technical specification report on new radio to support non terrestrial networks. This study covers the necessary adaptations to 3GPP channel models to accommodate air/space-based platforms. The above-mentioned study forms the basis from which uncountable researches and tests have been built up to date on this subject.

This work will cover and overview of mobile networks and satellite communications outlining the evolution, achievements and limitations of both systems. The second chapter will discuss non-terrestrial networks, as much it is a technology that has existed independently over the years, it is being redefined to represent the revolutionary integration between mobile networks and satellite communications. This new technology builds on the existing use cases 3GPP technologies while potentially introducing futuristic applications like holograms. Although there are still some crucial technological advancements to be made in order for these two systems to be fully integrated, the future is optimistic as a fully unified network is predicted for 2030.

The last chapter covers the practical work of an NTN channel model that will illustrate a communication link between an NTN terminal on earth and an air/space-based platform on different altitudes. The received signal will be observed under different environments for example urban, rural or rural wooded. It will be observed that the signal is better in remote environments as compared to an urban setting and NTN terminal that is stationary has a better reception than one that’s not.

Chapter 1

Overview of Mobile Networks and Satellite Communications.

1 Overview of Mobile Networks and Satellite Communications

1.1 Mobile networks

Mobile wireless systems are indispensable in today's world where the need of connectivity grows with every passing moment. A mobile network, though complex, can be simply defined as a network where the link between terminal nodes is wireless or non-material. Electromagnetic waves are responsible for this connection. Mobility and wireless though similar concepts refer to different types of communications systems. A mobile network or communication system offers the user the ability to be connected to the network despite movement from one point to another. A wireless system doesn't mean mobile, it provides a fixed or portable endpoint with access to a distributed network

Despite the different types of mobile networks for example Private/Professional Mobile Radio (PMR), Public Access Mobile Radio (PAMR), Aeronautics, Maritime and Military based mobile systems, this project is going to refer to Public Land Mobile Networks (PLMN). In this document reference to Mobile Networks will imply PLMNs unless stated otherwise.

In order to increase capacity, public commercial mobile networks are deployed in a cellular structure ranging from Macro cells up to femto-cells achievable in the fifth-generation networks. The diagram below shows the cellular structure where the cells are hexagonal.

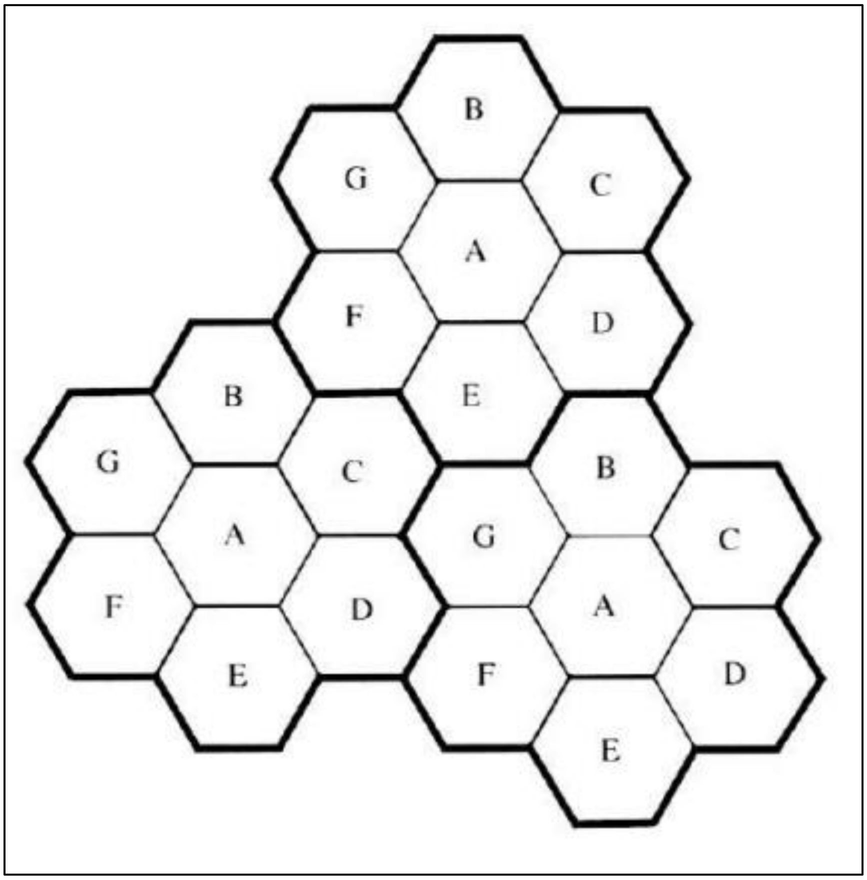


Figure 1: Cell structure [31].

1.1.1 Evolution of Mobile Networks

The evolution of public commercial mobile networks can be credited to the 3rd Generation Partnership Project (3GPP), with a consistent pattern emerging over the past four decades: the emergence of a new standard roughly every ten years, from the first generation in the 1980s to the fifth generation in 2020. Throughout this period, mobile wireless communication devices have undergone a remarkable transformation, becoming smaller and more affordable while simultaneously increasing in complexity and functionality, thus fueling their widespread adoption. Concurrently, advancements in Internet technology have fueled a substantial increase in network traffic, resulting in higher data rates. The ever-growing demand for larger network capacity and faster speeds has remained the primary driving force behind the evolution from one generation of mobile networks to the next.

1G

The first Generation of mobile networks which existed in the 1980s was completely analog deployed in different parts of the world in different standards. They offered voice services and low rate of about 9.6kbps circuit switched services and used Frequency Modulation (FM) for radio transmission. 1G mobile networks had limitations like the incompatibility of standards from different parts of the globe and obvious constraints in the services offered, while provoked the development of second-generation network. 1G networks are no longer in use in today’s world.

2G

The dawn of the digital era saw the emergence of 2nd generation networks, boasting greater bandwidth than their 1G predecessors. This enhancement enabled a broader range of services, including SMS and improved voice capabilities. Notable among these 2G systems were Global System for Mobile Communications (GSM), Digital Advanced Mobile Phone System (D-AMPS), and Interim Standard 95 (IS-95, known as cdmaOne). GSM 900, operating at 900 MHz, gained widespread adoption across Europe, North Africa, the Middle East, East Asia, and Australia. Expansion to GSM at 1800MHz and 1900MHz further facilitated global connectivity, while the availability of three-band handsets (900, 1800, and 1900 MHz) enabled seamless worldwide roaming.

Initially, 2G networks employed technologies like Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). Later, the introduction of CDMA played a crucial role in enabling a smooth transition to 3G. Another notable advancement in 2G was the introduction of General Packet Radio Service (GPRS), marking the advent of packet data and enabling mobile internet access. Often referred to as 2.5G, GPRS paved the way for Enhanced Data for Global Evolution (EGDE), offering improved efficiency and data rates at least three times faster than GPRS, hence earning the designation 2.75G.

The open architecture of GSM was a key feature, allowing maximum independence between network elements such as Base Station Controller (BSC), Mobile Switching Center (MSC), and Home Location Register (HLR). This approach streamlined system development, testing, and implementation, while facilitating an evolutionary growth path. The modular design of network elements ensured that modifications to one component had minimal or no impact on others, promoting scalability and adaptability.

The innovative features introduced by 2G networks laid a robust foundation for subsequent generations, shaping the evolution of mobile telecommunications.

3G

The deployment of the third generation of mobile networks has primarily followed two paths globally. The first path pertains to the extensively deployed GSM networks, which utilize Universal Mobile Telecommunications System (UMTS) WCDMA technology for 3G services. The second path applies to TDMA/D-AMPS and CDMA One networks, employing CDMA2000 to achieve 3G capabilities, particularly in existing CDMA networks across Asia and the US. While voice services and basic mobile internet were available in previous generations, the widespread demand for internet access has driven an increased need for multimedia data services.

Transitioning to WCDMA access technology necessitated the deployment of new base stations and the allocation of new frequencies. In 3G networks, the base station, known as the nodeB, along with the Radio Network Controller, forms the UMTS Terrestrial Radio Access Network (UTRAN). The adoption of higher frequencies compared to GSM systems—such as 900MHz in GSM and 2100MHz in UMTS—resulted in reduced cell sizes, increased capacity, and higher transmission speeds.

UMTS has undergone significant enhancements, offering broadband speeds surpassing its original design. These high-speed improvements are known as High-Speed Packet Access (HSPA). With UMTS, users can enjoy multimedia services on their mobile devices, including video streaming. With downlink speeds of up to 82 Mbps and uplink speeds of up to 11 Mbps, 3G networks are well-equipped to support these services. One notable distinction of 3G systems compared to 2G systems is the hierarchical cell structure designed to accommodate a wide range of multimedia broadband services across various cell types, utilizing advanced transmission and protocol technologies. The following figure shows the architecture of 3G and 2G and how they are interconnected to serve the Mobile Station (MS).

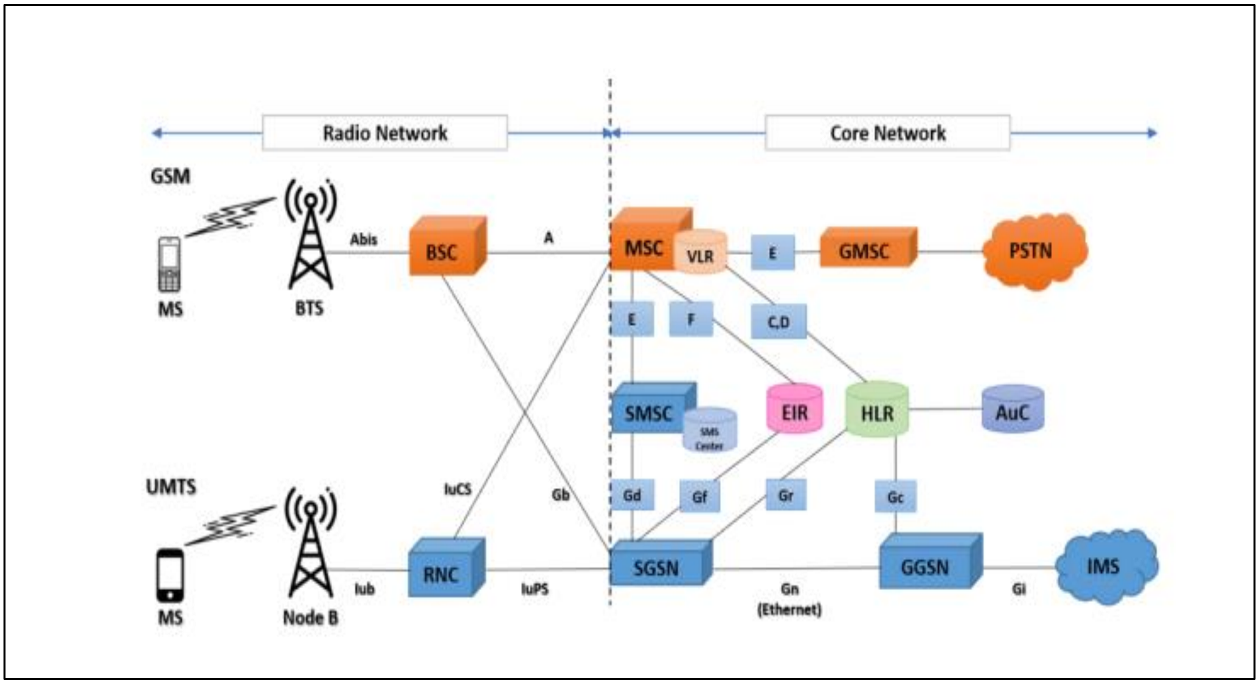


Figure 2 UMTS architecture connected with GSM [11]

3G networks represent a pivotal milestone in telecommunications, providing an advanced platform for delivering diverse multimedia services while ensuring efficient utilization of network resources and improved user experience.

4G

The evolution of Long-term Evolution (LTE), also known by its commercial name 4G, was driven by the need to have Internet-based services that were otherwise available at home via "fixed Broadband," on a mobile device, leading to the development and optimization of the concept "Mobile Broadband."

LTE does not meet the criteria of a true 4th generation network, so the term 4G is incorrect. It would be more accurate to refer to it as 3.99G. The true 4G access network, according to ITU-R, will be the successor to LTE: LTE Advanced. However, for obvious marketing reasons and to facilitate discussion, the term 4G is indeed used to refer to the network: LTE + Evolved Packet Core (EPC) = EPS.

The architecture of 4G consists of the main blocks and interfaces of this technology, namely the User Equipment (UE), radio interface (LTE-Uu), the Radio Access Network RAN, and the Core Network CN. There has been a general evolution in the 3GPP network architecture, System Architecture Evolution, that led to a new RAN with a single eNodeB node Evolved UTRAN (EUTRAN) and also a new core network architecture (Evolved Packet Core) in LTE. 4G uses a flat IP architecture, which allows devices to be identified using symbolic names, unlike the hierarchical architecture used in "normal" IP addresses. This system architecture is of greater interest to high-speed mobile network operators. 4G offers frequency flexibility ranging from 1.4 MHz up to 20 MHz for 4G, 20-100 MHz for 4.5G, and 4.75G. LTE has introduced many new technologies aimed at enhancing efficiency in spectrum utilization and providing the high data rates demanded by users.

1. Orthogonal Frequency Division Multiplexing (OFDM): LTE employs OFDM signals, enabling data transmission across parallel channels with orthogonal subcarriers. This architecture maximizes spectrum utilization and enhances resilience to radio interference.
2. Orthogonal Frequency Division Multiple Access (OFDMA): OFDM also serves as the basis for OFDMA, facilitating simultaneous separate frequency transmissions to and from multiple terminals. OFDMA operates in the downlink, while Single Carrier Frequency Division Multiple Access (SC-FDMA) is utilized in the uplink, with each subcarrier possessing a bandwidth of 180 kHz.
3. IP data: LTE operates as a fully IP-based network, with Voice over LTE (VoLTE) employed for voice transmission.
4. SAE: The term "SAE" refers to the System Architecture Evolution, encompassing the evolution of non-radio aspects such as the Evolution Packet Core network (EPC).
5. MIMO: Multiple Input Multiple Output (MIMO) technology, utilizing multiple antennas for transmission and reception, enhances signal quality and improves the signal-to-noise ratio (SNR).

   In terms of performance, 4G networks can deliver speeds of up to 100 Mbps for mobile connections and 1 Gbps for fixed or immobile connections. These ultra-high speeds enable a wide range of applications, including high-speed internet access, data-intensive user services, multi-user video conferencing, location-based services, telemedicine, HDTV streaming, on-demand high-definition video, video gaming, and telephony via VoLTE or Circuit Switched Fallback (CSFB).

5G

The advent of 5G marks the fifth generation of mobile networks, made possible by the innovative technology known as New Radio (NR). Currently, 5G exists in two distinct forms: non-standalone 5G (5G NSA) and standalone 5G (5G SA). Non-standalone 5G integrates 5G radio networks with existing 4G core networks (EPC - Evolved Packet Core), constituting the prevalent deployment mode of 5G thus far. Conversely, standalone 5G (5G SA) represents a comprehensive end-to-end 5G network architecture, utilizing 5G radios at the edge and a dedicated 5G core. Unlike its non-standalone counterpart, standalone 5G offers all the anticipated benefits of 5G without the constraints of 4G infrastructure. The two ways of deploying the 5G networks are illustrated in the figure below.

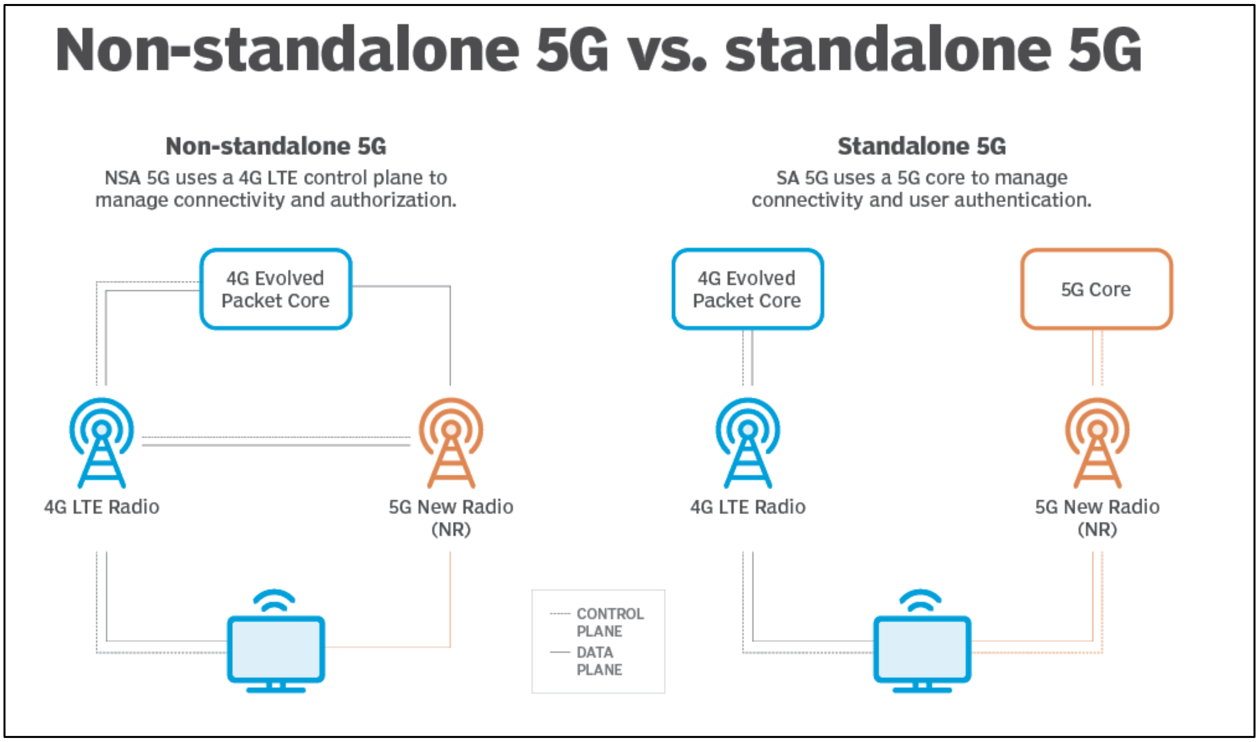


Figure 3: 5G deployment architecture [13]

The 5G system maintains a similar architecture to its predecessors, comprising User Equipment (UE), Next Generation Radio Access Network (NG-RAN), and the Core Network (5GC). Frequency bands for 5G are categorized into three: low, mid, and high. Each band offers distinct capabilities: the low band (below 1 GHz) extends coverage but at slower speeds, the mid band (1 GHz–6 GHz) strikes a balance between coverage and speed, while the high band (24 GHz–40 GHz) delivers high speeds with a smaller coverage radius. Notably, 5G bands exhibit greater flexibility compared to previous generations.

The use cases of 5G can be broadly categorized into three groups based on their requirements: Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC), and Ultra-Reliable Low Latency Communications (URLLC). Key technologies employed in 5G that have significantly transformed the cellular networks industry include:

a) **Massive MIMO**: This technology utilizes a very large number of antennas to serve numerous User Equipment (UEs) simultaneously to increase spectral and energy efficiency.
b) **Beamforming**: Beamforming is a specific signal processing technique that enables directional transmission. The figure below illustrates the main technologies that enable 5G i.e. massive MIMO and beamforming comparing them with $G antenna technologies.

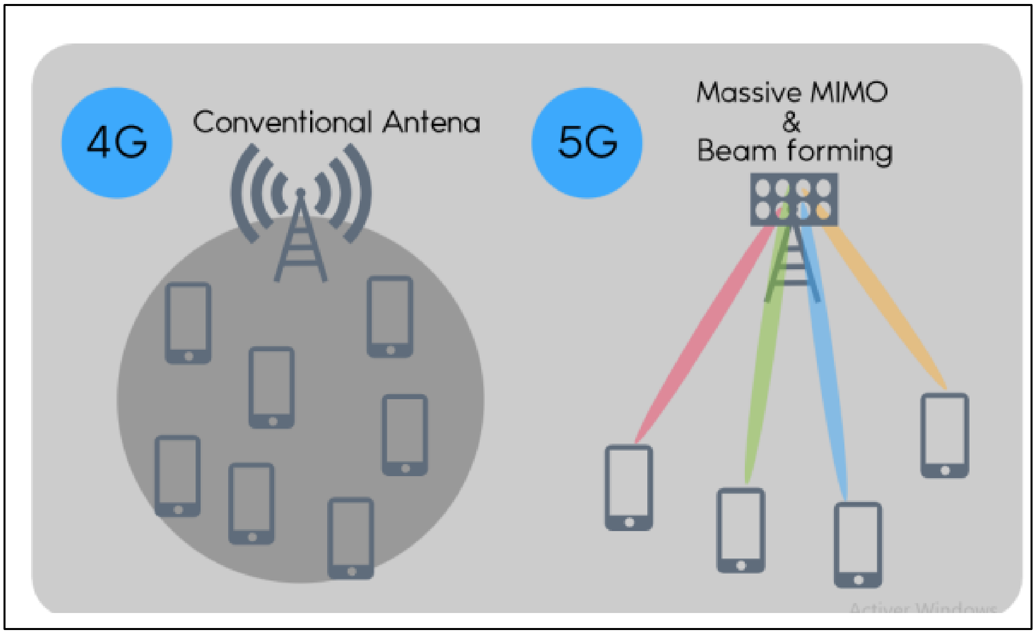


Figure 4:Antennas in 4G and in 5G[12]

c) **Hyperdense small-cell deployment** can be achieved in two ways: by overlaying a cellular system with small cells of the same technology, such as micro, pico, or femtocells (multi-tier HetNet), or by overlaying with small cells of different technologies unlike the single cell (Multi RAT HetNet).
d) **Self-Organizing Network (SON)** capacity is another crucial element of 5G. With the dense deployment of small cells, there is a need for intelligent adaptation to neighboring small cells to minimize intercellular interference. For instance, a small cell can autonomously synchronize with the network and intelligently adjust its radio coverage.
e) **Network slicing** stands out as one of the most critical aspects of 5G. By leveraging virtualization technologies like Software Defined Network (SDN) and Network Functions Virtualization (NFV), 5G network operators can deploy customized networks through the creation of multiple end-to-end virtual networks or "Network slices." Each network slice can be tailored with different functionalities, Quality of Service (QoS) levels, and user-specific criteria.
f) **5G mmWave**, also known as Frequency Range (FR2), operates in the high bands of 5G within the range of 24 GHz to 40 GHz. These bands offer substantial spectrum and capacity over short distances, leveraging technologies like massive MIMO to enhance capacity and extend coverage. Furthermore, they incorporate broad spectrum segments available for 5G alongside lower latencies.

1.1.2 Achievements and limitations of mobile networks.

The primary driving force behind the evolution of mobile networks across generations has been the imperative to enhance network capacity. This progression is evident in the substantial growth in subscriber numbers over the years. For instance, the United Kingdom boasted the highest number of 1G subscribers at 1.1 million, while by 2022, there were nearly 1 billion reported 5G subscribers worldwide, a figure projected to surge to 4.8 billion by 2028.

The expansion of mobile networks has facilitated a paradigm shift, enabling professionals to carry their offices with them. Mobile broadband services, once confined to office settings, are now accessible on portable devices, empowering individuals to work from anywhere.

The advent of high transmission speeds has brought about revolutionary changes in various industries, including telemedicine, video gaming, and virtual and artificial reality, among others.

However, despite the significant strides made in global connectivity, mobile networks still face limitations. Geographical constraints make it impossible to install base stations in certain areas, limiting network reach. Moreover, providing connectivity at sea or in the air remains a challenge due to the reliance on land-based infrastructure. Additionally, network congestion poses a persistent challenge, necessitating ongoing efforts to expand capacity to accommodate the growing number of mobile devices. The evolution of mobile networks is summarized in the figure below, showing services offered by mobile networks have improved through each generation.

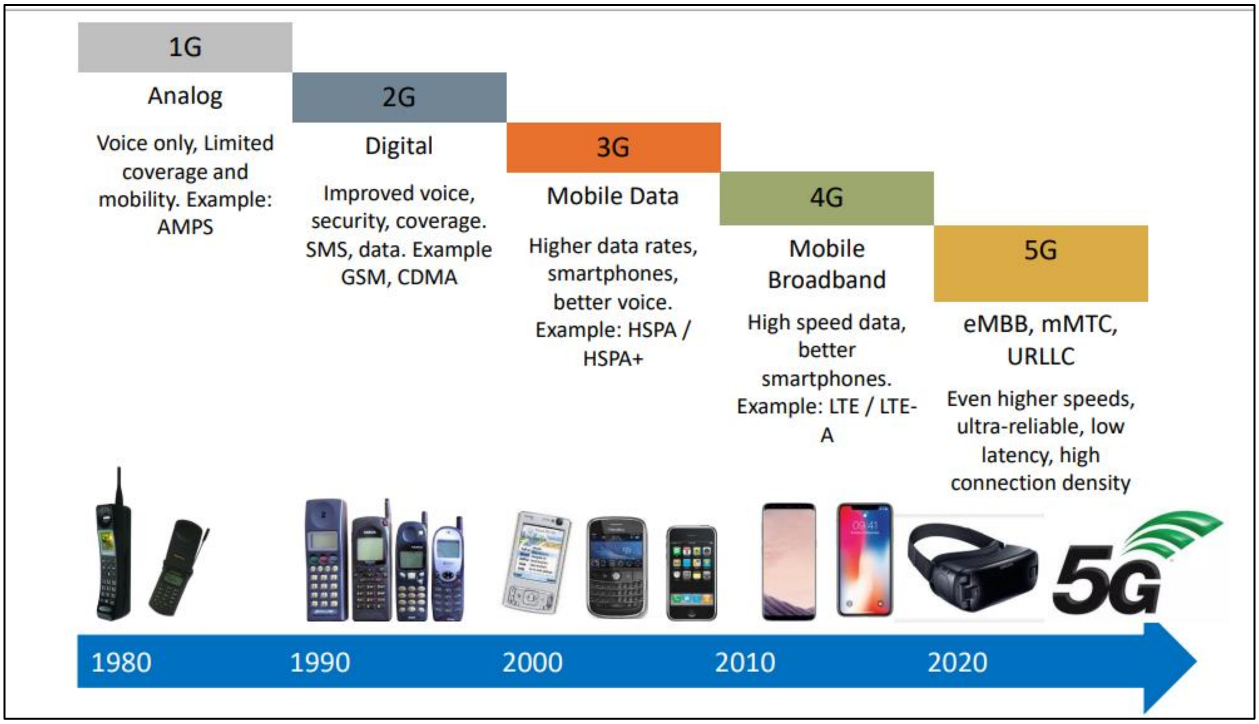


Figure 5 Summary evolution of mobile networks [12]

1.2 Satellite communications

Artificial earth satellites have been used in communications systems for over 60 years and they form an essential part of telecommunications systems worldwide. Aside from allowing people to access hundreds of television channels, satellites carry large amounts of data and telephone traffic that complement communication systems. Because very large areas on earth are visible from a satellite, they are able to connect users widely separated geographically.

Frequency allocation is an important factor in Satellite communications and to facilitate this process, the ITU divided the world into 3 regions (figure 6) namely: Europe Africa Region, North and South America Region and Asia, Australia and the South west Pacific Region.

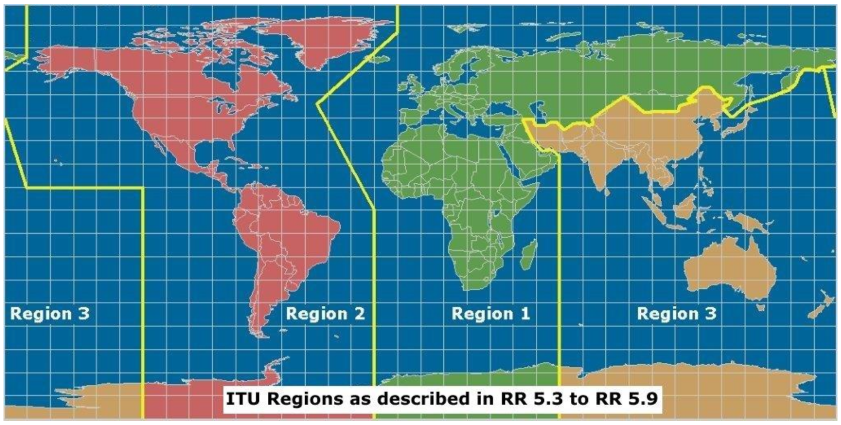


Figure 6:ITU regions [19]

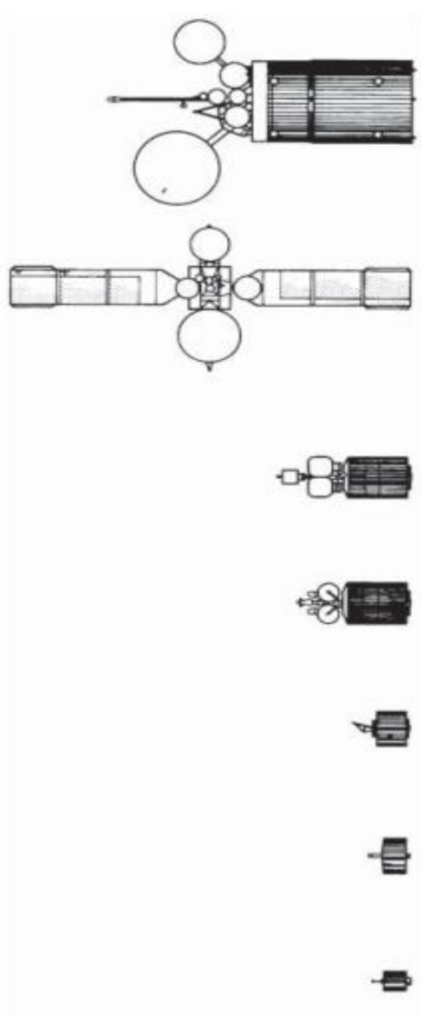
Some frequency band designations in common use in satellite services include L, S, C, X, Ku, K and Ka. Satellites provide many services like Fixed Satellite services (FSS), Broadcasting Satellite Services (BSS), Mobile satellite Services (MSS), Navigational Satellite services, Meteorological Satellite Services amongst others. There are many advantages to using Satellites, they can be summarized into: ubiquity, reliability and operability.

1.2.1 Evolution of Satellite Communications

Arthur C. Clarke is celebrated as the pioneer of satellites. In his influential paper from 1945, Clarke imagined a scenario where a satellite placed in a circular orbit around the Earth at a distance of approximately 36,000 km above the equator would match the Earth's rotational speed. This would allow the satellite to remain fixed over a specific point on the Earth's surface. Such a hypothetical satellite could then facilitate the transmission and reception of signals between any two points within its line of sight.

The era of satellite communications began with the launch of Sputnik, a Russian satellite, into space in 1957. Despite lacking communication capabilities, Sputnik's successful launch showcased the possibility of deploying satellites into space using powerful rockets. Years of subsequent research and experimentation ultimately led to the advancement of satellite technology as we know it today.

Intelsat, short for International Telecommunication Satellite, is an organization that was established in 1964. Their primary focus is to provide communication services through satellites placed in the Geostationary Earth Orbit (GEO). This specific orbit was chosen over Low Earth Orbit (LEO) and Medium Earth Orbit because it allows for a constant connection to any point on Earth, 24/7. A single satellite positioned in GEO appears to be stationary in reference to Earth, covering up to one-third of the planet. Intelsat divides international traffic into three regions: the Atlantic Ocean Region (AOR), the Indian Ocean Region (IOR), and the Pacific Ocean Region (POR). The first Intelsat satellite, Early Bird, was launched in 1965. Over the years, Intelsat satellites have undergone changes in their physical structure and channel capacity.



Designation: Intelsat	I	II	III	IV	IV A	V	V A/V B	VI
Year of first launch	1965	1966	1968	1971	1975	1980	1984/85	1986/87
Prime contractor	Hughes	Hughes	TRW	Hughes	Hughes	Ford Aerospace	Ford Aerospace	Hughes
Width (m)	0.7	1.4	1.4	2.4	2.4	2.0	2.0	3.6
Height (m)	0.6	0.7	1.0	5.3	6.8	6.4	6.4	6.4
Launch vehicles		Thor Delta		Atlas-Centaur		Atlas-Centaur and Ariane	Atlas-Centaur and Ariane	STS and Ariane
Spacecraft mass in transfer orbit (kg)	68	182	293	1385	1489	1946	2140	12,100/3720
Communications payload mass (kg)	13	36	56	185	190	235	280	800
End-of-life (EOL) power of equinox (W)	40	75	134	480	800	1270	1270	2200
Design lifetime (years)	1.5	3	5	7	7	7	7	10
Capacity (number of voice channels)	480	480	2400	8000	12,000	25,000	30,000	80,000
Bandwidth (MHz)	50	130	300	500	800	2137	2480	3520

Figure 7: Early Intelsat satellites [4]

Figure 8: More recent Satellites. Image credits: (a) and (b) Courtesy of SSL, © SSL 2018; (c) © Intelsat, S.A. 2018 and its affiliates. (d) Courtesy of ViaSat, © ViaSat 2018.[5]

In the 1970s and 1980s, there was rapid development of GEO satellite systems for international, regional, and domestic telephone traffic and video distribution. The demand for satellite systems grew steadily through this period, and the available spectrum in the 6/4 GHz band (C-band) was quickly occupied, leading to expansion into the 14/11 GHz band (Ku-band).

The ability of satellites to provide communication to mobile users has long been recognized and organizations like International Maritime Satellite INMARSAT have provided services to ships and aircraft although at a high price. Today satellites come in different sizes and shapes from CubeSats, $0.1m^3$ and 1 kg to GEO satellites weighing up to 6000kg. CubeSats and generally microsatellites can be joined to form great LEO constellations that provide internet access to the whole world.

The demand for satellite communications continues to rise. Satellites have also become integrated into complex communications architectures that use each element of the network to its best advantage. Examples are Very Small Aperture Terminals/Wireless Local Loop (VSAT/WLL) in countries where the communications infrastructure is not yet advanced and Local Multipoint Distribution Systems (GEO/LMDS) for the urban fringes of developed nations where the build-out of fiber has yet to be an economic proposition.

1.2.2 Achievements and limitations of Satellite Communication systems.

Satellite systems have significantly advanced global communication, personal and mobile connectivity, scientific exploration, and environmental monitoring, with achievements in improving precision, coverage, and integration with terrestrial systems, and have contributed to various fields including weather forecasting, oceanography, and space exploration.

The characteristic of a satellite system that makes it indispensable is its ability to cover a large geographical area despite the geographical relief making it possible to provide services to remote areas and places that are inaccessible by terrestrial networks. This characteristic is a major fuel for the development of non-terrestrial networks.

Despite the many advantages of satellite systems, there are still several challenges in this field. Firstly, the competition for the frequency spectrum which is an exhaustible resource. As the demand for satellite-based services increases the available frequency band is congested leading to the venturing into other frequency bands. Secondly, the cost of manufacturing and launching a satellite is high. Thirdly the limited life span of a satellite is a major limitation making this a very significant field of research on how to increase the lifespan of a satellite. Last but not final, Orbital Congestion, with an increasing number of satellites being launched, orbital congestion becomes a concern, particularly in popular orbits like low Earth orbit (LEO). Efficient orbital slot allocation and collision avoidance measures are necessary to ensure safe and sustainable satellite operations.

1.3 Conclusion

This chapter has gone through major feature of Mobile Networks and Satellite communications covering the evolution, achievements and limitations of both. It is evident that both fields have had major advancements from their beginning to the current state. It be clearly seen that they are both independent fields that have shared some common ground but the initialization and the growth and development of each does not depend on the other. There exist multiple opportunities for research advancements in these networks in the quest of providing quality services to users globally. The features of these two networks can be harnessed to create a hybrid network that will further the global interest of communication and connection. The next chapter will tackle the technology born from the integration of terrestrial networks and satellite communications.

Chapter 2

Non-Terrestrial Networks

2 Non-Terrestrial Networks

2.1 Introduction and Motivations

NON-TERRESTRIAL networks (NTNs), which include Unmanned Aerial Vehicles (UAVs), High Altitude Platforms (HAPs), and satellites in different orbits, are traditionally used for certain applications such as:

- ✓ Disaster management.
- ✓ Navigation.
- ✓ Television broadcasting.
- ✓ Remote sensing.

However, recent tremendous developments of aerial/space technologies coupled with reduced cost of their manufacturing and launching have enabled more advanced applications of NTNs, when integrated with terrestrial communication networks. Various new use cases and applications have been envisioned mostly focusing on providing continuous, ubiquitous, and high-capacity connectivity across the globe.

As defined by the 3rd Generation Partnership Project (3GPP), an [1] NTN is a network where spaceborne (i.e., GEO, MEO, LEO) or airborne (i.e., UAV and HAPS) vehicles act either as a relay node or as a base station, thus distinguishing transparent- and regenerative- satellite architectures. Orbiting the earth at an altitude of 36000 km, GEO satellites have a propagation time for a one-way radio wave of at least 120ms. Despite this being a considerable delay in time sensitive applications, their ability to cover large areas and offer a 24/7 connectivity makes them indispensable in the NTN venture. GEO satellites have already been used in mobile networks over the years as a backhaul channel. LEO satellites at 500km-2000km and MEO at 8000km-20000km have numerous applications, one remarkable application is the potential of LEO and MEO constellations providing satellite-based internet. For example, Starlink constellation that already provides satellite-based internet for over 70 countries. The figure below shows a general depiction of the NTN architecture:

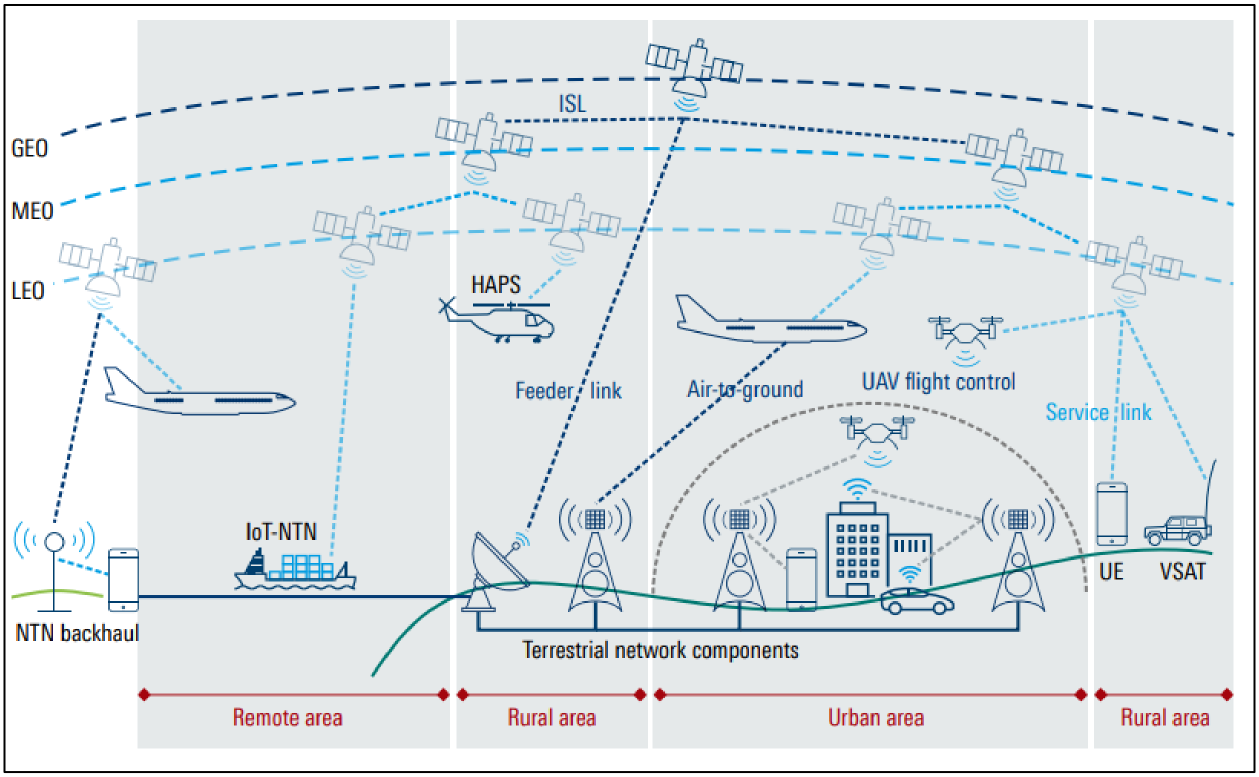


Figure 9 holistic view of NTN architecture [2]

The reason behind the creation of 3GPP was to have an organization that is in charge of international standardization of wireless communication technologies. Satellites and generally space/airborne stations play an important role in having a globally integrated communication system. The idea of integrating satellites into the ecosystem of terrestrial communications networks existed since the era of the 3rd generation networks, but due to commercial and cost issues, it was not implemented. 3GPP's release 17 is the first enabler of NTN connectivity also referred to as NR-NTN (New Radio-NTN) and will hopefully set the tone for future mobile networks.

The deployment of Terrestrial Networks (TNs) in remote and unreachable areas like rural areas, deserts, and oceans, is hindered by ground infrastructure and economic factors. User Equipment in these areas are under/unserved as they cannot access TN services. The use of NTNs in conjunction with TNs could provide a viable and cost-effective solution for continuous and ubiquitous wireless coverage thereby enabling network scalability. According to GSM Association (GSMA) statistics by 2020 mobile wireless communications had reached a coverage of 80% of the world's population but covered only 40% of the land mass. The major motivation for venturing into NTN is to ensure extreme coverage to any location on Earth and on the air. Integration of NTN into mobile communication networks also aims to provide connectivity despite the weather conditions and even in the case of natural disasters.

2.2 NTN Architecture and Implementation

Various architectures have been envisioned for the NTN that offer different kinds of services and applicable in different use cases. The NTN architecture is typically made up of the following network elements:

- ✓ **NTN terminal**: This refers to the typical UE or in the case where the NTN is not directly serving UEs it may be a terminal satellite system like a VSAT. In order to make the transition towards the use of NTN easy and adaptable for the user, the UE is required to be unmodified. This means a 5G commercial UE (smartphone, laptop etc.) will be able to access the NTN without noticeable change to the user.
- ✓ **Service link:** this is the radio link between the UE and the space/airborne station. Additionally, the use equipment may support another link to a terrestrial RAN so as to enable switching from one connection to another.
- ✓ **Space/airborne platform**: this refers to the network element that is not physically on earth (Satellite, HAPS etc.) and it can have either bent-pipe capacities or regenerative capacities.
    - Bent-pipe payload also known as transparent payload. Such a space/airborne platform performs operations like radio frequency filtering, frequency conversion and amplification. It corresponds to an analog RF repeater. The figure below shows a bent-pipe payload satellite incorporated in the 5G network.

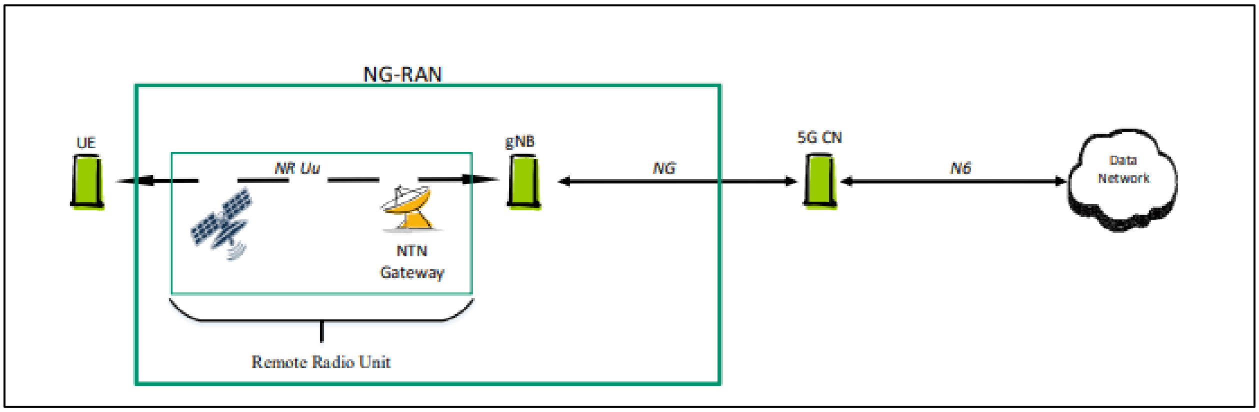


Figure 10:RAN Architecture with transparent satellite [14]

- A regenerative payload: this is equivalent to having base station (e.g. the 5G gNB) capacities. In addition to the functionalities present in the bent-pipe payload, there is demodulation/decoding, switching and/or routing, modulation/coding. The figure below demonstrates this architecture where, NR Uu is the radio interface on the service link between the UE and the satellite. Satellite Radio Interface (SRI) on the feeder link between NTN Gateway (NTN GW) and the satellite. SRI is a transport link between NTN GW and the satellite. This payload also provides for Inter-Satellite link (ISL) between satellites.

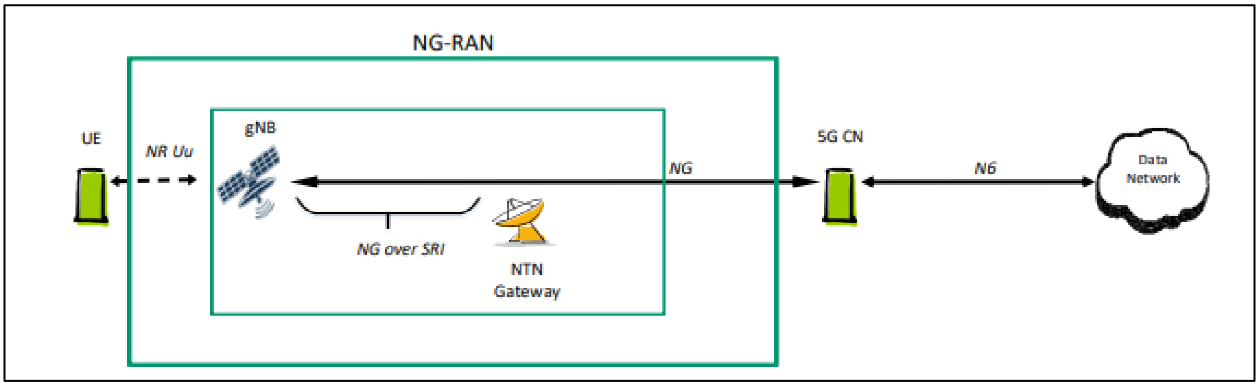


Figure 11:RAN architecture with Regenerative satellite [14]

- ✓ **ISL:** these are transport links between satellites it can be a radio interface or an optical interface.
- ✓ **Gateways**: Connect satellite or aerial access network to the core network.
- ✓ **Feeder Links**: Radio links between gateways and space/airborne platform also known as Satellite Radio Interface (SRI).

Points of presence is an element present in every NTN that allows a satellite network to access terrestrial internet. The following image shows all the elements of NTN architecture.

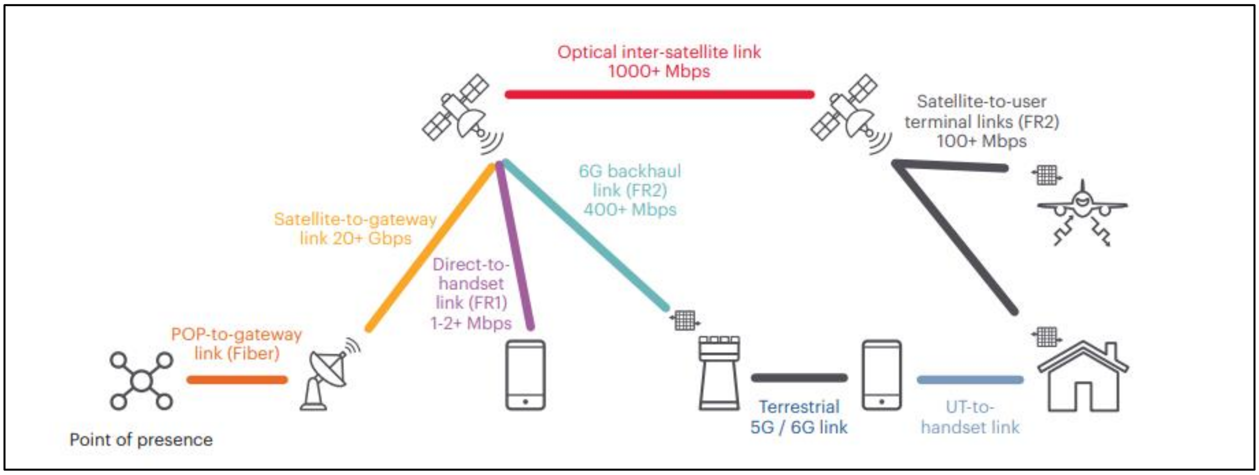


Figure 12:Elements of NTN [17].

Earth stations can be connected to each other through optical fiber links while the ISL are established by means of laser-optical links. ISL links have a data transfer speed of more than 1000Mbs. Feeder links between satellite to the gateway have transfer data rates of more than 20Gbps. NTN architecture is also influenced by the role the Non-terrestrial (NT) platform is playing as illustrated below.

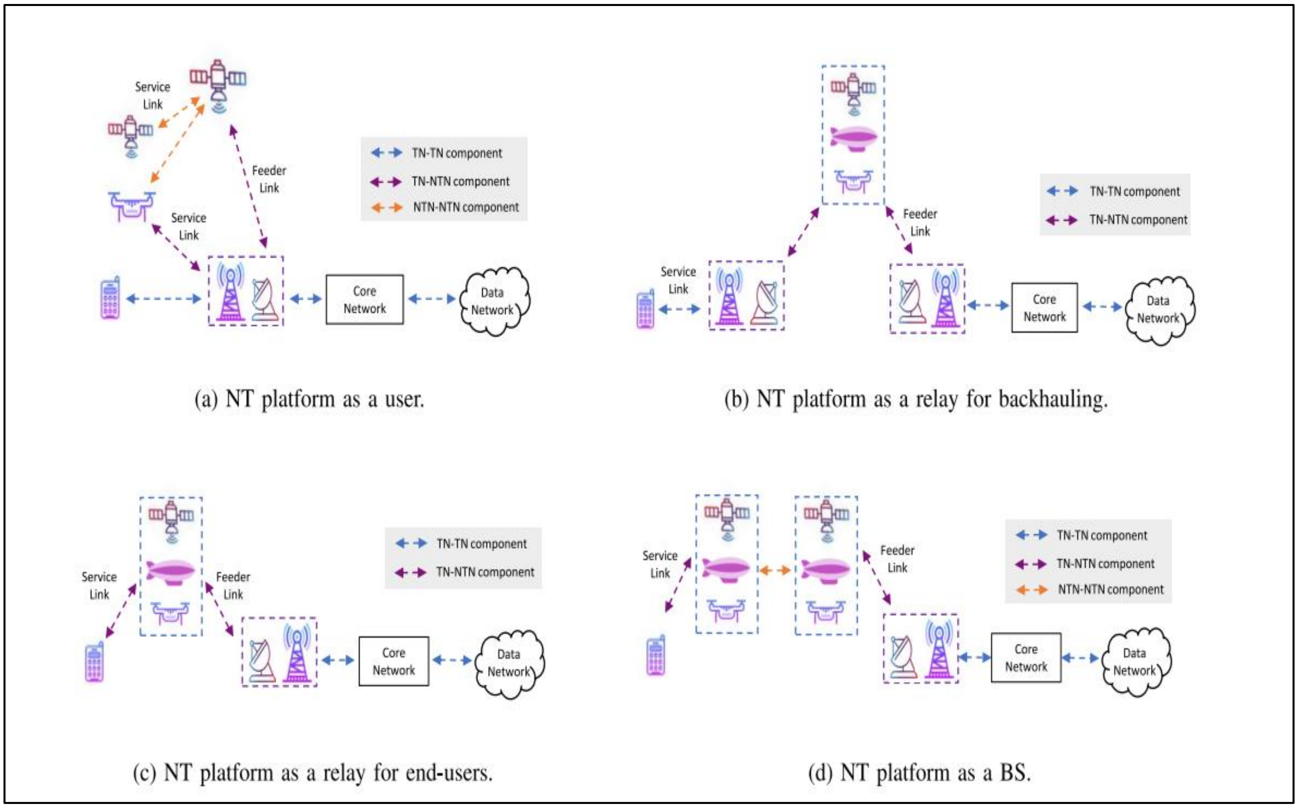


Figure 13:NTN architecture based on different roles played by the NT platform [6]

2.2.1 Frequency and spectrum allocation.

In any wireless communication technology, frequency allocation is the most important aspect to be considered. The frequency spectrum is a resource that is limited and rare that's why organizations like the International Telecommunication Union (ITU) play an important role in the managing of this resource. There are two distinguished types of access in satellite and aerial access networks; that is broadband access network and narrow or wide band access network. In this context broadband refers to at least 50Mbps up to a few hundred Mbps in satellite access on the downlink. While on the aerial access, broadband can go up to several Gbps. Broadband access network serves Very Small Aperture Terminals that can be mounted on a moving platform like, a train, bus, water-vessel, aircraft etc. the frequency allocated in this case is above 6GHz. In the case of narrow or wide band access network, data rates of less than 1 Mbps or 2 Mbps are considered. This serves terminal equipment with omni or semi directional antennas, e.g. a handheld device and the frequencies that can be used are below 6Ghz.

Several frequencies have been discussed for NTN usage including sub 6Ghz or FR1(Frequency Range one) but frequencies above 10GHz are also considered. FR1 bands for NTN are: The S-band frequencies 1980 MHz to 2010 MHz in uplink (UL) direction and 2170 MHz to 2200 MHz in downlink (DL) direction and also the L-band frequencies 1525 MHz to 1559 MHz DL together with 1626.5 MHz to 1660.5 MHz for the UL. The two bands n255 and n256 are the two key frequency bands allocated for NTN where "n" refers to New Radio and the numbers 255 and 256 are unique identifiers assigned to specific frequency ranges for the New Radio categories. The advantage of using FR1 band is that the path attenuation is low and that these frequencies are already in use in legacy communications so the equipment is already available. The obvious disadvantage is that these bands are already densely occupied so the usable bandwidth is restricted.

The second frequency band allocated for NTN is frequencies above 10GHz, FR2 this is the frequency range offering broadband services. The most targeted frequency band here is the Ka band with DL frequency between 17.7GHz and 20.2Ghz and UL frequency between 27.5Ghz and 30. The FR2 bands are n510, n511 and n512. FR2 offers the potential for significantly faster data rates and increased capacity in NTN applications. However, its higher frequency nature comes with trade-offs. The limitations of FR2, such as higher signal attenuation and shorter range, make it less effective for reaching users in remote areas and potentially requiring denser network infrastructure for adequate signal coverage. The figure below shows FR2 values as proposed by ITU.

Band	Downlink (space to earth)	Uplink (earth to space)
Ku-band	10.7 GHz to 12.75 GHz	12.75 GHz to 13.25 GHz and 13.75 GHz to 14.5 GHz
Ka-band (GEO)	17.3 GHz to 20.2 GHz	27.0 GHz to 30.0 GHz
Ka-band (Non-GEO)	17.7 GHz to 20.2 GHz	27.0 GHz to 29.1 GHz and 29.5 GHz to 30.0 GHz
Q/V-band	37.5 GHz to 42.5 GHz, 47.5 GHz to 47.9 GHz, 48.2 GHz to 48.54 GHz, 49.44 GHz to 50.2 GHz	42.5 GHz to 43.5 GHz, 47.2 GHz to 50.2 GHz, 50.4 GHz to 52.4 GHz

Figure 14:FR2 specifications based by ITU [2].

Due to long round trip times present in NTN communication Frequency-Division Duplexing (FDD) is used. This is because a Time-Division Duplexing (TDD) system has the challenges of Transmitter - Receiver (Tx-Rx) switching and with such long delays present in NTN communication a guard interval is necessary which affects negatively spectrum efficiency. The following table shows a summary of the frequencies allocated for NTN as proposed by 3GPP.

Table 1:Summary of 3GPP frequencies for NTN

NTN Satellite Band		Uplink	Downlink
3GPP FR1 L and S Bands	n256(FDD)	1980MHz-2010MHz	2170MHz-2200MHz
	n255(FDD)	1626.5MHz-1660.5MHz	1525MHz-1559MHz
Proposed 3GPP NTN FR2 Bands (Ka Band)	n510(FDD)	27.5GHz-28.35GHz	17.7GHz-20.2GHz
	n511(FDD)	28.35GHz-30.0GHz	17.7GHz-20.2GHz
	n512(FDD)	27.5GHz-30.0GHz	17.7GHz-20.2GHz

2.2.2 NTN use cases

Non-Terrestrial Networks (NTNs) are expected to play an important role in 5G and future communication systems. They offer connectivity solutions across various industries, from transportation and healthcare to energy, automobiles, public safety, and beyond. NTNs can be broadly applied in three main areas:

1. Ensuring continuous service: NTNs can provide network access in areas where traditional terrestrial networks are impractical or unavailable. This can bridge connectivity gaps in remote locations or challenging terrains.
2. Boosting network resilience: NTNs can act as a backup during emergencies or natural disasters that disrupt terrestrial infrastructure. They can ensure critical communication services remain operational even when terrestrial networks are damaged or overloaded.
3. Scaling network capacity: NTNs can help manage traffic congestion on terrestrial networks, especially during peak usage periods. By offloading data traffic to NTNs, terrestrial networks can maintain better performance and user experience.

Another important use case of NTN is acting as a backhaul network. In wireless communication where we have a RAN and a core network (CN) a backhaul is the interface between these two network components. NTN applications depend on the problem they are meant to solve and these may differ basing on different locations that this network is being implemented. The use cases can be sorted according to the location of the device as shown in the table below.

Table 2:Use cases according to device location.

Device location	Use case
Rural	Network resilience and emergency Fixed wireless access Wide-area connectivity Public protection and disaster relief (PPDR)
Urban	Overlay and traffic overload Hotspot on demand Network resilience and emergency Fixed wireless access
Remote	Network resilience Backhaul PPDR and emergency Wide-area connectivity
Isolated	Aeronautical Maritime Remote hotspots PPDR and emergency

Other and more specific applications of NTN include but not limited to:

1. Satellite Internet: NTN provides internet connectivity to remote or rural areas where traditional terrestrial internet infrastructure, like cables or fiber optics, is unavailable or difficult to install. Satellites orbiting the Earth beam down internet signals, ensuring that people in these underserved regions have access to the digital world.
2. Disaster Management: In the aftermath of natural disasters such as earthquakes, hurricanes, or floods, terrestrial communication networks are often damaged or destroyed. NTNs play a crucial role in these scenarios by providing reliable communication channels for coordinating rescue operations, delivering aid, and sharing critical information among responders and affected communities.
3. Agriculture: NTNs enable precision farming by delivering real-time data to farmers. This includes information on weather conditions, soil health, crop status, and more. Farmers can use this data to make informed decisions about planting, watering, and harvesting, leading to increased efficiency and productivity.
4. Maritime and Aviation: For ships and airplanes, staying connected is essential for navigation, safety, and passenger communication. NTNs ensure continuous connectivity across oceans and in-flight, where terrestrial networks are unavailable. This is crucial for real-time weather updates, route optimization, and maintaining contact with ground control.
5. IoT Connectivity: Many Internet of Things (IoT) devices, are located in remote or hard-to-reach areas, such as environmental sensors, industrial equipment, or wildlife trackers. NTNs support these devices by providing the necessary connectivity to send and receive data, enabling better monitoring and control of remote operations.
6. Energy and Environmental Monitoring: Remote energy facilities, such as oil rigs, wind farms, and solar plants, require constant monitoring to ensure optimal performance and safety. NTNs facilitate this by transmitting data on equipment status, energy production, and environmental conditions, aiding in maintenance and operational efficiency.
7. Education and Rural Connectivity: NTNs help bridge the digital divide by providing internet access to rural schools and communities. This enables students and educators in remote areas to access online resources, participate in virtual learning, and connect with the broader educational community, thereby enhancing educational opportunities.
8. Industries like Mining, Oil & Gas, Tourism, and Defense: These industries often operate in remote locations where terrestrial communication networks are sparse or non-existent. NTNs provide the necessary connectivity to support various operations, such as remote monitoring, coordination of activities, communication with headquarters, and ensuring the safety of personnel.

Another factor that influences the NTN application aside from the device location, is the altitude of the NT platform. Different altitudes pose different advantages and disadvantages which make them more suitable for one application and not another. Although more distant orbits result in increased latency, lower throughput, and greater power consumption, they offer the advantage of covering expansive surface areas, thereby facilitating connections in extremely remote areas. While the reduced throughput and heightened latency may be acceptable for low-bandwidth connections that would otherwise lack connectivity entirely, they can pose challenges in a network accommodating numerous simultaneous connections with consistent upstream (UL) and downstream (DL) traffic, necessitating low latency. A satellite in the GEO has a very large footprint on earth is can cover the entire hemisphere a maximum of 3 GEO satellites can offer global coverage. Its position being fixed relative to earth, also gives it an advantage of providing continuous coverage and no doppler shift. Satellites at this orbit also have a longer life span compared to other orbits. At a glance GEO satellite may appear the ideal solution for NTN but their long distance from the earth introduces a high latency in the propagation time, which makes them inappropriate for time sensitive applications and they also possess a greater pathloss. Another disadvantage is that they are expensive to launch per satellite compared to satellite in other orbits.

MEO satellites are in between GEO and LEO, while offering lower latency compared to GEO, they don't achieve the same level of real-time performance as LEO satellites. MEO satellites do not follow a fixed path around the earth unlike GEO satellites, which means that they require dual tracking to ensure continuous connectivity. Satellites in this altitude also introduce a doppler shift on the signal due to their movement. Since MEO doesn't excel in either latency or coverage compared to LEO and GEO, their use cases for communication are less compelling. MEO satellites offer distinct advantages, especially for navigational applications:

- They provide coverage over extensive geographical areas.
- They can be easily interconnected with other satellites, enhancing overall coverage.
- They can orbit the Earth along various trajectories, optimizing navigation services.

LEO satellites are closest to earth and this gives a crucial advantage due to their low latency. Theoretically they are able to provide the user with an experience comparable to being connected to a TN. They are smaller and cheaper per satellite to launch than GEO satellite Like MEO satellites they take multiple orbits around the earth and their constant movement introduces a doppler frequency shift greater than in a MEO satellite. This movement means that they require complex tracking and ground network. They have a limited coverage which means several up to hundreds of satellites are required to offer global coverage. LEO satellites have a shorter visibility time, this implies that to serve UEs in a specific area multiple satellites are required to handover from to another. The figure below summarizes the different orbits and their characteristics.

Orbit	Beam Footprint (KM)	Roundtrip Delay (MS)	Orbit Distance	Orbit Time	Satellite Lifetime	Number of Satellites Required	Doppler, 2 GHZ, 45 Degree Elevation (KHZ)	Velocity (KM/S)
LEO	50-1000	2-20	300 km to 3,000 km	1.5 hours	5-7 years	30-60	72.9-61.5	6.5-7.7
Medium Earth Orbit (MEO)	100-1,000	47- 167	7,000 to 25,000 km	2-8 hours	5-10 years	10-20	51.5-33.6	4-5
Geostationary Earth Orbit (GEO)	Entire hemisphere (200-3,500)	239	35,786 km	24 hours	10-15 years	3-6	0	0

Figure 15: Different orbits [20]

Integration of NT platforms to Terrestrial Networks is not only limited to satellites in orbit but as mentioned earlier in this document, it also includes HAPS and UAVs. HAPS operate in the stratosphere an altitude of 17km up to 22km and they have a range of application from communication, surveillance, environmental monitoring etc. They include balloons and airships. UAVs do not require a pilot and can be quickly deployed to provide connectivity in times of natural disasters and emergencies. They can be used for a number of applications including communications surveillance and delivery. HAPS and UAV offer a quicker, cheaper and temporary solution compared to satellites which are meant for long-term deployment. The figures below illustrate different NT platforms with their beam footprint and the use cases when integrated with TNs.

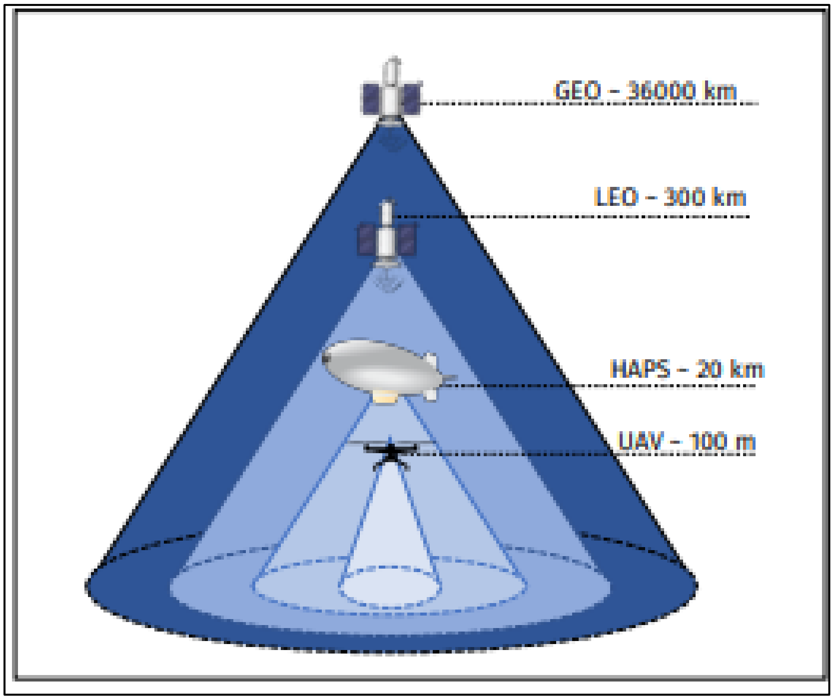


Figure 16: NT platforms and their beam footprints [25]

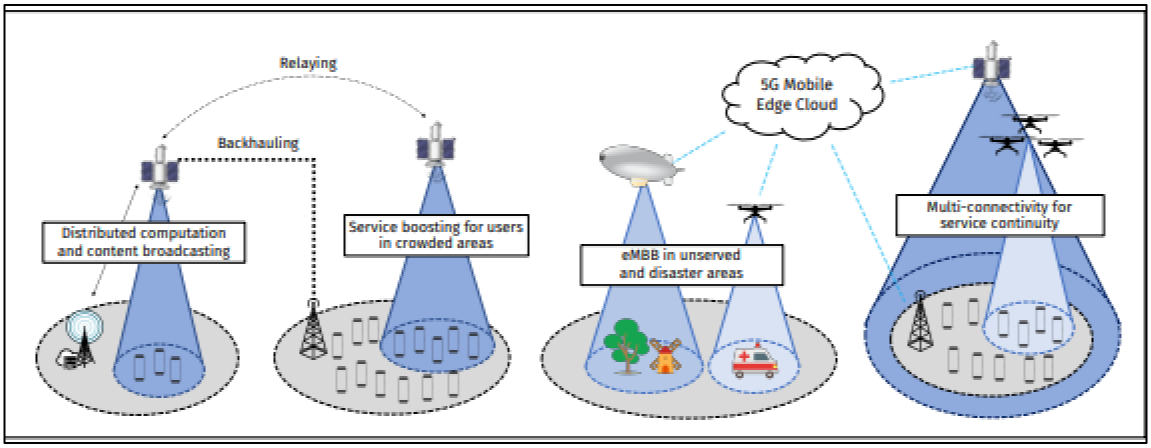


Figure 17: NT platforms integrated with TNs use cases [25].

In studying the uses cases, it is important to note that NTNs are meant as a compliment to terrestrial network and not to compete. The priority of NTN is ensuring global connectivity and basic service provision in wide coverage other than single user high data rates. It's important to highlight that satellite connections are exclusively accessible in outdoor settings. In indoor environments, direct utilization of the satellite access network by devices isn't feasible due to significant path loss. Therefore, amplification of the satellite signal becomes necessary through the installation of terminals on aircraft, vessels, trains, or buildings. Indoor conditions are primarily contemplated for High Altitude Platform Stations (HAPS) as they are positioned closer to Earth, resulting in reduced path loss compared to traditional satellite networks.

2.3 Role of Satellites in different mobile network generations.

2.3.1 1G-4G

As established earlier in this document satellite systems and terrestrial networks are independent of each other, they are systems of different nature, design and applications. This doesn't dismiss the fact that satellites have had a limited but evolving role in mobile networks over the years. In the first generation 1G, satellites were barely used to provide services for the general public. They were used to provide analog services like voice mainly on maritime scenarios, companies like INMARSAT offer these services.

Limited satellite use can be seen during the era of the second generation 2G, where they were used to provide services for high-end customers on aircrafts and certain land areas. Non-Geostationary Orbit (NGSO) satellite constellations i.e. Iridium and Globalstar gained the attention of research communities during this period in their ability to provide global satellite coverage. But they proved to be more expensive than GEO satellites and cellular networks in providing coverage hence satellite systems could not compete. The idea to combine satellite systems and mobile cellular networks started with the effort to support Global System for Mobile Communication (GSM) via satellite through GEO Mobile Radio (GMR) air interface.

It is in the 3G period that satellite networks operators decide to collaborate instead of compete with terrestrial cellular network operators. In UMTS features like location update, domain update and handover were added to support satellite access networks. UMTS marks the initial step towards the convergence of mobile and broadband systems by providing services to groups of users, such as the Multimedia Broadcast Multicast Service (MBMS). 3G technology aims to deliver MBMS services to users both inside and outside terrestrial coverage areas through the 3G cellular network or Satellite-Digital Multimedia Broadcasting (SDMB). SDMB systems typically involve the use of satellites to transmit digital multimedia content to receivers on the ground. This technology is commonly used for services like satellite radio, digital television broadcasting, and data services. To this end, the ITU established the IMT-2000 standardization framework and defined UMTS as a 3G global wireless system operating in the 2 GHz frequency band. Consequently, satellite systems were viewed as complementary to terrestrial networks, enhancing international roaming capabilities and providing coverage in sparsely populated areas to achieve ubiquitous service.

Satellites weren't entirely absent in 3G, their use was restricted to niche applications and specific scenarios. Several factors hindered the widespread adoption of satellites in 3G:

- Cost: Satellite communication was significantly more expensive compared to terrestrial solutions.
- Low Data Rates: Satellite technology at the time offered much lower data rates compared to what 3G networks were aiming to achieve.
- Limited Network Integration: Seamless integration between terrestrial and satellite networks wasn't well established, making handovers between these systems cumbersome.

While satellites played a minor role in 3G, the groundwork for future advancements was laid. The focus on data services and mobile internet access during the 3G era paved the way for exploring satellite integration in later generations like 4G and 5G, where data-intensive applications and the concept of Non-Terrestrial Networks (NTNs) are gaining traction.

The 4G Long-Term Evolution (LTE) system is designed to support IP-based traffic while achieving lower latency, higher data rates, and greater spectrum efficiency compared to UMTS. This places a significant burden on backhaul networks, necessitating the development of advanced techniques to enhance microwave backhaul. These techniques include Adaptive Modulation and Coding (AMC), interference mitigation and cancellation, higher-order modulations, packet header compression, frequency diversity, and multiple-input multiple-output (MIMO) systems. The issue of limited backhaul capacity becomes even more critical as the number of small cells in Mobile Network Operators (MNOs) infrastructure rapidly increases. To handle the vast amount of data traffic generated by end-users and Internet of Things (IoT) devices within these cells, backhaul links must be redesigned alongside improvements to the Radio Access Network (RAN). This making network backhaul a primary area for exploration in the 4G network. Satellites were considered as an option for backhaul link because of the following use cases:

- Remote Areas: For cell towers in remote locations with limited access to fiber optic cables or microwave links (traditional backhaul options), satellites offered an alternative backhaul solution.
- Traffic Offloading: In areas with congested terrestrial backhaul networks, satellites could potentially be used to offload some data traffic, improving network performance.

In an experimental analysis done on the impact of satellite communications on mobile networks in [30], A 4G LTE network was emulated with a terrestrial backhaul network and a second one with a High-Throughput Satellite (HTS) in the Ka band for a backhaul network. The results were based on Key Performance indicators (KPI) including Channel Quality Index (CQI), Modulation Coding Scheme (MCS) index, Downlink throughput, Frame Utilization (FU) and number Resource Block (RB) utilization ratios. It was concluded that as much as there were some adjustments to be before employing satellites as a backhaul network, there were a lot of promising results that make it an efficient venture. The following diagrams show the two architectures of this network.

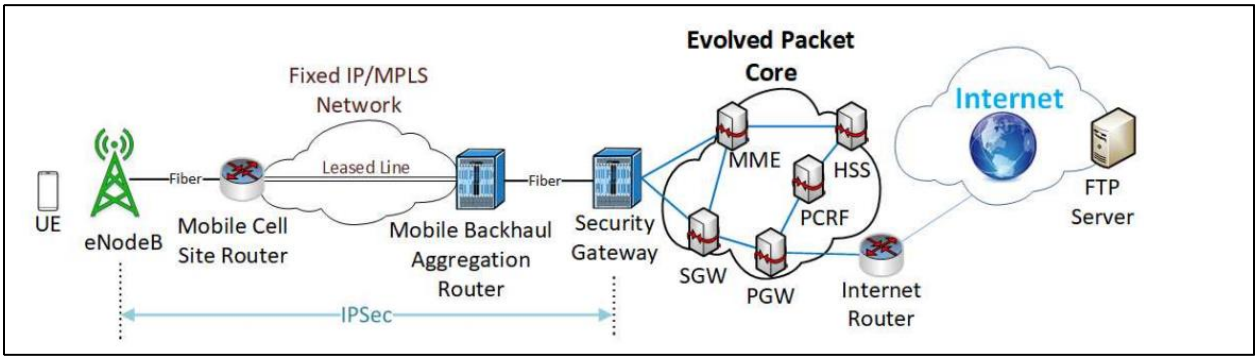


Figure 18:4G LTE architecture with terrestrial backhaul [30].

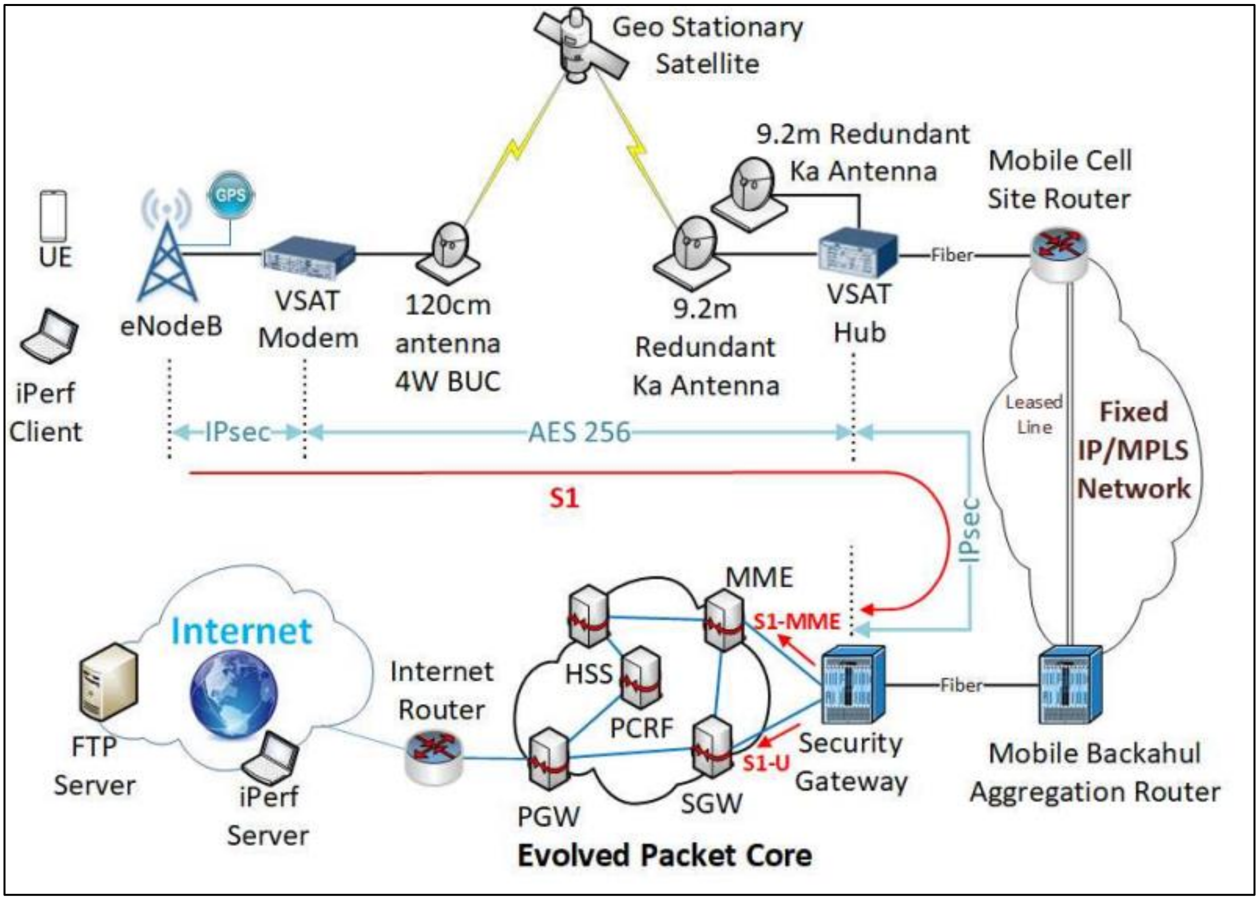


Figure 19: 4G LTE architecture with satellite backhaul [30].

Note: iPerf Client short for Internet Performance Working Group client, is a tool used for measuring network bandwidth between a client and a server.

During the 4G era, advancements in satellite technology started paving the way for future integration for example

- Lower-cost satellite development**:** Efforts were underway to develop smaller, cheaper satellites, making large constellations more feasible.
- Increased Bandwidth: Improvements in satellite communication technologies promised higher bandwidth capabilities.

The groundwork laid in 4G, with studies and pilot projects exploring satellite backhaul, set the stage for the more prominent role satellites are expected to play in 5G networks and beyond. The concept of Non-Terrestrial Networks (NTNs) that leverage satellites for broader communication services emerged from these earlier explorations. Further details about 5G NTN will be discussed in the following subtopic.

2.3.2 5G NTN.

From this current generation of mobile networks, terrestrial networks and satellites systems are considered from a different perspective [figure 20]. Unlike previous generations where satellite communication was limited or exploratory, 5G ushers in a new era where satellites are expected to play a more prominent role. It is in 5G that satellites are assigned as a mainstream solution to users, unlike in other generations like 4G where satellites were not in direct contact with the user but in the backhaul network. In 2022, the 3GPP published Release 17, marking the first instance of including both ground-based terrestrial networks and non-terrestrial network platforms in the 5G specifications, as well as any prior 3GPP cellular specifications. Release 17 introduced support for two types of non-terrestrial networks: 5G NR and narrowband-IoT (NB-IoT). 5G NR NTN enables satellite network access to handsets within the Frequency Range 1 (FR1) band, allowing for voice and data transmission in areas not covered by terrestrial networks. Meanwhile, NB-IoT NTN provides direct satellite access to IoT devices, supporting applications in agriculture, transportation, and other fields.

Release 18 also referred to as 5G advanced, scheduled for completion in 2024, introduces promising new NTN capabilities, coverage improvements, performance enhancements, and support for additional frequency bands. Some of these enhancements extend LTE support for NTN, while others primarily focus on boosting 5G NR NTN capabilities for IoT applications. An important aspect in this standard is the introduction of studies and work on integrating artificial intelligence (AI) and machine learning (ML), which lead to self-optimizing networks and predictive maintenance into the 5G network. Key improvements include enhanced mobility management and power-saving features for discontinuous coverage. Specific enhancements in Release 18 focus on:

- Improving NTN mobility: This involves modifying support for neighbor cell measurements to prevent the UE from losing coverage due to radio link failure, and adding support for signaling neighbor cell location and timing data for enhanced Machine Type Communication (eMTC) and NB-IoT.
- Advancing overall NTN throughput performance: This includes disabling Hybrid Automatic Repeat Request (HARQ) feedback to mitigate the impact of HARQ stalling on UE data rates and improving global navigation satellite system (GNSS) operation to reduce UE power consumption and create a new position fix for UE pre-compensation during long connection times. HARQ is an error correction technique it that allows a UE to automatically request a re-transmission in the case where a data packet is missing. It works on the principle that the transmitter cannot send another data packet without the acknowledgement of reception of the previous packet.
- Optimizing GNSS for power efficiency: This focuses on improving power efficiency for long-term connections.
- Supporting new scenarios in higher frequency bands: This includes deployments in frequency bands above 10 GHz, such as the introduction of extended L-band and frequency division duplexing (FDD) LTE band operation for IoT NTN.

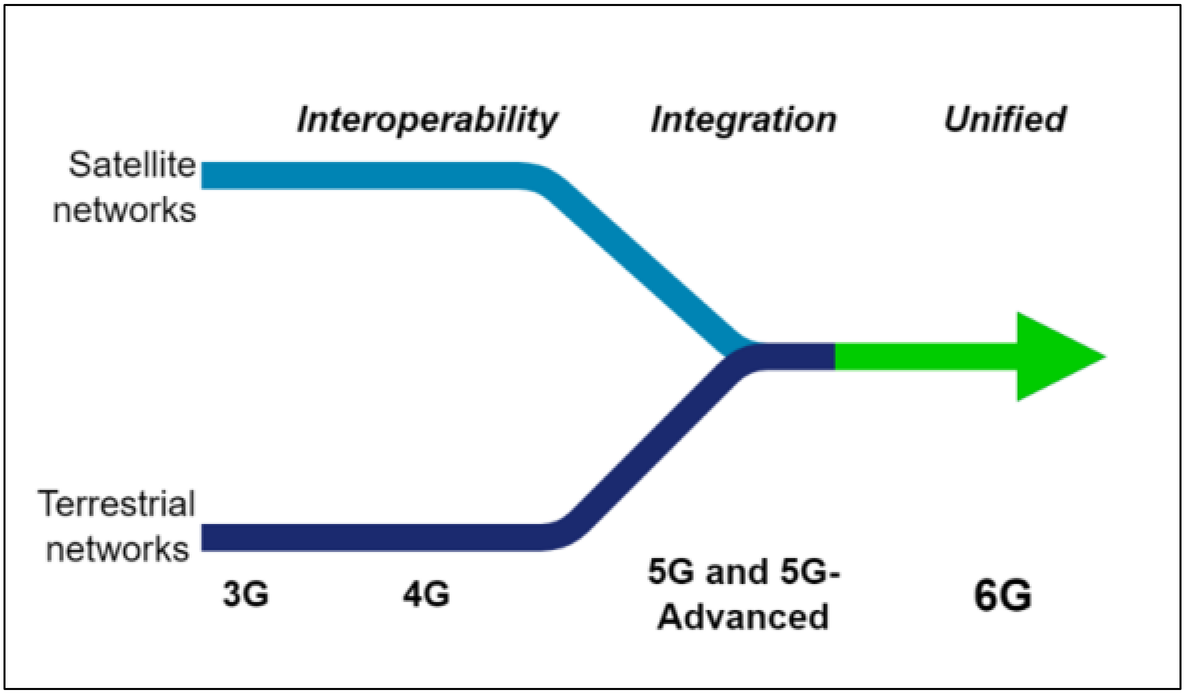


Figure 20:Convergence of NTN and TN [33.]

5G NTN services

As mentioned earlier in this document services offered in 5G can be categorized into enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC) and Ultra-reliable low latency communications (URLLC). NTNs can be integrated into 5G to enhance these use cases in the following ways:

- **Enhanced Mobile Broadband (eMBB):** Providing high-speed internet access and data capacity in remote areas can be difficult with only terrestrial infrastructure due to limitations in building and maintaining cell towers. Satellites in NTNs can offer an alternative solution for eMBB in remote locations, HTS in GEO, MEO and LEO can be used to carry high bandwidth content. They can provide a wider coverage area, allowing users to access high-speed internet even where terrestrial networks are unavailable.
- **Massive Machine Type Communications (mMTC):** Connecting a vast number of low-power devices (sensors, meters) in geographically dispersed areas can be challenging for terrestrial networks alone. Low Earth Orbit (LEO) satellite constellations in NTNs offer a potential solution for mMTC. These constellations can connect a large number of devices over a wider area, even in remote locations, due to their dense network design.
- **Ultra-Reliable Low-Latency Communications (URLLC):** Applications like autonomous vehicles and remote surgery require extremely low latency (signal travel time) and high reliability, which can be difficult to achieve solely with terrestrial networks. There are ongoing discussions and research on integrating NTNs with URLLC. While latency remains a challenge for traditional satellites, advancements in technologies like Low Earth Orbit (LEO) satellites or using a combination of terrestrial and satellite networks (network

slicing) could potentially offer solutions for specific URLLC applications in the future. The following table summarizes the integration of NTN into 5G use cases.

Table 3: 5G NTN use cases

5G use case	Challenge	NTN integration
eMBB	High-speed internet access in remote areas.	Offers wider coverage and an alternative solution where terrestrial infrastructure is limited.
mMTC	Connecting a massive number of devices in remote locations.	LEO constellations provide a solution for connecting a large number of devices over a wider area.
URLLC	Ultra-low latency and high reliability.	Ongoing research on integrating NTNs with URLLC.

In essence, 5G is a turning point for satellite communication in mobile networks. From limited use cases in previous generations, satellites are poised to become a mainstream solution for extending coverage, enhancing network resilience, and supporting the data-hungry applications of the future.

2.3.3 The 6G

While 5G was originally designed as a PLMN which in later releases was developed to support NTN, 6G is meant to be achieved by a unification of TN and NTN as illustrated in figure 20. The space segment will not only be a relay of the terrestrial signal but organically integrated as network node. The 6G is a multi-dimensional network: it is a 3D unified network meaning there is a third network element in the air/space. Multi-band as there will be the use of different bands and the integration and exploration of higher frequency bands even predictively beyond 65GHz into mm Wave and terahertz range. Applications in this frequency range will have to be short rage but characterized by very high throughput and micro antennas, for example insect-sized robots. Thirdly a multilayer architecture that can clearly be seen the figure below, the vertical connections are more than one giving it this multilayer structure.

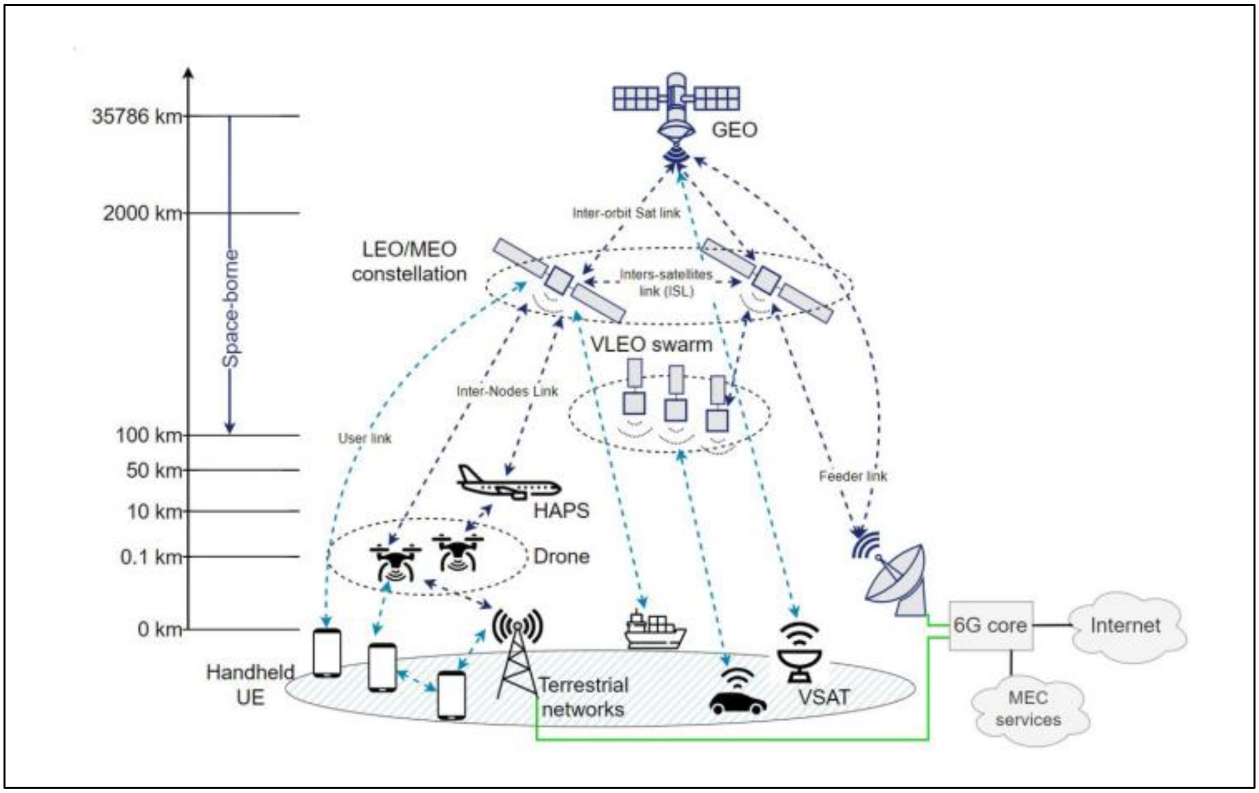


Figure 21:6G multidimensional architecture [33].

NTN in the 6G network will build upon 5G use cases i.e. eMBB, URLLC and mMTC by the inclusion of new spectrum and AI. Emerging applications for 6G may include:

- Holographic Type Communications (HTC): These require extremely high bandwidth to ensure excellent quality for transmitting hologram data from remote locations.
- Multi-Sense Networks: These networks provide a fully immersive experience by involving not only acoustic, optical, and tactile senses but also the senses of smell and taste.
- Time Engineered Applications: This category includes industrial automation, autonomous systems, and massive sensor networks where real-time response is crucial, making the time factor extremely important.
- Critical Infrastructure: Applications in this area focus on essential safety operations in emergency situations.

Similar to 5G, 6G network technologies will continue to utilize Software-Defined Networking (SDN), Network Functions Virtualization (NFV), and network slicing. However, 6G is expected to advance these concepts significantly, enabling highly customized network slices tailored to individual needs and applications, thereby creating a truly personalized quality of experience. This approach, involving personalized network slices, will heavily rely on extensive edge computing and result in a complex distribution of network responsibilities between the core network and edge computing nodes.

The ITU-R IMT-2030 envisions 6G as a significant advancement towards unifying communication technologies to deliver sustainable, resilient, and reliable network capabilities. These networks will support interactions between humans and their physical environment through real-time digital modeling. The table below summarizes this subtopic, showing different mobile networks generations up to predictions for 6G.

Technology	Novelty	Description
1G	· Voice · Low data-rate applications	Satellite systems are considered independent from terrestrial systems due to their features (i.e., covered distances, exploited radio spectrum, design, cost, applications, and targets).
2G	· Aeronautical and maritime services	The satellite coverage is limited to areas unreachable by the terrestrial network. Therefore, satellites are still proprietary and in competition with the traditional cellular network.
3G	· Broadband and multimedia services	The 3G technology represents the first step towards the convergence of satellite and terrestrial networks (i.e., the satellite air interface is fully compatible with the terrestrial UMTS network infrastructure).
4G	· Hybrid/integrated satellite-terrestrial networks ·HTS	Satellite communications are considered indispensable for achieving the global roaming where the terrestrial network infrastructure is impossible to be installed and economically expensive.
5G	· SDN/NFV based NTN-terrestrial networks · IoST · Cognitive NTN-terrestrial networks · NOMA based NTN-terrestrial systems	The integration of NTN into the terrestrial network is a key purpose to provide connectivity anywhere and anytime. To achieve this goal, the following requirements need to be provided: · *multi-connectivity* allows users to be served at the same time by the two different RANs (i.e., NTN and terrestrial network); · *service continuity* ensures handover between different RANs.
6G	· NTN based on holographic radio · NTN based on non-radio frequencies (i.e., optical, and others) · Satellite communications based on Artificial Intelligence.	Space-aerial-terrestrial networks will achieve even more success in 6G. Drones will be exploited as base stations to provide connectivity in hotspots and remote areas, and will be supported by NGSO satellites in backhauling and coverage extension. Since several features will be introduced in 6G, satellite communications might be revolutionized with holographic radio, non-Radio Frequency, and Artificial Intelligence.

Figure 22:Satellites in technologies from 1G-6G [1].

2.4 Key Technology enablers for NTN

Integration of NT platforms into the TNs ecosystem is a technology that brings with it a number of new applications and capacities which are evidence to the great technological advancements in the world of telecommunication. This subtopic will look at the technologies that are responsible for the NTN technology. Some of which have already been implemented in the 5G and others which are in the research and development stage to be employed in future releases. These technologies are applied to different aspects of the network, for example the physical architecture, the frequency spectrum software aspects among others to ensure that it delivers the defined use cases. The technologies are as follows:

1. **SDN and NFV**: As mentioned earlier SDN contributes to architecture optimization and combined with network slicing it enables the deployment and management of NFVs. By providing centralized control and network programmability, SDN can facilitate smoother handovers between terrestrial and satellite networks within NTNs, ensuring uninterrupted connectivity for users. NFV allows for efficient allocation of virtualized network functions based on real-time traffic demands across both terrestrial and satellite segments in NTNs.
2. **Hybrid payload**: This is a technique that will allow a communication satellite to carry more than one payload destined to different communication functions. It will allow the satellites to cater for a wider range of services within the NTN. While it is a technology

that is under development as it requires a complex satellite design, it is a promising technology for future networks.

3. **Cognitive radio/spectrum**: Is a technology designed to improve efficiency and flexibility of radio spectrum usage by dynamically adapting transmission or reception parameters in real time to avoid interference and optimize performance. In the case where NTN and TN share the same bandwidth this technology can be employed.
4. **Non-orthogonal multiple access (NOMA)**: This is a technology in use in 5G, which is a variation of the orthogonal multiple access (OMA) technology that allows a user to be served in each orthogonal carrier. NOMA allows for more than one user to be served in one orthogonal carrier this increases network capacity. NOMA technology has brought and will bring numerous advantages to NTN in the future.
5. **Mm Wave**: No matter the challenges, like high signal pathloss that come with higher frequencies, the millimeter wave technology cannot be set aside in communication networks. This is because of the high bandwidth that is available at these high frequencies which is necessary to meet consumer needs. Solutions are being proposed for developing new waveforms and modulation schemes, such as impulse-based ultra-wideband (UWB) modulation. In this approach, information is encoded based on the characteristics of the transmitted pulse, offering a viable method to reduce the non-linear signal distortion commonly encountered at high frequencies.
6. **Beamforming**: As NTNs have cover a large area compared to TN, highly directional beamforming technique is necessary to compensate for pathloss especially in the case of high frequency bands like Ka.
7. **Large phase-array antennas**: As part of the expectations and recommendations for future unified networks, the UE is expected to remain the same and still support satellite access. For this requirement to be achieved there are trials and research going on in order to have large phase-array antennas on the satellite.

We can group the technologies used in NTN according to different aspects as shown in the figure below.

	Technology	Advantage
Architecture	Nano/pico satellites	Small component costs, low latency, low energy consumption
	Gallium Nitride (GaN)	Feasible to install, small form-factor and more efficient components
	Multi-layered networks	Better spatial and temporal coverage by deploying satellites in different orbits
	Solid-state lithium batteries	Safe and efficient source of power
	Software Defined Networking (SDN)	Improved flexibility, automation, agility through Virtualization Network Functions (VNFs)
	Flexible payloads	Dynamic adaptation of beam patterns, frequency, and power allocation
	Hybrid payloads	Better trade-off between performance and payload complexity
Spectrum	Millimeter waves	Feasibility of ultra-fast connections, antenna gain, spatial isolation and security
	UWB modulation	Reduced non-linear signal distortion by encoding the transmitted pulse
	Cognitive spectrum	Reduced interference through dynamic spectrum utilization in different frequency bands
	Optical communications	Feasibility of terabits-per-second connections through extreme bandwidth and directivity
Antenna	Reconfigurable phased antennas	Reduced power consumption, size and weight
	Metasurface antennas	Component miniaturization, high directivity, low sidelobes, fine beamwidth control
	Inflatable/fractal antennas	High-directivity in dynamic scenarios
	Coherent antenna arrays	Maintainability, scalability, flexibility, robustness to single points of failure
	Multi-beam architectures	High spectrum efficiency through spatial diversity
Higher layers	TCP spoofing	Fast TCP full-buffer capacity through TCP acknowledgements
	TCP multiplexing	High performance by splitting TCP session into multiple data flows

Figure 23:Technology enablers in NTN [25].

2.5 NTN features and challenges.

The main characteristics of NTN that make it differ from TN is the altitude, coverage area and movement of the NT platforms. Unlike TN where only the UE is in mobility, in NTN we have the satellite or air-based platform in movement. Even in the case of a GEO satellite where the movement is quasi static, a small movement is still accounted for. These features introduce certain challenges in the non-terrestrial networks which will be covered below.

1. **Propagation delay**: This a crucial aspect and challenges with NTN as the higher the altitude of the NT platform the longer the propagation delay. As seen in the use cases different altitudes are suitable for different applications. Furthermore, satellite users on the ground or in the air will encounter varying propagation delays in different parts of their cells due to the extensive coverage areas. This variation will impact the initial access and synchronization of users located at both the cell center and the cell edge.
2. **Path Loss**: The loss of signal strength as it is propagated is also influenced by the distance of the NT platform from the earth. The longer the distance the higher the pathloss. For NT platforms on lower altitudes like UAVs and HAPS the delay and losses are within the terrestrial networks range.
3. **Doppler effect**: This effect introduces a frequency shift in the signal due to the movement of the transmitter or receiver and this the NTN scenario both the sender and the receiver are in movement. The higher the altitude the lower the doppler effect. NT platforms on lower altitudes like LEO at 600km with a carrier frequency of 2Ghz introduces a doppler shift of 48Khz. The doppler shift introduced is 10 times higher that which in experienced in a terrestrial communication having the user inside a speed train. In addition to considering doppler effects in the determination of sub-carrier frequency in OFDM other means can be used mange them. 3GPP release 17 uses the Global Navigation Satellite System (GNSS) data in the UE to predict satellite position and movement and thus compensating doppler effects on the receiver’s side.
4. **Coverage, throughput and handover (HO)**: NTNs generally have a bigger coverage than TNs. The higher the position of the NT platform the larger the beam footprint, means a larger area in under network coverage. For GEO satellites the footprint is static but for non-geostationary orbits (NGSO) it is varying in terms of time and space. Because of this, in order to ensure continuity of service handover procedures must be employed in NGSO satellites. The smaller the beam footprint the higher the throughput, thus favoring the services that require high data rates.
5. **Deployment:** Lower altitude NT platforms like UAVs and HAPS are quicker and cheaper to deploy compared to satellites higher in orbit. Although they offer a temporary, they can be quickly integrated with terrestrial networks in times of emergencies.
6. **Security:** As is consistent with all communications that depend on radio waves as a transmission support, interceptions eavesdropping and signal tampering are security concerns. Stochastic beamforming is a proposed physical layer approach that uses multi-antenna system in the terrestrial base to create green interference.

The following table shows the technical features in TNs and NTNs

Table 4:Different features on NTN and TN.

Feature	**Terrestrial Network**	**Non-Terrestrial Network**
Coverage on earth	Up to 100 km	Up to 3500 km (GEO satellite)
Propagation delay	Up to 0.67ms for 100km cell size	Up to 540ms (GEO with transparent payload)
Propagation Path Loss	138 dB (100km cell & 2GHz fc)	190 dB (GEO satellite & 2GHz fc)
Doppler shift	1KHz (high speed train& 2 GHz fc)	48 KHz (600 km altitude LEO satellite & 2GHz)
Handovers	Triggered when users move from one cell to another	Periodic HO due to NGSO satellite movement.
Network deployment	Long-term deployment	Temporary or long-term depending on the NT platform

2.6 Conclusion

This chapter has discussed NTN technology covering its different aspects from the motivations of venturing into this technology and the challenges. While NTN is a broad subject and has not been covered to its entirety in this chapter, it is clear that, 5G and future systems will increasingly rely on non-terrestrial components to deliver services globally. These components are uniquely capable of extending coverage to areas where terrestrial infrastructure is either impractical or cost-inefficient, and they play a complementary role in offloading significant traffic, especially in highly congested regions. However, the distinct technical characteristics of non-terrestrial channels, which differ significantly from terrestrial ones, present various challenges that necessitate innovative solutions. After imagining a new solution for telecommunication, the next step is the realization. One of the early steps is channel modelling as it allows to concretize the idea answering the question “how” before other aspects of the network are implemented. The next chapter will cover the practical work which involves the simulation of an NTN channel.

Chapter 3

Practical work: NR NTN Channel Model.

3 Practical work: NR NTN Channel Model.

3.1 Introduction and channel modelling methodology

Channel modeling in radio propagation is a crucial aspect. The propagation medium being susceptible to weather conditions like rain and thunder and considering propagation in different scenarios like urban, suburban, rural etc. channel modeling takes all these factors into consideration, to optimize the propagation in this dynamic environment. NTN being a new technology most NTN simulators like 5G Vienna are owned by specific institutions and not available for use to the general public and/or require specific commercial license for operation. This project uses a predefined MATLAB model that employs the recently added satellite communications toolbox that enables the simulation and calculations of different aspects of the NR NTN network. This model allows the simulation of links between the user equipment and the air/space-borne station in different environments (Urban, Rural, Suburban etc.) with their velocities and it also allows to visualize different characteristics of the received signal.

An NTN channel model should meet the following requirements:

- ✓ Support a frequency range from 0.5 GHz -100GHz two frequency bands are targeted in particular for NTN applications, below 6Ghz and Ka bands.
- ✓ It should also meet the UE mobility requirement access. For satellites that can serve an aircraft in motion speeds of up to 1000km/h should be accommodated and for HAPS that are envisioned to offer services to high-speed trains a velocity of 500km/h should be accommodated in the channel model.

In both satellite access and mobile cellular access, the propagation can either be Line of Sight (LOS) or Non-Line of Sight (NLOS). The following figures depict NLOS propagation and LOS propagation respectively.

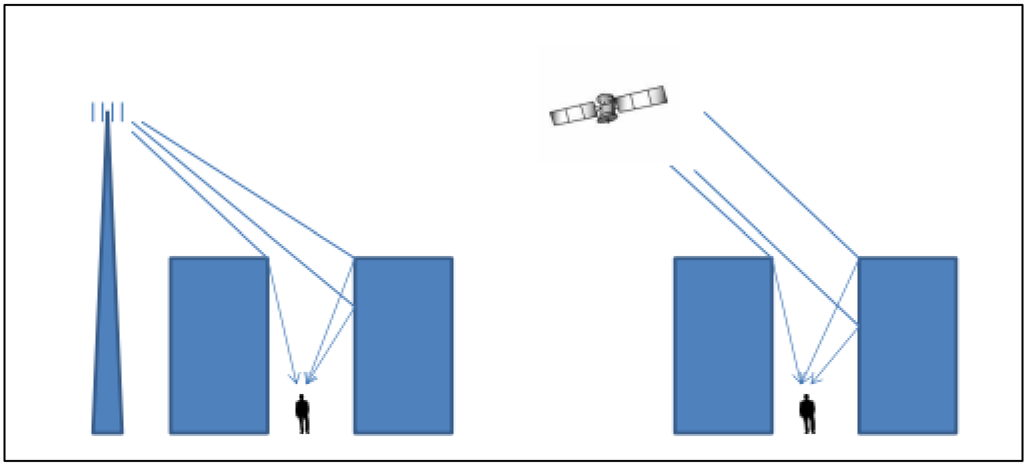


Figure 24 NLOS cellular propagation and satellite propagation. [14]

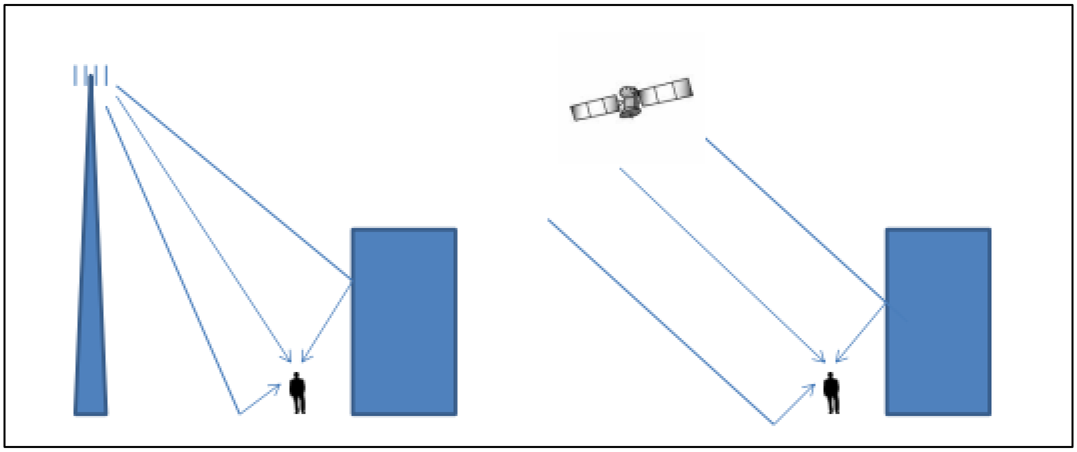


Figure 25: LOS cellular propagation and satellite propagation.[14]

In both scenarios the propagation is almost similar, although a difference can be noted in the angular spread in the case of a terrestrial base station (on the left) and satellite. The satellite propagation has an angular spread of zero because of the large distance between it and the earth which is advantageous, as it means that the signal is focused in a certain direction without scattering. Due to this, the signal is stronger and more reliable with minimum interference. The figure below shows a conceptual drawing of mixed satellite terrestrial channel showing different effects of the propagation medium from the satellite to the user.

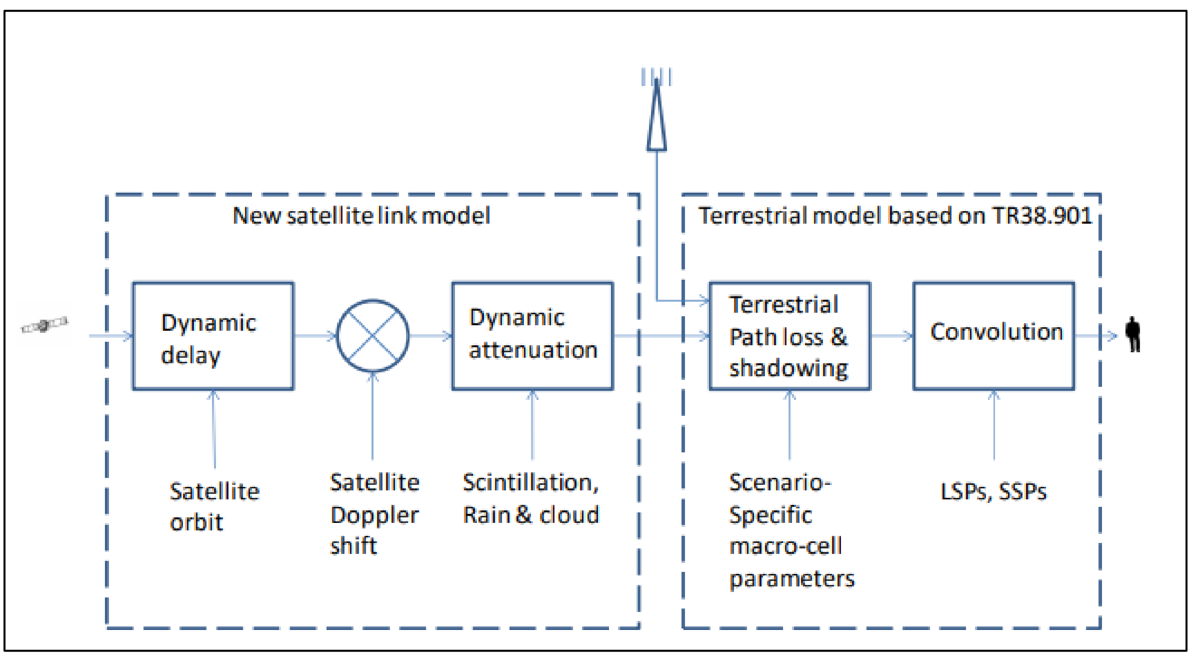


Figure 26: Satellite combined with terrestrial channel [14]

LSP: Large Scale Parameters. SSP: Small Scale Parameter

The orbit of the satellite in use introduces a dynamic delay in the propagation time. A satellite in the GEO has a one-way propagation time from approximately 120ms which is more compared to other air/space borne stations at lower altitudes from the earth. A LEO satellite at 600km has a one-way propagation time of 2ms while a MEO satellite at 8000km has one of 22ms. The satellite doppler shift is due to the satellite orbit, elevation angel and carrier frequency. According to 3GPP in [14], the satellite doppler shift is defined as:

Equation 1:Doppler shift

$f_{d, sat} = (V_{sat} /c) *((R/ R+h) \cos(\alpha_{model})) *f_c$

where:

c is the speed of light.

R is the radius of the earth.

h is the satellite altitude.

f_c is the carrier frequency.

V_{sat} is the satellite speed.

Equation 2:Speed of satellite.

$V_{sat}= \sqrt{} (GM/ (R + h)^2)$

G is the gravitational constant.

M is the mass of the earth.

Tropospheric effects like attenuation, caused by weather phenomena, and scintillation affect the signal depending on the frequency. Signal attenuation is negligible for signals below 1GHz and small for frequencies up to 10 GHz. For frequencies above 10GHz the signal attenuation is large. Increasing frequency and decreasing path elevation angle cause scintillation effects to increase. On entering the terrestrial scenario, the signal is exposed to environment specific parameters like pathloss and shadowing. Let us consider a rural environment characterized by trees, a roadside tree-shadowing model as recommended by ITU in, Propagation data required for the design systems in the land mobile-satellite service [16], can be used. Cumulative fade distribution measurements at 870 MHz, 1.6 GHz and 20 GHz have been used to develop the extended empirical roadside shadowing model. The extent of trees along the roadside is represented by the percentage of optical shadowing caused by roadside trees at a path elevation angle of 45° in the direction of the signal source. The model is valid when this percentage is in the range of 55% to 75% [17]. Other environments characterized by other structures, for example buildings, will also have a shadowing effect related to it. Lastly small-scale parameters (SSPs) majorly influenced by multipath propagation are taken into account before the signal can finally reach the user.

3.2 Simulation of NTN channel.

The channel that will be considered in this practical work is the narrow band flat fading channel, where the frequency response of the channel affects, in the same way, all the frequencies within the signal. The radio propagation medium being one which experiences dynamic changes, the above situation is possible in a small window of observation. A channel is considered flat fading if the UE bandwidth is inferior to the channel bandwidth. As described in Study on channel models for frequencies from 0.5GHz-100GHz [14], the ITU two-state model for terrestrial radio links can be used as simplified alternative to model satellite links for Land Mobile Satellite Services (LMSS) if the following requirements are met:

- ✓ S band scenario (2GHz- 4GHz).
- ✓ Minimum elevation angle is 20˚.
- ✓ Quasi-LOS conditions i.e. fading margin is approximately 5dB.
- ✓ Channel bandwidth is maximum 5MHz.
- ✓ Environment is rural, urban or suburban.

3.2.1 Narrow band flat fading channel

In this practical, for the narrow band flat fading channel, we will consider LMSS scenarios rural and urban for both S - band and Ka- band. The NTN narrow band channel is modeled for single input single output (SISO) simulations. The deployment scenarios described by 3GPP are the following:

- ✓ GEO and Ka-band with VSAT relay as NTN node and transparent payload, for a stationary VSAT for example one mounted on a house or any other structure.
- ✓ GEO and S-band with handheld UEs as NTN node and transparent payload.
- ✓ LEO and S-band with handheld UEs as NTN node & regenerative payload.
- ✓ LEO and Ka-band with VSAT relay as NTN node & regenerative payload.
- ✓ HAPS in S- or Ka-band with handheld UEs as NTN node & regenerative payload.

The MATLAB narrow band flat fading channel model supports satellite links on the LEO. In this practical the received signal will be observed in different environments and angles to determine their effect.

The first step is to set the channel parameters as shown in the figure below. It should be noted that the values of the parameters are changed during the practical according to the different scenarios the figure below is for the sake of illustration.

```
%common parametres to be used for both narrow band flat fading channel and
%selective frequency tdl channel
commonParams = struct;
commonParams.CarrierFrequency = 2e9;             % In Hz
commonParams.ElevationAngle =90;                % In degrees
commonParams.SatelliteAltitude =36000000;         % In m
commonParams.MobileAltitude = 0;                 % In m
commonParams.MobileSpeed = 3*1000/3600;          % In m/s
commonParams.SampleRate = 7680000;               % In Hz
```

Figure 27: Channel parameters in MATLAB Code

The figure that follows shows the code for doppler calculations for both the UE/ Mobile terminal and the satellite.

```
% Set the random stream and seed, for reproducibility
commonParams.RandomStream = "mt19937ar with seed";
commonParams.Seed = 73;
% Set the number of sinusoids used in generation of Doppler spread
commonParams.NumSinusoids = 48;
% Calculate the Doppler shift due to satellite movement
satelliteDopplerShift = dopplerShiftCircularOrbit(...
    commonParams.ElevationAngle,commonParams.SatelliteAltitude,...
    commonParams.MobileAltitude,commonParams.CarrierFrequency);
% Calculate the maximum Doppler shift due to mobile movement
c = physconst('lightspeed');
mobileMaxDoppler = commonParams.MobileSpeed*commonParams.CarrierFrequency/c;
```

Figure 28 Doppler calculations code

The next step is to initialize the channel, shown in the figure below;

```
% Initialize the NTN flat fading narrowband channel
ntnNarrowbandChan = p681LMSChannel;
ntnNarrowbandChan.SampleRate = commonParams.SampleRate;
ntnNarrowbandChan.CarrierFrequency = commonParams.CarrierFrequency;
ntnNarrowbandChan.ElevationAngle = commonParams.ElevationAngle;
ntnNarrowbandChan.MobileSpeed = commonParams.MobileSpeed;
ntnNarrowbandChan.SatelliteDopplerShift = satelliteDopplerShift;
ntnNarrowbandChan.RandomStream = commonParams.RandomStream;
ntnNarrowbandChan.Seed = commonParams.Seed;
ntnNarrowbandChan.Environment = "Urban";
ntnNarrowbandChan.AzimuthOrientation = 0;
ntnNarrowbandChan.FadingTechnique = "Sum of sinusoids";
ntnNarrowbandChan.NumSinusoids = commonParams.NumSinusoids;
```

Figure 29:Flat fading channel initialization.

The following MATLAB command allows to visualize channel information and thus allowing to visualize that the filter delay is 0 which is consistent with a flat fading channel. In a narrowband flat fading channel, the channel delay filter primarily represents the overall time delay experienced by the signal. Since all frequencies experience similar gain, the filter doesn't introduce any frequency-selective effects.

```
p681ChannelInfo = info(ntnNarrowbandChan)
```

```
struct with fields:

                  PathDelays: 0
          ChannelFilterDelay: 0
   ChannelFilterCoefficients: 1
         NumSamplesProcessed: 0
```

Figure 30:Flat fading channel information

The last step is to visualize the spectrum of the received signal, aided by the code shown in the figure below.

```
ntnNarrowbandAnalyzer = spectrumAnalyzer( ...
    SampleRate = ntnNarrowbandChan.SampleRate);
ntnNarrowbandAnalyzer.Title = "Received Signal Spectrum " ...
    + "NTN narrowband with " + string(ntnNarrowbandChan.Environment) + " environment";
ntnNarrowbandAnalyzer.ShowLegend = true;
ntnNarrowbandAnalyzer.ChannelNames = "Rx Antenna 1";
ntnNarrowbandAnalyzer(narrowbandOut)
```

Figure 31: MATLAB code to visualize signal spectrum.

The following images show the signal spectrum in different scenarios. It should be noted that in all the scenarios the satellite is in LEO.

The first scenario is a communication between a satellite in LEO and a handheld UE as the NTN node. The carrier frequency in in the S band and the link will be observed in different environments and the elevation angle at 20, 50 and 90 degrees.

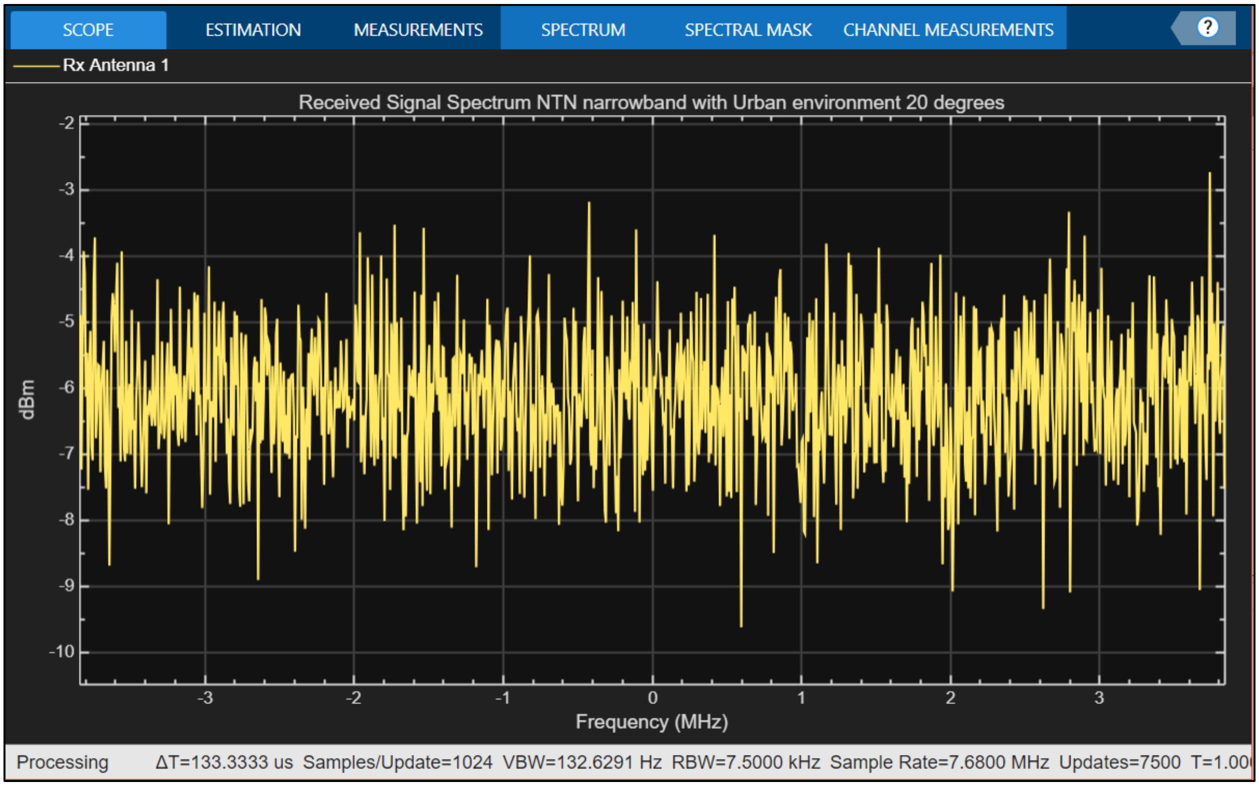


Figure 32: Signal spectrum in urban environment, S-band downlink, UE, 20 degrees.

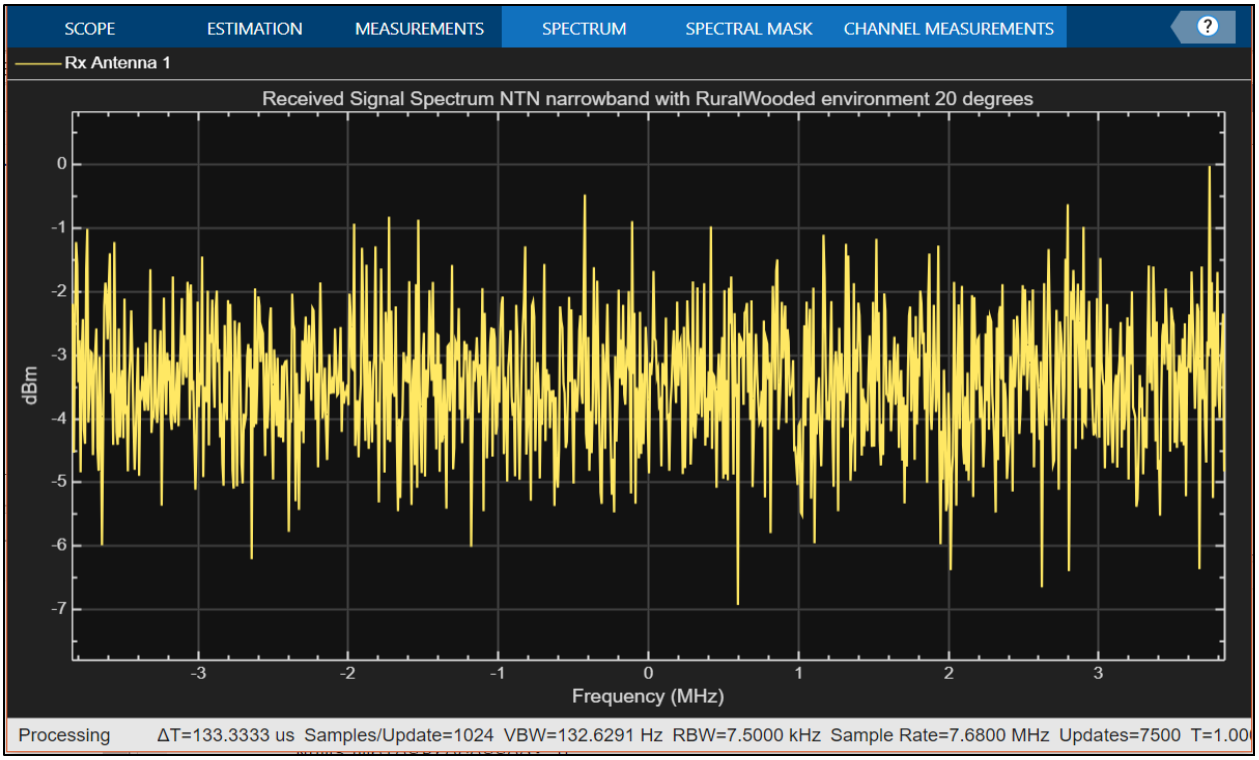


Figure 33:Signal Spectrum rural environment, S- band downlink, UE, 20 degrees.

In the following figures the elevation angle is increased to 50 degrees.

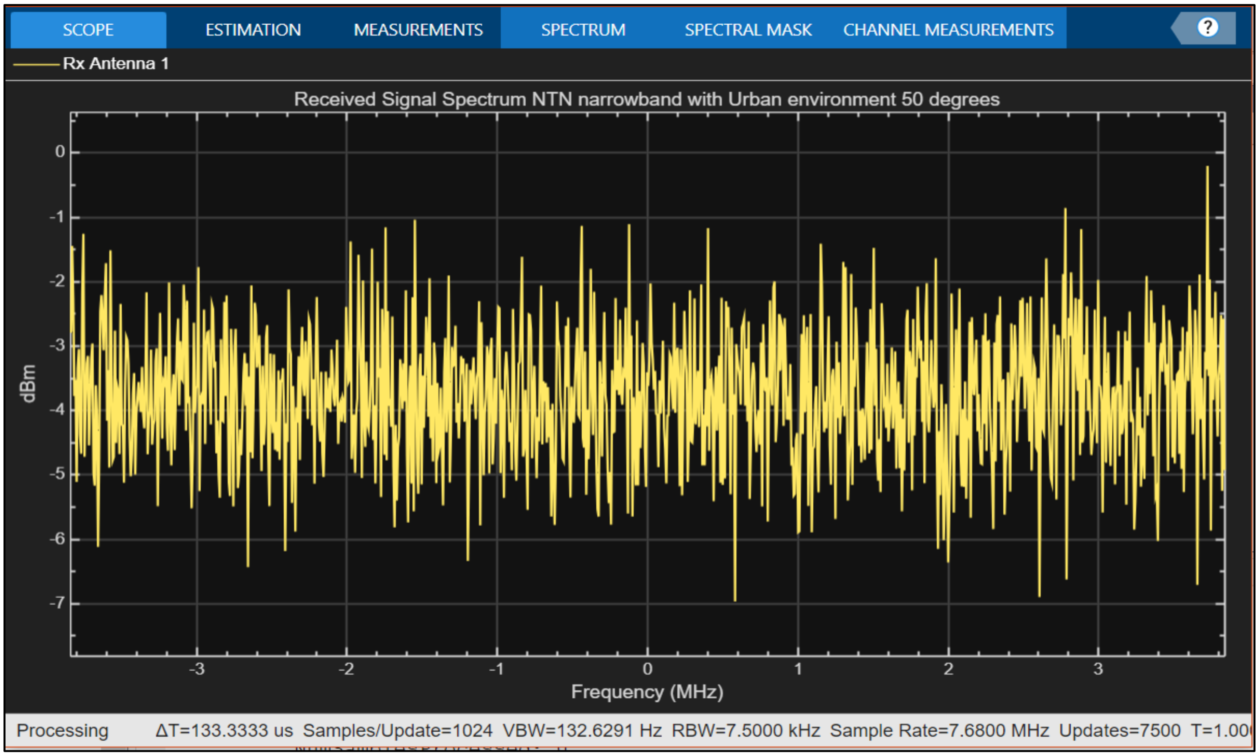


Figure 34:Signal Spectrum urban environment, S-band downlink, UE, 50 degrees.

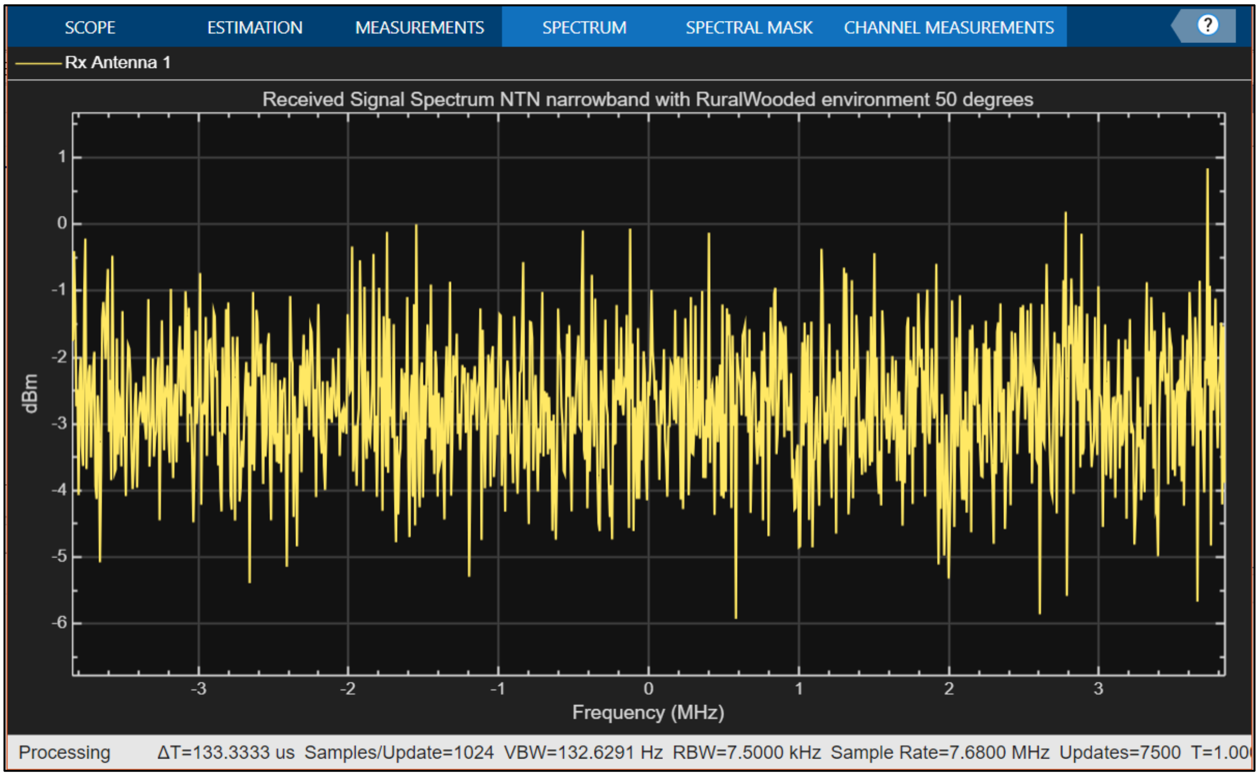


Figure 35:Signal Spectrum rural wooded environment, S-band downlink, UE, 50 degrees.

The following figure show the signal spectrum at an angle of 90 degrees.

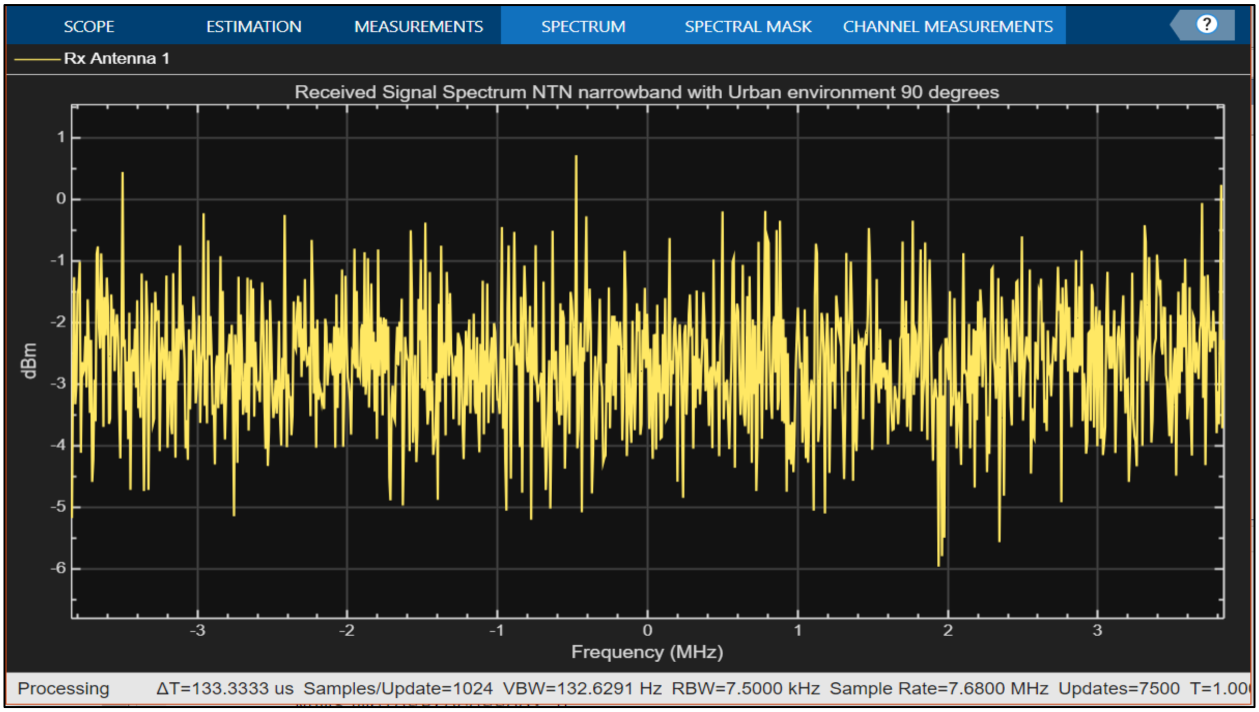


Figure 36: Signal Spectrum urban environment, S-band downlink, UE, 90 degrees

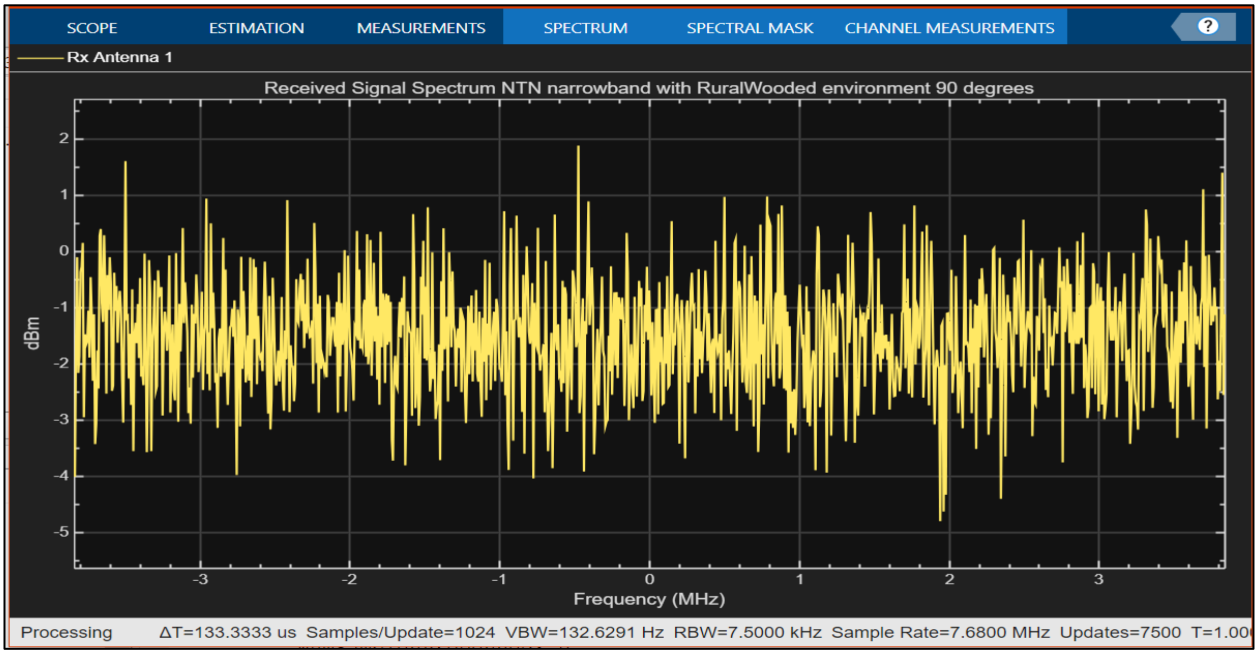


Figure 37:Signal Spectrum rural wooded environment S-band downlink, UE, 90 degrees.

Moving to the Ka band the NTN node is a VSAT terminal the received signal will be observed in different environments and elevation angles starting with 20 degrees.

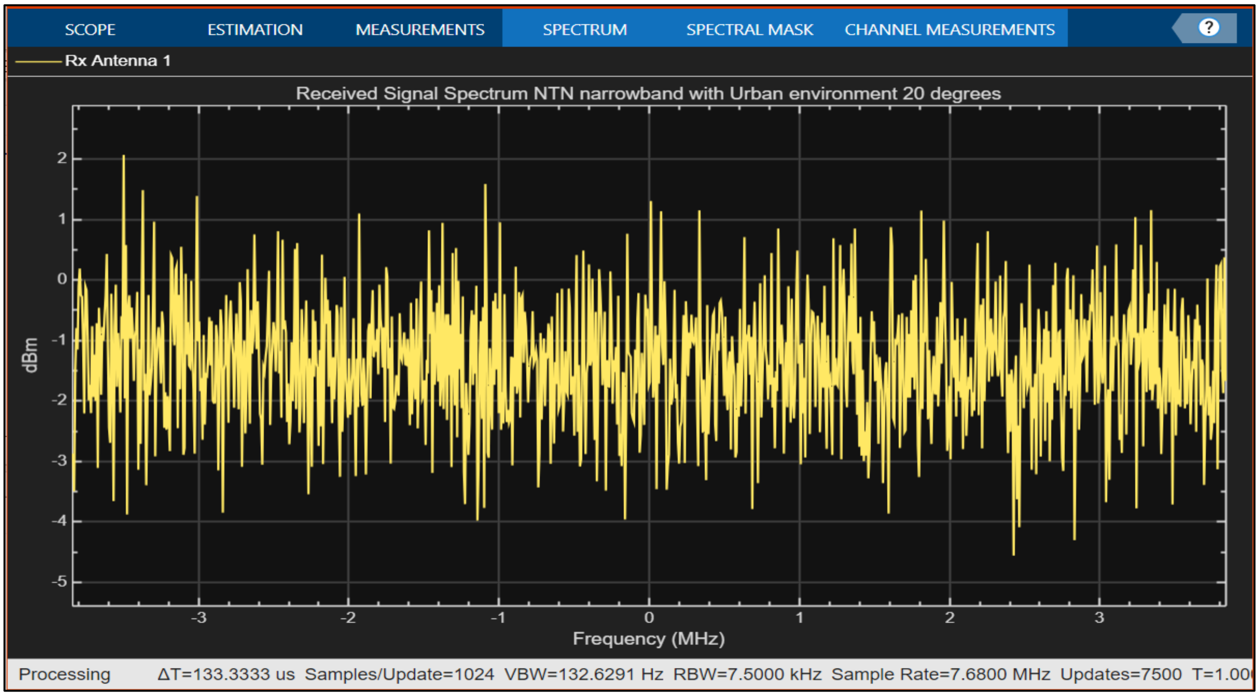


Figure 38: Signal Spectrum urban environment Ka-band downlink, VSAT, 20 degrees.

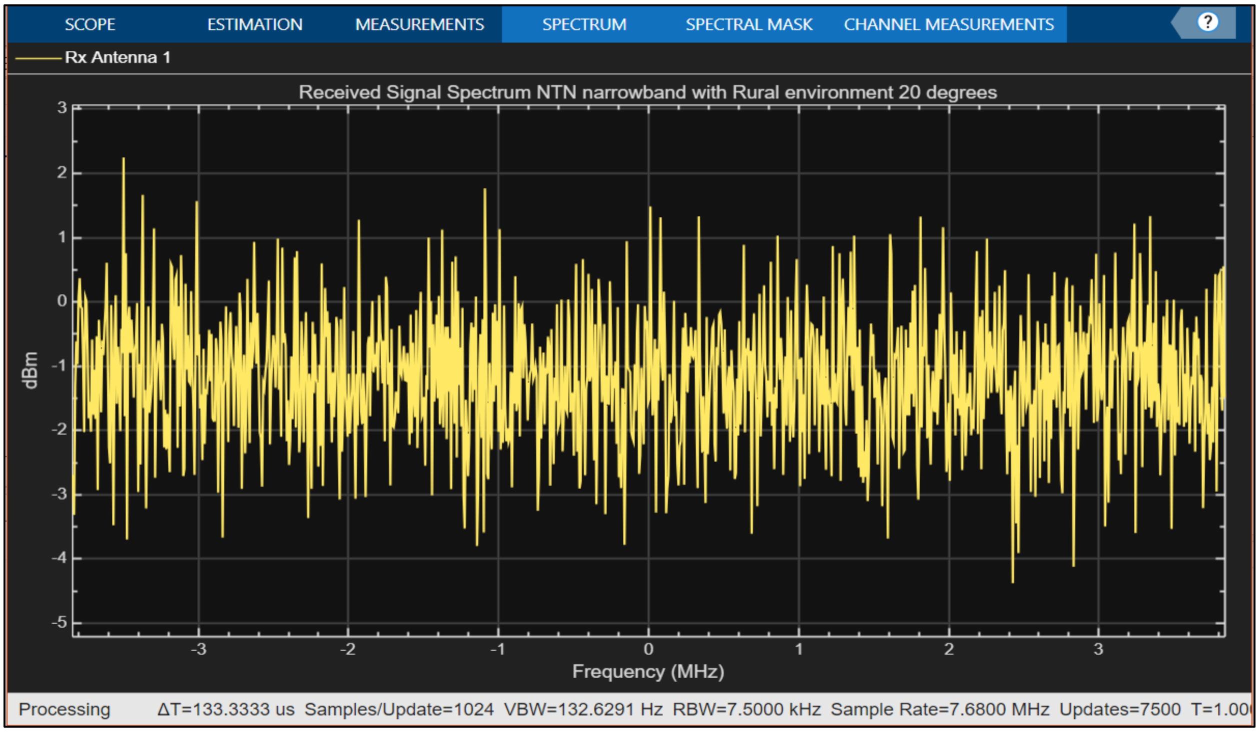


Figure 39:Signal Spectrum rural environment Ka-band downlink, VSAT, 20 degrees.

The following are the spectra of the signal at 50 degrees.

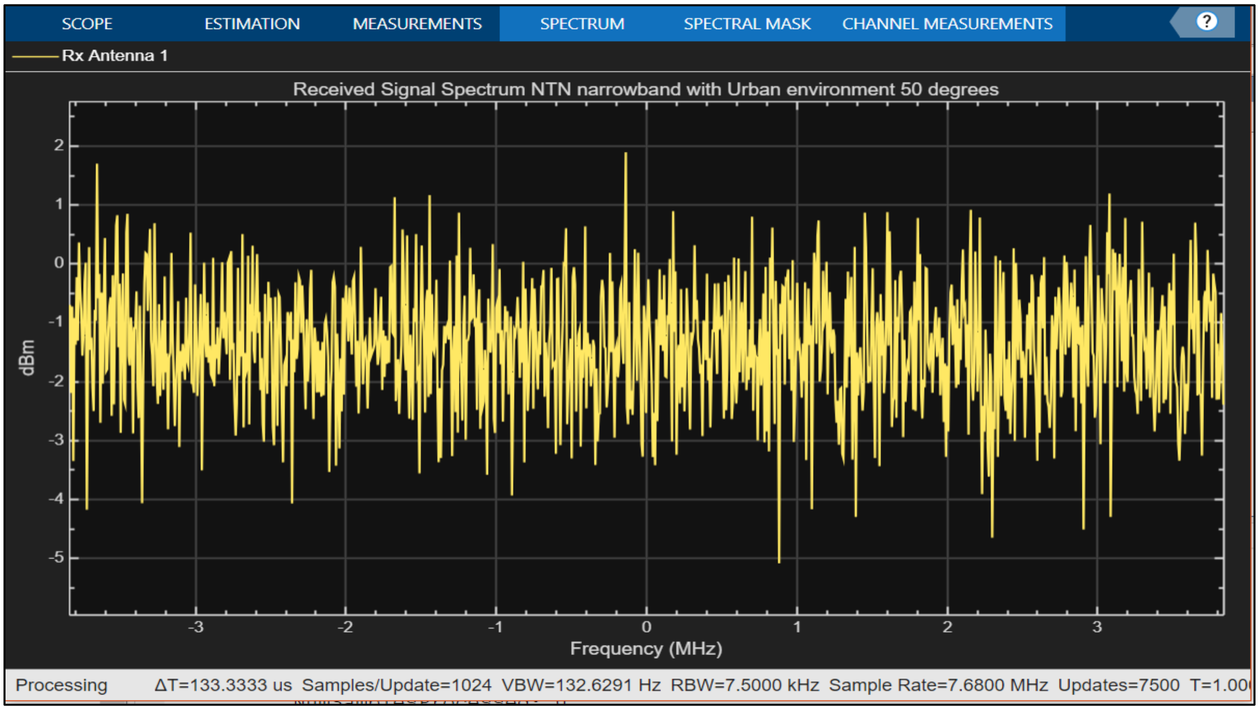


Figure 40:Signal Spectrum urban environment Ka-band downlink, VSAT, 50 degrees.

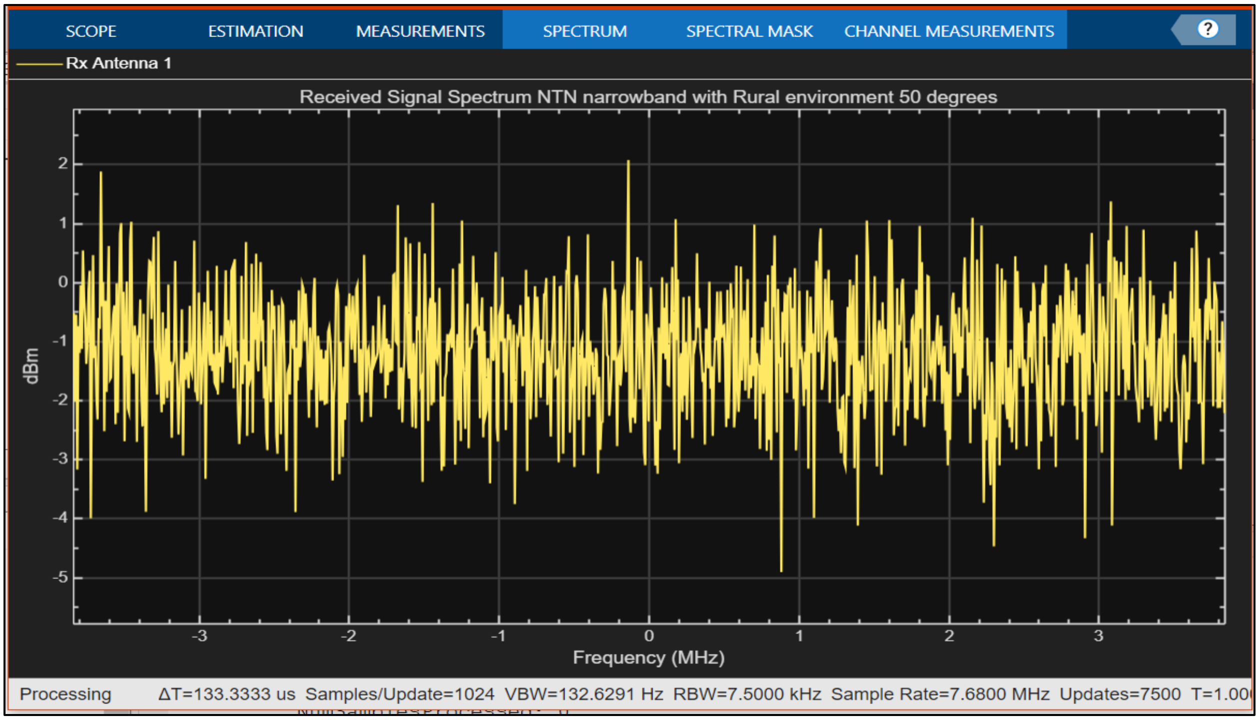


Figure 41:Signal Spectrum rural environment Ka-band downlink, VSAT, 50 degrees.

The following shows the received signal at an angle of 90 degrees.

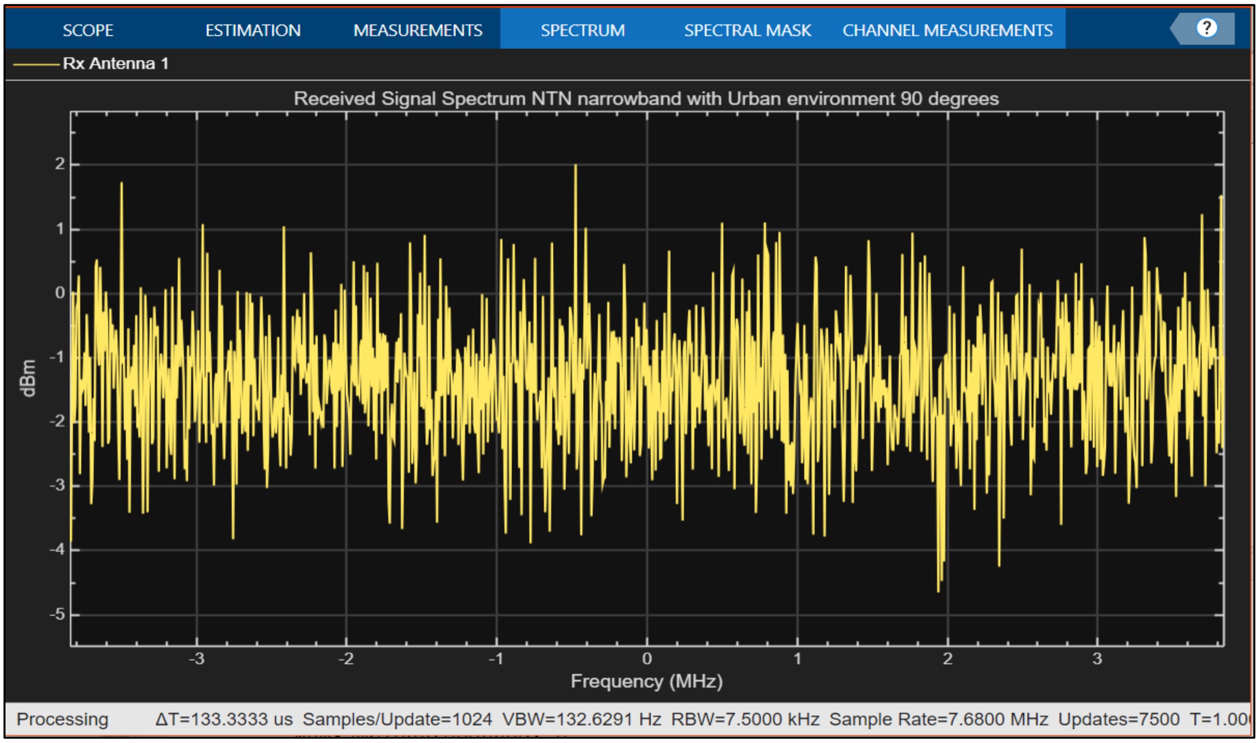


Figure 42:Signal spectrum urban environment, Ka band downlink VSAT, 90 degrees.

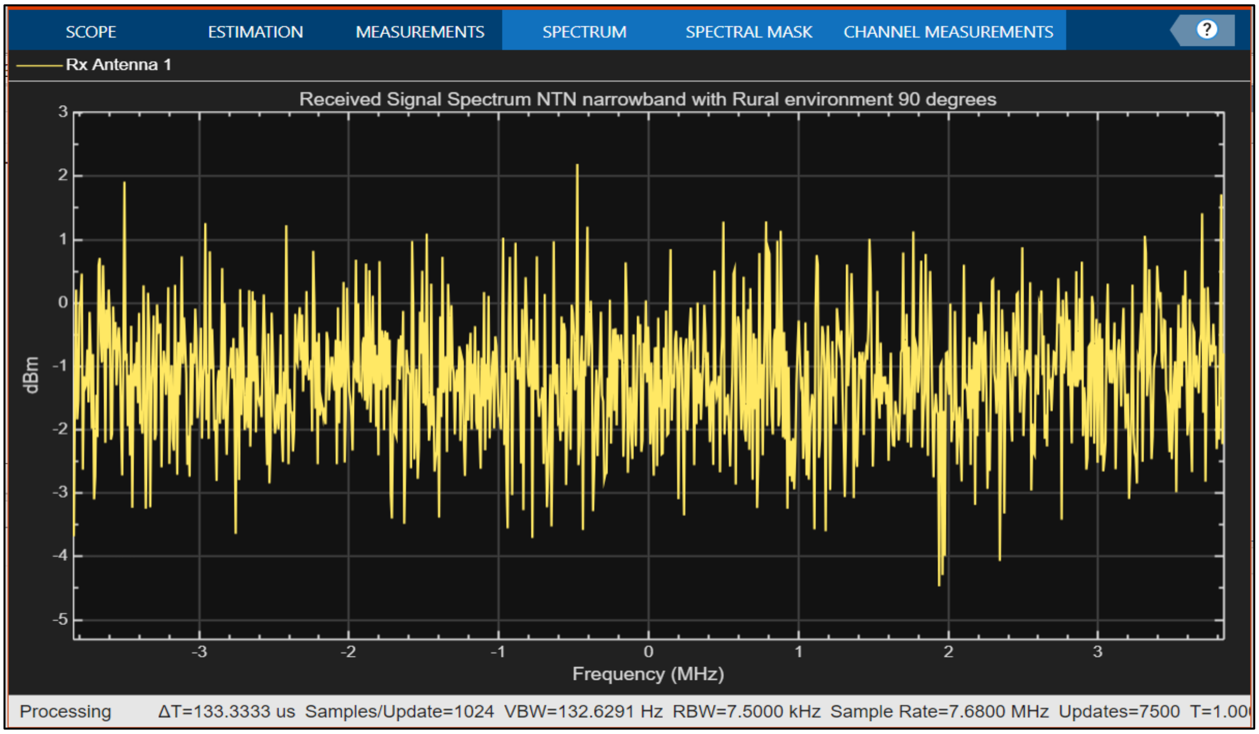


Figure 43 signal spectrum rural environment, Ka-band downlink VSAT, 90 degrees.

One of the requirements in channel modelling is the ability to support a User Terminal with high mobility e.g. an aircraft or a high-speed train. With a satellite altitude of 500km (LEO constellation), carrier frequency of 20 GHz (Ka band) and a mobile speed of 500km/h for the train the following signal spectrum is achieved in different elevation angles.

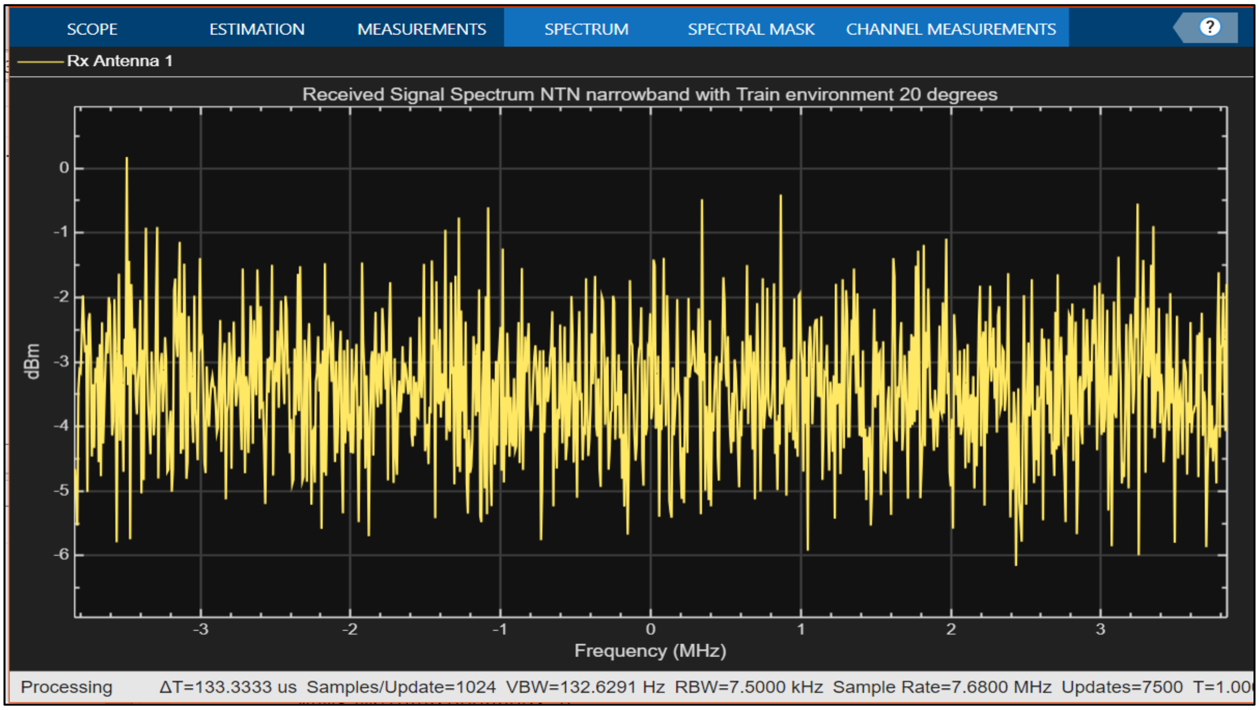


Figure 44: Signal Spectrum Train environment Ka-band downlink, VSAT, 20 degrees.

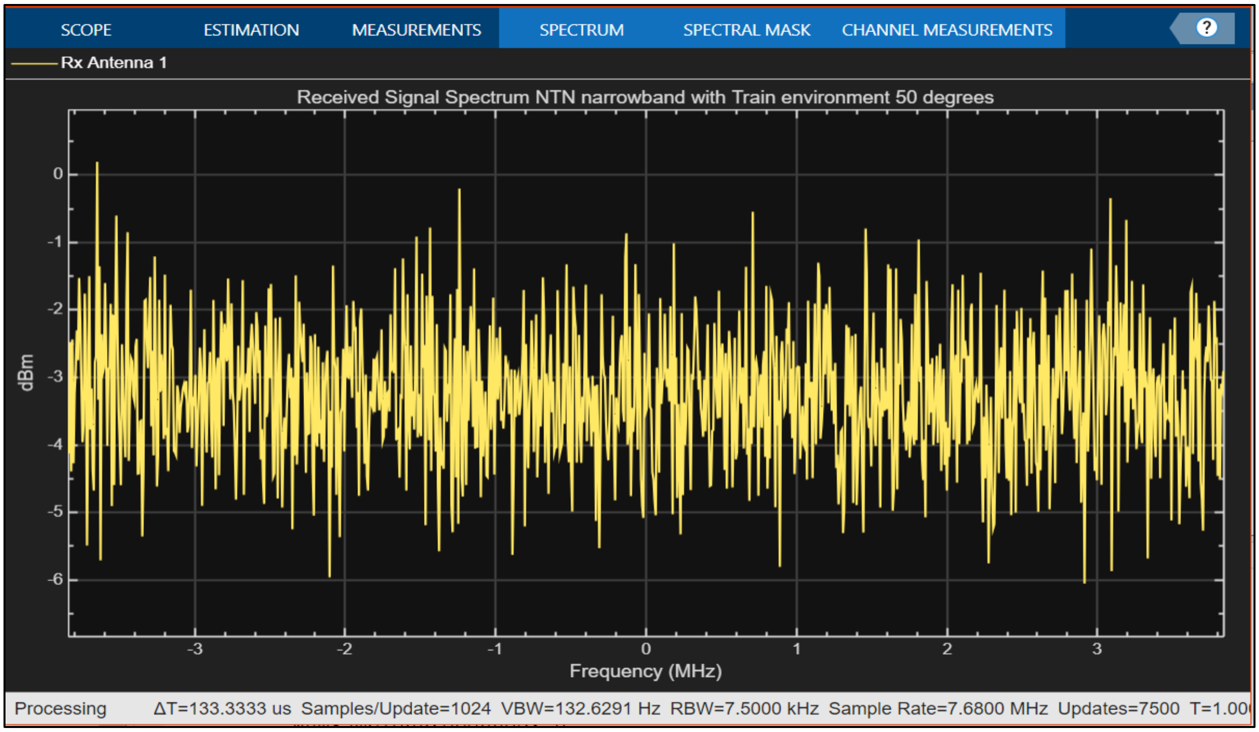


Figure 45: Signal Spectrum Train environment Ka-band downlink, VSAT, 50 degrees.

The following figures illustrate the received signal by the train at 90 degrees.

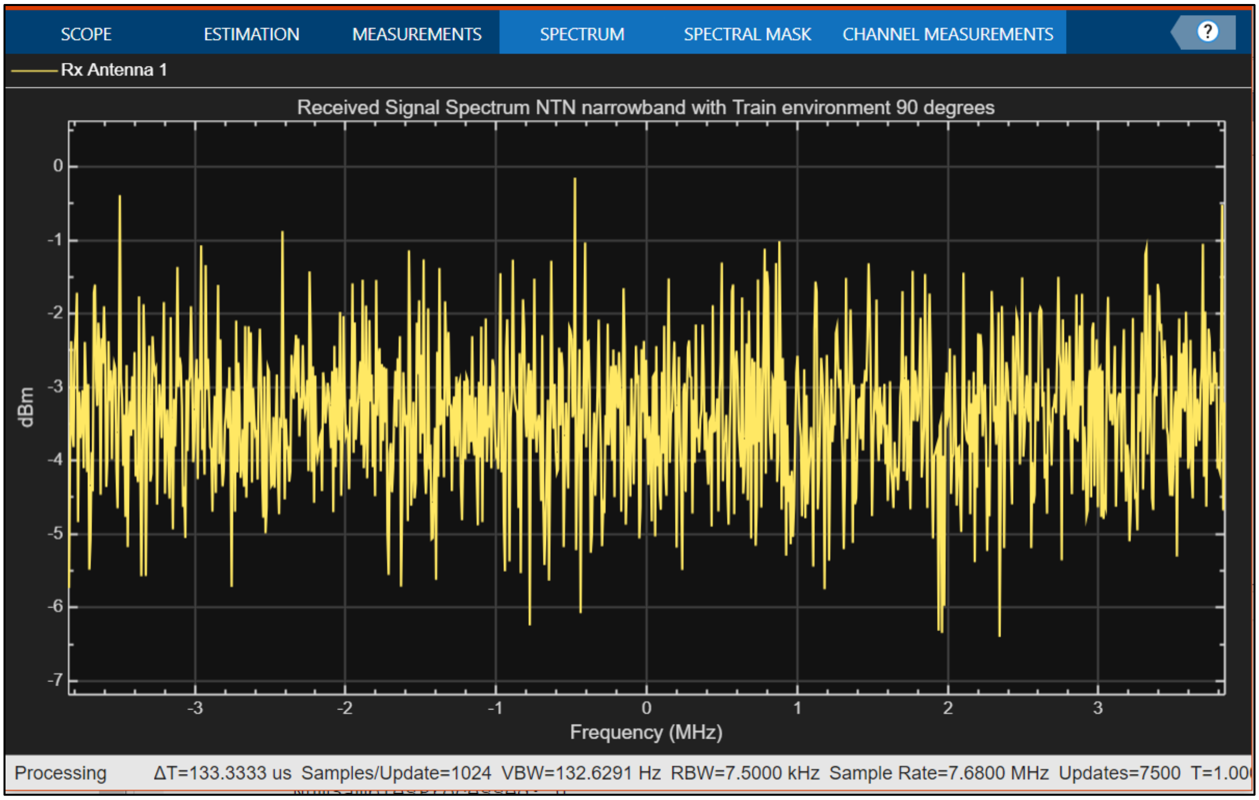


Figure 46: Signal Spectrum Train environment Ka-band downlink, VSAT, 90 degrees.

3.3 Results and discussion

Firstly, a summary of the results from the narrow band flat fading channel are expressed in the table below.

Table 5:Summary of results from narrow band flat fading channel.

NTN node	**Environment**	**Frequency Band**	**Max. received power(dBm)**	**Elevation angle (degrees)**	**Mobile speed**
UE	Urban	S	-2.6	20	3km/h
	Suburban	S	-2.1	20	3km/h
	Rural Wooded	S	0	20	3km/h
UE	Urban	S	-0.7	50	3km/h
	Suburban	S	0.7	50	3km/h
	Rural Wooded	S	0.9	50	3km/h
UE	Urban	S	0.7	90	3km/h
	Suburban	S	0.8	90	3km/h
	Rural	S	1.9	90	3km/h
VSAT	Urban	Ka	2.1	20	0km/h
	Suburban	Ka	2.1	20	0km/h
	Rural	Ka	2.2	20	0km/h
VSAT	Urban	Ka	1.9	50	0km/h
	Suburban	Ka	1.9	50	0km/h
	Rural	Ka	2.1	50	0km/h
VSAT	Urban	Ka	2.0	90	0km/h
	Suburban	Ka	2.0	90	
	Rural	Ka	2.2	90	0km/h
High Speed terminal	Train	Ka	0.2	20	500km/h
High Speed terminal	Train	Ka	0.2	50	500km/h
High Speed terminal	Train	Ka	-0.1	90	500km/h

From the table above we can observe that in the scenarios the signal received in the rural environment is slightly stronger than in the urban. This is because in a rural setting there are less obstacles, like buildings and sky scrapers, in the propagation medium and so the multipath phenomenon is at minimum. The signal received in direct path and hence it is stronger.

At the Ka frequency band, the received signal is seen to be stronger than in the S band as much as frequency is directly proportional signal attenuation. This is because the NTN application in Ka band requires that the NTN terminal be a VSAT which can be mounted on a structure, the structure can be stationary for example a house or a moving vehicle like a train. The S band applications of

NTN concern handheld UE that are generally in a relatively slower speed. A VSAT terminal consisting of an antenna with a larger surface area compared to a handheld UE, captures the signal better because of the effective surface area of the antenna. Also, in the case where the VSAT terminal is not mounted on moving vehicle the doppler effect is zero and hence the received signal is better.

Equation 3:Gain of a parabolic antenna.

$$G= 10 \log (4\pi Se/ \lambda^2)$$

Where G is the antenna gain.
Se the effective surface area of an antenna.
$Se= Sr*\eta$

Equation 4:effective surface area of a parabolic antenna.

η is the efficiency of the antenna given by the manufacturer

λ is the wavelength.

From equation 3, it can be seen that the gain of an antenna is directly proportional to the effective surface area thus a larger surface area like in the case of a VSAT, the gain added to the received signal is more.

It can be seen that the received signal is weaker at lower elevation angles compared to when the angle is 90˚. Reducing the elevation angle increases the distance between the air/space-based platform and the UE, which implies a higher pathloss. The figure below shows a communication link between an NTN terminal with an air/space-borne platform at a first position P1 and at a second position P2, illustrating different elevation angles. At a lower angle the signal path is more horizontal than vertical meaning there are likely to be more obstacles in the path.

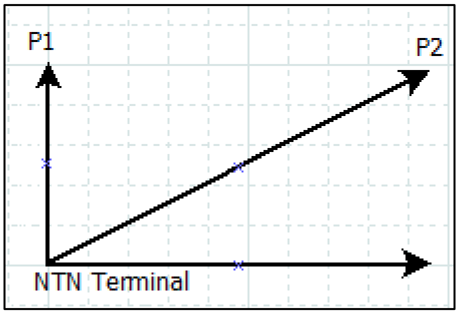


Figure 47: Elevation angles and propagation distance.

In the scenario where a link between a high-speed train and a LEO satellite is simulated. The received signal is weaker compared to other environments this because both the satellite and train are in movement and this affects the quality of the signal. As much at 20 degrees and 50 degrees the maximum received power is higher than at 90 degrees, looking at the signal spectrum we can observe that at the lower angles the general received power is lower than when the angle is 90. The higher the NTN terminal speed the lower the quality of the received signal.

3.4 Conclusion

The practical has simulated an NTN channel in quasi-ideal scenarios as the narrow band flat fading channel is a model that is more or less ideal. This channel works with the hypothesis that, the channel affects the frequency components of the signal in the same way during the transmission which is rarely the case for a radio propagation. This means that the results obtained can be considered the best possible values. Basing on the figure below that shows system design requirements for NTN terminal receiver sensitivity with the parameters altitude and elevation angles. For a communication between LEO (600km) and an NTN terminal on earth with an elevation angle of ninety degrees a minimum of -117dBm can be received by the NTN terminal.

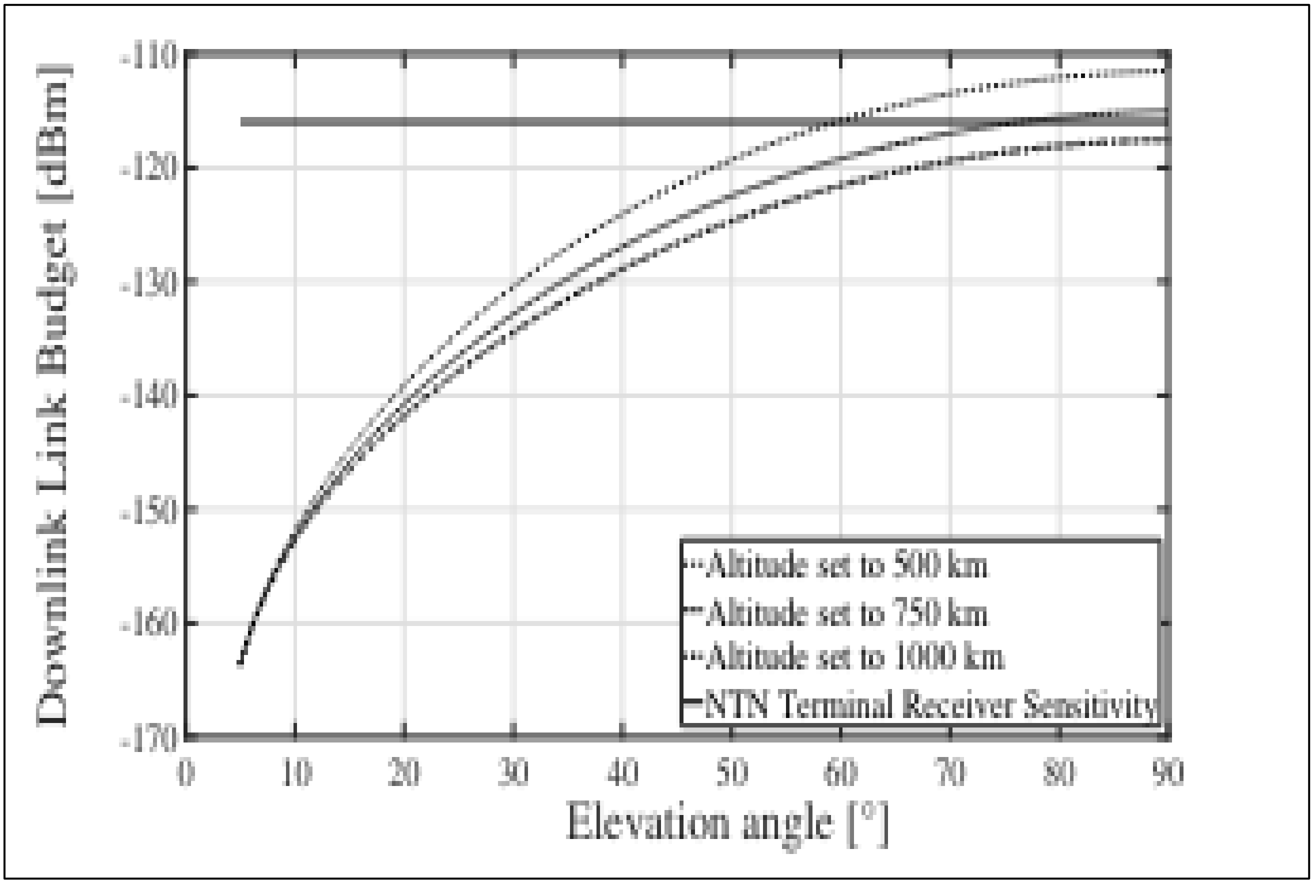


Figure 48:Reference values for receiver sensitivity [34]

The results are therefore good, they leave enough room for dynamic radio channel propagation medium effects that can affect the signal negatively and still be able to successfully decode the received signal.

Conclusion.

From the results obtained in this project it can be seen that NTNs are able to provide solutions for the problems that motivated this venture. Allowing service provision in rural/less densely populated areas or geographical inaccessible areas by terrestrial networks like the sea. Combining the features of satellite communication with terrestrial networks to achieve service ubiquity, reliability and scalability. At a glance, the integration of terrestrial networks seems like a magical solution to achieve these connectivity goals. However, a lot of work needs to be done especially in the adaptation air/space-based platforms to provide services to UE that are expected to remain the same morphologically. There is need for research in radio frequency design and conception, in order to come up with components that will enable UE to be served by NTN while maintaining their physical forms.

Realizing this project was a fairly challenging matter as NTN is a technology that is in development. Foundational principles for its realization have been laid down by organizations like 3GPP, ITU IEEE among other international bodies concerned with telecommunications. However new information is constantly being added but under the protected wing of test industries which makes it unavailable for public use. In my quest to come as close as possible to a realistic NTN channel through modeling the tapped delay frequency selective channel I hit a license wall that prevented me from going further in my practical work. A tapped delay frequency selective channel considers a much more realistic approach where the channel affects the frequency components in a signal in different ways. This depicts more accurately the dynamic radio propagation medium and the results obtained are closer to real life situations. Simulating real life conditions for satellite end-to end links remains a major challenge in NTN deployment. Despite the open challenges present in the NTN technology, it presents a timely solution to rising user needs and it represents the next step in the evolution of telecommunications networks.

Personal perspective

Working on this project has allowed me to put to work the knowledge acquired in the course of my studies especially from modules like radio communications, mobile networks, radio frequency conception and satellite communication systems. Seeing how mobile networks can be combined with satellite systems to achieve a monumental hybrid technology raises the question; how many other technologies, transmission networks can be incorporated in order to create a global network that matches the evolving user needs. A particular interest of mine lies with optical networks and how it has revolutionized the fixed network in proving the highest possible data rates. Aside from laser beam intersatellite links, I believe optical technology can be integrated in the same context to ameliorate service provided to mobile users. The National Institute of information and Communication Technology (NICT) in Japan, in their special issue for space-based ICT issue number 1 2021 page 8-9 talks about the prospect of optical feeder link technology. With their project, ETS9, they aim to realize a 10Gpbs communication link with GEO satellite and a terminal on earth while using the technology High speed Communication with advanced Laser Instrument (HICALI). From this it can be predicted that the trend of unified networks will in future involve most if not all communication technologies coming together to compliment instead of compete with one another, in order to meet user demands.

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