5G NTN TAKES FLIGHT: TECHNICAL OVERVIEW OF 5G NON-TERRESTRIAL NETWORKS

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PREFACE AND DISCLAIMER

5G non-terrestrial networks (NTN) is a technology aiming to enable 5G user terminals on or close to the earth's surface to connect to non-terrestrial base stations located on satellites. We consider it to be a technology that has still to undergo much long-term evolution. The objective of this white paper is to provide an overview of the major aspects of the technology and corresponding challenges. We have tried to incorporate the latest state of the technology involved, representing the current status of the standardization work ongoing in 3GPP. As 5G NTN is evolving and will no doubt continue to evolve, note that the information provided in this white paper is subject to change and expansion.

There are two major market ecosystems driving and innovating both the technology and business use cases and services: wireless communications and aerospace. We note that 5G NTN results in convergences between these two ecosystems. We admit that as the author's background is the wireless ecosystem, we assume that the greatest innovations to arise from the development of NTN will be on the wireless side. Beyond doubt, this white paper concentrates on the wireless perspective. It is not our intention to diminish the contribution of the aerospace ecosystem which will be essential to the success of 5G NTN. Do not underestimate the significance of aerospace issues, but accept our apologies that we decided to produce this white paper with the focus on 5G. For the wide range of information Rohde & Schwarz provides for the aerospace ecosystem, refer to our website at www.rohde-schwarz.com.

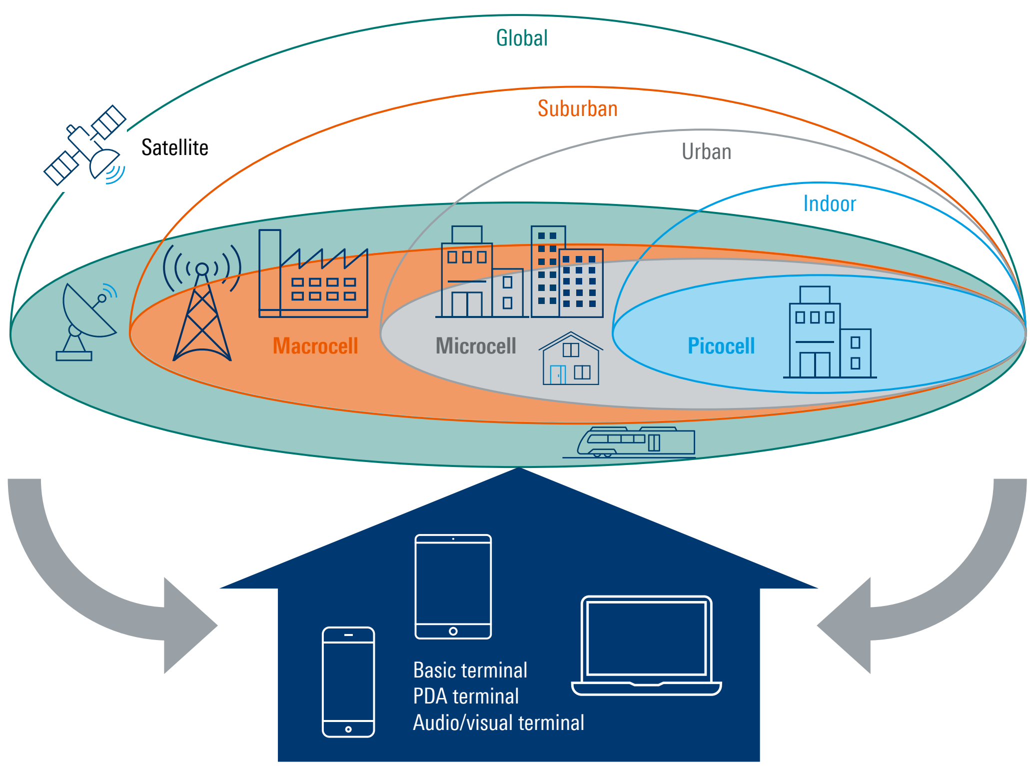
We hope our wireless ecosystem expertise can help contribute to the success of 5G NTN, and readers find the content of this white paper valuable and informative.

The author

1 INTRODUCTION

"It's like déjà-vu all over again" could be a first reaction when contemplating the 3GPP Release 17 initiative to incorporate non-terrestrial networks (NTN) into the 5G system. Already in the mid-90s, the International Telecommunications Union (ITU) launched with its International Mobile Telecommunication initiative IMT-2000 a vision of global wireless access in the 21st century. This led to the founding of the standardization organization 3GPP (Third-Generation Partnership Project) to start international standardization of the third-generation wireless communications technologies. Prominent examples are the CDMA2000® led by the standardization organization 3GPP2 and the Universal Mobile Telecommunication System (UMTS) with its two pivotal radio access technologies (RAT) wideband code division multiple access (WCDMA) and time division code division multiple access (TD-CDMA). As major targets, the IMT-2000 initiative raised the two attributes "flexibility" and "globalization". Peak data rates up to 2 Mbps in hotspots and average data rates of up to 384 kbps under mobile conditions were presented as objectives to be fulfilled by the future public land mobile network (FPLMN). Those objectives should be supported by both terrestrial and satellite based communications systems. Due to more commercial and cost reasons, the initial dream of satellite based communications did not become reality in those days.

Figure 1: ITU program IMT-2000



PDA	Personal digital assistant
2 Mbit/s	Picocell and indoor
384 kbit/s	Pedestrian and low-speed vehicular
144 kbit/s	High-speed vehicular

In the meantime, the situation has changed. The evolution of wireless technologies culminating in the flexibility of the 5G system accompanies the evolution in the aerospace domain. Launching rockets and satellite constellations with lower orbit do not represent an insurmountable technical challenge and become reality in many applications. Commercial and private satellite systems are being deployed and offer their business to the ecosystem. 3GPP Release 17 is the first enabler of NTN connectivity and hopes outline a long term technology evolution and a wider proliferation of NTN use cases.

Non-terrestrial networks – their facets

The term "non-terrestrial networks" represents a plethora of connection scenarios, ranging from satellite based communications via airborne stations but also taking into account connection scenarios like air-to-ground or unmanned aerial vehicles (UAV) flight control as depicted in Figure 2. The holistic contemplation depicts the various satellite based connectivity scenarios where the satellites differ in their flying altitude like GEO, MEO and LEO and their coverage area. There is also a distinction in the UE type, i.e. whether it is a handheld device or a very small aperture terminal (VSAT) UE with assumed better receiver capabilities, e.g. parabolic antennas or higher TX power.

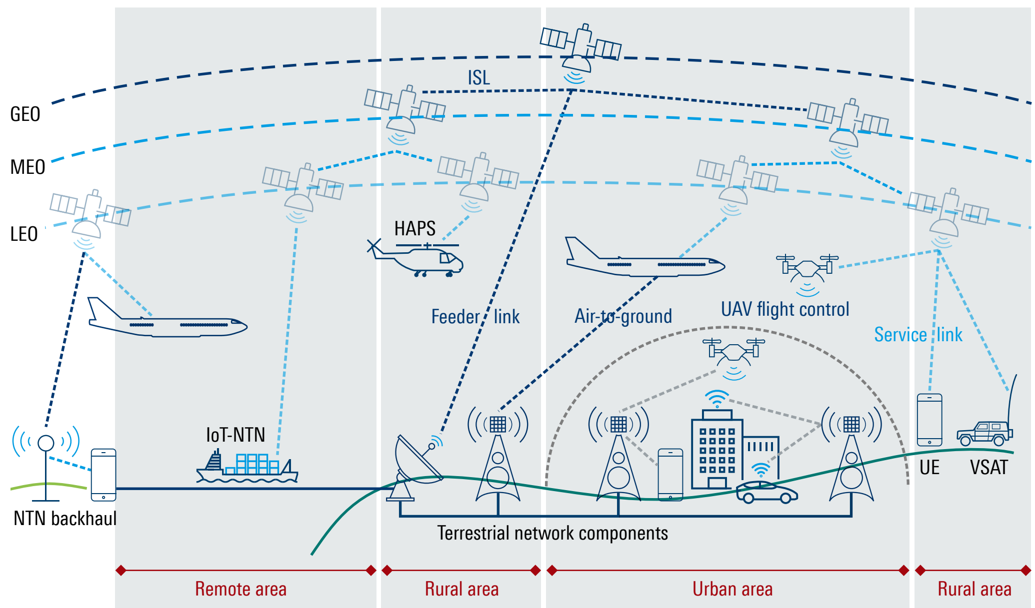
In addition to satellite based connectivity, 3GPP also permits, even if this is assumed for later releases, the incorporation of airborne stations, so-called high altitude platform systems (HAPS) like helicopters, balloons or airplanes. Air-to-ground (ATG) communications aims at the provision of in-flight connectivity for airplanes by the radio connection to terrestrial base stations. Thus, in a wider sense those air-to-ground communications belong to NTN communications, but for the sake of brevity, those details will not be discussed in this white paper. A major difference of such air-to-ground communications compared to legacy terrestrial networks is the larger cell size and probably the steering of the base station antenna radiation towards the sky, while in terrestrial networks a base station antenna is typically down-tilted to avoid an overrange and interference situation. With sophisticated directional antenna arrays, it is possible to implement a kind of tracking methodology to direct the radiation to a single airplane only. Even if ATG is not directly considered a full non-terrestrial network, it can profit from some of the same technical solutions like delay handling or frequency compensation.

5G NTN not only provides connectivity services to user terminals, via satellite connections, a terrestrial gNB may connect to the 5G core network. This setup is described as NTN backhaul.

The last technology worthy of mention, which can also be considered as NTN, is the flight control of unmanned aerial vehicles (UAV) or unmanned aerial systems (UAS) in general, as discussed in 3GPP Release 17. From a high-level perspective, UAV includes two variants. First a UE type UAV, where communication from gNB to a UE is aerial. The new technology aspects are the updated UAV communications for command and control via three different methods: network based, i.e. an airborne drone communicates via the 5G network with a flight control function; direct communications, i.e. like in V2X two drones communicate over the 5G NR sidelink direct communications; and lastly, a pre-defined flight plan, i.e. the 5G network and UAS control function will pre-define a static flight route. For the sake of brevity, we will not delve further into the UAV technology aspects in this white paper – the study results conducted by 3GPP are presented in [TR 23.754]. Second is the UxNB, where a NodeB integrated into a UAV either operates as relay or has onboard processing capabilities. The latter scenario is part of the HAPS connectivity considered as a future technology evolution within NTN.

There are various use cases and services offered by satellite NTN and from a high-level perspective, 5G NTN faces questions like: "Will NTN differ much from terrestrial 5G?" or "will NTN differ from legacy satellite constellations?". When considered in greater detail, these questions query aspects like spectrum usage, satellite constellations, radio link waveforms or architecture. It is not the ambition of this white paper to answer all of those questions, many of them will be answered by the market. Only as one facet, when we want to compare terrestrial NR with NR-NTN? We should keep a realistic view on the technology. Given the RF challenges, the spectral circumstances like frequency ranges or available bandwidth and the satellite constellation, we assume the first 5G NTN deployments will focus on ubiquitous connectivity and coverage. With respect to the expected data rates, NTN 5G cannot compete with terrestrial 5G, so our primary understanding is that 5G NTN will complement terrestrial 5G systems. The primary objective is to actually provide connectivity, but not extremely high throughputs.

Figure 2: General connectivity overview of non-terrestrial networks



Non-terrestrial networks – business cases and future evolution

With respect to the business-related contemplation of NTN, one can identify a convergence between the traditional wireless communications ecosystem and the legacy aerospace ecosystem. Major industry and academia players from both sides foster and leverage the further evolution and the innovations enabling a successful introduction of non-terrestrial networks. The incorporation of NTN into the 5G system represents a step into the general aspect of flexible, hierarchical and dynamic networks, also described as three-dimensional (3D) networks. Characteristic of such evolution is not only the cell size ranging from small cells like indoor or outdoor picocells and macrocells and 5G high-power high-tower (HPHT) for broadcast up to satellite cells with extremely large cell sizes of hundreds of kilometers. With network evolution, a look into the crystal ball to see how 6th generation networks (6G) will develop also reveals aspects like dynamic cell inclusion, self-organizing and self-coordinating networks and joint communications where flexible network components and functions interoperate to provide the best quality of service connection for multiple services and applications. A buzzword "beyond cellular" is often used to describe this three-dimensional network architecture with intelligent nodes. Probably the major difference between 5G and 6G with respect to the NTN technology evolution is the fact that the 5G NTN is considered as a "workaround" to enable NTN connection in a network like the 5G system that at the outset has been designed for terrestrial communications. An outlook to 6G envisages that all kinds of cells from static indoor small cells up to flying airborne and spaceborne stations interoperate with the advent of 6G and provide a dynamic network.

Figure 3: Convergence of communications and aerospace ecosystems driving the evolution of NTN up to 6G unified networks

Non-terrestrial networks – current situation in the standardization

So, let us take a closer look at the current propositions and proceedings within the standard developing organizations (SDO) like 3GPP. The main motivation for 3GPP to have started a study to include non-terrestrial networks in the 5G system is to create an open standard for a common RAT and system access allowing operators, system vendors and device manufactures to incorporate NTN into their service offerings. As the incorporation of NTN represents a technology evolution, 3GPP started the study in Release 15 [TR 38.811] with the focus on channel models and deployment scenarios. After completing the study on scenarios and channel models, 3GPP continued with a follow-up Release 16 study [TR 38.821] on solutions for adapting 5G NR to support NTN. The main objective of this study is the identification of a feature set that enables NTN within the 5G system with the motivation to reduce the impact on the existing 5G system to a minimum level. The feature set in the study includes architecture aspects, protocol layer enhancements and physical layer aspects. Based on the successful outcome of the Release 16 study, 3GPP decided to start a work item on NTNs in Release 17. The major objective is to specify enhancements necessary for LEO and GEO based NTNs while also targeting implicit support for HAPS and air-to-ground networks for future deployments. This involves the physical layer aspects, protocols and architecture as well as the radio resource management, RF requirements, and frequency bands to be used. The primary focus is on transparent payload architecture with earth-fixed tracking areas and frequency-division duplexing (FDD) systems where all UEs are assumed to have global navigation satellite system (GNSS) capabilities [Ref. 10].

In a simplified service-oriented perspective, the vision of 3GPP goes into two deployment and service scenarios, which is also aligned with the triangle of services published in 2015 by the ITU IMT-2020 initiative describing the eMBB, mMTC and URLLC KPIs [Ref. 1]. One is the support of 5G NR for NTN (NR-NTN), which mainly focuses on mobile broadband services. The second service aspect is the motivation to support low data rate, principally best effort QoS services, machine type oriented as Internet of Things via satellite, or IoT-NTN.

As the major motivation to foster NTN communications we identify the request to provide ubiquitous connections all over the globe. According to several market statistics like those issued by industrial organizations, e.g. the GSMA, in 2020 wireless communications technologies reached a coverage of more than 80 % of the world's population, but with a coverage of less than 40% of the world's landmass. NTN satellite based communications may tackle this aspect and focus on worldwide ubiquitous coverage in maritime, remote and polar areas.

Document structure

The objective of this white paper is to provide a technology description of the 3GPP initiative NTN in an informative way. Chapter 1 provides a concise introductory overview of the NTN technology aspects, use cases and a summary of the major challenges anticipated.

Chapter 2 starts with a brief overview of today's commercial and private satellite constellations corresponding to the state-of-the-art scenario.

NTN requires a change of the 5G system architecture to incorporate airborne and spaceborne stations. Those architectural aspects and a reminder of the general satellite constellations are described in chapter 3.

NTN represents a paradigm change in the wireless world because by being incorporated into a satellite or airborne device, the NTN gNB base station is no longer static and fixed and may move at a certain velocity. This causes some issues on the RF interface with respect to mobility, polarization, carrier frequency stability and obviously some time delay due to the large distance between the UE and the NTN gNB. Chapter 4 presents these challenges, focusing on the RF and physical layer.

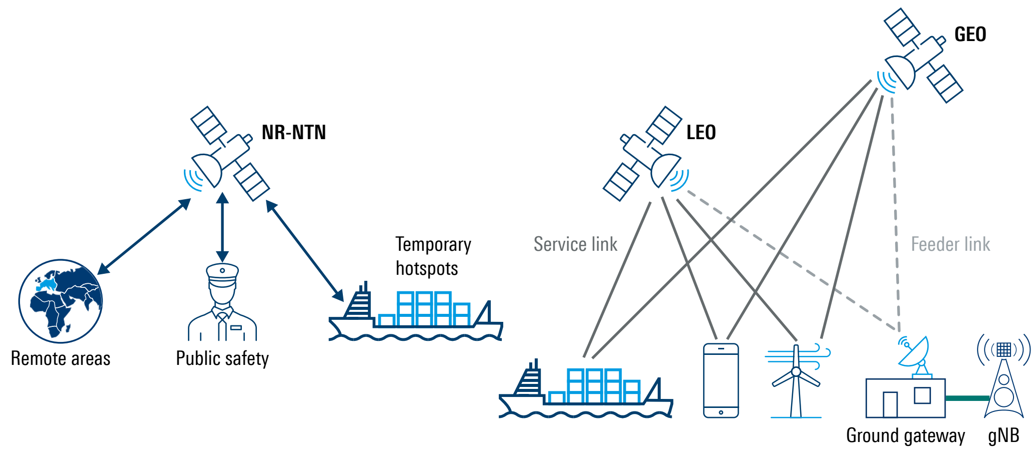
The 5G procedures applied in 5G for aspects like radio access, mobility in connected and idle mode, reliable data transfer, network selection or power saving will require some amendments to optimize the NTN support. Chapter 5 provides an overview of these procedures and the relevant optimization amendments.

We consider NTN as a technology evolution starting with a first enabler as Release 17 but several technology extensions are either on the standardization horizon or are part of an ample research activity. Chapter 6 describes the technology outlook for NTN within the next releases and delineates an evolution path into the next generation of wireless communications 6G.

1.1 NR-NTN

With the current evolution of NTN, two major directions became apparent with respect to use cases, architecture and possible technology aspects. The first direction relates to the enhancement of 5G NR to incorporate non-terrestrial communications within the 5G system. Use cases follow the 5G services of eMBB in a short assessment. The technology is described as NR-NTN and Figure 4 delineates the first envisaged use cases and architecture setups. The following chapters will describe further details of the NR-NTN technology and its challenges.

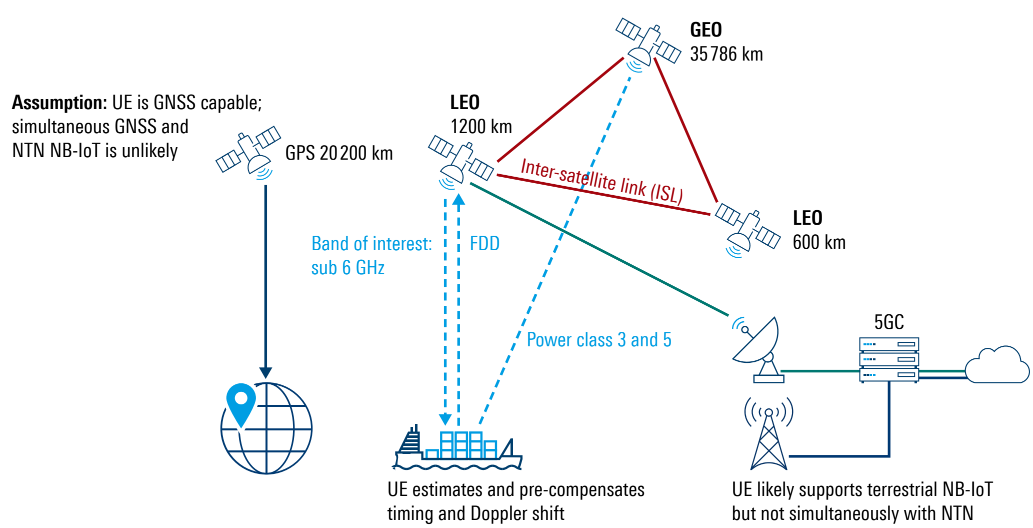
Figure 4: New Radio non-terrestrial networks (NR-NTN)



1.2 IoT-NTN

The second technology direction in the background of NTN is the extension of the general Internet of Things (IoT) by non-terrestrial connectivity and is described as IoT-NTN. The difference to NR-NTN is its overall lower complexity. The radio link continues with the adaptation of NB-IoT for NTN connections; device and satellite complexity is less. Devices assumed to have a low complex antenna type, no specific polarization support or optional second RF chain and unlikely to have a specific beamforming methodology in operation at the UE entity. One primary characteristic of IoT-NTN is the lack of QoS support. IoT-NTN communications will be on a best-effort approach, but compared to NR-NTN the aspects of energy efficiency and power saving play a pivotal role. The work started in August 2021 with minimal scope, with the initial steps aimed at key functionalities. Both RATs eMTC and NB-IoT are included with equal priority and in the first potential deployments, EPC connectivity is the considered core network in charge. 5GC may follow in a later deployment phase. Standalone deployment is prioritized in Release 17, applying a transparent bent-pipe satellite architecture and assuming the UE possesses GNSS capabilities to pre-compensate time and frequency.

Figure 5: Internet of Things with non-terrestrial networks (IoT-NTN)



The study conducted in [TR 36.763] lists some enhancements and study items that are not covered by NR-NTN and should be discussed further. It is assumed that cellular IoT features up to Release 16 are supported for IoT-NTN and both multicarrier as well as single carrier operation serves as the baseline. Agreement and consensus were reached to consider UE power consumption impacts due to GNSS positioning fix, while the additional SIB reading effort for satellite ephemeris information acquaintance does not contribute significantly to energy consumption. Long PUSCH and PRACH transmission enhancements allow the UE to perform time and frequency pre-compensation in a segmented approach. The traffic is intermittent anyhow, but enabling the segmented pre-compensation approach means that new UL gaps and time units and duration of segments need to be aligned. The same applies to aspects like a validity timer for UL synchronization, i.e. how long can the UE assume to maintain valid satellite ephemeris information. To enhance DL synchronization [TR 36.763] proposes a new channel raster with step sizes greater than 100 kHz and an optional ARFCN indication in MIB. For sporadic short transmissions assumed to be the characteristics of IoT-NTN, the UE wakes up from idle mode (or power save mode), accesses the network, performs UL and/or DL data transfer for a short period and goes back to idle. Before accessing the satellite network, the UE acquires its position via GNSS fix. Note that there is no simultaneous GNSS and IoT-NTN operation requested by the UE, so there is no need to re-adjust the position during the brief IoT-NTN connection. 3GPP needs to further study aspects such as validity of a GNSS position fix, details of acquiring a GNSS position fix and duration of the short transmission. Many other RF-related aspects like timing relationship enhancements or HARQ operation involve the same methodologies as NR-NTN, with the exception that the focus is still on keeping UE complexity, UE power consumption and UE costs as low as possible. For example, the HARQ process extension is excluded in IoT-NTN.

1.3 Six major technology challenges in satellite communications

In the literature on satellite communications technology, six major technology challenges are described that need to be solved before satellite constellations can be properly enabled. For the sake of brevity, we will not delve into all technical details of those six key technologies.

Antenna design and phased array antennas, as beamforming plays a pivotal role in satellite connections, to either improve the antenna gain to mitigate propagation attenuation but also to leverage coverage and addressability aspects as well as interference reduction. Technology evolution needs to aim at multi-beam, agile and scalable digital phased array antennas with high integration density and excellent receiver sensitivity performance.

Inter-satellite link (ISL) will be a technology supporting the satellite constellations with inter-satellite communications, typically high frequency radio or optical links (FSO). There are two major reasons necessitating inter-satellite links, one is that a satellite needs connectivity to the ground station and does not always have visibility to that, so the ISL will provide such connectivity in a multi-hop scenario. Second is the lesson learned from terrestrial networks with the multi-access edge computing technology (MEC) where a local cloud is brought closer to the antenna. But MEC is only successful if it is interconnected to either core cloud or other MECs. In a long-term deployment perspective, we assume that spaceborne stations will become intelligent network nodes, resulting in the incorporation of MECs into space and their interconnection via ISL.

Routing, scheduling and networking require the enhancement of today’s sophisticated terrestrial network management, scheduling and routing mechanisms to incorporate airborne and spaceborne network nodes. Especially with LEO satellites, where the satellite propagates relative to the earth, the coverage or capacity is not constant. There will be areas where the satellite capability overpowers the requested capacity like in low populated remote areas, and there will be areas where one satellite is not sufficient, so intelligent capacity routing and planning will be needed. Broadly speaking, we also understand the aspects of mobility and interworking between terrestrial and NTN networks under the umbrella term of "networking" listed here as one of the major challenges. This also includes the obvious aspects of interference and spectrum availability.

Automation and satellite constellation management. This is a topic that we will not further discuss in this paper. A satellite is much more than just a device in space. There is a need for permanent maintenance and control of the flight path (TM-TC), the interference management with respect to frequency channels and ISL routes used and also satellites need to be launched into the orbit or removed from the orbit. Human interaction should be as low as possible to be cost-efficient and to allow fast control. The proliferation of artificial intelligence and machine learning algorithms will also find its way into satellite constellation control automation.

User devices (UE) for mega constellation and mass market NTN unified networks. In the past, satellite ground terminals were assumed to be stationary with LOS to the sky and using large antennas, e.g. our well-known satellite-TV parabolic antennas. With 5G NTN there will be various types of handsets, ranging from low complexity IoT devices and handheld smartphones up to very small aperture terminals (VSAT) with beamforming capabilities. Manufacturers of such devices will probably need to develop new frontends to cover the new frequency bands or will need to implement new RF chains to enable NTN connectivity.

NTN-specific challenges regarding the RF interface that will be explained in further detail in this white paper include the extended time delay and RTT, the carrier frequency offset or Doppler shift, the high path attenuation or link budget and the polarization mismatch or Faraday rotation. Those high-level challenges will result in further impacts on the protocol architecture and procedures.

It is not our intention to ignore or preclude additional challenges from our list of the six major challenges, but as we consider them as obvious and not directly related to NTN and for reasons of brevity, we do not want to delve further into them. Such challenges arise from the requirement to keep the deployment and development costs of satellites and handsets to a minimum, to maintain complexity at an affordable level and to keep the overall NTN system in an economically healthy state. This is certainly a challenge for the business case that needs to be solved by satellite operators, satellite vendors and handset manufacturers. A concise overview and market estimation of NTN business cases is provided in [Ref. 22].

2 COMMERCIAL AND PRIVATE SATELLITE CONSTELLATION – OVERVIEW

The era of commercial communications satellites started on April 6, 1965 with the launch of Intelsat 1, also known as "Early Bird", into a geostationary orbit (GEO). Whilst GEO communications satellites are ideal for providing television, radio and data broadcasting over large areas, their use for telephony services is limited due to the high latency of signals traveling over 36 000 km into space and back. Despite this obvious disadvantage, various operators have been successfully offering voice and data services over GEO satellites.

In the 1990s, with the advent of terrestrial cellular communication systems, plans for global low-latency telephony and data (Internet) services via constellations of medium earth orbit (MEO) and low earth orbit (LEO) satellites emerged. Early systems such as ICO, Iridium, Teledesic and Global Star however failed commercially due to the extremely high costs of such mega constellations.

Frequency division multiple access (FDMA) and/or time division multiple access (TDMA) with QAM or QPSK modulation are widely used in a RAN optimized for satellite links. Modulation and channel coding are either proprietary such as Inmarsat’s Broadband Global Access Network (BGAN) or based on international standards (such as DVB-S/-RCS/-S2/-S2X) [Ref. 38]. The RAN connects to an operator-specific core network architecture that interfaces with the (mobile) phone network.

Whilst many satellite operators seem to prefer the ETSI/DVB satellite standards for the air interface, operators of emerging **NewSpace satellite constellations** and high-altitude platforms may consider using modulation and coding schemes that were developed in the context of 5G mobile communication systems.

In the last decades, several organizations, private companies or governmental initiatives started to provide connectivity services based on satellite based systems. Key characteristics are that they typically operate as a standalone and closed-perimeter networks applying proprietary waveforms on the radio link layer and providing communications services to their customers. One example is the satellite network Iridium that started to offer voice communications to customers worldwide in the early 2000s but for commercial reasons they did not succeed as the land based operators and service providers and to avoid bankruptcy, they were acquired by the US government and nowadays Iridium-2 is in operation. More recent networks launching services are Lightspeed, Starlink, OneWeb or Kuiper [Ref. 31]. They offer data rates in the range of 300 Mbps per user and latency is several tens of milliseconds. Both payload types are supported across the various systems, are transparent and regenerative, similar to the 3GPP approach described in chapter 3.10. Satellite technology has taken a quantum leap forward with respect to architecture aspects like the evolution from bent-pipe parabolic reflector antennas to multi-beam phased array digital beamforming [Ref. 20]. Here, a concise overview of those private satellite mega constellations is given, with four networks as examples [Ref. 9], based on the current status. The reader should be aware that some of the information and figures given are subject to change.

Table 1: Overview of commercial satellite constellations (examples)

Constellation	Lightspeed	Starlink	OneWeb	Kuiper
Operator	Telesat	SpaceX	OneWeb	Amazon
Country	Canada	USA	UK	USA
Owner	New Telesat (Loral Skynet, Public Sector Pension Investment Board of Canada)	Elon Musk	British Crown, Indian Bharti Company, Softbank, Hughes Network	Jeff Bezos
Budget	$5 billion	N.A., > $10 billion	N.A., approx. several $billion	$10 billion
Target customer	industrial consumers: aeronautical, maritime, enterprise, telecom and government networks	broadband internet, consumer market, military, governments	broadband internet, consumer market	broadband internet, consumer market
Manufacturer of satellites	TAS France	SpaceX	OneWeb Satellites (Airbus and OneWeb)	N.A.
Number of satellites (current estimate)	298 satellites in six polar orbits, 11 satellites on 20 orbits close to the equator	phase 1: 1584, phase 2: 2824, phase 3: 30000	650, then 1980, finally 6372	3236

The International Telecommunication Union (ITU) manages and coordinates worldwide the spectrum allocation (see also chapter 3.2) and is indirectly responsible for the allocation of satellite constellations [Ref. 19]. The operator of NTN networks needs to regulate their spaceborne station via their local regulatory body. Approval is granted with the notification document that contains parameters like orbit information (e.g. altitude, inclination), number of satellites and frequency bands.

SpaceX Starlink

Starlink is a satellite network operated by the US aerospace company SpaceX aiming at internet access provisioning to terrestrial subscribers. The owner of SpaceX is Elon Musk, its headquarters is in Hawthorne, California. The FCC notification allows Starlink to deploy about 11927 LEO satellites up to 2027. Long term, up to 30000 satellites are planned [Ref. 24]. The satellites are deployed in different orbital planes with altitudes ranging between 540 km to 1300 km. Characteristic of the Starlink constellation is that the latitudes of interest are served by multiple satellites. In a first trial, Starlink achieves data throughputs up to 93 Mbps for individual users, approximately 16 Gbps capacity per satellite and latency values of 31 ms with the drawback that the terrestrial coverage area does not exceed 60° latitude in the northern hemisphere. Future objectives are terrestrial coverage beyond those latitudes and data rates up to 300 Mbps. As user terminal, Starlink provides a stationary VSAT with about 60 cm phased-array antenna. SpaceX Starlink uses the Ku-band 10.7 GHz to 12.7 GHz in downlink direction and 14 GHz to 14.5 GHz in uplink direction. In addition to that, frequency bands in the Ka-band are also allocated below Kuiper and frequencies from the V-band around 37 GHz to 50.4 GHz are allocated [Ref. 9], [Ref. 32].

Amazon Kuiper

With the project Kuiper, the e-commerce retailer Amazon under the leadership of Jeff Bezos is breaking into the communications market. The objective is to launch in the medium term up to 3236 satellites in a LEO constellation with altitudes between 590 km to 630 km [Ref. 31]. Similar to Starlink, Kuiper too follows the approach of covering the latitudes of interest with multiple satellites. Data rates envisaged reach up to 400 Mbps. Kuiper uses the frequency spectrum in the Ka-band, 17.8 GHz to 20.2 GHz for downlink direction and 27.5 GHz to 30 GHz for uplink direction. Due to the large guard band between UL and DL, it is challenging to develop one common user terminal with a phased array antenna for both duplex directions. In comparison to SpaceX Starlink, as of 2021, Kuiper has not yet deployed any satellites [Ref. 24], [Ref. 32].

OneWeb

OneWeb is a purely British company planning to deploy up to 650 satellites in orbital planes [Ref. 31]. Due to financial issues, OneWeb opened chapter 11 claims in 2020. The British government and the Indian company Bharti Global invested in OneWeb to rescue it from bankruptcy [Ref. 25]. OneWeb uses an altitude of about 1207 km and in contrast to Starlink and Kuiper, the orbital planes also include coverage of the polar regions. With such a constellation architecture, OneWeb achieves elliptical beam footprints with a wide inner axis and low height, whereas Starlink achieves elliptical footprints closer to a circular shape.

Telesat Lightspeed

Telesat is currently the fourth largest satellite constellation aiming to provide internet access services [Ref. 31]. The overall constellation consists of about 298 satellites in two shells, one with 1000 km altitude and one with 1248 km altitude [Ref. 9]. The advantage of such a constellation is a uniform and evenly distributed coverage or satellite visibility across the earth’s sphere.

Other satellite systems

Besides these four satellite constellations, there are other companies and consortiums entering this type of business. AST&Science is a consortium aiming to use handheld devices like smartphones for satellite based internet access. The disadvantage of the AST&Science approach is the huge size of the spaceborne stations as they rely on large phased-array antenna apertures [Ref. 9]. At the LEO altitude, such large satellites present a collision risk and permanent navigation maneuvers are envisaged, causing some criticism in the industry. With O3b, the company SES aims to create a satellite constellation using MEO satellites at an altitude of 8000 km. Due to the higher altitude, a lower number of high throughput satellites are necessary to achieve the coverage goals.

Chinese satellite systems

In response to the two projects of the US based satellite companies SpaceX Starlink and Amazon Kuiper, the People’s Republic of China started the project China SatNet, consisting of 12 992 satellites [Ref. 26]. They operate at orbit altitudes of 508 km, 590 km and 600 km in the lower orbit and at 1145 km in the higher orbit. With respect to frequency usage, China SatNet requested the 37.5 GHz to 42.5 GHz range for the DL and the 47.2 GHz to 51.4 GHz for the UL.

3 NTN ARCHITECTURE AND CONSTELLATION ASPECTS

Like the 5G system in general, the non-terrestrial networks too will try to operate in various architecture setups and offer various kinds of services, driven by different use cases. This chapter introduces such architectural aspects, provides an overview of the NTN use cases and discusses the major aspect of spectrum availability. As satellites may operate in various constellation scenarios and to better understand terms like "orbit", "ephemeris" or "constellations", a short digression is given into the math behind such constellations.

In a simplified architecture model, three elements are present in every space mission: The space segment or satellite, the ground segment consisting of e.g. gateway, terrestrial baseband functions (e.g. gNB) and core network (e.g. 5GC) and lastly the user segment given as the user equipment UE [Ref. 31].

Terms and expressions used in NTN context and how we comprehend them in this white paper
In the remainder of this white paper, we define the terms given below as follows:

Satellite is the airborne or spaceborne station that provides NTN radio access to the UE and is connected via the feeder link (SRI) to the terrestrial 5GC functions. The abbreviation SAN (satellite access node) is used. There is no further classification whether the constellation is LEO, MEO or GEO or whether access is provided by a HAPS or UAS station. The term "satellite" will be used within this white paper as a general term and we do not distinguish further between transparent or regenerative payload or whether the satellite stations apply some disaggregation architecture aspects like gNB-DU or gNB-CU split or IAB or others. If this distinction is worthy of mention, it is explicitly explained.

Service link is the 5G radio access provided to the UE, i.e. the radio interface (Uu) in a non-terrestrial network constellation.

Satellite radio interface (SRI) or feeder link describes the connection between the satellite and the gateway. It operates on the same or different frequency as the service link and in non-transparent architecture it may be a specific radio technology (SRI). Future deployments consider frequencies in the mmWave spectrum as well as optical (FSO) connections (> 190 THz).

gNB corresponds to the 5G term gNB as a protocol anchor inheriting the protocol layers for user and control plane [Ref. 1]. The gNB includes a radio access network part to provide the radio interface (Uu) to the UE, the gNB baseband functions and in the opposite direction, the gNB connects via the NG interfaces to the 5GC functions. We understand the gNB as a logical term that may include the function of the satellite in the context of this white paper, but the term gNB is agnostic to a specific hardware architecture. If non-terrestrial connectivity feature should be explicitely emphasized, we suggest to use the term NTN gNB.

5GC is the general term for the 5G core network providing several functions like session and mobility management, user plane function and many others. The 5GC uses a service based architecture where certain functions provide their services [Ref. 11].

sNB as the satellite NodeB enhances the term gNB with the possibility of satellite access, i.e. the sNB contains the gateway function to connect to the satellite station. Moreover, the sNB is a protocol anchor, like the gNB, and logically divides into a distributed unit (DU) and a centralized unit (CU) to split between the user and control plane. Optionally a disaggregated architecture is possible; there is no distinction whether the sNB is fully operational in space or whether it is split between a spaceborne and terrestrial part.

Gateway describes the terrestrial station that connects the gNB (or 5GC) functions to the satellite station. From the perspective of 5G technology, the gateway offers a transparent transport service between those entities and is agnostic to the applied SRI RATs.

NTN gNB is a logical term introduced to separate a terrestrial RAN gNB from a gNB that provides NTN connectivity. The NTN gNB can be either onboard a satellite when considering regenerative payload, or the NTN gNB may correspond to a terrestrial gNB that provides NTN connectivity via transparent payload.

UE and VSAT describe the terms for the end user terminals. The user equipment (UE) is the general expression. In further detail with respect to this white paper, the UE allows a certain mobility and is typically a handheld device. Some satellite constellations consider as user terminals the very small aperture terminals (VSAT), which are not handheld devices, most likely stationary devices mounted on buildings or vehicles. The main characteristic is the better receiving capability due to enhanced antenna performance and the higher TX power. A typical example of such a VSAT is the CPE type of UE.

Backhaul describes an ample term used in various contexts. In this white paper we use the definition of backhaul in the sense of wireless communications, where we distinguish between the radio access network (RAN) and a core network (e.g. 5GC) and the backhaul represents the interface between them. Scenarios where e.g. a CPE with satellite connectivity uses a fallback connection via terrestrial network, often also referred to as backhaul, are not considered as backhaul in this white paper.

3.1 NTN use cases

3GPP conducted a study on scenarios and requirements for next-generation access technologies covering an ample facet of use cases ranging from indoor hotspots to satellite based extensions of the 5G system [TR 38.913]. Considering satellite communications services one may state that the provisioning of information via satellite is not very new to the ecosystem as it can be seen in the current deployed satellite constellations. With respect to wireless communications, one may cluster the services into broadcast satellite services (BSS) like the well-known satellite TV broadcast, fixed satellite services (FSS) where a stationary UE, e.g. a VSAT, connects to a satellite for internet access and the mobile satellite services (MSS) representing similar use cases as known from terrestrial RAT. This chapter focuses on the use cases possible with NTN and, for the sake of brevity, we will not delve into the business revenue opportunities of NTN; see [Ref. 22] for further information on that.

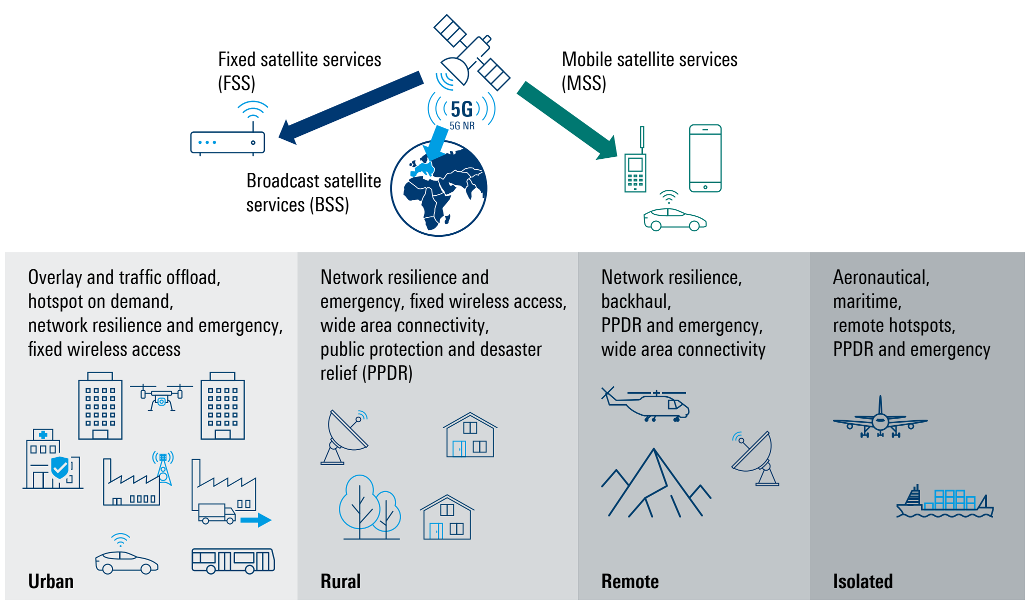
Fixed satellite services (FSS)

Represents the internet connectivity provisioning to stationary UEs, e.g. VSAT. From a business case perspective, such services have an objective similar to the fixed line connectivity. The advantage of FSS is its wide coverage and capability to provide connectivity services to underserved or remote areas. It describes the major business model for some proprietary constellation systems, e.g. SpaceX Starlink (see chapter 2). Note that future deployments may consider a kind of mobility with the VSATs, e.g. vehicle or airplane mounted systems are possible. A subset of the FSS service could also be the future deployment of IAB or backhaul connectivity of terrestrial 5G systems.

Broadcast satellite services (BSS)
At first glance, the reader may see a déjà-vu effect as those services correspond to the well-known satellite television broadcast (e.g. DVB-S2). With 5G NTN it is possible to use such systems to broadcast information to either all or a group of UEs and services like software update, or information provisioning to regions or UE groups are the target applications. Another business model is the outsourcing of traffic, especially if it is relevant to multiple UEs spread over a large coverage area, such broadcast based systems improve the overall system efficiency.

Mobile satellite services (MSS)
Corresponding to the services offered by legacy terrestrial networks, but with the advantage of wider coverage areas and therefore of ubiquitous connectivity. The drawback or realistic consideration is that the NTN services complement terrestrial 5G systems but it is unlikely that 5G NTN data rates can compete with data rates that can be achieved in terrestrial networks. In simple terms, we state that NTN prioritizes worldwide connectivity and basic service provisioning in a wide coverage instead of single-user high data rates. Continuing the realistic view, our assumption is that for MSS, the handheld UE is located outdoors. The maximum UE velocity is 500 km/h for handheld (train or ship-mounted) and up to 1200 km/h for aircraft-mounted VSAT type terminals.

Figure 6: 5G NTN use cases – examples



Following market statistics, the proliferation of wireless connectivity reaches more than 80% of the world's population nowadays, but only about 40% of the globe's landmass receives coverage by cellular radio signals. So, the first obvious motivation for NTN services is to provide ubiquitous coverage. From a realistic viewpoint, given the physical layer circumstances and obstacles like bandwidth, carrier frequency, path attenuation, polarization mismatch or large delay and Doppler shift, we conclude that NTN does not target extremely high data rates. Furthermore, NTN is considered to leverage ubiquitous coverage and it is more a complement to terrestrial 5G than competition. In the first deployments using FR1 frequencies we assume a maximum bandwidth of typically 20 MHz and, due to the high path attenuation, the data rates will not be comparable to terrestrial systems. In a later deployment, when NTN may use frequencies in the FR2 range, higher bandwidths are also possible and assuming stationary UEs like VSAT with high gain, one may expect higher data rates.

3GPP focuses on more than just coverage for underserved areas. On a high level, these four use cases are categorized [TR 22.822]:

- **Service continuity** targets the provisioning of RAT coverage where it is unfeasible through terrestrial networks, e.g. in maritime or remote areas. This shall support service continuity between land based 5G access and satellite based access networks owned by the same operator or by an agreement between operators [TR 22.822]

- **Service ubiquity**, somehow motivated by the background of mission critical communications (MCX), targets permanent system availability. Especially in natural disaster or cataclysm situations leading to outage or destruction of terrestrial network architectures. Via NTN connections, the system availability can be resumed and obtained in a short time, described as public protection disaster relief (PPDR)

- **Service scalability** follows the general aspect of traffic management strategies. Enhancements of traffic steering like the offloading of traffic from terrestrial to non-terrestrial communications provides a better system efficiency, especially when considering the wider coverage range of NTN gNB and BSS offloading

- **5G system backhaul services** representing situations where the end user device (UE) is still connected to terrestrial RAT but the NTN connection serves as backhaul connection to the core network. NTN backhaul targets local base station deployment providing RAT coverage in isolated areas and performs the core network connection in a more feasible way via NTN connections. Note that there are various ways of performing backhaul deployments. One can connect a terrestrial gNB like an IAB node using a 3GPP radio interface connection to the spaceborne NTN gNB. Other options can be that the terrestrial gNB uses a core network interface connection like the F1 interface transparently over the spaceborne station

In addition to those major use cases, 3GPP targets some 5G use cases for satellite access networks that focus on more detailed services compared to the four high-level use cases above. The study conducted and presented in [TR 38.811] describes use cases, e.g.:

- eMBB connectivity including broadband connectivity to UEs in underserved areas but also connectivity services to fixed cells and mobile cells

- Network resilience, trunking (NTN backhaul to a cluster of terrestrial cells) and edge network delivery prevent complete network connection outage, allow the provisioning of connectivity services in isolated areas or traffic steering. As satellite networks are not subject to the same weather conditions and man-made disasters that happen to terrestrial communications systems, they bring to the network an important component of resiliency

- Hybrid and broadcast connectivity allowing a terrestrial 5G connection overlaid by a non-terrestrial network connection, for example to offload broadcast or multicast services into the wide range NTN

- Wide-area IoT (IoT-NTN) extends the already known use cases for IoT devices by a satellite connection to allow deployments in underserved areas

- Public safety authority services including the fast and wide range distribution of public alert messages and internal communications within emergency responders either in a local area or in a wide coverage range. The latter allows the extension of such communications, apart from the already implemented device-to-device (D2D) connections as they are limited in connection range

- Aerial based access networks complement the NTN portfolio allowing services e.g. hotspot on demand, regional area public safety or fixed cell interconnection when no terrestrial backhaul is feasible

- Temporary use of satellite connectivity describes a use case driven by e.g. disaster relief situations (PPDR) where a terrestrial network outage can be mitigated and relieved by the temporary use of NTN connectivity

- HAPS-specific use cases e.g. fixed wireless access (FWA) supported by quasi-stationary UAV (e.g. balloons), temporary hotspots or disaster recovery [Ref. 23]

Another comprehensive overview of 5G NTN services is provided in [TR 22.822] and [Ref. 12]. The document [Ref. 23] describes additional use cases and scenarios with the focus on airborne stations like HAPS, and [TR 38.913] provides a general overview of the study related to next-generation scenarios and requirements.

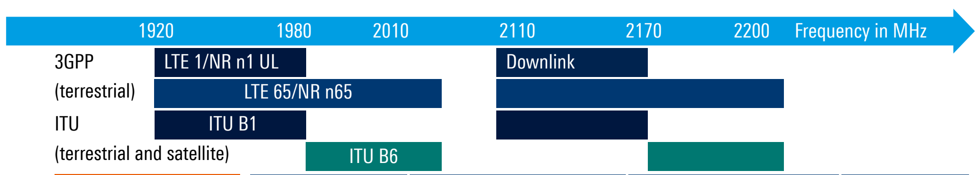
3.2 Frequency spectrum aspects

Like any wireless technology, the obvious and most relevant aspect for communications is the available frequency spectrum. Due to the fact that satellites are most likely not restricted to one particular country or region, an international harmonization of frequencies applied to satellite communications is essential. Organizations like the ITU support such coordination initiatives, as certain frequency bands will be used in some regions for terrestrial PLMN while other regions may permit NTN PLMN usage. In cases where a company wants to launch a satellite, the approval process first involves the licensing authority of the responsible government institution in their country. Once this institution has approved the filing for operation, it submits the frequency request to the ITU in accordance with the regulations of the international treaty governing the use of radio frequencies. The key objective of the ITU radio regulations is the avoidance of harmful radio interference, other issues or regulations like physical objects in space or debris and collision avoidance are handled by different organizations, e.g. UNOOSA. There is a possibility that a country can "reserve" spectrum for satellites in LEO constellations, so-called "warehousing", but obligations exist, e.g. a certain percentage of satellites need to be deployed within a given time, otherwise the warehousing is canceled.

Frequency range 1 (FR1)

Currently, several frequency ranges are discussed for NTN, some of them in the legacy spectrum sub 6 GHz, or FR1, but also frequencies beyond 10 GHz are in discussion. The current FR1 bands discussed for NTN are: The S-band frequencies 1980 MHz to 2010 MHz in uplink direction and 2170 MHz to 2200 MHz in downlink 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 [Ref. 15]. The two bands n255 and n256 are agreed within 3GPP as the first two frequency bands for NTN [Ref. 15]; the prefix "n" for NR band will probably change to "s" for satellite bands. Figure 7 shows the frequency number details of these two bands as well as the bandwidth, the maximum transmission bandwidth configuration in number of resource blocks (#RB) and subcarrier spacing aspects [TS 38.101-5]. The advantage of these frequency ranges is the lower path attenuation and the fact that they are already used in legacy communications, thus components are already available. The disadvantage is the well-known spectrum crunch as those bands are already densely occupied, thus the usable bandwidth is restricted. Dimensions up to 40 MHz overall bandwidth are envisaged as maximum [TR 38.811]. NTN will continue to use the methodology of a bandwidth part (BWP) as defined in 5G NR, thus a UE is configured with one or more BWPs (see also [Ref. 1]) and the UE does not need to be aware of the SAN channel bandwidth. It is possible to divide the overall SAN channel bandwidth into segments using different numerologies. A concern is the interference and, for instance, there is a need to ensure that cross-border issues are solved between those countries that permit the spectrum usage for NTN purpose and those that choose the spectrum for terrestrial usage. For example, the 3GPP frequency bands 1/n1 and band 65/n65 for LTE and NR usage will partly overlap with the ITU recommendations B1 and B6 allowing that spectrum for terrestrial and satellite usage [Ref. 13], as shown in the upper part of the figure below. Further aspects of spectrum usage are provided in [Ref. 12]. 3GPP sets a higher priority for spectrum within the FR1 range but coordination work and interference mitigation techniques need to be investigated and applied. A quote from the ITU WRC decision [Ref. 13] states: "A unique situation exists for the frequency arrangements B6 and B7 and parts of arrangements B3 and B5 in the bands 1980 MHz to 2010 MHz and 2170 MHz to 2200 MHz, which have been identified for the terrestrial component of IMT and the satellite component of IMT. Co-coverage, co-frequency deployment of independent satellite and terrestrial IMT components are not feasible unless appropriate mitigation techniques are applied. When these components are deployed in adjacent geographical areas in the same frequency bands, technical or operational measures need to be implemented if harmful interference is reported."

Figure 7: Frequency spectrum in the S-band and L-band (FR1) for NTN usage



3GPP, first NTN bands for S-band and L-band

NTN band no.	Uplink	Downlink	Duplex
n256	1980 MHz to 2010 MHz	2170 MHz to 2200 MHz	FDD
n255	1626.5 MHz to 1660.5 MHz	1525 MHz to 1559 MHz	FDD

3GPP, bandwidth and subcarrier spacing for NTN bands and RB no.

NTN band no.	SCS in kHz	5 MHz	10 MHz	15 MHz	20 MHz
256	15	yes	yes	yes	yes
	30		yes	yes	yes
	60	–	yes	yes	yes
255	15	yes	yes	yes	yes
	30		yes	yes	yes
	60		yes	yes	yes
		RB no.	RB no.	RB no.	RB no.
Max. transmission bandwidth configuration	15	25	52	79	106
	30	11	24	38	51
	60	–	11	18	24

In February 2022, the 3GPP plenary agreed the work on the new sub-specification [TS 38.101-5] for NTN UE RF and demodulation requirements, which will then contain further details on the discussed frequencies and how they should be applied to NTN services. One difference to the existing specifications [TS 38.101] is that with NTN UEs, the current skeleton [TS 38.101-5] assumes a distinction whether some RF characteristics should be evaluated in conducted or radiated requirements. The latter allows, for example, the consideration of the beamforming antenna gains when contemplating the maximum radiated output power. Due to issues concerning coordination with adjacent bands, the NTN frequency band n255 uses the higher part of the spectrum for the UL direction while band n256 uses the higher part for the DL. Therefore, the default TX-RX frequency separation is 190 MHz for band n256 and –101.5 MHz[1)] for band n255. Both bands use the channel raster of 100 kHz and the RF channel position is identified by a channel number (NR-ARFCN). See [TS 38.101-5] for details on numbering and channel raster. To enable cell acquisition and synchronization, NTN follows the same principle as 5G, the cell will transmit an SSB, the frequency position of this SSB follows the raster of the global synchronization frequency raster (GSCN). To reduce the complexity of the synchronization process, the time pattern of the SSB as well as the subcarrier spacing is

[1)] Note: In band n255 the uplink direction takes the higher portion of the spectrum.

restricted. Band n256 supports only 15 kHz SCS for the SSB and only case A mapping is allowed, while band n255 supports 15 kHz or 30 kHz SCS and SSB mapping case A and case B are possible (see also [TS 38.213] or [Ref. 1]).

Frequency range 2 (FR2)

The 3GPP study [RP-212144] proposes to discuss NR-NTN above 10 GHz as this is the crucial frequency range offering broadband services. Such higher frequency range discussion covers multiple aspects including already existing bands up to new bands in the long-range scope. The highest priority band is the Ka-band with uplink direction between 17.7 GHz and 20.2 GHz and downlink direction between 27.5 GHz and 30 GHz, as referenced in the ITU information regarding frequencies envisaged for use in satellite communications [Ref. 19].

Table 2: Frequency ranges beyond 10 GHz envisaged for satellite communications, based on 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

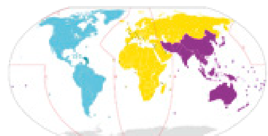
At the world radio conference WRC-23, the ITU is to consider the frequency bands 17.7 GHz to 18.6 GHz, 18.8 GHz to 19.3 GHz and 19.7 GHz to 20.2 GHz for space to earth (downlink) transmissions and 27.5 GHz to 29.1 GHz and 29.5 GHz to 30 GHz for earth to space (uplink) transmission [Ref. 19]. In addition, WRC-23 is assumed to tackle the regulatory aspects for inter-satellite links and will consider studies regarding new spectrum needs along with new allocations for mobile satellite services. The upcoming WRC-23 will be pivotal. It will ensure the continued facilitation of rational, efficient and economic use of radio frequencies and any associated orbits, including LEO. As an example of the international spectrum coordination and its regions, [RP-193234] presents an initial subset of the frequency proposals for NTN (see Figure 8).

The FR2 frequency range is currently considered in Release 17 with a lower priority for three major reasons:

- The discussed frequencies in the Ku- or Ka-band fall into the spectrum gap that is currently between FR1 and FR2, so first of all, 3GPP needs to agree on how to handle the spectrum between 7.125 GHz and 24 GHz.
- The frequencies in FR2 that will be used for NTN follow the FDD duplex mode, compared to all other FR2 bands that are TDD mode. Consequently, 3GPP needs to enhance the 5G specifications to enable FDD also in FR2.
- The introduction of FDD in the FR2 probably results in interference aspects between TDD and FDD that need to be analyzed further.

For NTN, those frequencies will use the FDD duplex scheme due to the long delay. A TDD system has the challenge of TX-RX switching and with such long delays, a guard interval that becomes necessary between TX-RX switch would be detrimental to spectrum efficiency. In a future extension, incorporating airborne stations like HAPS and other air-to-ground (ATG) stations like helicopters, drones, UAV, etc., TDD duplex schemes too are not explicitly excluded. In a future evolution, carrier aggregation of different NTN bands will be possible.

Figure 8: NTN spectrum– overview FR1 and FR2



RP 193234 proposes various frequency bands for HAPS, GEO, non-GEO NTN in FDD and TDD for the various ITU regions

Ka-band: GEO

	Region 1	Region 2	Region 3
Downlink (space to earth)	17.3 GHz to 20.2 GHz	17.7 GHz to 20.2 GHz	17.7 GHz to 20.2 GHz
Uplink (earth to space)	27.5 GHz to 30.0 GHz	27.0 GHz to 30.0 GHz	27.0 GHz to 30.0 GHz

Ka-band: non-GEO

	Region 1	Region 2	Region 3
Downlink (space to earth)	17.3 GHz to 20.2 GHz	17.7 GHz to 20.2 GHz	17.7 GHz to 20.2 GHz
Uplink (earth to space)	27.5 GHz to 29.1 GHz and 29.5 GHz to 30.0 GHz	27.5 to 29.1 GHz and 29.5 to 30.0 GHz	27.5 GHz to 29.1 GHz and 29.5 GHz to 30.0 GHz

S-band: GEO and non-GEO

	Region 1	Region 2	Region 3
Downlink (space to earth)	2170 MHz to 2200 MHz	2160 to 2200 MHz	2170 to 2200 MHz
Uplink (earth to space)	1980 MHz to 2010 MHz	1980 to 2025 MHz	1980 to 2010 MHz

S-band: HAPS

	Region 1	Region 2	Region 3
Downlink (space to earth)	2110 MHz to 2170 MHz	2110 to 2160 MHz	2110 to 2170 MHz
Uplink (earth to space)	1885 MHz to 1980 MHz and 2010 MHz to 2025 MHz	1885 to 1980 MHz	1885 to 1980 MHz and 2010 to 2025 MHz

Additional spectrum regulation for ISL, ground stations and HAPS

Today's satellite constellations (see chapter 2) also use the Q-band and V-band for the feeder link between the satellite and the ground station. As the ground station is stationary and is assumed to allow more complex antenna designs, larger arrays with sophisticated beamforming methods allow the usage of these higher frequencies for that particular use case.

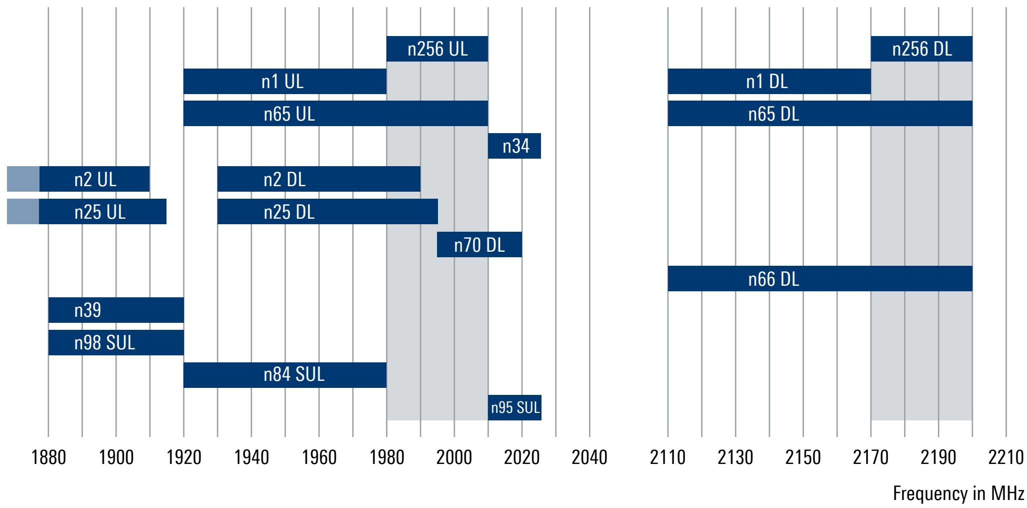
Besides the spectrum aspects for the service link, international regulation needs also to consider spectral aspects for the feeder link between the satellite and ground station and inter-satellite links. Future spectrum coordination and regulation will need to cope with the technology evolution and include spectrum considerations for airborne stations like HAPS or UAV as well.

Under ITU regulations, the only spectrum where HAPS can currently act as a cellular base station is 2.1 GHz. In cooperation with terrestrial bands, the main HAPS bands for mobile services include the spectrum 1885 MHz to 1980 MHz, 2010 MHz to 2025 MHz and 2110 MHz to 2160 MHz. However, WRC-23 agenda item 1.4 is looking to consider HAPS mobile services in certain frequency bands already identified for IMT: 694 MHz to 960 MHz; 1710 MHz to 1885 MHz and 2500 MHz to 2690 MHz [Ref. 23].

NTN-related RF co-existence aspects

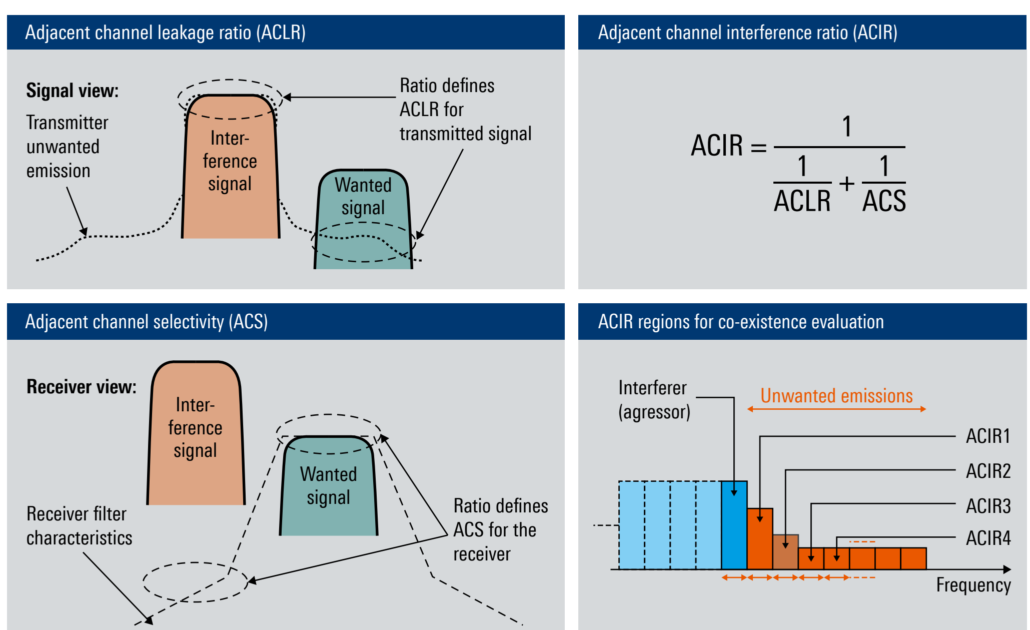
Contemplating the interference situations on the RF layer is leveraged by two facts that result due to the introduction of NTN. First, the cell or beam coverage overranges country and terrestrial cell borders and second, the location of the used spectrum either overlapping or adjacent to existing 5G bands. For such reasons, 3GPP started a study initiative to further investigate such co-existence aspects [TR 38.863]. To foster the need for co-existence analysis, the following figure shows the adjacent and overlapping 5G terrestrial bands relative to the envisaged NTN band n256.

Figure 9: Co-existence aspects, adjacent and overlapping 5G bands relative to NTN band n256



The terrestrial band n65 fully overlaps the NTN band n256, band n66 fully overlaps the downlink, bands n2, n25 and n70 partly overlap band n256 and band n1 as well as n84 and n95 are adjacent. The **adjacent channel interference ratio (ACIR)** is used as a metric to analyze the potential co-existence aspects. There are the two quality criteria ACLR and ACS for transmitter and receiver performance and the ACIR is the combination of both (see Figure 10). The **adjacent channel leakage ratio (ACLR)** is a transmitter quality criterion defining the unwanted emissions in the adjacent bands. The **adjacent channel selectivity (ACS)** defines the receiver's ability to suppress an interference signal on an adjacent channel. To obtain a holistic view, the combination of the two leakages on adjacent channels is used. The ACIR is the ratio of the power transmitted on one channel to the total interference received by a receiver on the adjacent channel due to both TX and RX imperfections. To obtain a better evaluation criterion, the distance between the interferer and victim band is relevant as shown at the bottom right of the figure.

Figure 10: Adjacent channel interference ratio (ACIR)



The 3GPP co-existence analysis in [TR 38.863] investigates combinations between terrestrial and NTN networks where either terrestrial or NTN is the interferer and both UL and DL combinations are discussed. Further details like the beam constellations, UE RX and TX parameters, power levels, etc., are presented in the study. The co-existence aspects between NTN and NTN mainly occurring in situations where the gNB is based on HAPS is left for future investigations.

3.3 User equipment capable of NTN

This chapter shall provide a concise overview of UE or terminal characteristics that are assumed to be relevant for NTN connectivity. In the technical evolution, initial terminals act as customer premises equipment (CPE) connected to GEO satellites and the NewSpace networks deploy such terminals as agnostic interfaces between the satellite (more likely LEO) and the end-user communications device [Ref. 16]. This UE behavior is also described as the indirect connectivity where, for example, a CPE provides the function of an intermediate node with satellite access. For the sake of brevity, we will not delve further into this indirect mode.

In a high-level general view, three possible types of UEs exist: A UE capable of only terrestrial 5G, a UE of only NTN (NR-NTN and/or IoT-NTN) or a UE that is capable of both. Cell selection and mobility scenarios between NTN and terrestrial networks are only relevant for the third type of UE.

In a first categorization, we distinguish between two different UE types: handheld and stationary. The **handheld UE** is comparable to smartphones or IoT devices and, as its name implies, it is allowed to move. The assumption is that there are no specific enhancements in the UE with respect to TX performance. In other words, the handheld UE has a maximum TX power of 23 dBm, defined as power class 3 (PC3), and no specific antenna gains at the RX side are assumed. The **very small aperture terminal (VSAT)** is a term that describes UEs that are primarily stationary, i.e. permanently mounted on buildings or probably mounted on moving platforms like vehicles or airplanes. 3GPP allows a higher TX power of 33 dBm and it is also assumed that such UEs provide a much higher antenna gain, probably due to sophisticated phased array antenna patterns or parabolic antenna shapes. The study conducted in [TR 38.811] assumes those characteristics as the minimum RF capabilities for the UEs that were considered to operate in either the S or L-band as well as the Ka-band.

Table 3: NTN UE RF parameters – example [TR 38.811]

	Very small aperture terminal (fixed or mounted on moving platforms)	Handheld or IoT devices (3GPP class 3)
Transmit power	2 W (33 dBm)	200 mW (23 dBm)
Antenna type	60 cm equivalent aperture diameter (circular polarization)	omnidirectional antenna (linear polarization)
Antenna gain	TX: 43.2 dBi, RX: 39.7 dB	TX and RX: 0 dBi
Noise figure	1.2 dB	9 dB
EIRP	45.75 dBW	–7 dBW
Gain-to-noise-temperature ratio (G/T)	18.5 dB · K^{-1}	–33.6 dB · K^{-1}
Polarization	circular	linear

In addition to these minimum RF capabilities, a UE capable of NTN should obviously support some of the mechanisms described in later chapters. In the first phase of deployments, a major capability required by the UE is the GNSS support, i.e. the UE needs to locate its terrestrial position based on GNSS or terrestrial RAT. This information is then used by the UE to pre-compensate for time and frequency adjustments.

To describe the satellite access frequencies and UE performance requirements, 3GPP agreed on a sub-specification [TS 38.101-5] that is proposed and available as an initial skeleton at the time of writing this white paper. The first NTN frequency bands n255 and n256 consider a UE maximum TX power of 23 dBm. To tackle co-existence issues to adjacent bands, an additional emission requirement can be signaled by the network per band. In such cases, the UE has to apply an additional power reduction value. The minimum controlled UE output power is –40 dBm. Other TX performance characteristics like transmit OFF power, frequency error and modulation quality reuse the requirements currently specified for terrestrial 5G UEs [TR 38.101]. As coexistence to adjacent bands is a huge concern with NTN, the network can signal as part of the cell handover message an additional spurious emission requirement. In such cases, the UE power emanating into the adjacent channel should not exceed a limit (e.g. –80 dBm from the edge of the bandwidth for band n255). Future versions of this specification may define updated numbers of unwanted emissions like ACLR and SEM masks.

The receiver performance parameters of the UE have not been finally agreed at the time of writing this paper. Adaptations are necessary; for example, the RX sensitivity of the UE needs to be agreed on due to the link budget issues with NTN. An example of a link budget calculation is given in Table 12. A requirement with regard to the UE RX part is a two antenna port receiver in all bands. Apart from the receiver sensitivity (*REFSENS*), the specification defines performance parameters like a maximum input level, adjacent channel selectivity and blocking resistance with assumed in-band, out-of-band or narrow band interferers. Other requirements are RX testing aspects as spurious response, where a CW interferer at any other frequency should not cause a wanted signal degradation, intermodulation resistance and spurious emissions caused by the receiver chain.

3GPP defines certain UE feature lists (see [R1-2200780]), e.g. uplink time pre-compensation, enhancements on timing relationships, reporting of UE-specific TA compensation, increased number of HARQ processes, polarization signaling support, performance enhancements or HARQ codebook enhancements that correspond to UE capabilities supporting and enabling NTN within the UE. Some of these user-plane-oriented sub-features like RACH adaptation, HARQ RTT timer extension, other timers in MAC, RLC and PDCP that adjust to longer RTTs are considered as essential and therefore mandatory for UEs supporting NTN. Some sub-features e.g. timing advance reporting capability, HARQ disabling or new logical channel mapping rules are optional for the UE-supporting NTN. The UE control plane considers sub-features like soft TAC update and SMTC enhancements, e.g. two parallel SMTCs, as essential. Other control plane sub-features like cell stop timer based neighbor cell measurements, location based cell reselection, up to four SMTCs and conditional handover enhancements are optional for the NTN UE.

Another design aspect of the UE architecture is the used polarization. Most likely NTN links use the circular-polarized scheme (see chapter 4.5). In the simplest architecture, the UE may apply a linear polarization only, either vertically or horizontally polarized, and tolerate a 3 dB polarization loss. With a more complex configuration, the UE may apply two RX branches for each horizontal and vertical polarization and achieve a 3 dB combining gain. In the uplink direction, the assumption in [TR 38.821] is a single linear polarization at the UE TX side and the satellite can either tolerate the 3 dB polarization loss and use the opposite circular polarization for other links to obtain higher satellite capacity, or the satellite may soft-combine within its RX chain the two circular polarizations and obtain a 3 dB gain.

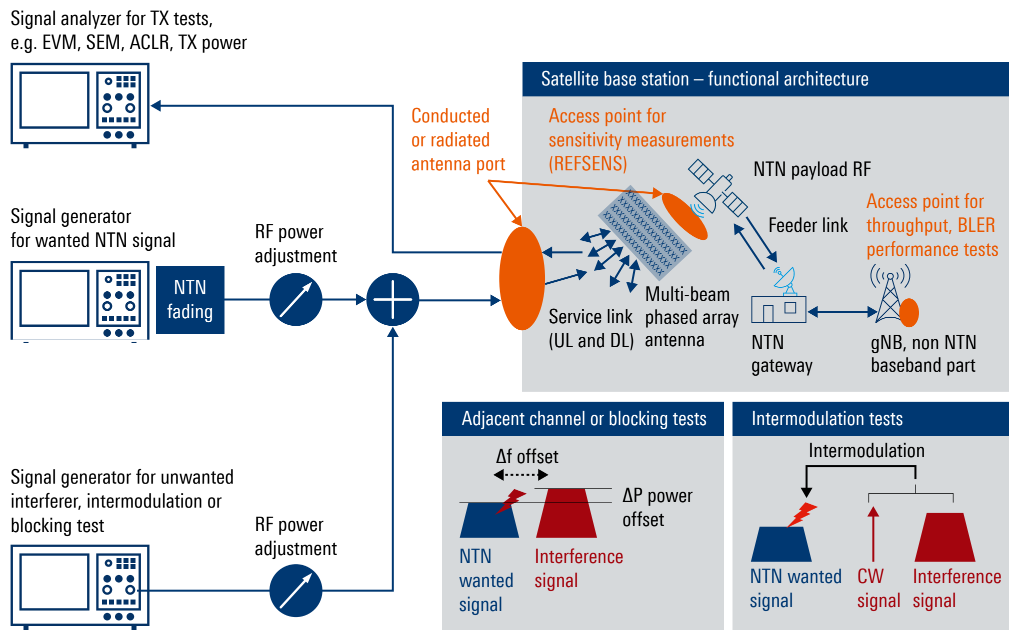
3.4 Satellite access node radio transmission and reception

In addition to the constellation and orbital aspects of satellites, 3GPP considers some RF aspects of satellite access nodes (SAN), similar to the existing specifications of base stations RF characteristics [TS 38.104]. The objective of this chapter is to consider a SAN as an RF base station and to outline what RF capabilities should be provided and how testing and measurement can ensure its performance. RF aspects of such satellites are specified in [TS 38.108]. A initial draft skeleton is agreed and contains the RF framework parameters for TX and RX evaluation and further updates are likely. The transmitter is characterized via metrics such as TX power, power dynamics, unwanted, TX signal quality like EVM, frequency or time alignments. Similar to terrestrial base stations, the receiver-characterizing metrics include sensitivity, selectivity, dynamic range and blocking resistance. Compared to the different base station types in [TS 38.104], a SAN is assumed to be of type hybrid "H" or over-the-air "O", corresponding to conducted and over-the-air (OTA) radiated connections respectively. As one essential capability of a satellite node will be beamforming, the radiated setup allows the consideration of an antenna gain in the RF metrics and, in addition to TX power, metrics like EIRP are also being considered as test parameters. Due to the assumption that the satellite antenna exists as multi-beam phased array antenna, certain OTA antenna test scenarios will complement the RF testing. The parameters with respect to the NTN frequency bands n255 and n256, like channel bandwidth, subcarrier spacing and channel raster, follow the definition for the UE RF characteristic (see Figure 7).

Besides the general RF characteristics, a SAN will also be evaluated with respect to its performance, i.e. criteria like the achievable throughput under various conditions will be defined. Such conditions include RF sensitivity and interference rejection testing shown in Figure 11. RF sensitivity outlines as a metric the throughput that should be achieved when the RX power level is at a minimum boundary, and such a satellite base station test setup applies a certain fading profile in the uplink direction. Interference testing setups will include an interferer that may be in a common channel or adjacent band as well as blocking tests for out-of-band interferer situations. The potential intermodulation product generated by two active transmissions impacting the NTN band RX performance is also one of the testing fields in the overall context of receiver performance. The aspects of co-existence (see also chapter 3.2) are another relevant test metric, but one should consider that e.g. co-existence between terrestrial and NTN mainly affects the UE on the ground. Access node co-existence should consider uplink scenarios, especially potential interferences generated by ground gateways overlapping beams in space.

Major challenges in the background of satellite RF testing are the architecture details of a sNB as DUT. Discussion topics include questions as to whether the NTN payload part can be evaluated standalone or whether the NTN infrastructure under test includes the feeder link and the gateway as well as some terrestrial baseband functions within the gNB remainder architecture (see also chapter 3.10). In the logical setup of such a satellite base station in Figure 11, the antenna port of the NTN payload RF serves as the access point for sensitivity measurements while the throughput is captured based on MAC layer transportation blocks with positive CRC counting, thus the access point for those throughput performance tests is above the MAC layer in the protocol stack, which is implemented in the gNB base band part. Depending on whether the satellite uses transparent or, in future, the regenerative architecture approach, an optional feeder link plus gateway has to be assumed to be part of the DUT architecture.

Figure 11: Satellite base station RF testing setup



Many of the RF parameters for satellite access nodes are not yet defined in the current specifications. The study [TR 38.821] uses several assumptions during the simulation process that will most likely be implemented in real RF components.

Table 4: Satellite access node RF parameters – example [TR 38.821].

Satellite orbit	GEO	LEO-1200	LEO-600
Satellite altitude	35 786 km	1200 km	600 km
Satellite antenna pattern	beamforming antenna with approx. 10° beamwidth		
Payload characteristics for DL transmissions			
S-band (i.e. 2 GHz)			
Equivalent satellite antenna aperture	22 m	2 m	2 m
Satellite EIRP density	59 dBW/MHz	40 dBW/MHz	34 dBW/MHz
Satellite TX maximum gain	51 dBi	30 dBi	30 dBi
3 dB beamwidth	0.4011°	4.4127°	4.4127°
Satellite beam diameter	250 km	90 km	50 km
Ka-band (i.e. 20 GHz for DL)			
Equivalent satellite antenna aperture	5 m	0.5 m	0.5 m
Satellite EIRP density	40 dBW/MHz	10 dBW/MHz	4 dBW/MHz
Satellite TX maximum gain	58.5 dBi	38.5 dBi	38.5 dBi
3 dB beamwidth	0.1765°	1.7647°	1.7647°
Satellite beam diameter	110 km	40 km	20 km
Payload characteristics for UL transmissions			
S-band (i.e. 2 GHz)			
Equivalent satellite antenna aperture	22 m	2 m	2 m
Gain-to-noise-temperature ratio (G/T)	$19\ dB \cdot K^{-1}$	$1.1\ dB \cdot K^{-1}$	$1.1\ dB \cdot K^{-1}$
Satellite RX maximum gain	51 dBi	30 dBi	30 dBi
Ka-band (i.e. 30 GHz for UL)			
Equivalent satellite antenna aperture	3.33 m	0.33 m	0.33 m
Gain-to-noise-temperature ratio (G/T)	$28\ dB \cdot K^{-1}$	$13\ dB \cdot K^{-1}$	$13\ dB \cdot K^{-1}$
Satellite RX maximum gain	58.5 dBi	38.5 dBi	38.5 dBi

[TS 38.108] defines the satellite access node TX and RX characteristics. The current status considers only FR1, the satellite constellations GEO and LEO with two orbit altitudes (600 km and 1200 km) and two SAN types 1-H and 1-O. The TX characteristics describe parameters like the maximum TX power based on the manufacturer declaration, output power control ranges and dynamics, transmit signal quality (EVM, frequency error and time alignment) as well as unwanted emission aspects (SEM, ACLR, spurious emissions). As NTN transmissions may excess country borders, 3GPP defines the possibility of regional requirements. E.g. operating band unwanted emissions requirements may be put into place for certain regions to protect terrestrial 5G bands from NTN interference. The RX performance is measured in the same way as in 5G NR; based on a fixed reference channel (FRC), the satellite should achieve a throughput > 95 % of the maximum throughput at the reference sensitivity level. Typical *REFSENS* values for a conducted 1-H test setup are in the range of –99 dBm. The conducted test setup measurement access point for sensitivity testing is downstream of the antenna array, thus the sensitivity level does not consider the antenna gain (see Figure 11). In addition, the RX performance includes in-band selectivity, blocking, intermodulation and spurious emission testing.

The current test procedures in [TS 38.108] describe conducted (1-H) and radiated (1-O) conditions. The type 1-O radiated characteristic requires multi-beam capability of the satellite, and at least 8 transceiver units per satellite are required as minimum.

RF testing aspects of future releases will then need to consider the additional frequency bands for NTN, especially mmWave frequencies with wider bandwidth and changes on the RF due to enhanced beamforming methodologies. One optional aspect to be discussed is whether and, optionally, how to include the ISL aspects in such an RF testing concept. In a future step, 3GPP plans to introduce some SAN conformance testing scenarios in a newly created specification [TS 38.181]. Initial setup proposals are described in [R4-2111460].

3.5 Satellite constellations

NTN is a Release 17 work item and uses spaceborne stations to communicate with terrestrial UEs. Like all satellite services, the NTN satellites operate from an orbit circulating the earth (see Figure 12). The mathematical description model of such orbit constellations is based on the Kepler mathematics laws (see chapter 3.8).

These **satellite orbit** aspects play an essential role in aspects of satellite network planning, e.g. capacity planning, coverage and interference planning [Ref. 31]. Without delving too deeply into those complex satellite constellation planning topics, our ambition is to present only the fundamentals of such aspects.

A **satellite constellation** is a group of artificial satellites working together as a system, probably interconnected via links and following the same coverage objective. An **orbital shell** within a satellite constellation refers to a collection of circular orbits with the same altitude and potentially the same inclination. Often such orbits within a shell are evenly distributed in celestial longitude [Ref. 9].

We can identify three major parameters influencing the total amount of satellites that are needed to fulfill a certain coverage and capacity target:

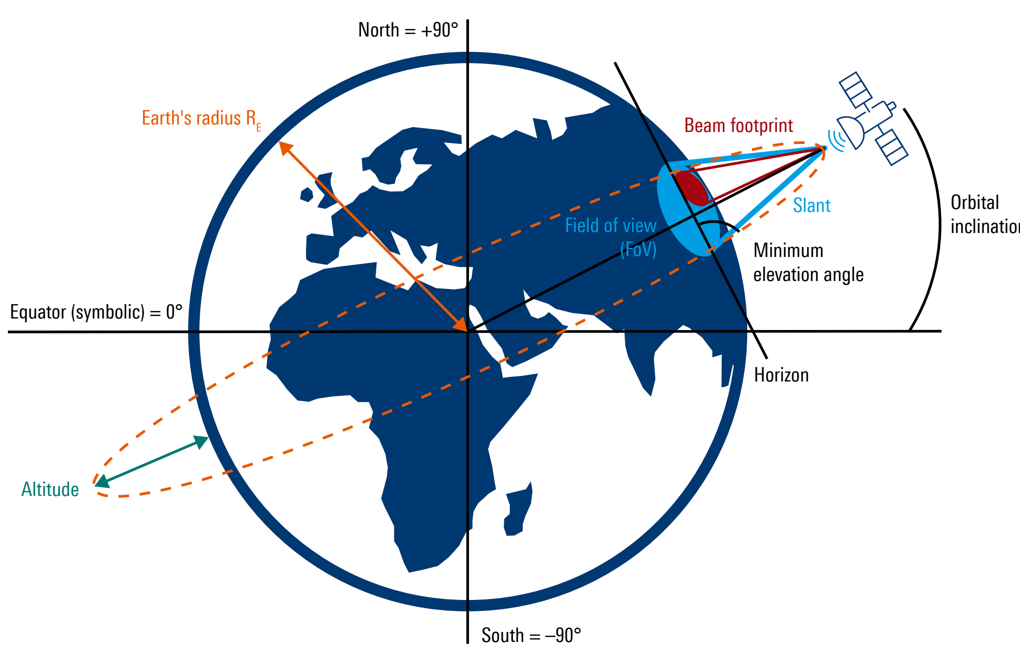
- Elevation angle, i.e. the angle between the user terminal's horizon (tangential to the earth's radius on the surface at the user's current position) and the line between the UE and the spaceborne station. The minimum elevation angle represents the lowest elevation of the spaceborne station's visibility from the UE perspective

- Satellite altitude or orbit altitude, defined as the distance between the medium earth sea level and the current satellite position on its orbit in a perpendicular line

- Inclination angle between the earth's equator and the ellipse of the satellite orbit

In addition to these three parameters, there is the parameter or term "slant" that is the length of the direction between the satellite and the UE assumed to reside at the maximum edge of the coverage surface, i.e. UE being at the minimum elevation angle. The altitude of the satellite and the elevation angle define an area on the earth's sphere that corresponds to the so-called **field of view (FoV)**. This FoV corresponds to a theoretical coverage area (see Figure 12). Within the FoV, a terrestrial device would be able to receive a sufficient field strength of the satellite TX electromagnetic radiation and would be able to transmit a signal towards the satellite. Obviously, the FoV depends on the satellite orbit altitude and the minimum elevation angle. Note that this FoV does not directly correspond to our coverage area. In the real world, a satellite uses one or more beams to provide radio coverage on the earth's surface. The coverage of one of these beams is defined as the beam footprint. For certain reasons, e.g. interference aspects with respect to other satellites, phased array antenna architectures with their respective beamforming methodologies and the addressability of the satellite, entire coverage of the possible FoV area is unlikely. With addressability or satellite pass we refer to the situation whereby a LEO satellite moves relative to the earth, thus it is only visible for a certain period of time and secondly, the FoV also depends on the inclination angle or elevation. As a side note, the addressability presupposes an established connection from the satellite to the ground gateway. In summary, our assumption is that 100% coverage and 100% availability of a satellite based connection is not realistic.

Figure 12: General constellation aspects of satellite based networks



In general, four different orbit constellations are described:

- **Low earth orbit (LEO)** satellites operate in a circular orbit around the earth, with an altitude between roughly 500 km to 2000 km, travel at a speed of about 28 000 km/h and have an orbital period of around 90 minutes. As their altitude is not that high, the launching of LEO satellites does not require high propulsion rockets and is therefore more cost-efficient. Another obvious advantage due to the shorter distance is the lower round-trip time (RTT) which is typically less than 30 ms. The size of a LEO satellite is also assumed to be small, typically < 1 meter perimeter or even in the range of a dozen centimeters (nano satellites) and the weight will be under 500 kg. The assumption is that NTN uses a beamforming mechanism at the satellite station. A typical beam footprint of a LEO satellite ranges between 100 km to 1000 km. The drawback of LEO satellites is that they operate in harsh environments (atmospheric gases are still likely in this environment) and so they have an assumed lifecycle of less than 10 years

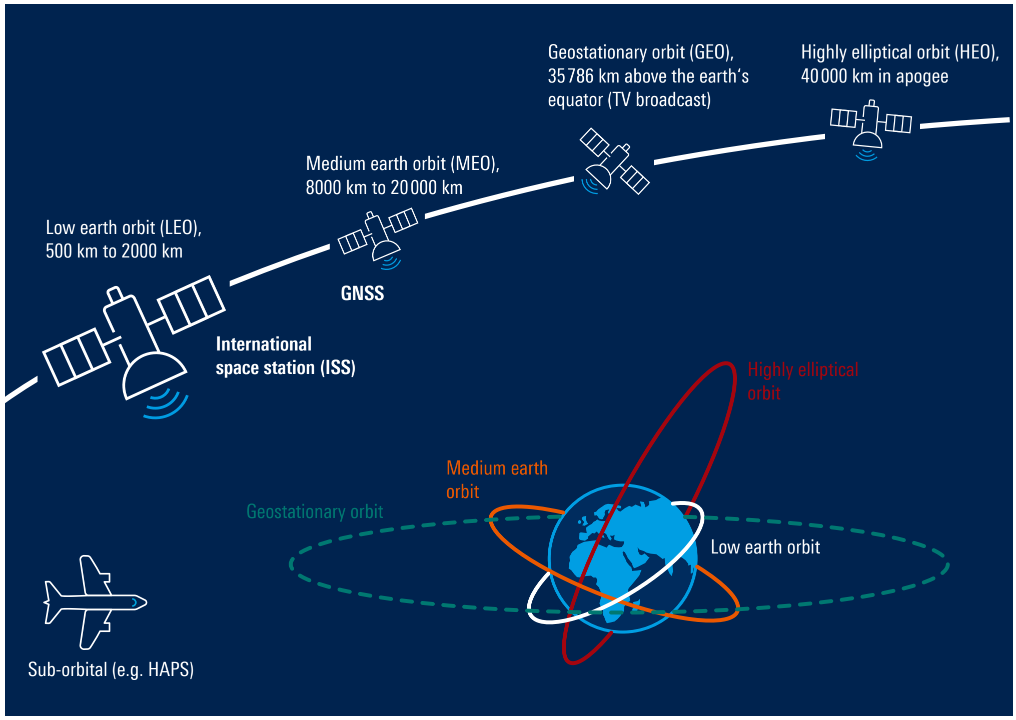
- **Medium earth orbit (MEO)** satellites operate in a circular orbit around the earth with an altitude between 7000 km to 25 000 km, travel at a velocity of about 13 800 km/h and have an orbital period of around 6 to 12 hours. Famous examples of MEO satellite constellations are the GNSS for positioning services. The beam footprint is similar to LEO constellations

- **Geostationary earth orbit (GEO)** operating in a circular orbit around the earth with an altitude of 35 786 km above the equator resulting in a notional station keeping its position fixed in terms of elevation and azimuth angle with respect to a given point on the earth. Beam footprint sizes range from about 200 km when narrow beams are considered and up to 4000 km when large beam sizes are used. The velocity of such a GEO satellite is 11 070 km/h and the orbit period corresponds to one day. Famous examples of GEO satellites are communications satellites like Intelsat or media satellites for TV broadcast like Astra or Eutelsat to name just a few. Due to the larger distance, the RTT of a GEO satellite is about 544 ms

- **High elliptical orbit (HEO)** satellite operate in an elliptical orbit around the earth. With such an orbit shape, a longer satellite visibility from the earth point can be obtained, e.g. when the desired coverage service area is a remote area e.g. the pole regions such a HEO would be more beneficial. Drawbacks are the elliptical orbit shape requiring some control and the resulting floating delay, time or orbit variant frequency drift and the non-constant coverage area. In the current releases of 3GPP NTN, the HEO satellites are not considered

- **High altitude platform systems (HAPS)** is a generic term covering all objects that can be airborne, e.g. airplanes, balloons, helicopters or drones (UAV). They can operate very flexibly at altitudes from several hundred meters up to about 15 km, have a beam footprint with diameters of just a few kilometers up to 100 km on average and, due to the shorter distance, the RTT reaches ranges known from terrestrial networks up to few milliseconds only. From a use case perspective described beforehand, HAPS constellations target hotspot provision or short-term system recovery and connectivity resumption. Further details on HAPS constellations and scenarios can be found in [Ref. 23].

Figure 13: Satellite constellation scenarios and some examples



For 3GPP based NTN, the initial target satellite constellations are LEO and GEO satellites. GEO satellites are likely to be terrestrial networks as they have a constant coverage size and are visible from the UE all the times. The obvious differences are the larger delay and the large cell size, which necessitate traffic management strategies. With a LEO satellite we observe a paradigm change in our cellular vision as now the base station is no longer stationary from the perspective of the UE. Consequently, the cell is not always visible, but rather becomes visible and then disappears (birth-death scenario). Chapter 4.3 discusses this aspect further.

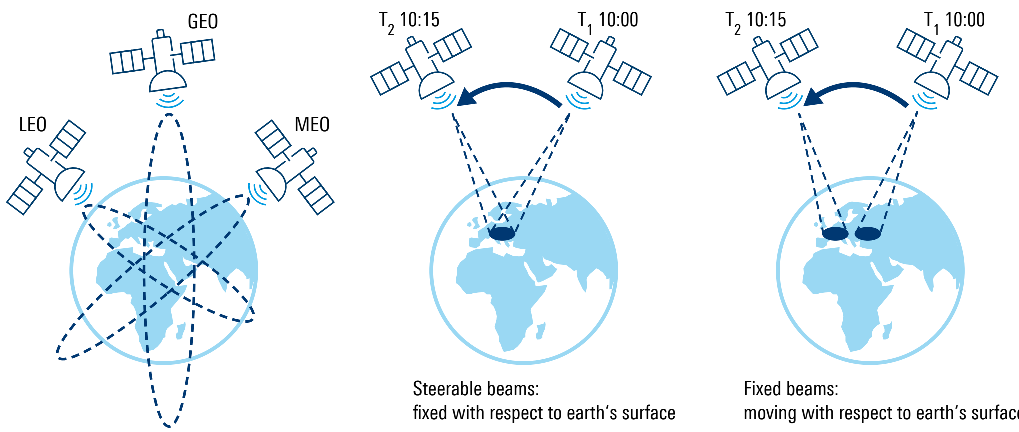
There are also additional satellite constellations, e.g. a satellite not always facing the earth: it is directed towards the sun when using its solar panels for energy harvesting and its communication part is directed towards the earth's surface to provide communications services while it is in the earth's shadow. Thus, satellites offer time-limited addressability. While in terrestrial networks, the TX power and the path attenuation determine the maximum cell coverage or network reachability, it is the visibility time of the satellite that determines the reachability in NTN. To support UE with measurements configuration and mobility aspects, the proposal is that in its system information, a quasi earth-fixed cell broadcasts a cell stop time with respect to the current coverage area.

Beam footprints

With respect to beam footprint, two types of satellite beamforming methods are discussed: The satellite beam footprint with respect to earth is either static or moving. Satellites whose beam footprint may move over the earth surface, or steerable satellite beams that produce an earth-fixed beam with respect to its surface. Thus, we distinguish between **moving beams** and **earth-fixed beams**. A satellite with static TX beams results in a moving beam scenario from the UE perspective and produces a beam moving relative to a fixed position on earth. A satellite with an earth-fixed beam represents the situation where the satellite possesses steerable beam capability. As the satellite orbits the earth, the satellite beams are adjusted so that it can continue to cover the same geographical area. In this case, as long as the satellite is above the horizon relative to the given geographical area, the beams can be adjusted to cover that area. The advantage of the earth-fixed beam footprint is a longer visibility from the UE perspective. In both scenarios, the UE will observe a time-variant carrier frequency deviation or, in other words, the Doppler shift of the carrier frequency monitored by the UE is not constant over the connection time. Furthermore, the Doppler rate depends on the angular velocity based on elevation angle and satellite speed. Chapter 4.4 discusses this aspect further. With the moving beam footprint, the satellite visibility is shorter in time and the UE experiences sudden birth and death of the satellite.

Figure 14: NTN constellation and beam footprint aspects

Platform	Altitude	Orbit	Beam footprint
GEO	35 786 km	Position fixed in elevation/azimuth relative to a given earth point	200 km to 4000 km
LEO	500 km to 2000 km	Circular around the earth, not stationary relative to a given earth point	100 km to 1000 km



The document [Ref. 12] presents further details and study results regarding how long a satellite is visible to the UE. This obviously depends on the orbit altitude, the beam footprint radius, the satellites velocity, the UE velocity, the direction of the UE and satellite movements in relation to each other and whether we assume a moving or fixed beam scenario. For a LEO constellation and the fixed beam scenario, the time the satellite remains above the horizon relative to the UE location is approximately seven to ten minutes. For the moving beam scenario, according to the values presented in a table in this document [Ref. 12], the times the UE remains under the beam coverage range from approx. 6 seconds to approx. 130 seconds, depending on the beam footprint size.

3.6 NewSpace satellite – architecture evolution

The technology evolution from 5G to non-terrestrial networks is also accompanied by the technical leaps made in the satellite industry over the last decades where we observe major changes in satellite architecture and scenarios. With respect to the use cases and scenarios, we have already described how legacy broadcast services (BSS) have been complemented by fixed (FSS) and mobile satellite services (MSS) with high and very high throughput satellites (HTS). Today, features like wideband signal transmission and reception, digital signal processing in the baseband and digital active beamforming using sophisticated phased array antennas are the norm. Whereas initial satellite applications targeted the GEO constellation, NewSpace satellites will be launched into non-geostationary satellite orbits (NGSO). In this chapter, the term "NewSpace" in connection with satellites refers to satellites with on-board processing capability and digital beamforming antennas supporting multi-beam scenarios where a single satellite is able to generate hundreds of simultaneous beams in RX and TX. The ecosystem of satellites covers a wide range of applications, e.g. navigation systems (GNSS), TV broadcast satellites and, of course, many satellite constellations providing communication services. In this respect, the 5G system is considered as another piece within this ample world of satellite services, but the focus of this white paper is 5G NTN communications. Only for completeness, please note that the satellites flight conditions in the atmosphere face rough flight conditions and temperature changes, thus applied optimizing methodologies need to work properly also under harsh and extreme conditions.

Phased array antennas for 5G NTN

One challenging aspect is outlined in greater detail in chapter 4.2. Due to the great distances between the ground terminals and the satellite, highly directive antennas should be engaged. Such an antenna aims to fulfill two major aspects: high antenna gains to overcome the attenuation and a high directivity to minimize unwanted emissions. A technical solution providing high-gain beamsteering functionality are phased array antennas. To recap, phased array antennas are antenna combinations (arrays) where either analog or digital phase shifters and amplitude controllers allow directional radiation of the signal. The advantage of phased array antennas is their flexibility and their capability to generate a large number of spot beams with high gain. In addition, a sophisticated beam management allows the generation of nulls, which reduces interference. The detrimental high path loss and the requirement to keep the cost and complexity of the handsets as low as possible motivate the engineers to continuously evolve the antenna performance of the satellite in order to improve the antenna sensitivity and gain as a countermeasure against the high path loss. Traditional satellites in the past focused primarily on wide beam footprints and simple TX and RX antenna chains, mainly parabolic reflector types, often referred to as bent-pipe satellites. An overview of such satellites and their technology evolution is provided in [Ref. 20]. Newer constellations aim at NGSO to boost the delivery of flexible commercial use cases like internet service provisioning in ubiquitous coverage scenarios.

The satellite engineers pursue the objective of developing fully flexible software-defined satellites with fully digital beamforming capability. Market analysis states that flat panel antenna (FPA) based non-GEO (NGSO) high throughput satellites (HTS) are expected to dominate future non-terrestrial broadband communication. Technologies such as electronically steerable multi-beam antennas and transparent or regenerative digital on-board processing (see chapter 3.10), as well as the usage of inter-satellite and/or multi-satellite connectivity with extremely fast signal handover processes [Ref. 20] are the driving trends. This technology evolution is accompanied by the tremendous progress in launching multiple smaller size satellites into LEO constellations and the maturity of electrical steerable silicon based phased array antennas. While initial satellite architectures used mechanically steered antennas to direct their beams, newer deployments apply electronically steered phased array antennas (ESA) to enhance the agility and reduce the overall size and weight. Challenges are the overall complexity, cost and energy consumption as well as heat dissipation. The latter requires highly efficient power amplifiers. A phased array antenna system simultaneously processes several signal streams with separate beamformers, up and downconverters, sampling stages and filters. Satellite antenna architectures use the same known principles of analog, digital or hybrid beamforming [Ref. 1]. Similar to the evolution in the electronic industry, the satellite industry also innovates on a higher integration level in silicon using substrates like GaAs, SiGe and CMOS technology. As an example, such a TX phased array antenna for the Ku-band at 14 GHz with size of 37 cm × 34 cm and 1024 elements achieves an EIRP of 44 dBW and has a power consumption of 160 W [Ref. 21]. Thus, we can conclude that the technology known as massive MIMO in the 5G system will also find its way into satellite architecture.

To ensure the quality and correct operation of antenna arrays, measurement quantities like radiation pattern, directivity, half-power beamwidth, EIRP or side lobe level (see [Ref. 2] and [Ref. 36]) verify the performance of such antennas. The test setup requires an OTA connection.

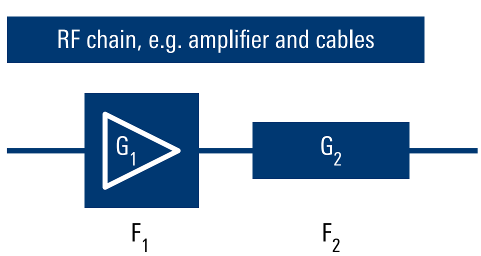
Optimizing the phased array antenna sensitivity

A high-sensitivity, efficient and affordable front end solution is the key enabler for LEO satellite communications. It is assumed that such phased array front ends will be incorporated not only in the satellites but also in the ground gateway and in some cases also in the UEs (e.g. VSAT type UE). Challenges are the size of the antenna array as they may contain about 500 to 4000 array elements (e.g. for Ka-band arrays) and this drives complexity and cost. The receiver sensitivity is the key figure of merit (FoM). The signal-to-noise ratio (SNR) that is visible at the receiver depends on the TX EIRP, the path attenuation PL, the antenna performance indicated as the gain-to-noise-temperature ratio G/T (see chapter 4.2) and the logarithm of bandwidth B and Boltzmann constant k.

$$SNR = EIRP - PL + \frac{G}{T} - 10 \cdot \log_{10}(k \cdot B)$$

The objective for the RX antenna design is to optimize the G/T ratio. One method is, of course, antenna gain G enhancement. With a phased array architecture, the antenna aperture or number of elements influences the gain. The disadvantage is that this comes at the expense of higher complexity and form factor. Looking at the term G/T, apart from increasing the enumerator value G, one can consider decreasing the denominator value T. Another entity that can enhance this G/T parameter is a low noise amplifier (LNA), which has the task of boosting the received signal by a sufficient level above the noise floor to support subsequent processing stages in the RX chain. The noise figure (NF) of the LNA influences the overall RX sensitivity, i.e. it may decrease the antenna noise temperature T in the G/T term. By way of a reminder, we use the Friis noise factor formula [Ref. 3] that is used to compute the cumulated noise factor F in a cascaded chain of RF systems. In Figure 15, we take the simple example of an RF chain consisting of an amplifier and a cable that are cascaded. A simple question could arise: Which of the two entities should be placed first? From the perspective of gain or attenuation (e.g. a negative gain), the signal is agnostic as the overall gain is the linear combination of all gains: $G_1 + G_2 + G_3 + \ldots$, but with respect to the overall noise factor, the formula presented by Friis reveals the situation that the overall noise factor is primarily influenced by the noise factor of the first RF stage. The noise factor of subsequent stages is diminished by the gain of the entities. In summary, the method by which an LNA with a good noise figure behavior is placed in the first row of the RF chain represents a good design choice.

Figure 15: The Friis formula for noise factor accumulation – reminder



$$Noise\ factor\ F = \frac{SNR_{input}}{SNR_{output}}$$

$$Noise\ figure\ NF = 10 \cdot \log_{10}\left(\frac{SNR_{input}}{SNR_{output}}\right)$$

$$\boxed{F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + \cdots}$$

A possible receiver architecture difference between a satellite phased array versus a typical 5G base station array is the disaggregation into multiple subarrays as beamformers and the placement of additional LNAs directly in front of the beamformers, optionally extended by an additional filter to eliminate spurious counterfeits. The disaggregation into several subarrays could bring the advantage of reduced losses in the panel [Ref. 35].

In addition to the aperture size, which influences the gain, the key figures of design are then the NF of the LNA and the efficiency of the power amplifier. Only for completeness, please note that the satellites flight conditions in the atmosphere face rough flight conditions and temperature changes, thus applied optimizing methodologies need to work properly also under harsh and extreme conditions.

NewSpace satellite capabilities – outlook

In Release 17 it is assumed that the UE has GNSS capabilities to determine its terrestrial position. For satellites this is not mandatory and not in the scope of 3GPP, but technology deployments also consider the implementation of GNSS capabilities in LEO satellites to be used for orbit management and flight control purpose (TM-TC) (see Figure 43).

Apart from the aforementioned capabilities and technology evolution for satellites, we should also consider the baseband signal processing, especially the evolution towards OBP and processing-integrated satellites. It is also the signal processing chain that needs to cope with challenges like RF path loss, deterioration due to atmospheric and weather conditions and SNR impact, absolute and time-variant delays and Doppler frequency shifts. By way of an example, we would like to remind you of the different protocol architecture in satellite broadcast technologies like DVB-S2X [Ref. 38] where the satellite needs to meet the requirement that the broadcast data has to be decoded simultaneously by multiple RX entities that face completely different channel propagation conditions. A study conducted in [Ref. 30] investigates aspects of signal processing and spatial precoding techniques based on channel status information as well as the onboard processing complexity inside satellites. The precoding techniques applied in such multi-beam satellites differs from terrestrial base stations as multi-beam does not fully correspond to massive MIMO. For example, the co-channel or inter-beam interference in such multi-beam situations does not decrease when the number of beams increases and, unlike terrestrial situations where a UE is typically injected with multiple interferers from surrounding cells, the amount of interfering satellites in NTN is considered to be low.

Future satellite architectures do not only require a higher integration of onboard processing but also consider multiple ISL and feeder link connections to ground stations.

3.7 Orchestration, management and planning aspects

The introduction of NTN into 5G systems requires the adaptation of management and orchestration methodologies as well as the introduction of flight control and planning and deployment analysis before the launch of satellites. The objective of this concise chapter is to provide a reminder of such methodologies as they either continue the existing technology evolution of wireless communications networks or correspond to new methodologies for the ecosystem. The background is the convergence between the wireless ecosystem and the aerospace ecosystem, thus for example the aerospace industries that are very familiar with aspects like satellite constellation planning, flight control and management (e.g. TM-TC) may have to learn from the communications industries with regard to aspects like networking, traffic flow and QoS management and vice versa. 3GPP does not directly tackle aspects like satellite flight control. In the evolution of communications networks, we observe technologies like self-organized networks (SON), service management and orchestration (SMO), operations automations and maintenance (OAM) or network function virtualization (NFV). NTN does not directly require enhancements of those concepts but it raises the level of necessity. Obviously, once a satellite is launched into space it will become challenging to send an engineer to such an SAN for hardware maintenance. Thus, such autonomous SMO methodologies are a mandatory prerequisite for the success of NTN. In the first deployment phases, NTN is introduced as a complement to the terrestrial networks, either as a satellite based overlay network to an existing terrestrial RAN or as a standalone satellite network that is the only service provisioning network, e.g. in remote areas. From a technology viewpoint, the first deployments of NTN apply the transparent architecture where the core network is considered to be based on the ground (see chapter 3.10). Later generations will introduce more flexibility in the airborne or spaceborne architecture entities. For example, initial satellite orbit constellations will most likely be controlled by terrestrial flight control centers but in future constellation some kind of autonomy will probably be applied [Ref. 26]. Below are a number of key technologies associated with network planning and maintenance.

Network and routing

This term tackles the aspect of traffic routing and networking to enable the provision of connectivity services across the entire earth sphere and the optimized QoS-oriented data flow. In particular the fact that LEO satellites may not have a permanent feeder link connectivity to the ground gateway means that the enhancements of ISL and intelligent plus automated traffic routing will become an essential part of future NTNs. Current ISL architecture models use the so-called "+grid" where one satellite is connected to its four neighbor satellites. Like the symbol + analogy corresponding to the satellites in front, behind, to the left and to the right (see Figure 29). While such constellations provide a resilient and redundant connection, they are not optimized for low latency and several researches are ongoing to optimize this ISL routing [Ref. 9]. Another aspect of networking is the software-defined networking (SDN) concept that is already enabled in 5G by the separation into CP and UP and allowing a centralization of the control entity. The modularity of the CP architecture allows future deployments of onboard processing units into the satellites [Ref. 26]. The networking aspect culminates in the introduction of MEC allowing better data traffic management and lower latency applications even with the long delays of NTN.

Operations, automations and maintenance (OAM)

The aspect of automation is certainly not only related to NTN and it is not our intention to present all facets of network orchestration and automation aspects in this white paper, but mega satellite constellations and the evolution towards nomadic nodes requires a sophisticated network orchestration and automation management, not only for OPEX reduction purposes. Research is ongoing on artificial intelligence methodologies introduced in such network management applications [Ref. 9]. The network disaggregation split between CU and DU introduced by 3GPP [Ref. 11] allows in NTN the deployment of satellites with onboard processing capability while the network management is terrestrial based. The role of OAM is, for example, to pre-configure the network entities with information like addresses, interfaces and protocol layer details over the 3GPP-defined F1 interface. In addition, NTN may also apply hierarchical or hybrid architecture models from the O-RAN alliance where the gNB is split into the O-RU and O-DU and the network management (e.g. SMO) can either connect to the O-RU directly (hybrid) or via the O-DU (hierarchical). Such OAM methodologies are agnostic of the RAN itself and can be applied on both terrestrial and non-terrestrial networks; see [Ref. 11] for further details on 5G architecture aspects.

Flight control, telemetry and telecommand (TM-TC)

This aspect is not directly related to 5G but with the introduction of NR-NTN it becomes obvious that incorporation into the 5G system is necessary. The major difference is that from legacy networks we assume that the controller (or network operator) has the global view of the entire network, which includes accessibility and monitoring capability. With new large-scale satellite networks spanning the entire earth sphere, one single controller may be insufficient to enable a fast response. Consequently, a distributed control plane becomes necessary, but the placement of such controllers with respect to the architecture of the CP and the QoS requirements of the UP demands some enhancements, described in the literature as the dynamic controller placement problem (DCPP). In the LEO architecture there is currently a three-segment approach, consisting of the segments ground, satellite or space and end user terminal. The aspects of flight control are the responsibility of the ground segment and include coverage, cost and performance. Future deployments require an onboard flight control functionality, especially when network nodes like UAV are considered as UxNB. With respect to the satellite constellation, there are various aspects that would exceed the perimeter of this white paper. For examples, satellites traveling on a certain orbit with constant angular separation are called "street constellations" or "Walker constellations" when distributed symmetrically (see Figure 29). Lastly it should be mentioned that the orbit constellation should also consider aspects such as the end of life of satellites and their de-orbiting processes to avoid space debris. These orbit management and flight control aspects accompany the aspect of networking and routing, but to include them here would greatly increase the size of the document. An overview of these technologies is given in e.g. [Ref. 26] and [Ref. 27].

Satellite link planning and constellation planning

With the arrival of NewSpace satellite technology and 5G NTN, both satellite link and constellation planning need to provide a sound foundation for the technology. While in early GEO satellite constellations, a classic link budget calculation between gateway and satellite suffices, the complexity of the new constellations with their LEO and MEO satellites requires precise modeling and optimization. Such planning does not only need to consider atmospheric and weather conditions but also considers regulatory requirements across different countries [Ref. 20]. The latter not only ensures successful operation but also prevents interference with other constellations or terrestrial networks.

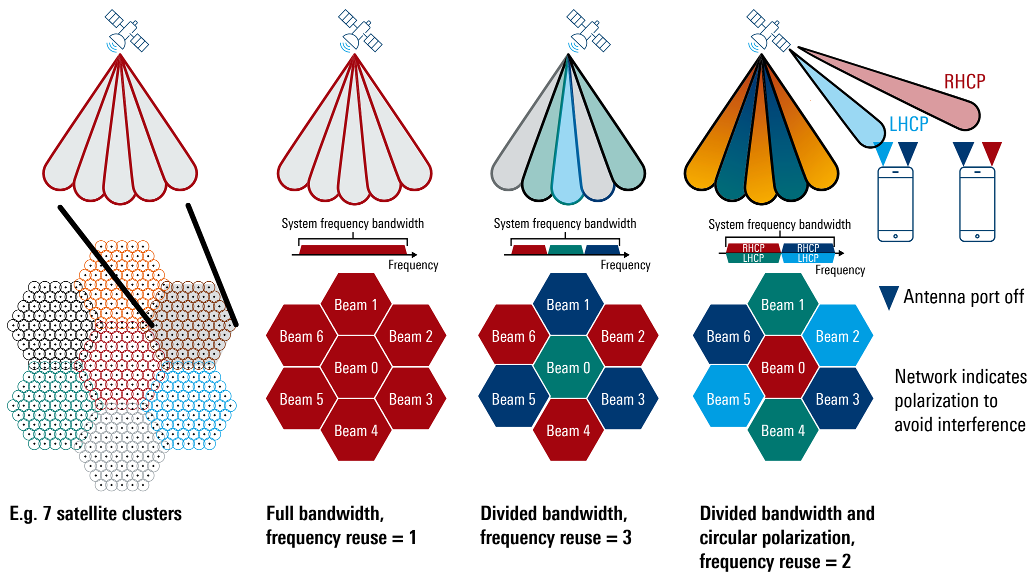
The aspects of satellite constellation planning would fill a complete white paper on its own, thus, we only present a high-level concise overview of major aspects. The objective is to provide seamless coverage across a certain geographical region by a satellite constellation on one specific orbital shell. The essential design parameters will then be (see also Figure 20):

- Minimum elevation angle at which a UE can connect to the satellite
- Orbit altitude
- Inclination angle of the satellite orbit

Based on those three parameters, one can compute the field of view (FoV), but even if the satellite is capable of multi-beam it is unlikely that the entire FoV corresponds to the coverage area. Another exacerbating factor is the real-world spectrum allocation to GEO and NGSO and the resulting spectral protection of GEO satellites. Specifically, the ITU recommendation 1503 [Ref. 29], for example, suggests an exclusion zone angle that serves as a boundary for the NGSO satellite to stop operation. Consequently, the FoV of one satellite should not be considered as the coverage area of this satellite. To provide wider coverage, more satellites will become necessary; a study presenting some results for various orbits and constellations as well as possible addressability figures versus deployment costs is given in [Ref. 9].

Considering the spectrum allocation requirements in terms of coverage and capacity planning, several methodologies and procedures are discussed. Such methods include the optional clustering of satellites as a swarm and the bandwidth part (BWP) aspects of the 5G technology. One method to provide a certain coverage for a specific region, but considering the facts that the FoV does not provide entire coverage, is the possibility to group satellites and their beams into a so-called cluster. The left part of the Figure 16 shows the example of a cluster of 7 satellites that is used as an assumed constellation for coverage planning. As far as interference aspects are concerned, various proposals exist and the study in [TR 38.821] simulates some of them. In 5G there is the aspect of the bandwidth part (BWP), originally introduced to enable the theoretical configuration of multiple numerologies and UEs with different capabilities [Ref. 1]. One idea is now to use such BWP configurations as a parameter to configure a certain spectral reuse by applying a certain BWP bandwidth to each specific satellite beam. The following figure provides some examples. In addition to the BWP spectral configuration, the satellite operator may also consider the polarization as a potential parameter to separate between satellite based links. The example given at the right side of the following figure uses the LHCP and RHCP to separate radio links and may therefore offer a higher capacity per satellite with the impairment of a higher interference risk and the need to signal the applied polarization for each UE.

Figure 16: Satellite cluster and frequency reuse aspects



An important aspect of satellite constellation planning, but not discussed further here, is the addressability of potential customers by LEO satellites. With NGSO constellations, the satellite will most of the time travel over geographical areas where only a small number of customers are reachable. In this case, we use the term addressability as the time given in percent where a LEO satellite does provide connectivity services to end users [Ref. 9]. Such addressability planning will of course be an essential prerequisite for any business case and investor relationship discussions [Ref. 22].

The outcome of several studies related to NGSO satellite constellations is that a single constellation will be unlikely capable of providing the required performance with respect to coverage and capacity.

In-orbit testing (IOT)

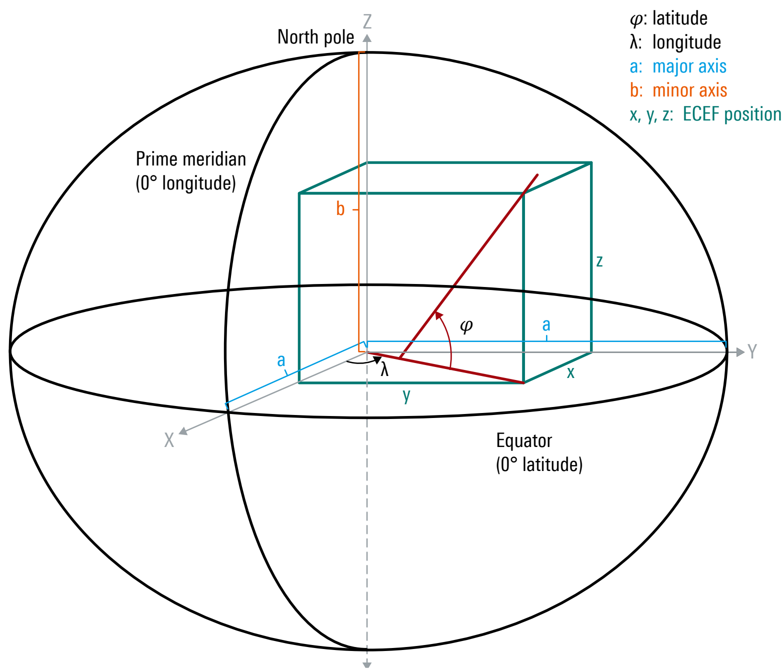
For sake of brevity we do mention this term only. In-orbit testing allows the measurement of the satellite performance during operation with a minimum of interaction by the operator. It is not explicitly related to 5G NR, it is furthrmore a general topic of any kind of satellite constellations. Further details can be found on the Rohde & Schwarz satellite testing webpage.

3.8 Brief digression into orbit constellation topics (Kepler physics)

The objective of this concise digression into orbit constellation aspects is to describe the basics of the mathematical approach to describe satellite trajectories. This refers to the medieval scientist Johannes Kepler (1571 to 1630) who first started to describe the planet constellations in the heliocentric system by formulating a mathematical background. Today, these constellation aspects are presented as the Kepler laws and form the fundamental scientific background of all the satellite constellations and modern astronomy. The experienced reader may skip this chapter, but we thought it would be helpful to present these aspects in a concise manner. There is additional information available in the literature, e.g. [Ref. 14], [Ref. 17] and [Ref. 18].

Johannes Kepler was one of the first scientists, like Galileo Galilei, to understand that the solar system is based on a heliocentric model, i.e. the sun is located at the center of this system and the planets orbit around it. He began by describing the planetary trajectory as an ellipse that is defined by certain parameters. These parameters are used as the satellite ephemeris parameters to describe a satellite's trajectory. To understand such a model, an earth-centered, earth-fixed (ECEF) coordinate system is used [TR 38.821].

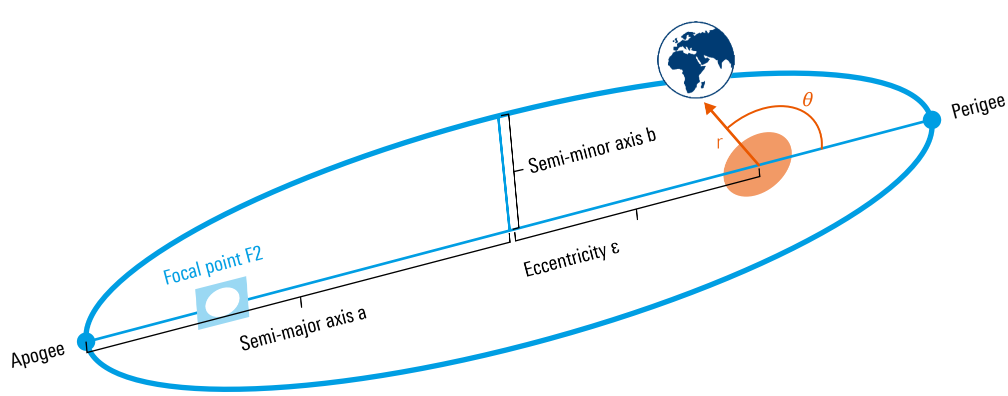
Figure 17: Earth-centered, earth-fixed (ECEF) coordinate system



Johannes Kepler described the trajectory of a planet as an ellipse that has the sun as the focal point. This results in Kepler's First Law in today's astronomy and describes the first two essential satellite ephemeris parameters.

Kepler's First Law states that the orbit of every planet is an ellipse with the sun at one of the two focal points.

Figure 18: Elliptical planetary orbit according to Kepler's First Law



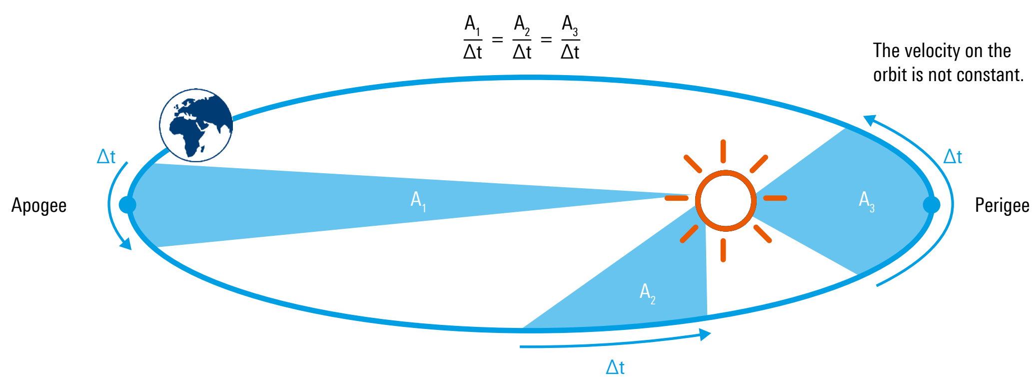
The position of the planet is given in polar coordinates: radius r = distance to the sun and angle θ = angle from its current position to the major axis passing through the perigee (shortest distance r). Apogee is when θ = 180° and r is at its maximum.

Kepler's Second Law describes the surface and velocity aspect of the elliptic trajectory. The velocity is not constant on the ellipse.

Kepler's Second Law states that a line segment joining a planet and the sun sweeps out equal areas during equal intervals of time.

Or in other words, the surface A described by an object that travels on an elliptical trajectory during a time interval Δt is always constant. In the below figure, the three surfaces A_1 to A_3 are identical: $A_1 = A_2 = A_3$.

Figure 19: Surface aspects of the elliptical trajectory of a planet, Kepler's Second Law



Kepler's Third Law describes the aspect of different velocities of each planet on its individual elliptical trajectory and the orbital times.

Kepler's Third Law states that the square of a planet's orbital period is proportional to the cube of the length of the semi-major axis of its orbit.

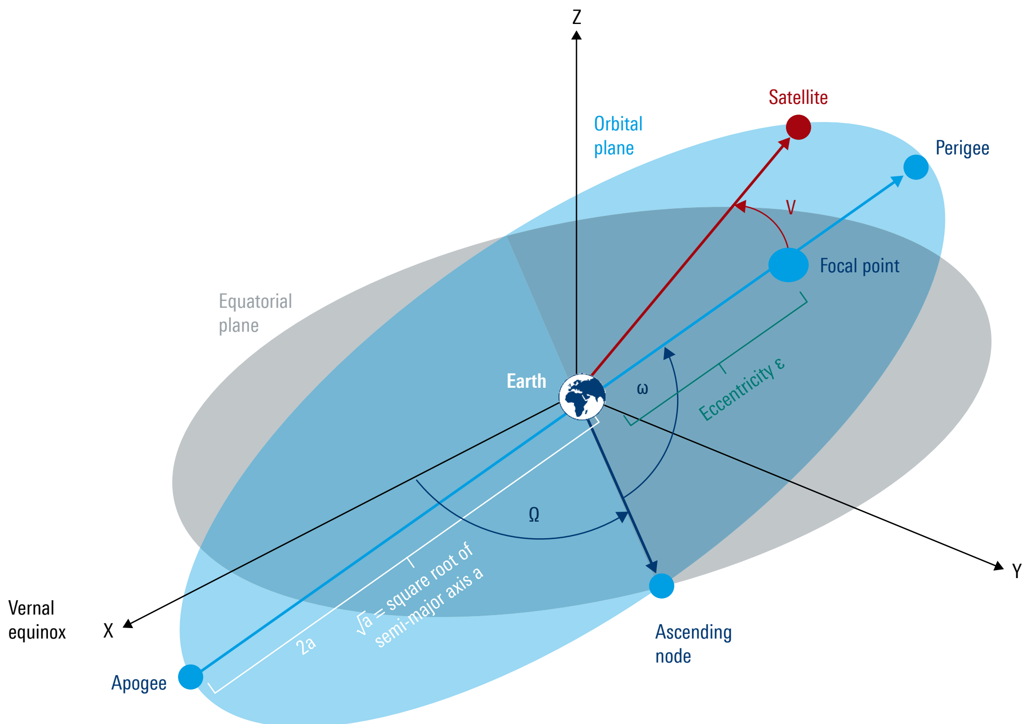
3.9 Ephemeris

The ephemeris data contains information about the orbital trajectory. Shape and position of the orbit in space, the position of the satellite at a given time and its velocity.

Generally, the ephemeris consists of 6 major parameters:

- Two parameters for the shape of the orbit, e.g. its **semi-major axis a** and **eccentricity ε**
- Three parameters for its orientation relative to earth, e.g. **inclination i**, **right ascension of the ascending node Ω**, and **argument of periapsis ω**
- One parameter as a reference point in time, the **epoch**

Figure 20: Ephemeris parameters for satellite constellations



NTN introduces the paradigm change in cellular network topology that the base station is, with respect to the UE, no longer stationary. Especially when considering a LEO constellation, the satellite only becomes visible when the elevation angle between the terrestrial UE and the satellite is above a certain minimum elevation and the satellite disappears when it drops below that minimum elevation angle. By way of analogy, this corresponds to the known day and night time effect and astronomical information like sunrise and sunset. Thus, the NTN connection experiences a cell birth-death situation and there is a limited connection time between the UE and one specific satellite. Consequently, unlike terrestrial networks where the assumption is that the base station signal is already omnipresent and cell search procedures tackle the challenge of acquiring the cells' synchronization signals and system information in a fast and efficient procedure, the NTN situation is more complex. A UE after a cold start has no information at all about the network. To overcome such disruptive situations that mar the cell search procedure, one idea is to pre-configure the UE with satellite assistance information, e.g. the ephemeris information. The literature defines the term "ephemeris" used in astronomy or celestial navigation as the trajectory of satellites in the sky, i.e. the position and possible velocity over time. Or in other words, it describes a table of data values giving the calculated positions of a celestial object at regular intervals through a period [Wikipedia].

In 5G NTN, the satellite assistance or ephemeris information, together with the UE terrestrial location information can be used to help UEs to perform measurements supporting cell selection and reselection. Ephemeris information included in SIB, in addition to the physical cell ID (PCI) and frequency information, is beneficial to the UE.

Especially considering IoT-NTN where power saving aspects play a pivotal role, satellite assistance information can be used for the handling of coverage holes or discontinuous satellite coverage in a power efficient way. For a UE, it should be possible to predict discontinuous coverage based on the satellite assistance information. To the extent that is possible/reasonable, the UE is expected to not attempt to camp or connect when there is no satellite coverage. To the extent that is possible/reasonable, the network is expected not try to reach UEs that are out of coverage [TR 36.763].

Ephemeris data contains the information about the orbital trajectories of artificial satellites, i.e. the shape and position of the orbit in space, the position of the satellite at a given time and its speed. The idea is that the system information block (SIB) will provide information on the serving satellite position, velocity and time (PVT). The proposal [R2-2007574] provides details on the satellite position and satellite velocity with a total size of roughly 144 bits, with the broadcasting of such SIB information every few seconds to impact the validity of the content. The neighbor satellite ephemeris can be provided via SIB broadcast with a format similar to the serving satellite info or via dedicated RRC signaling.

The study [TR 38.821] describes two possible sets describing such ephemeris information:

- Set 1: One possible option is to provide the location of the satellite in coordinates (x, y, z), e.g. ECEF coordinates. This location information is sufficient for GEO; for other constellations, additionally a velocity vector $(\overrightarrow{v_x}, \overrightarrow{v_y}, \overrightarrow{v_z})$ and again a reference point in time are needed. The study mentions the drawback of this method: for LEO satellites, that it prevents the UE from extrapolating the satellite track for more than a very short time because LEO satellites move at high velocity resulting in the situation that the given location in ECEF may be outdated and, secondly, as the satellite travels in an elliptical orbit, a velocity vector representing a linear movement trajectory does not help that much. So, as a result, a LEO satellite may broadcast an updated location or ephemeris information every few minutes.
- Set 2: In general, ephemeris data consists of six parameters, which fully describe an orbital plane and a seventh parameter as time information, the epoch:
  - Two parameters for the shape of the orbit, e.g. its semi-major axis and eccentricity
  - Three parameters for its orientation relative to earth, e.g. inclination, right ascension of the ascending node, and argument of periapsis
  - One parameter as a mean anomaly at a reference point in time
  - One time information, the ephemeris reference time also named the epoch

The first five parameters can determine an orbital plane, and the other two parameters are used to determine the exact satellite location at a given time (see chapter 3.6).

Table 5: Ephemeris parameters

Ephemeris parameters	
Orbital plane parameters	
$\sqrt{a}$	Square root of semi-major axis (semi-major axis)
ε	Eccentricity (eccentricity)
i_0	Inclination angle at reference time (inclination)
Ω_0	Longitude of ascending node of orbital plane (right ascension of the ascending node)
ω	Argument of perigee (argument of periapsis)
Satellite level parameters	
M_0	Mean anomaly at reference time (true anomaly and a reference point in time)
t_{0e}	Ephemeris reference time (the epoch)

In satellite communications, the ephemeris information is expressed in an ASCII file using a two-line-element (TLE) format. This TLE data encodes a list of orbital elements of an earth-orbiting object in two 70-column lines. An example of such a TLE element is given in [TR 38.821 Annex A].

Table 6: First line of the TLE element encoding satellite orbit information

Field	Columns	Content
1	01 to 01	Line number (1)
2	03 to 07	Satellite number
3	08 to 08	Classification (U: unclassified)
4	10 to 11	International designator (last two digits of launch year)
5	12 to 14	International designator (launch number of the year)
6	15 to 17	International designator (piece of the launch)
7	19 to 20	Epoch year (last two digits of year)
8	21 to 32	Epoch (day of the year and fractional portion of the day)
9	34 to 43	First time derivative of the mean motion divided by two
10	45 to 52	Second time derivative of mean motion divided by six (decimal point assumed)
11	54 to 61	BSTAR drag term (decimal point assumed)
12	63 to 63	The number 0 (originally this should have been "ephemeris type")
13	65 to 68	Element set number; incremented when a new TLE is generated for this object
14	69 to 69	Checksum (modulo 10)

Table 7: Second line of the TLE element encoding satellite orbit information

Field	Columns	Content
1	01 to 01	Line number (2)
2	03 to 07	Satellite number
3	09 to 16	Inclination (degrees)
4	18 to 25	Right ascension of the ascending node (degrees)
5	27 to 33	Eccentricity (decimal point assumed)
6	35 to 42	Argument of perigee (degrees)
7	44 to 51	Mean anomaly (degrees)
8	53 to 63	Mean motion (revolutions per day)
9	64 to 68	Revolution number at epoch (revolutions)
10	69 to 69	Checksum (modulo 10)

Ephemeris provisioning

One challenging aspect is the storage and provisioning of the ephemeris information. 3GPP agrees to extend the system information broadcast, e.g. introduction of SIB19 with NTN information. The minimum representation of the ephemeris requires at least six double-precision floating point numbers, plus some overhead. For this reason, considering NTN constellations with an abundant number of satellites, the ephemeris data can be quite substantial. The document [R2-1914195] provides an example of 5000 LEO satellites and the six ephemeris parameters, each of them represented by a 64 bit number, which would result in several hundreds of kilobytes. Note that this information needs to be stored close to the hardware, thus probably in the USIM card where memory size is an issue. As a countermeasure and due to the fact that several satellites typically share a common orbital plane, this white paper proposes only the provisioning of the common ephemeris data instead of each single satellite in order to save memory size.

The discussion within 3GPP about various possibilities of pre-provisioning the ephemeris to the UE is ongoing. One idea is to store certain information in the UE memory (e.g. USIM) indexed by a satellite ID, and the SIB broadcast is extended by such a satellite ID. The second idea, reducing the complexity of the UE memory but extending the signaling information content, is to broadcast ephemeris information via system information. To support mobility in idle and connected mode, a satellite may provide ephemeris information of neighbor cells via SIB or direct RRC signaling.

The pre-provisioning of ephemeris data to the UE shortens the cell acquisition time, e.g. the time to determine the reference signal and system information for frequency and time synchronization. In particular, assuming a UE with highly directional antennas to overcome the link budget challenge, such a UE must search the entire sky from horizon to horizon in a cumbersome and tedious search procedure as the antenna lobe or RX beam shape corresponds only to a fraction of the overall sky area. In addition, the rapid movement of LEO satellites further complicates this initial search. Another advantage of a priori knowledge of the satellite ephemeris in the UE is the RACH procedure as the UE may pre-adjust time and frequency and prepares for extended response times due to longer RTT. To prevent such an extensive time-consuming search procedure, a future enhancement is the idea of providing the UE a priori by a file in the USIM, containing such ephemeris information. So as not to conflict with the typical memory size of 128 kbyte of such an USIM, this ephemeris information contains common orbitals plane information only.

In a second stage, the system information of the first satellite or NTN cell that the UE acquires will complement the ephemeris information by provisioning further information, like the exact location of the NTN gNB with respect to the orbital plane. This procedure allows the UE to pre-estimate the frequency deviation, known as the Doppler shift, for carrier frequency pre-compensation and it allows the UE to pre-compute or assume the expected RTT for the random access procedure.

To allow some flexibility and to prevent a loss in accuracy of prediction values, it might be necessary to update the ephemeris information stored in the USIM. A validity timer determines the frequency of such updates, typically arranged via explicit NAS signaling.

In NTN situations, additional signaling information may be provided to the UE a priori, complementing the ephemeris data:

- Frequency range defining the NTN operating frequency bands. Similar to the legacy applied frequency list of neighbor cells in terrestrial RAT, NTN may also support the UE with frequency information to avoid tedious initial access procedures.

- Polarization information associated with the satellite constellation. Such information is helpful as, for example, the circular polarization schemes LHCP or RHCP are orthogonal to each other, thus the receiver should apply the same polarization scheme as the transmitter.

- A maximum RTT, beyond which the UE is not allowed to camp on a cell to control some capacity aspects of the network and avoid the UE accessing a satellite that is at a great distance.

3.10 5G NTN architecture details

Apart from the satellite constellation aspects, extension of the 5G system to incorporate non-terrestrial networks entails adaptation of the existing 5G system architecture. Especially on the radio access network (RAN), the obvious change from a terrestrial base station to an airborne or spaceborne satellite access station results in a number of amendments. These RAN extensions will be explained below in greater detail. Besides the modification and enhancements of the RAN, a study conducted in 3GPP investigated the impact on the overall 5G system architecture including the 5GC [TR 23.737]. Chapter 3.10.1 describes the 5GC and system architecture components enabling the introduction of NTN.

On a high-level contemplation, a NTN architecture needs radio access from the terrestrial UE to the satellite, referred to as the "service link", and in a second step, the satellite needs to be connected to a terrestrial gateway, referred to as the "feeder link". In a general aspect to allow some separation, the service link is described as the NR Uu interface, so the well-known 5G RAT and the feeder link is described as satellite radio interface (SRI). This SRI can either be the 5G NR waveform or another proprietary or standardized waveform in a later version of the architecture specifications. Future deployments consider the mmWave in the range from 30 GHz to 300 GHz for Gbps data rate connections. The advantage in addition to the wide bandwidth and therefore very high throughput is the resilience to clouds and bad weather; only heavy rain reveals the susceptibility to rain fading. It is anticipated that future networks will also implement free space optical (FSO) feeder links with frequencies beyond 190 THz that provide data rates up to Tbps and distances up to 1000 km. The key advantage is that these optical frequencies do not fall under international regulation control, but the major disadvantage is the propagation aspect. FSO links do not propagate through clouds. The gateway will connect further to the backhaul and core network functions and certainly to the application services. Besides the direct feeder link between satellite and gateway, there is also the possibility of an inter-satellite link (ISL). This is required particularly in LEO constellations because the satellite may not always have connectivity to the earth based gateway, especially when you consider the satellite being over a maritime region. In addition, the ISL may be used for control message exchange like mobility or handover scenario control, for traffic management purposes and for satellite flight control independently of 3GPP. Satellite constellations like LEO or GEO have the advantage of a known or predictable trajectory, which facilitates the routing of the connection to the ground station. Airborne stations like low or high altitude platform systems (LAPS or HAPS) may not be on a predictive flight route and therefore require some control of the feeder link routing and steering. Targeting an NTN-capable RAN deployment, two possible architecture options are discussed within 3GPP: the transparent mode (chapter 3.10.2) and the regenerative mode (chapter 3.10.3). Release 17 deals primarily with the transparent mode architecture. For completeness, additional chapters delve into further aspects of NTN used for backhaul connections support, inter-satellite link aspects and the extension of the dual connectivity (DC) feature by NTN connectivity.

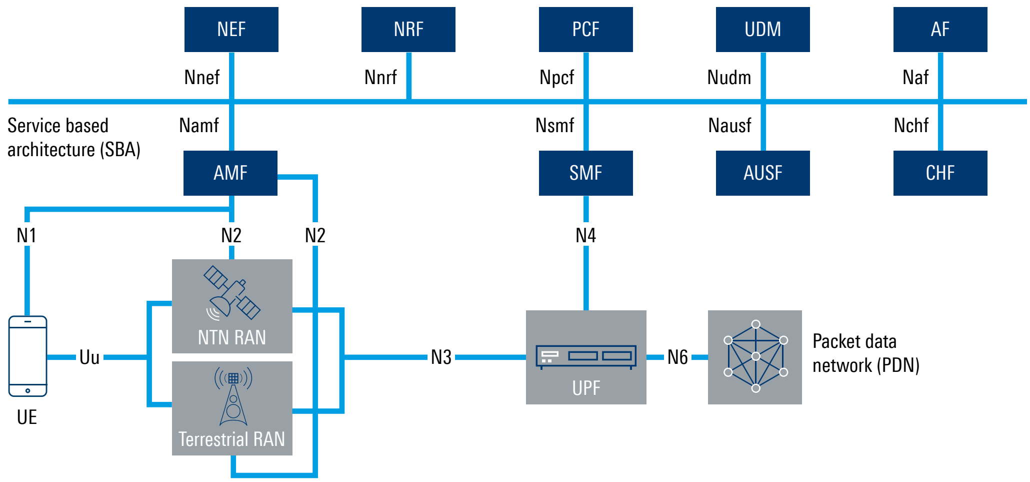
3.10.1 5G system architecture, core network and service based architecture

In 2018, 3GPP launched a study to investigate whether the current PLMN system architecture can be extended to support NTN connectivity and what possible impacts result. The main objective is the reuse of functions and architecture entities as far as possible. As a significant architectural characteristic, 5G system abandons the evolved packet system (EPS) point-to-point interface concept and introduces a network function concept where system entities or network functions offer a service that can be retrieved by other entities or functions. Only some interfaces reuse the legacy point-to-point model. Nevertheless, many concepts and system functionalities are similar to those in EPS, e.g. the separation into control and user plane. A good overview of general 5G architecture aspects is given in [Ref. 11].

Based on the use cases and services requirements outlined in e.g. [TR 22.822], the 3GPP architecture group identifies the main network functions, how these functions are linked to each other, and the information they exchange. One of the main parts of the study was to identify the potential impact on the 5GC network due to NR-NTN access, i.e. identify potential differences in functional behavior and interfaces compared to terrestrial NR.

The 5GC reference architecture, with the main network functions, is shown in Figure 21.

Figure 21: System architecture supporting NTN



In the 5G system architecture, the major impact due to the introduction of NTN is considered to occur in the RAN where possible architecture models support transparent or regenerative architectures. In the figure above, we logically split between a terrestrial RAN and an NTN RAN; they can operate as shared RAN or in parallel, e.g. in dual connectivity, or they can operate separately, orchestrated by different or the same operators. The user plane connectivity stays unchanged as the user plane function (UPF) provides data connectivity to the UE. As a minor impact, the UPF may interact with the possibility of establishing multiple PDU connections in parallel, and with respect to the session management, the UPF needs to tolerate the long delays associated with NTN connectivity. While data transmission is ongoing over the user plane (UP) connection, the UE or the network can activate another UP connection over another RAN under condition of a loss of terrestrial coverage, RAN notification or SMF signaling decision.

One notifiable aspect of 5G is the strong and sophisticated quality of service (QoS) framework that defines different QoS flows and introduces a specific protocol (SDAP) to leverage, maintain and manage the QoS support. This framework stays unchanged, with small enhancements, particularly by the definition of additional QoS service classes tolerating the extended end-to-end delays which in many cases might be beyond what is today allowed by the standardized 5G QoS classes. Especially the packet delay budget in the case of a GEO constellation leads to the introduction of the 5QI value of 10 in [TS 23.501] where the delay budget is extended to 1100 ms.

Table 8: 5G NTN quality of service

Parameter	Value
5QI value	10
Resource type	non-guaranteed bit ratio (non-GBR)
Default priority level	90
Packet delay budget	1100 ms
Packet error rate	10^{-6}
Default maximum data burst volume	–
Default averaging window	–
Example services	Video (buffered streaming), TCP-based (e.g. WWW, email, chat, FTP, P2P file sharing, progressive video) and any service that can be used over satellite access type with these characteristics

To support various QoS profiles and flows that possibly differ from QoS profiles that are possible in terrestrial RAN, 3GPP proposes the introduction of new types of the information element RAT type that is part of the gNB ID within the global RAN node ID. Apart from the existing values "NR" and "LTE", the addition of the values "NR (LEO)", "NR (MEO)", "NR (GEO)" and "NR (OTHERSAT)" is suggested. With this RAT type, the core network functions (e.g. AMF and SMF) may select the most appropriate RAN for a given QoS request. A possible amendment to the existing concept requests the notification of the policy control function (PCF) and the application function (AF) about the use of satellite access or satellite backhaul, to inform services about a potential longer RTT. Services that require a short delay, like URLLC, will probably avert the usage of NTN connectivity if possible. The 3GPP system today has significant possibilities for differentiated charging control function (CHF) and PCF, e.g. it is possible to offer 5G connectivity services over a non-3GPP RAT like Wi-Fi. Under discussion is whether this methodology is to be extended to allow a differentiation between terrestrial NR and NTN, e.g. LEO or GEO, as they offer a different service profile. The proposal, as mentioned before, is to introduce the new radio access technology (RAT) types value. This allows 5GC network functions for session management (SMF), PCF, CHF as well as the service layer (e.g. AF) to be aware of when the UE is using satellite access [Ref. 10].

The long delays that result due to satellite based communications require the extension of existing timers for mobility and session management in order to avoid a connection timeout due to pending response messages; see chapter 5.5.

A major extension occurs with respect to the access and mobility management function (AMF) as traditional terrestrial networks provide coverage within a single country, fulfilling the legal aspects of the respective regulatory organization. A satellite based communications system does not stop coverage at the border and 3GPP is investigating an extension to support NTN within inter-country or international ocean coverage. One possible extension is the connection of the RAN to several AMFs or 5GCs located in different countries, depending on the UEs location within a certain coverage area; see also chapter 5.11. The network repository function (NRF) allows for the dynamic discovery of other network functions, and an extension due to NTN introduction allows the NRF to coordinate such a selection of the correct AMF to enable cross-country NTN connectivity, or the NRF supports the selection of the correct service management function (SMF). The impact on security and authentication functions like the unified data management (UDM) and the authentication service function (AUSF) are considered to be low; a possible extension may define some access policies or barring rules for certain UE types or USIM profiles to prevent or permit NTN connectivity. Similar to the behavior of the network exposure function (NEF) exposing the capabilities of network functions like monitoring or provisioning capability to external applications, e.g. a notification to an external application that a UE has become available [Ref. 11]. A possible impact is a longer out-of-reach period indication.

[TR 23.737] describes further details on PLMN selection, especially in cross-country coverage situations. Some examples are that the AMF performs a location request procedure from the UE when a connection is established over NTN RAN to ensure that the UE is in a permitted region or country.

3.10.2 Transparent NTN NG-RAN architecture

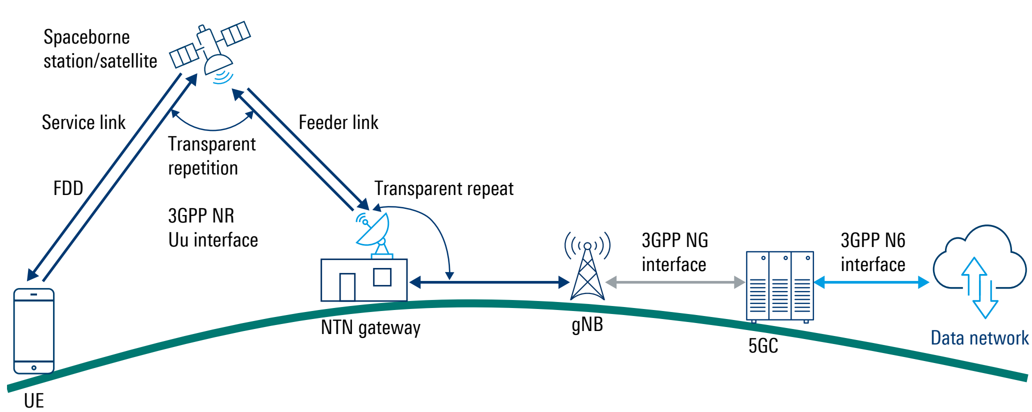
Also known as the bent-pipe method behaving like a repeater in space and simplified by the expression "what goes up, must come down". The major aspect in the transparent architecture is the disaggregation of the legacy term "base station" into the components satellite, ground gateway and gNB functions. The satellite functions implement RF filtering, frequency conversion, RF amplification and RF transmission and reception in both the uplink and downlink direction. A pivotal characteristic is that the waveform or RAT is repeated between the serving and feeder link by an unchanged payload. By way of analogy and simplification, the functions of the satellite station correspond to the analog RF repeater concept. A frequency carrier change is probably applied to avoid interferences between the serving and feeder link, but this is up to the manufacturer and the operator. The document [TR 23.737] defines the functionality of the transparent payload as the electromagnetic waves that are transmitted from the earth's surface and converted by a satellite receive antenna into an electric signal, which is channel-filtered and amplified by a low-noise amplifier (LNA). The signal is then frequency-converted. A high-power amplifier (HPA) finally delivers the signal to a transmitting antenna generating a reconditioned electromagnetic wave towards the earth's surface where the receive gateway is located.

The advantage of the transparent architecture is the independency on the radio waveform, so any amendments here do not require changes in the spaceborne station. The disadvantages are the amplification of noise because the satellite does not perform any channel equalization or noise cancellation, the vulnerability against jamming attacks and the lack of ISL connections for traffic steering.

The termination of the 5G NR air interface (Uu) with respect to the protocol anchor is in the terrestrial gNB function. The gateway function has no explicit task with respect to 5G NR; it is probably a parabolic antenna or antenna array with beamforming capabilities to steer the feeder link heading towards the satellite station. A broad range antenna would be unfeasible as this gives rise to the interference between satellites. The architecture depicted in the delineation of Figure 22 is only in a symbolic sense; certain deviations are possible. E.g. the gateway and the gNB can be incorporated into the same hardware cabinet or the gNB functions are offered to several satellites. Only in the opposite view, a satellite is only connected to a single gNB to clarify the protocol termination point. To avoid misunderstandings, it is possible for a satellite to be connected to multiple gateways or gNBs, but in such cases, the payload is logically split. A better explanation would be from the perspective from the UE: one specific UE data connection to the 5GC is routed via a single gateway or gNB. Exceptions are the multi connectivity scenarios.

The connection between the UE and the terrestrial gNB includes at least the serving and the feeder link, but also several ISLs in between are possible in future extensions. [TR 38.821] states that the regenerative payload is required for initial ISL implementations, which is why the ISL is not depicted in Figure 22.

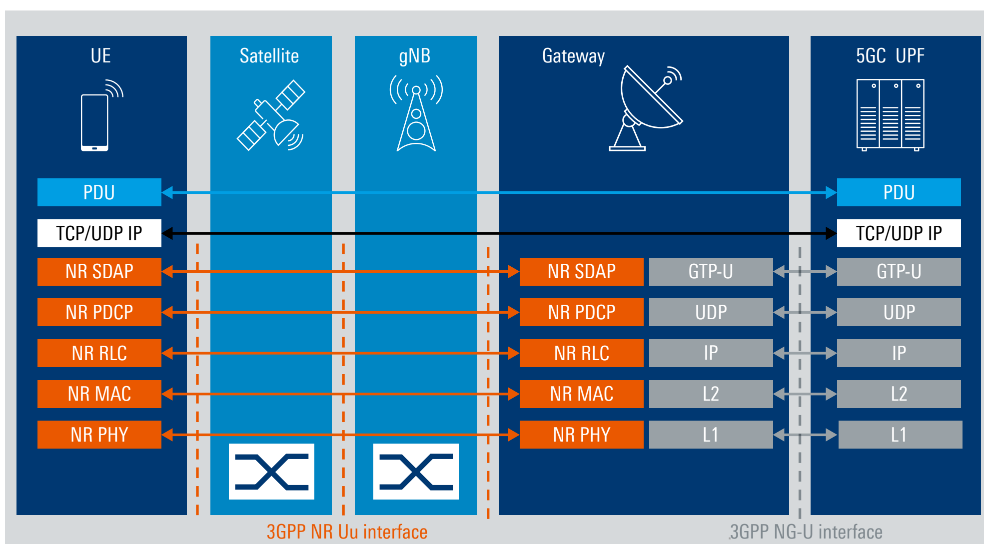
Figure 22: Transparent NTN NG-RAN architecture



[TS 38.300] defines in greater detail the architecture of the gNB in a non-terrestrial RAN, e.g. the gNB may be subdivided into non-NTN infrastructure gNB functions and the NTN service link provisioning system, which is described by our term "satellite". The NTN part of the infrastructure model is subdivided into the NTN service link provisioning system, which is the NR user and control plane and the NTN control function. The NTN service link provisioning system may consist of one or more NTN payloads and NTN gateways. The term "NTN payload" is introduced to provide some flexibility and future upgradability; it describes the architecture components on board a spaceborne (or airborne) vehicle, providing a structure, power, commanding, telemetry, attitude control for the satellite (or HAPS) and possibly a suitable thermal environment and radiation shielding. The NTN control function controls the spaceborne vehicles as well as the radio resources of the NTN infrastructure. In other words, it can be considered as part of the network SMO function. It provides control data, e.g. ephemeris or other flight control information, to the non-NTN infrastructure gNB functions of the gNB. Subsequent provision of NTN flight control data to the gNB is beyond the scope of 3GPP and may be vendor-specific.

With respect to the 5G NR protocol architecture, there is not much difference between the terrestrial RAT layer model and NTN. The only differences are the additional intermediate entities satellite and ground gateway in the protocol layer model, which are transparent to the data flow. As explained, with the transparent architecture, the termination of the radio interface is within the terrestrial gNB. This represents an important topic with respect to latency or RTT aspects as the one-way latency includes the serving and feeder link. Like in 5G NR, the user plane protocol using the IP transport layer terminates in the end-to-end (E2E) entities UE and 5G user plane function (UPF). There can be proprietary mapping procedures applied to map the 5G radio interface on an SRI or gateway to the gNB transport interface for tunneling and transport services. The following figure describes the transparent protocol architecture structure of the user plane.

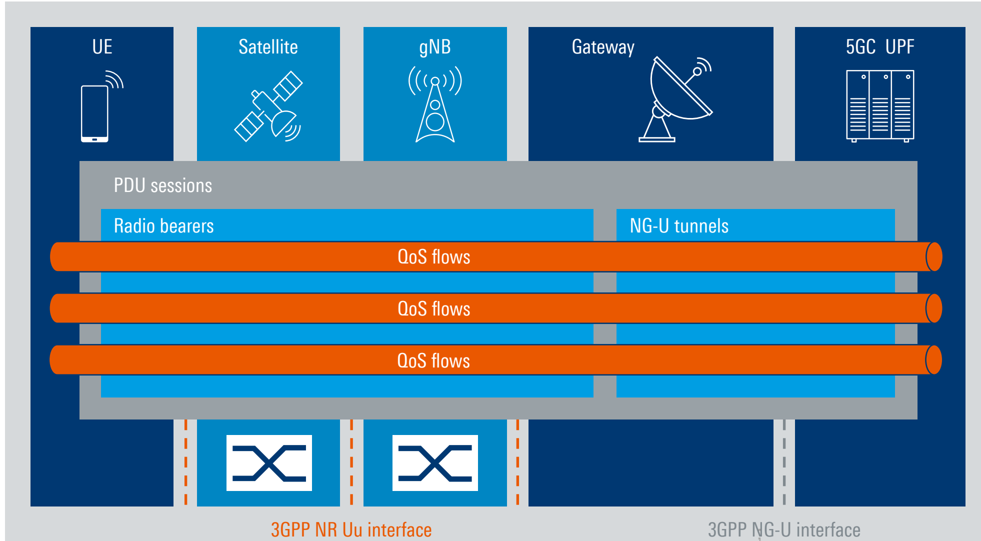
Figure 23: Transparent NTN NG-RAN protocol architecture – user plane



The control plane protocol structure has a similar model: the RRC protocol layer tunnels between the UE and the terrestrial based gNB through the satellite and gateway, and the NAS control messages terminate in the 5G core network functions like AMF or SMF [TR 38.821].

Like 5G NR, the 5G NTN also bolsters and leverages QoS aspects. The connection inheriting a certain QoS profile is described as QoS flow and terminates in the two endpoints UE and UPF, thereby providing E2E QoS management to offer flexible, agile and dynamic services. Aspects like network slicing or QoS management handling already known from the 5G system are not changed due to the integration of NTN. Amendments to the existing QoS profiles adapt to longer RTT. The gNB is required to map the QoS flows onto the relevant radio bearers that include the NTN link, and to translate between the QoS flow on a radio bearer and the corresponding NG-U tunnel of the core network connection.

Figure 24: Transparent NTN NG-RAN architecture – QoS and bearer model



In a summarized, shortened view, the transparent payload architecture does not require many modifications to the existing 5G NG-RAN architecture model. Some changes are required, particularly some physical layer timers to adapt to the long delay of the feeder and service link. See subsequent chapters for information on these challenges and how to tackle them.

3.10.3 Regenerative NTN NG-RAN architecture

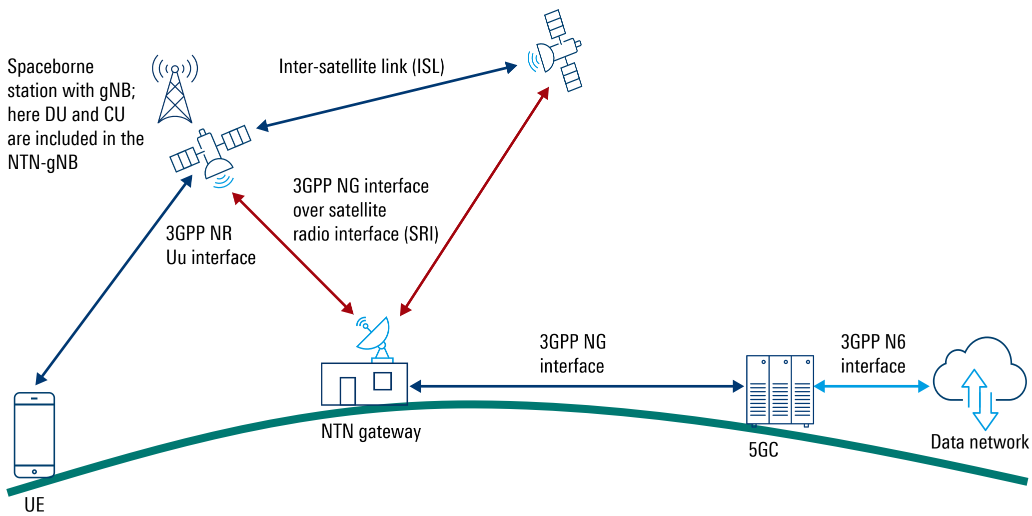
The regenerative architecture deals with the three components satellite, gateway and gNB, but allows some combinations. The major difference to the transparent payload architecture is that the gNB functions are incorporated into the satellite itself. The regenerative architecture model raises the complexity of the satellite hardware and computing power and is discussed within 3GPP at a lower priority in Release 17 and envisaged for later releases. Further separations are made in the optional disaggregation of the gNB functions into the distributed unit (DU) and the centralized unit (CU). The regenerative payload architecture supports both architecture models: the satellite node can directly incorporate the DU and CU, and via the feeder link to the gateway there is a direct connection to the 5G core network (5GC). Alternatively, the satellite can only host the DU functions of the gNB and therefore the feeder link to the terrestrial gateway carries the F1 interface over the SRI and the CU is terrestrial based. The document [TR 23.737] defines the regenerative payload functionality as the implementation, where an on-board processor (OBP) is inserted between the LNA and the HPA. This OBP allows conversion of the air interface between the uplink and the downlink. It allows bits or packet errors to be corrected before they are retransmitted, or packets to be routed between beams. Ultimately any network function can be implemented, at the expense of power and mass, thanks to an OBP (including gNB CUs or DUs, or any function attached to a 5GC).

One advantage of the regenerative architecture is the reduction of latency as the Uu interface terminates in the satellite that incorporates the entire NTN gNB functionality, thus the single-way latency only includes the service link. Buffer management, link control or retransmissions need to be implemented in the regenerative mode satellite and this increases the afore-mentioned complexity aspect.

A second advantage is the possible deployment of an NTN with multiple ISL connections between the satellites, especially a swarm LEO constellation where only a few LEO satellites have access to the gateway. The implementation of DU and probably CU functionality into the satellite give them a better autonomy, but at the expense of higher complexity. Sophisticated ISL traffic steering methods leverage ubiquitous coverage and allow intelligent and efficient traffic management in future deployments. For the sake of simplicity, Figure 25 does not show the gNB-DU payload processing case where the CU is terrestrial based. As a kind of priority, [TR 38.821] requires a regenerative payload for the optional ISL deployment.

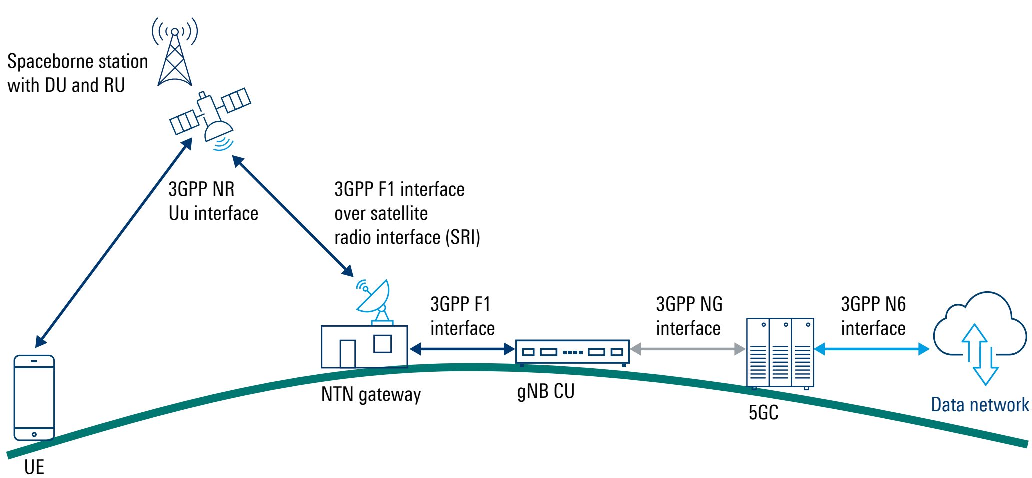
Lastly, as a third advantage we would like to mention that with the regenerative architecture we obtain an independency between the service and feeder link, possibly allowing the usage of mmWave or FSO feeder links with very high throughput.

Figure 25: Regenerative NG-RAN architecture (DU and CU in satellite)



For completeness, the following figure depicts the regenerative architecture where only the gNB-DU function is implemented into the satellite, but the gNB-CU is still on the ground. This architecture will not be discussed further. More details can be found in the 3GPP documents, e.g. [TR 38.821].

Figure 26: Regenerative NG-RAN architecture (CU on ground)



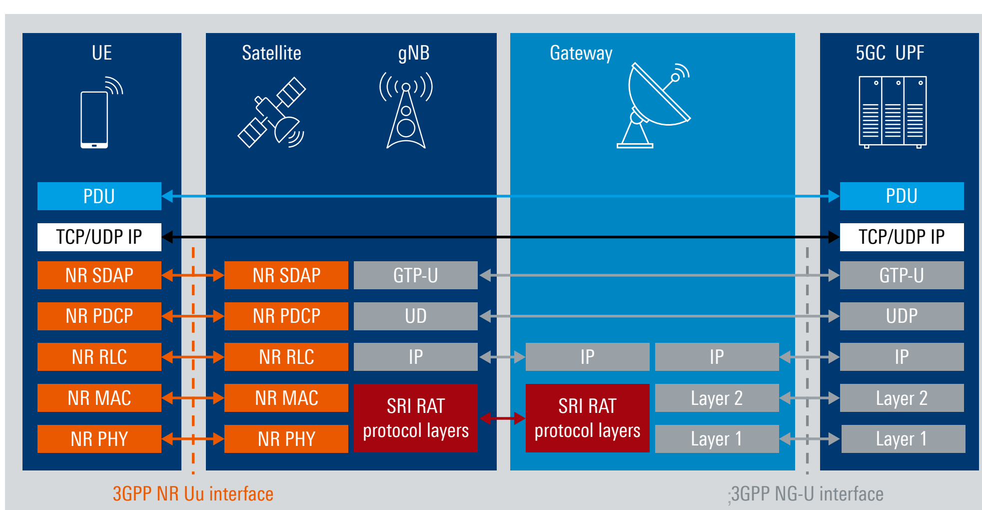
While the regenerative architecture may offer a better delay management, it has the drawback that the SRI link needs to be specified. It is a transport link between the gateway and the satellite and carries either the F1 interface between DU and CU or it carries the NR-U interface between gNB and 5GC. As both F1 and NG-U interfaces are midhaul or backhaul connections in the 3GPP architecture typically using a cable connection like Ethernet or fiber optics, it is necessary to standardize a radio link that is capable of transporting this data over the satellite to the ground interface. As 5G introduces a virtualization concept of network functions, future deployments may include several gNBs within one satellite.

This regenerative payload option is being considered for standardization for 3GPP Release 18 and beyond with three potential design options [Ref. 12]:
- Full gNB on board
- Deployment of gNB-CU on the ground, gNB-DU on board the satellite, which faces challenges with regard to handling the F1 interface
- gNB on the ground and applying an O-RAN like architecture, where the lower layer split (LLS) connects DU and RU. The radio unit (RU) is on satellite, which is faced with challenges in the fronthaul interface (e.g. O-RAN alliance proposal) that is not standardized in 3GPP

In the protocol layer architecture, we can observe that the Uu interface terminates in the satellite containing all the NTN gNB functions and that there is the SRI link to transport the user and control plane data from the regenerative mode satellite via the gateway to the 5GC. To enable transparent user plane data transport, the user PDUs are transported over the GTP-U protocol in a tunnel procedure between the satellite containing all the gNB functions and the 5GC.

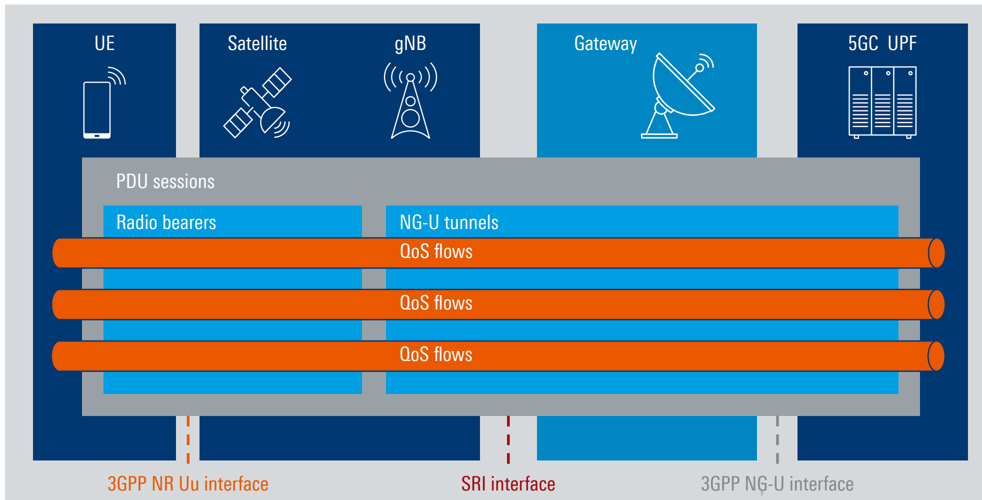
The control plane architecture is similar to the user plane. The RRC terminates within the satellite gNB function, so here too we assume a shorter reaction time for RRC-specific radio link control procedures at the expense of higher computation power being required within the satellite itself. In the case of the alternative disaggregated architecture where the satellite carries the DU functions and the CU is still on ground, the control plane like the RRC protocol layer also terminates on ground, hence the long delay like that in the transparent architecture prevails. To transport NAS messages between the gNB and the 5GC functions AMF or SMF, the NG-AP protocol establishes a tunnel between them across the gateway and the SRI link.

Figure 27: Regenerative NG-RAN architecture – user plane protocol stack



Similar to the transparent payload architecture, the regenerative payload too bolsters QoS support and leverages various QoS flows with specific profiles. The difference is the termination of the radio bearers in the satellite based gNB and the "longer" NG-U tunnel from the satellite gNB to the 5GC UPF. The disadvantage is that the NG-U interface includes the new SRI link and that some adaptations with respect to QoS management and network slicing over SRI are probably required in such future deployments. It is particularly important to bear in mind that in such an architecture the NG-U interface includes the NTN feeder link between the gateway and satellite, thus longer delays should be expected and a corresponding timer and counter adaptation is required.

Figure 28: Regenerative NG-RAN architecture – bearer and QoS flow aspects



Our description of the regenerative architecture focuses on the gNB processing including CU and DU functionality. Further details on the disaggregated architecture where only the DU function is satellite based and CU is on the ground can be found in [TR 38.821].

3.10.4 NTN backhaul and IAB

This short section is more for completion aspects to describe the possibility of a satellite based backhaul and the option to apply methodologies of integrated access backhaul (IAB) in combination with NTN. Both methods are not considered as highest priority by 3GPP, e.g. the IAB satellite excess is currently precluded in Release 17. With the backhaul concept, a terrestrial base station or gNB is connected to the 5GC via a satellite based connection or alternatively future deployments allow cellular backhaul (CBH) via HAPS gateways [Ref. 23]. This does not directly require an update of the current RAT, the existing NG interface is routed via a satellite, i.e. the terrestrial RAN connects via the N1, N2 and N3 interface over satellite to the 5GC functions AMF, SMF and UMF. Deployments need to consider aspects like enhanced RTT and potentially missing neighbor cells that may cause radio link drops at the cell edge. The advantage compared to 5G NTN is that the terrestrial gNB has a fixed position with respect to the satellite and methodologies like RTT pre-compensation by TX timing advance are possible and highly directional antennas with high gain can be applied. For the sake of brevity, we will not delve further into this NTN backhaul infrastructure.

A specific sub-feature of backhauling is the term "trunking" that corresponds to the provisioning of satellite based high throughput to aggregation nodes and not only to a single cell.

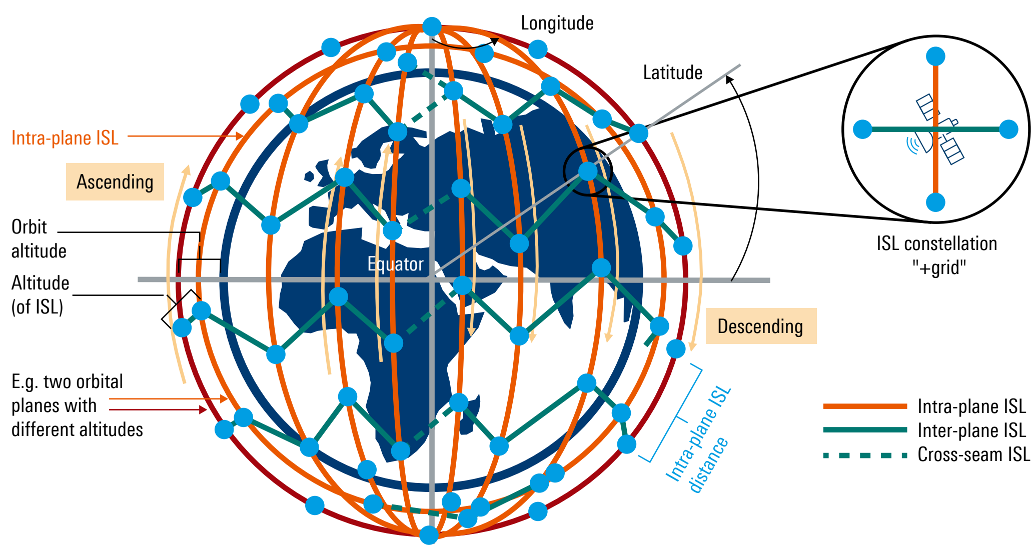
A future deployment of NTN not only includes additional aerial and celestial platforms, but also combines the dynamic deployment of additional cells by integrated access backhaul (IAB) methods with those from NTN. So, an IAB node can be connected via 5G NR, which is satellite based, to its terrestrial donor cell. The advantage of such an architecture are flexible and fast deployments of 5G networks providing terrestrial coverage. Such a use case is public protection disaster relief (PPDR) where the objective is to regain and provide terrestrial communications after a natural disaster in a very fast deployment process. Investigations consider the IAB node as an aerial vehicle, i.e. a UAV that is connected via an NTN link to the IAB donor cell. As this requires additional complexity, like the routing of the link, capacity management and dynamic handling of those IAB nodes, 3GPP will consider these IAB NTNs in a future release.

Note that the opportunity to apply a NTN backhaul connection does not provide a monopoly situation. We may also consider situations where an NTN backhaul complements the terrestrial NG interface connection of the RAN, for example to apply traffic management methods.

3.10.5 Inter-satellite link (ISL)

ISL is a transport link between satellites to transfer high-speed data and optionally control information for satellite navigation and flight control like telemetry and telecommand (TM-TC). ISL may be a radio frequency based WLAN (radio frequency inter-satellite link, RF-ISL), e.g. IEEE 802.11n [Ref. 6], or an interface based on the optical frequency layer, e.g. laser (optical inter-satellite link, O-ISL) [Ref. 8]. The technical aspects of ISL are mentioned in this paper only for completeness, the definition of the ISL technology may be based on 3GPP or non 3GPP. The technological evolution of NTN will then entail adaptations and amendments to the ISL technologies applied. NTN transparent architecture will require an ISL for user data transfer between satellites, probably to forward user data to the satellite that has connectivity to the ground station. Hence the ISL plays an essential role in the overall satellite constellation as ubiquitous coverage also requires connectivity to the ground stations and the 5GC, which is not possible for every orbital constellation point. In technical terms, the situation where such a ground-to-satellite link is available is described as a satellite pass. Optionally the ISL carries additional control information (e.g. TM-TC), e.g. a collision avoidance maneuver control. Obviously ISLs represent an important design factor when contemplating the overall system capacity within a satellite constellation, and future NTNs will use ISL not only for terrestrial service provisioning but also for capacity and load balancing. With further details, such an ISL can be a link between a LEO satellite and a stationary GEO satellite or the ISL can be between different LEO satellites and depending on the orbital constellation and satellite velocity such an ISL may be intermittent and fluctuating. A further distinction is made between intra-plane ISLs describing satellites on the same orbital plane and inter-plane ISLs for satellites on different orbital planes. Furthermore, the ISLs between satellites may move in near-opposite directions and in such cases the term "cross-seam ISL" applies. The constellation of satellites including their ISL connections can be aligned in various topologies. A famous one is the Walker star LEO constellation where one satellite has a +grid ISL structure. Corresponding to the +character it connects to satellites before and after on the same orbit as well as neighbor satellites; see Figure 29. Further details on such ISL constellations and the corresponding RF aspects are provided in [Ref. 31].

Figure 29: LEO satellite constellation with ISL (Walker star constellation)



Future technology extensions like the NTN regenerative mode or full organic nodes incorporating MEC and core network functions may require the transfer capability of 5GC interface protocol stacks, e.g. F1 or N2 or N3 interfaces, on the ISL.

The implementation of ISL based on radio frequency methodologies has certain advantages but also disadvantages. Positive is the common nature of the hardware entities used for RF-ISL compared to the feeder and service link – all three are RF based, probably also in similar frequency ranges, which allows the reuse of certain RF components. The propagation characteristics of RF do not require a very stringent directional transmission or pointing between TX and RX entities, but a more dispersed RF connection may cause interference on other RF-ISL connections. A final drawback of the RF-ISL is the need for frequency coordination: the ITU has described in the WRC19 report certain frequency ranges for ISL, e.g. 22 GHz to 24.75 GHz, 27 GHz to 27.5 GHz or 66 GHz to 81 GHz [Ref. 7].

The optical ISL (O-ISL) does not require spectrum coordination, and laser based optical links are less prone to interference and most likely the wider bandwidth of the optical link supports higher data rates. The main disadvantage is the requirement of a tight acquisition, tracking and pointing (ATP) system due to narrow beam divergence [Ref. 8]. Some additional undisputed challenges for the O-ISL system designer result from atmospheric and solar conditions. Unpredictable atmospheric conditions can degrade the performance of the link. Another factor influencing the O-ISL link quality is the impingement of the sun relative to the laser based transmitter and receiver causing solar background optical radiations that have a negative impact on system performance. Future NTN constellations will move towards so-called mega constellations incorporating thousands of LEO satellites. So, it is anticipated that the neighborhood relationships for ISL connections need to be adapted frequently, also resulting in dynamic ISL connection switching or handovers, ISL connection establishments and releases. In addition, the movement of the satellites in relation to each other will also result in an ISL Doppler shift. Due to the required ATP precision, an initial ISL connection setup requires a certain amount of time. Current estimates are in the range of up to 50 seconds and re-establishing existing ISL connections may still take up to 20 seconds. But ISL connections will lay the foundation for software-defined networking, intelligent routing and resource allocations in such mega constellations.

3.10.6 Interworking between terrestrial and non-terrestrial networks and multi connectivity aspects

The aspects of interworking between different RATs and multi connectivity within a 5G system are extended by the addition of NTN as an additional RAT, allowing several theoretical combinations of multiple links in a simultaneous or non-simultaneous procedure or certain mobility scenarios. In a first approach we would like to contemplate the aspect of interworking between terrestrial and NTN connectivity. The primary focus with respect to the use cases and services offered is the service continuity, thus 3GPP requires service continuity between terrestrial and NTN, which can be achieved by mobility scenarios such as inter-RAT handover or by dual connectivity scenarios. Remember that with the 5G system two modes are possible: non-standalone (NSA) as interworking between LTE and 5G NR and 5G NR standalone (SA). 3GPP decided not to consider NSA supporting NTN, thus the NSA based aspects (such as Xn mobility between NTN gNBs and terrestrial eNBs, MR-DC, secondary RAT data volume reporting, traces, etc.) are currently treated as low priority in 3GPP Release 17 activities [Ref. 12]. Future deployments are expected to transition between NTN and terrestrial, and an interaction between LTE and 5G NTN is anticipated.

In the first deployment phase, the interworking between NTN and terrestrial networks follow the existing procedures of UE mobility in idle and connected mode.

With respect to spectrum usage (see chapter 3.2) it is challenging if not impossible to operate terrestrial and non-terrestrial networks in co-exist mode over the same frequency within the FR1 range in the same geographical area. It requires regulation and coordination, probably by regional or state-level regulators to decide whether a specific spectrum band shall be used and for which purpose. Cross-border coordination is mandatory since NTNs using satellites cover areas that span different countries. For FR2 there is a possibility for coexistence with certain limitations, as the propagation of FR2 is affected by a higher path loss and, due to beamforming techniques, it can be regionally distributed and confined. But this is to be studied further in 3GPP. Even if it is technically possible, co-channel or coexistence with adjacent services should be managed and regulated by regional regulators.

The cell selection and reselection rules valid for the UE stay unchanged with respect to the current 5G system, but to enable possible deployments of terrestrial and NTN cells in the same frequency band or to enable different constellations (e.g. GEO and LEO) in the same band, the introduction of a new system information parameter, "network type indication", is considered by 3GPP. Besides the existing terms like PLMN and cell ID or frequency list, such a parameter may help the UE during the cell (re-)selection procedure.

Multi connectivity is in principle a kind of NSA operation between NTN and terrestrial, such as running one connection with NTN and another leg connection with terrestrial. It is currently not precluded in standards, but it can be potentially challenging. Running Xn connections between an NTN gNB and a terrestrial gNB is itself very challenging due to the many constraints like UP flow control and other factors.

Even if 3GPP has decided not to include NTN dual connectivity in the first Release 17 rollout, future upgrades are anticipated [Ref. 12], and this chapter will delve a little bit further into some details of such a multi connectivity operation. Only for completion, in our understanding of multi connectivity we do not include a device that occupies two UEs and supports dual registrations. Such a multi UE device is considered as a single UE in the UE case, but network access is not precluded for such device types.

As far as the application scenarios are concerned, we distinguish between NR-NTN and IoT-NTN as this may have an impact on the implementation of multi connectivity. For NR-NTN, the simultaneous use of the two RATs is the primary focus with respect to multi connectivity, while in the IoT-NTN case, it is assumed that the UE supports both RATs, but not in simultaneous operation for complexity and power saving reasons. For the sake of brevity, we will not discuss the IoT-NTN multi connectivity further in this white paper as this is not likely to be implemented. With NR-NTN multi connectivity, two scenarios are likely:

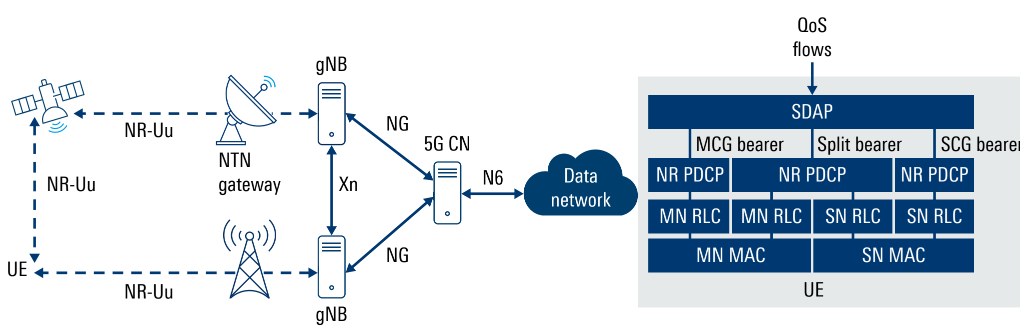
- Multi connectivity between one NR-NTN access link and one terrestrial-based NR access link
- Multi connectivity between two NR-NTN access links

The NR-NTN in such a multi connectivity scenario does not distinguish between transparent and regenerative payload. Both architecture models are possible, but remember that transparent mode has priority.

Motivation for the simultaneous operation of such multi connectivity setups are the higher data rates that can be obtained, especially when considering cell edge situations with underserved terrestrial access and the provision of data rates in a homogenous procedure along the connection time, e.g. imagine a train traveling across a terrestrial RAT well and underserved regions.

With respect to the 5G bearer concept of MCG, SCG or split bearer in such a dual connectivity situation, there is no major change at all [Ref. 1]. The only difference is that the QoS parameters accompanying the bearer traveling over the NTN link need to be adapted accordingly to tackle the challenges like long delay, buffer management and frequency drift to name just a few.

Figure 30: Multi connectivity between NR-NTN and terrestrial 5G NR and bearer model



In this context, multi connectivity is defined as the capability for the 5GC to establish, for a given UE, simultaneous multiple sessions, each of these sessions taking the benefits of the characteristics (such as coverage, broadcast capability) of different access networks (terrestrial and satellite), in the forward and/or return direction. [TR 23.737] extends the view shown in Figure 30 by differentiating between GEO and NGSO access in addition to a potential terrestrial access. Thus, multi connectivity deals with certain combinations across these three RANs: terrestrial, GEO and NGSO.

There are several deployment options for NTN, starting with the simple question as to who will operate such an NTN constellation. It can be traditional mobile network operators (MNO) with terrestrial PLMN that expand their operation by adding an NTN component and offering services as shared network operation, or there can be new players especially focusing on NTN, referred to as satellite network operators (SNO). In the latter case, NTN can operate in a kind of roaming scenario. The mobility and interworking procedures between terrestrial and NTN with respect to the operator deployments are defined by the existing policies for PLMN selection, e.g. the configuration of a preferred visited PLMN (VPLMN) within the UE as we know it today from roaming scenarios. For example, a shared NTN can apply the configuration details of the equivalent home PLMN settings that are already possible in terrestrial networks [TS 23.122]. As already mentioned, the assumption with respect to the UE capability is that the UE possesses GNSS capabilities. The knowledge of the UE position may also be used to confine the PLMN selection process. For example, we assume both sides, UE and AMF, are aware of the UEs location to be country A and from this a list of possible PLMNs is logically available and the AMF may influence the proper PLMN selection by NAS registration permission or reject signaling. The study [TR 23.737] proposes a kind of country or region-specific PLMN selection to tackle the increase in complexity resulting from such cross-country border coverage. Issues resulting and related to emergency call, lawful interception, charging and billing, and public warning notification can be controlled and managed by such region based PLMN selection agreements; see [TR 23.737] for details. This is valid for either direct satellite network coverage or for situations where NTN is only used for terrestrial RAN backhaul. Further aspects of such inter-network coordination, service level agreements, emergency call handling, lawful interception and roaming scenarios are provided in [TR 23.737], [TS 23.501] and [Ref. 12]. For the sake of brevity, we will not delve further into these deployment scenarios.

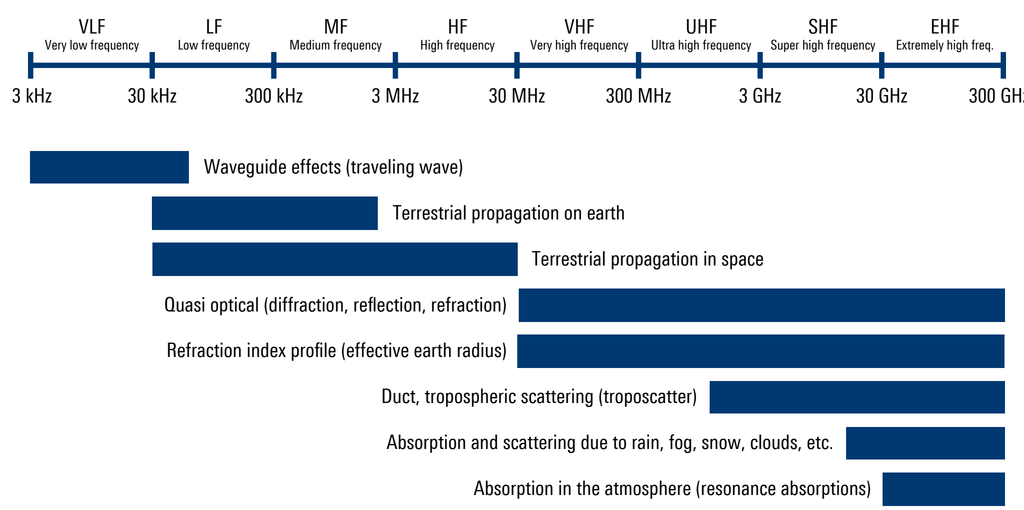
4 NTN RF ASPECTS AND CHALLENGES

The 5G system was originally designed for terrestrial networks as the legacy public land mobile network (PLMN) expression and the enhancements starting with Release 17 will adapt 5G NR to also allow non-terrestrial network communications. Obviously, NTN uses wireless radio communications in different frequency ranges. This chapter deals with the RF propagation aspects and the resulting challenges, with the focus on NTN propagation aspects in contrast to the well-known channel models or fading profiles in terrestrial propagation conditions. Firstly, we introduce some aspects of channel models and propagation details when contemplating NTN, based on a 3GPP study that was conducted during Release 15 [TR 38.811]. Due to the nature of NTN itself we face additional challenges that are presented in this chapter in greater detail. The large distance between the terrestrial UE and the satellite has an impact on the link budget or high path attenuation. In addition, this huge distance is responsible for the large time delay or RTT, which also varies depending on time and the elevation angle. A paradigm change compared to terrestrial networks, where we use the term "base station" to indicate its stationary nature, a LEO satellite travels at a certain velocity which causes a frequency carrier deviation, aka Doppler shift. And lastly, the ionospheric radio wave propagation is responsible for a rotation of the polarization of the waveform, known in academic circles as Faraday rotation.

4.1 NTN channel model aspects

We would like to start this subchapter on channel model aspects for NTN with a quick reminder of the radio wave propagation aspects, especially as they are represented by the ITU in a general propagation characteristic versus carrier frequency approach. This view considers cable-borne or waveguide-borne waves, terrestrial propagation on earth like the well-known multipath propagation (MPP) as well as atmospheric aspects.

Figure 31: Dominant propagation characteristics versus frequencies



The degradation types of the radio channel include the already known impacts described as interferences contributed by inter cell, intra cell, adjacent or common channels as well as unwanted out-of-band emissions. For the sake of brevity, we will not delve further into those interference aspects. From a high-level perspective, the fading divides into the large scale fading and small scale fading. Large scale fading, known as log-normal fading or shadowing, mainly depends on the distance between TX and RX resulting in an attenuation (FSPL) and the propagation of the radio wave between both. Small scale fading is influenced by the multipath propagation situation and Doppler shift of the carrier frequency. It depends on signal bandwidth, relative velocity and scattering and reflection environments. Considering NTN links, we distinguish between obstructed or unobstructed propagation. The unobstructed link considers a line-of-sight (LOS) dominance in the scattering profile that does not exhibit a rich scattering environment. As far as frequency is concerned, the unobstructed link is preferably given at carrier frequencies beyond 10 GHz as we assume a VSAT type UE with directive antenna arrays. The obstructed link considers non-LOS outdoor situations and influences impinge from scatterers in the vicinity of the UE. Note that the main designation for NTN is outdoor connectivity. The description of the propagation profile uses long-term channel effects and dynamic channel effects. To simplify the channel propagation mitigation and modeling, the idea of a correlation area is introduced. Such a correlation area is an "area" with assumed similar fading characteristics and the simplification that all UEs within such a correlation area experience similar propagation to the NTN gNB.

Unobstructed link propagation details

Long-term channel effects (first-order statistics):

- Attenuation due to precipitation (rain, snow, hail, …)
- Gaseous absorption (oxygen, vapor, …)
- Cloud attenuation (liquid water models from ITU)
- Tropospheric scintillations (fast fading, varying refractive index)
- Signal depolarization (Faraday rotation)
- Increase in sky noise (previous effects may cause an increase in noise)
- Total attenuation (e.g. free space path loss)

Dynamic channel effects:

- AWGN dynamics due to rain fading
- Statistic models for second-order statistics like fade slope, fade duration

The obstructed link does not necessarily consider LOS with a high dominance or even non-LOS in the scattering profile. As far as frequency is concerned, the obstructed link is preferably given at carrier frequencies below 6 GHz.

Obstructed link propagation details

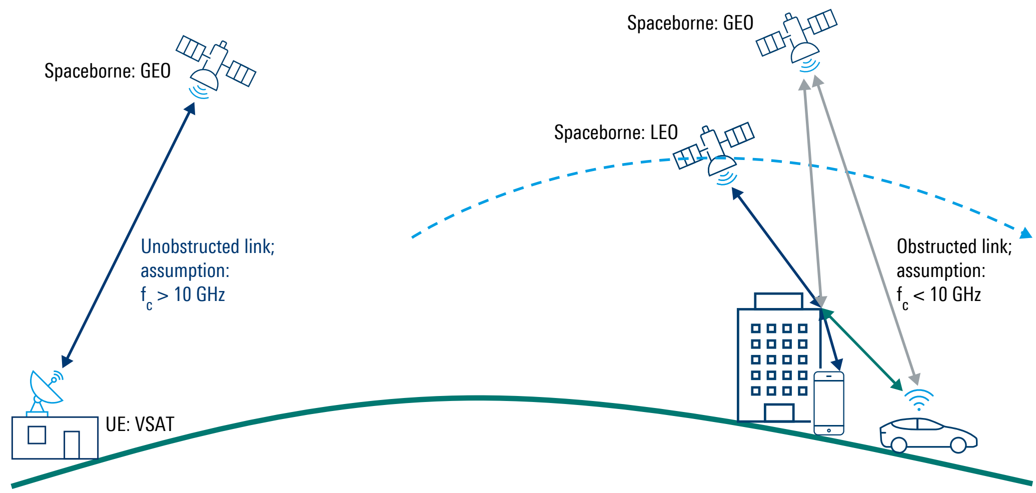
Long-term channel effects with two main signal components (first-order statistics):

- Direct signal, most likely LOS signal
- Diffuse multipath or NLOS, scatterers in UE vicinity

Dynamic channel effects:

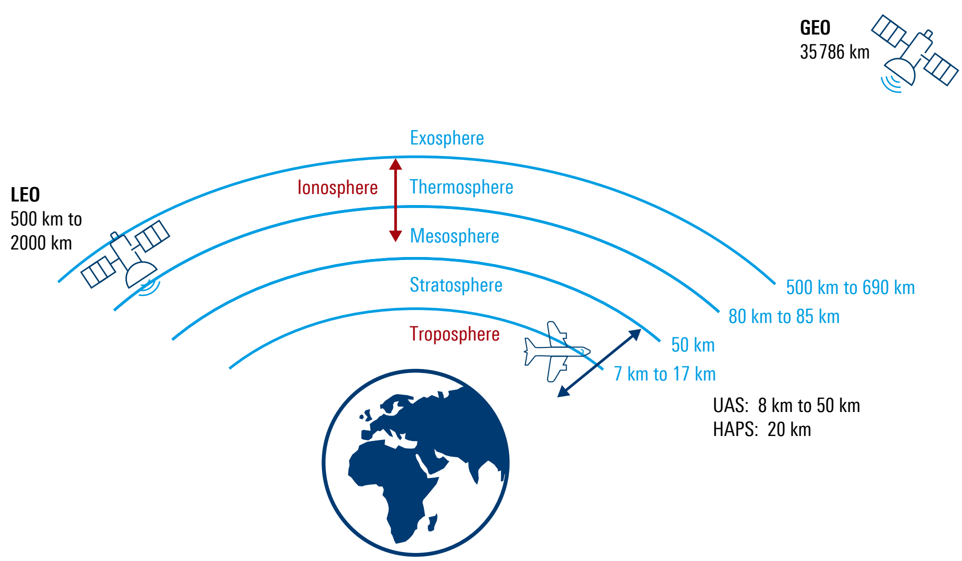
- Time dispersion of signal, narrowband – wideband
- Rate of signal variations: very slow, slow and fast (urban, suburban, rural, mountain, maritime, etc.)
- Movement of LEO: combinations of statistical distributions, no constant statistical channel model
- Doppler shift

Figure 32: Obstructed and unobstructed NTN link scenarios



GEO or LEO radio propagation is additionally affected by atmospheric effects. Therefore, a fading model needs to consider the atmospheric aspects as well.

Figure 33: High-level overview of fading emulation, atmospheric influence



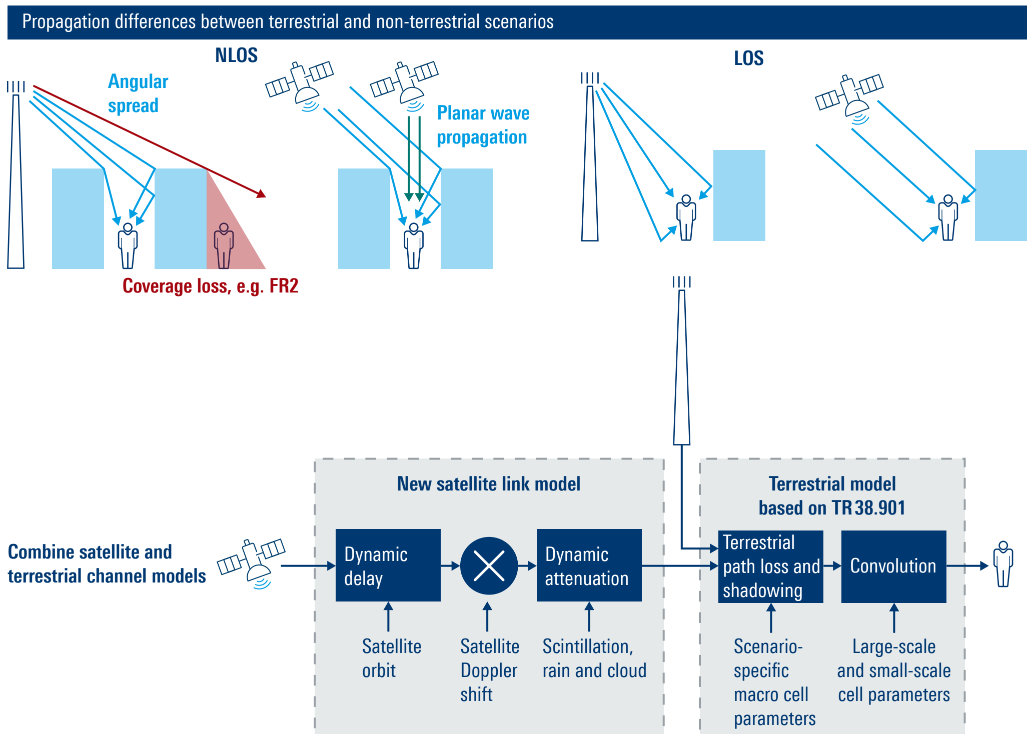
In its study item [TR 38.811], 3GPP considers channel models based on those two ITU recommendations:

- ITU-R P.681 that defines the Land Mobile Satellite channel with measurements up to 20 GHz
- ITU-R P.618 that describes atmospheric effects such as gas attenuation, scintillation, rain and cloud attenuation.

Differences between terrestrial and NTN channel modeling

There are some marginal differences between the terrestrial channel modeling and NTN, e.g. NTN assumes primarily LOS scenarios with MPP resulting from nearby objects. Also, situations of NLOS are possible. And the angular spread seen by the satellite is almost zero, whereas in terrestrial scenarios, it covers a certain angular range, as can be seen in the left part of Figure 34. Thus, the major difference is that the satellite signal propagation is primarily homogenous except for the nearby scattering. The idea is to combine terrestrial fading models [TR 38.901] with satellite channels in a hybrid conceptual architecture, as shown in the lower part of Figure 34.

Figure 34: Fading differences for terrestrial and NTN, combination of both models



The 3GPP study item [TR 38.811] is motivated by the main objective to develop NTN channel models based on the existing legacy terrestrial channel models. The study investigates channel models focusing on NTN deployment scenarios including urban, suburban and rural.

In a typical terrestrial propagation scenario, we know multipath propagation (MPP) as the typical phenomenon and channel models exist for scenarios, e.g. urban, dense urban, rural or hilly terrain. Even mobility scenarios, e.g. high-speed train, are covered with specific channel models. With satellite, the channel propagation is dominated by the large distance between TX and RX causing a high attenuation. But also, as shown in Figure 34, the large distance causes a kind of planar wave propagation, different paths to be almost parallel, and the angular spread is thus close to zero. The large-scale parameters (line-of-sight probability, angular spread, delay spread, etc.) are therefore different from the terrestrial case and depend on the elevation angle of the serving satellite [Ref. 10].

As far as the path loss is concerned, this is mainly influenced by the free-space path loss (FSPL) component, but additionally, there is an influence by the nearby surroundings like buildings, hills, tree foliage, etc., as they may result in components responsible for clutter loss and shadow fading. Compared to terrestrial propagation aspects, with NTN we face another influencing parameter with respect to the attenuation. The path loss can be mathematically described as a function of the elevation angle. Chapter 4.2 and [Ref. 10] provide further details. This elevation angle will also play a major role in future channel models assuming HAPS or UAVs as airborne gNBs instead of higher altitude satellites, as the elevation angle will be much different in such situations. The elevation angle of the LOS path of the satellite/HAPS versus the ground horizon from the UE perspective will be the most relevant parameter in such channel models.

The channel models also include parameters to account for absorption by atmospheric gases, as well as ionospheric and tropospheric scintillation losses. These losses may be of interest only for low elevation angles and/or in certain other conditions (e.g. at low latitudes, during periods with high solar activity, etc.). These models discuss scintillation losses as dynamic, elevation and whether they are dependent on parameters with the consequence that the overall path loss will suffer from a kind of jitter.

The study presented in [TR 38.811] developed two fast fading models. A more generic and frequency-selective model is based on the terrestrial model but adjusted to the satellite geometry with different values and correlations for delay and arrival angles. Similar to clutter loss and shadow fading, values are tabulated for different elevation angles and for the frequency ranges FR1 and FR2. Alternatively, a simpler two-state model assuming flat fading can be used to study certain situations (e.g. low frequencies, large elevation angles, and near-line-of-sight) [Ref. 10]. For such flat fading conditions, a channel model for link-level simulation is considered as unnecessary [TR 38.811].

To enable an emulation of propagation and fading effects, 3GPP additionally developed clustered delay lines (CDL) and tapped delay lines (TDL) (described below) for NTN link-level simulations.

With respect to coverage aspects, there is another topic resulting from LEO or GEO satellite constellations and distinguishing between vertical and horizontal coverage. Our assumption is that the wave emitted by a terrestrial based antenna travels parallel to the ground and radio propagation is affected by buildings, foliage and the shadowing effects of the non-flat surface leading to the known coverage holes experienced in current RATs. A GEO satellite is modeled as a kind of perpendicular position that generates a vertical coverage with respect to the earth surface, potentially leveraging urban area coverage as the horizontal and vertical coverage are fairly correlated.

4.1.1 Large-scale fading aspects

The study in [TR 38.811] defines some details of the channel emulation aspects and a dependency of those large-scale parameters on the elevation angle is considered. The aspects covered include:

- LOS probability describing a percentage of a line-of-sight condition between the UE and spaceborne station, depending on the elevation angle and the situations dense urban, urban and rural. [TR 38.811] provides a table with detailed percentage values.

- Path loss and shadow fading describes the path loss on the link between the UE and SAT, influenced by the four factors: free space path loss (FSPL), attenuation due to atmospheric gases, attenuation due to ionospheric and tropospheric scintillation and optionally a building entry loss; chapter 4.2 provides further details.

- Angular spread from TX, as shown in Figure 34; the angular spread in NTN is assumed to be approximately zero and exhibits a planar wave behavior. Possible reflections result from nearby scatterers and reflectors.

- Delay spread as a large-scale parameter typically describes the power delay profile due to multipath propagation. Characteristic in NTN is that the absolute delay between TX and RX will dominate and that the ratio of the delay spread due to MPP versus the absolute delay is considered to be low.

- Outdoor-to-indoor (O2I) penetration loss considers an additional attenuation depending on the building type, but less relevant as NTN is primarily designated for outdoor. As the aspects of outdoor-to-indoor penetration loss are independent of NTN and also occur in traditional terrestrial networks, most of those aspects are already discussed and described in the literature, e.g. the ITU recommendation [ITU-R P.2109] contains a building entry/exit-loss model.

- Attenuation by atmospheric gases which is entirely caused by absorption depends mainly on frequency, elevation angle, altitude above sea level and water vapor density (absolute humidity). The ITU recommendation [ITU-R P.676] describes such atmospheric attenuation aspects for calculating gaseous attenuations. At frequencies below 10 GHz, it may normally be disregarded.

- Rain and cloud attenuation, based on the ITU recommendation [ITU-R P.618-13], but disregarded for f < 6 GHz.

- Ionospheric scintillation, corresponds to rapid fluctuations of the received signal amplitude and phase. Ionospheric propagation shall only be considered for frequencies below 6 GHz. Details of scintillation affects include the ionospheric location, the frequency and the time of day. [TR 38.811] describes certain models.

- Tropospheric scintillation corresponds to rapid fluctuations of the received signal amplitude and phase, only considered for higher frequencies. Tropospheric scintillation is a phenomenon that causes rapid amplitude and phase fluctuations of signals from satellite communication systems. Unlike, ionospheric scintillation, the effect of tropospheric scintillation increases with the carrier frequency of the signal, being especially significant above 10 GHz. In this case, the signal fluctuations are caused by sudden changes in the refractive index due to the variation of temperature, water vapor content, and barometric pressure. Besides the increase with the carrier frequency, the effects of scintillation also increase with low elevation angles, due to the longer path of the signal, and receiving antennas for wider beam width.

The document [TR 38.811] describes some frequency-selective fading models as a minor difference between satellite or terrestrial fading profiles. The main difference is the impact of the elevation angle on satellite connections and the local scattering.

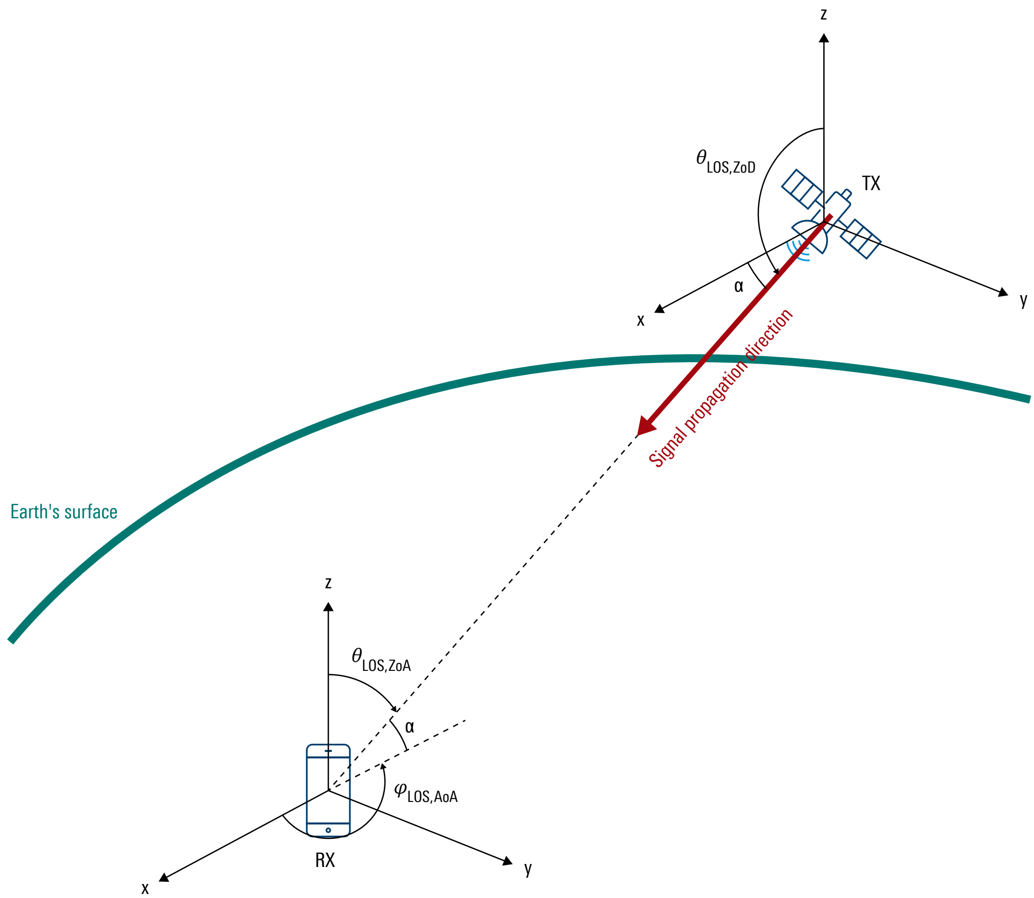
4.1.2 Small-scale channel models for link level simulations

Small-scale channel models, also referred to as fast fading, describe the dynamic channel behavior. The two documents [TR 38.901] and [TR 38.811] describe the two channel models discussed for link-level simulations: tapped delay line (TDL) and clustered delay line (CDL).

Clustered delay line (CDL)

The CDL channel model is valid for frequencies in the S and Ka-bands and describes a three-dimensional model, describing propagation in elevation and azimuth. Different to the TDL model, the CDL describes the channel in time (e.g. delay spread), frequency (e.g. Doppler shift, frequency selective fading) and also spatial information (e.g. AoA aspects). A clustered delay line (CDL) is a type of channel model where the received signal is composed of a number of separate delayed clusters. Each cluster contains a number of multipath components with the same delay but different AoD and AoA. There are models for LOS and also NLOS and all models incorporate the elevation angle between the UE and satellite, but also the azimuth angle and the azimuth and elevation angular spreads. Characteristics of the NTN channel models are the omission of certain angles, i.e. the azimuth and zenith angles spread of departure (AsD and ZsD) are ignored due to the large distance.

Figure 35: Elevation angle between UE and NTN gNB



The CDL channel models for LOS and NLOS are given as tables depending on the elevation angle α, and the various lines in the table describe the channel coefficient parameters with additional parameters per cluster. As a major characteristic, the CDL models contain spatial attributes, e.g. AoD, AoA, ZoD and ZoA. A generic structure of such a table is given as below; see [TR 38.811] for the exact values.

Table 9: CDL parameters

Cluster no.	Delay	Power (attenuation)	AoD	AoA	ZoD	ZoA
1	…	…	…	…	…	…

Additional parameters per cluster

AsD	AsA	ZsD	ZsA	XPR
…	…	…	…	…

The additional parameters per cluster contain the indication of angles spread of arrival and departure in azimuth and zenith (AsD, AsA, ZsD, ZsA) in degrees as well as a cross-polarization mismatch (XPR) in dB.

The document [TR 38.901] defines CDL models for the frequency range from 0.5 GHz up to 100 GHz with a maximum bandwidth of 2 GHz for both the LOS and NLOS condition. Several terrestrial models exist, differing in various delays and delay spread as well as angular spread scenarios. For NTN situations, [TR 38.811] introduces two additional models for each LOS and NLOS situation, differing in the shorter or longer delay spread assumption scenario and the power angular spectrum configuration for LOS situations.

Tapped delay line (TDL)

Essentially, a tapped delay line is a hardware entity generating a delay line with at least one "tap", i.e. where the signal can be captured before the output of the line, somewhere along the delay line. Optionally this tap can be scaled and interpolated with other taps. A common example is the emulation of a multipath propagation scenario where each tap then corresponds to one multipath component of the scattering situation or power delay profile [Ref. 1]. The terrestrial TDL models are defined for the frequency range from 0.5 GHz to 100 GHz and a maximum bandwidth of 2 GHz.

The TDL channel models for LOS and NLOS are given as tables depending on the elevation angle α and the various lines in the table describe the channel coefficient parameters of the individual taps simulating a multipath component. A generic structure of such a table is given as below; see [TR 38.811] for the exact values.

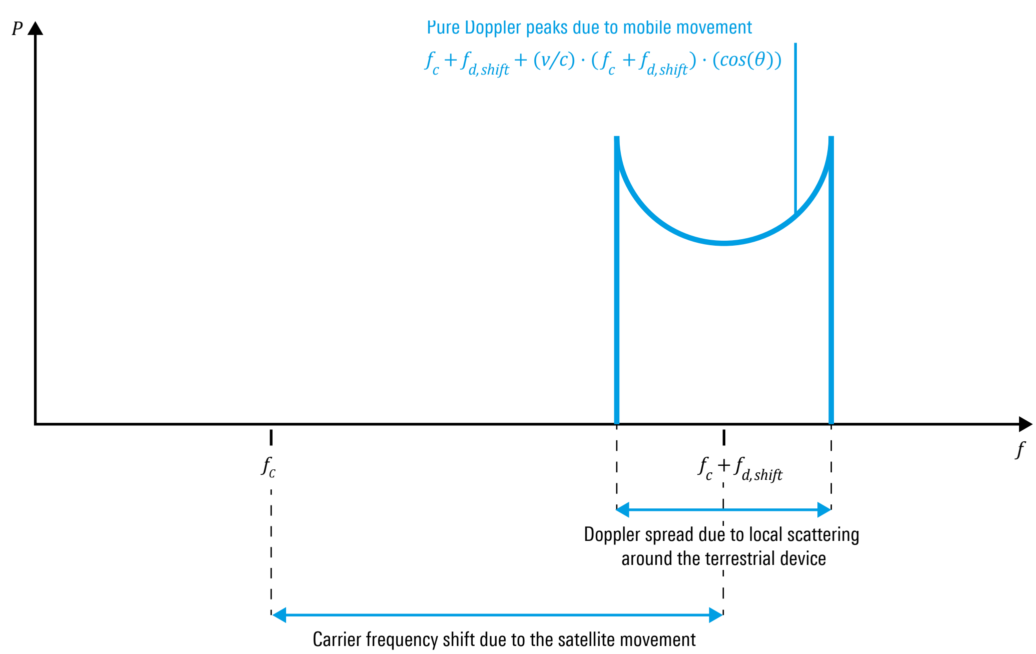
Table 10: TDL parameters

Tap no.	Delay	Power (attenuation)	Fading distribution
1	…	…	…

The difference between the LOS and NLOS models is the fading distribution, which is either Rayleigh based or Rician based in case of a dominant LOS component.

The TDL models for NTN are filtered from CDL models assuming isotropic UE antennas and can be scaled to achieve the desired delay and the delay spread. Unlike terrestrial models, an additional Doppler shift due to satellite motion is introduced. The parameters influencing the Doppler shift are the satellite velocity, elevation angle, carrier frequency, local scattering around the UE and the UE motion speed (see Figure 36), which is considered relative to the satellite. The TDL models used in the simulations correspond to just a few TTI duration, thus the satellite speed, satellite elevation angle and UE speed should be considered to be constant. Note that this is not the case for longer connection times (see chapter 4.4).

Figure 36: Doppler power spectrum in NTN LOS conditions



4.2 Path attenuation and link budget

Obviously, the long distance between the UE and the satellite will evoke and cause a high path attenuation. In 3GPP, several link budget discussions were conducted and studies are undertaken with certain example parameters and simulation results, e.g. [TR 36.763] or [TR 38.811]. With the technology evolution of antennas, the objective is to tackle the path loss with highly directive antennas providing a high antenna gain [Ref. 21]. The overall path loss or link budget is influenced by the path loss of the propagation channel, the antenna gain and power level of RX and TX as well as the noise figure of both entities and, last but not least, additional losses.

Path loss

Certain parameters influence the link budget, primarily the well-known **free space path loss (FSPL)** equation [Ref. 2].

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

In this equation, the receiver power P_{RX} depends on the transmit power P_{TX}, transmit antenna gain G_{TX}, receive antenna gain G_{RX}, the wavelength λ, the distance between TX and RX antenna d and the exponent γ representing the loss of the medium between both antennas. For simplification, we use the value $\gamma = 2$ corresponding to only air as the medium [Ref. 3].

In the study phase, 3GPP assumes the composed path loss based on the components: Basic path loss PL_0 corresponding to plain air FSPL, attenuation due to atmospheric gases PL_g, attenuation due to atmospheric scintillation PL_s and a building entry path loss PL_e.

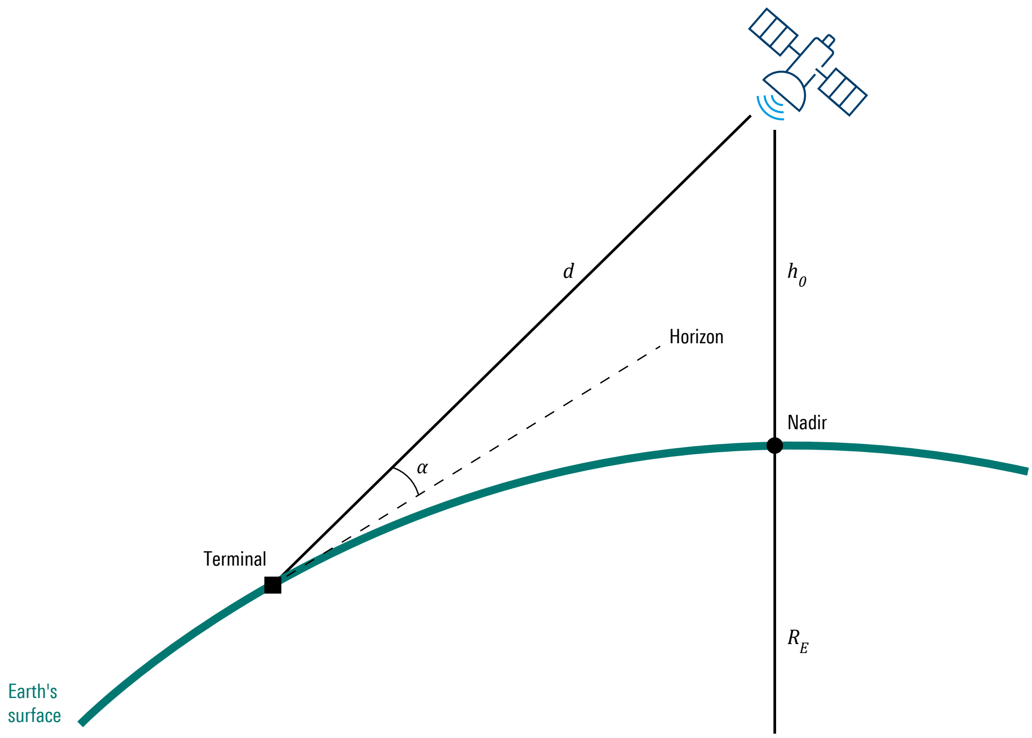
$$PL = PL_0 + PL_g + PL_s + PL_e$$

To allow fast and simple computation, the FSPL is defined in [TR 38.811] as a function of the distance d between the UE and the satellite and the carrier frequency f_c:

$$FSPL_{d,f_c} = 32.45 + 20\, log_{10} f_c + 20\, log_{10}\, d$$

The distance d between the UE and the satellite is calculated based on the elevation angle α and the satellite altitude h_0.

Figure 37: Distance d between UE and satellite as a function of the elevation angle and the orbit altitude



$$d = \sqrt{R_E^2 \sin^2 \alpha + h_0^2 + 2h_0 R_E} - R_E \sin \alpha$$

α : elevation angle (angle at which the UE sees the satellite, e.g. minimum elevation, approx. 10°)

R_E : earth's radius = 6371 km

h_0 : satellite altitude

In this calculation, the earth is considered as a perfect sphere with a constant radius R_E of 6371 km.

The link simulations consider in addition to the FSPL a clutter loss (CL) caused by surrounding buildings and objects on the ground and a shadow fading (SF) which is a zero-mean normal distribution with a standard deviation [TR 38.811].

Antenna gain-to-noise-temperature ratio (G/T)

In satellite communications, the figure of merit (FoM) **antenna gain-to-noise-temperature ratio G/T** characterizes the receive or transmit chain performance. In this term G/T, the parameter G represents the antenna gain in dB (see [Ref. 2] for details) at the receive frequency and the parameter T corresponds to the equivalent noise temperature of the RF chain in Kelvin. Unlike the gain, which only evaluates the antenna, this FoM represents the performance of the entire chain. An RF chain consists of the antenna itself (= antenna gain) together with the subsequent RF chain (e.g. an amplifier, such as LNA, and processing chain entities like bandpass filter, cables, etc. with a certain NF). The G/T is a kind of abstract model, where the antenna noise temperature T implies that the noise power output of the antenna is equal to the thermal noise power generated in a resistor at a temperature of T_A. Note that the antenna temperature is the summation of the antenna temperatures of the receive chain entities, e.g. antenna, RF chain, and it does not correspond to the physical antenna temperature, but rather an interpretation of the noise power detectable at the antenna flange. According to physics, every object with a physical temperature above zero Kelvin radiates energy or so-called noise. In other words, every antenna produces noise in a given environment. The amount of energy radiated is usually represented by an equivalent temperature T_B, also known as the brightness temperature. This brightness temperature is a function of the carrier frequency, polarization of the emitted energy, emissivity and the molecular structure/temperature of the object [Ref. 3]. In summary, the antenna temperature is a parameter that describes how much noise an antenna produces, depending on the given environment like the antenna gain pattern and the thermal condition. That is why the antenna temperature is sometimes also referred to as antenna noise temperature. In the case of the reception situation of an antenna, the antenna picks up radiation or noise radiated by various sources: man-made e.g. other transmitters or radiation emanating from natural sources e.g. solar radiation, sky noise, galactic noise and atmospheric noise caused by lightning flashes and absorption by oxygen and water vapor molecules followed by the re-emission of radiation. Special attention should be paid with respect to a satellite receive antenna that targets the UL signal transmitted by the UE. In this situation, the earth already provides a certain noise floor. Noise from these sources could enter the receiver through all three dimensions, diminished more or less by the spatial directional gain $G(\theta, \varphi)$ in that particular direction. Thus, in antenna theory, we can describe the antenna temperature T_A in Kelvin as a function of all brightness temperature emissions integrated in a spherical manner and consider the spatial gain component of the antenna in this direction, using the azimuth angle θ and the elevation angle φ to describe the sphere [Ref. 3]:

$$T_A = \frac{\int_0^{2\pi} \int_0^{\pi} T_B(\theta, \varphi) G(\theta, \varphi) \sin\theta \, d\theta d\varphi}{\int_0^{2\pi} \int_0^{\pi} G(\theta, \varphi) \sin\theta \, d\theta d\varphi}$$

Assuming there are no losses between the antenna itself and the receiver, one can express the transferred noise power P_r in watts as:

$$P_r = k \, T_A \, \Delta \mathrm{B}$$

In this equation, k corresponds to the Boltzmann constant ($1.38 \cdot 10^{-23}$ J/K), T_A is the antenna temperature and ΔB represents the analysis bandwidth. Note that in real systems, we would also have to include the temperature of the receiver T_R in the overall contemplation, thus our temperature T in the G/T term would be given as $T = T_A + T_R$.

The G/T parameter is the ratio of the gain of the antenna divided by the antenna temperature. In [TR 38.811], 3GPP assumes the following formula for the computation of the G/T value:

$$\frac{G}{T} = G_A - NF - 10 \log\left(T_0 + \frac{T_A - T_0}{10^{0.1 \cdot NF}}\right)$$

In this equation, G_A describes the antenna gain in dBi, NF is the noise figure in dB, T_0 the ambient temperature (290 K) and T_A the antenna temperature (290 K with 0 dBi gain or 150 K with > 30 dBi gain). Only as side note, it should be reminded to the environment temperature changes depending on whether the satellite faces towards the sun or is on the shadow side of the earth. Thus, the G/T calculation may consider several environment temperature conditions.

Noise figure

Remember: The noise figure (NF) is a measure of degradation of the SNR caused by the entities in the RF chain. As an example, we consider the RF chain as being the receiver chain and use the general term T for the antenna temperature. Let us assume an ideal receiver as two ports: input and output. Here, the SNR at the input would be the same as the SNR at the output. Unfortunately, a real receiver generates internal noise artefacts so that the SNR at the receiver output is considered to be lower than the SNR at its input. The NF is the SNR at the input divided by the SNR at the output in decibels and describes an additional amount of noise contributed by the receiver to the noise from the source as a performance metric (see also Figure 15). Another perspective considers the NF as the increase in noise power, referring to the receiver noise due to the receiver chain components, assuming an ambient temperature T_0 = 290 K and the receiver noise temperature of T.

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

For the sake of brevity, we will quote just a few numbers presented in [TR 38.811] which describe the G/T for the S-band frequencies as approx. 14 $dB \cdot K^{-1}$ for GEO constellations and approx. –12 $dB \cdot K^{-1}$ to –18 $dB \cdot K^{-1}$ for LEO constellations.

Link budget

In summary, those parameters influencing the link budget and that should be considered:

- ▶ UE power class, e.g. 20 dBm or 23 dBm
- ▶ UE noise figure, e.g. assumption approx. 9 dB
- ▶ Satellite TX power, e.g. 33 dBm/MHz EIRP for a LEO satellite
- ▶ Satellite antenna gain, e.g. 30 dBi for LEO satellites
- ▶ Channel bandwidth and carrier frequency
- ▶ Other losses; see [TR 36.763]

Table 11: Link budget aspects – other losses

Other losses	GEO (35 786 km)	LEO (1200 km)	LEO (600 km)
Scintillation losses	2.2	2.2	2.2
Atmospheric losses	0.2	0.1	0.1
Polarization loss	3	3	3
Shadow margin	3	3	3

- ▶ Polarization loss of 3 dB assuming linear polarization at the UE and circular polarization at the satellite
- ▶ Position of the UE within the beam, e.g. beam center in the center beam or beam edge in an outermost beam
- ▶ Path attenuation, e.g. approx. 160 dB for LEO and up to approx. 190 dB for GEO

The resulting carrier-to-noise ratio (CNR) of the transmission link between the satellite and UE is described in [TR 38.821] as:

$$CNR = EIRP + G/T - k - FSPL - PL_g - PL_s - PL_e - PL_{AD} - B$$

EIRP is the effective isotropic radiated power, G/T the antenna-to-noise-temperature ratio, k the Boltzmann constant (–228.6 $dBW \cdot K^{-1}/Hz$), FSPL the free space path loss, PL_g the attenuation due to atmospheric gases, PL_s the attenuation due to atmospheric scintillation, PL_e a shadowing margin, PL_{AD} an optional degradation due to feeder link losses in transparent architecture and B the channel bandwidth. An example showing LEO link budget results is given in the following table [TR 38.821].

Table 12: Link budget results

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

Due to the high path attenuation, UE RX power levels at a low range, e.g. < –110 dBm, could be possible. This poses additional challenges for the designers of the RX chain in the UE because in the device architecture it is unlikely that a separate RX chain for such values will co-exist beside the current architecture.

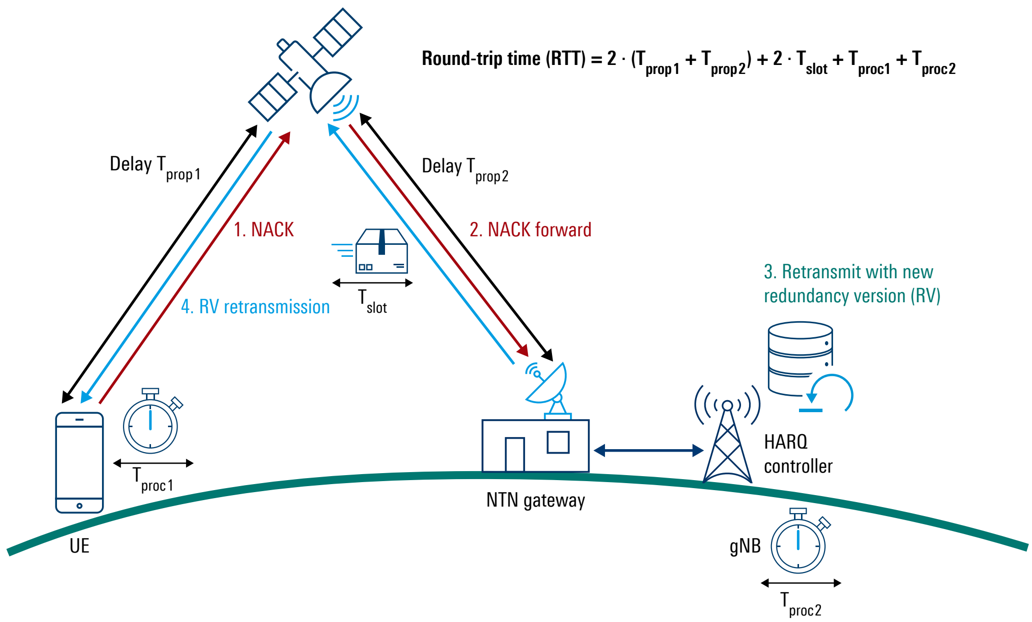
4.3 Round-trip time and differential time delay

One of the most challenging NTN characteristics which inhibits the introduction of low-latency communications in NR-NTN is of course the round-trip time (RTT) or long latency due to the large distance between the terrestrial UE and the satellite. To make matters worse, this RTT depends on the elevation angle and is time-variant. Typical one-way latency values range from 30 ms to 40 ms in LEO and up to 544 ms in GEO constellations. Remember that in transparent mode architecture (see chapter 3.10.2) the overall RTT is two times the "UE to satellite to ground gNB" path. Future architecture models using the regenerative architecture and even incorporating multi-access edge computing (MEC) methods into the satellite will improve the overall latency, but as the speed of light cannot be accelerated, there will always be a hampering factor due to the propagation delay. Higher layer protocols need to cope with these extended RTTs, as explained in later sections. But the motivation for NTN is not the low-latency aspect with the 5G services: NTN tackles the problem of underserved regions and non-existent coverage. By way of a reminder, we would like to reiterate that in free space, electromagnetic waves travel at the speed of light compared to optical fiber which is around 1.47 times slower [Ref. 31], thus long distance connections via satellites may exhibit a speed improvement compared to terrestrial connections.

Round-trip time – definition

The round-trip time, influenced by various parameters, is calculated as shown in Figure 38. The assumption in this contemplation is the reception of a PDU at the UE side with negative CRC check. Thus, the RTT starts with the NACK message transmission and terminates with the reception of the PDU retransmission. Here, the transparent architecture is applied. Besides the propagation delay occurring between UE and satellite and satellite to ground gateway, some system parameters and processing times also need to be considered. In the overall RTT, the time T_{slot} is the system time corresponding to the duration of a PDU or NACK message and corresponds to subframe or slot durations in 5G. The overall processing time $T_{proc1} + T_{proc2}$ includes the UE and network reaction times. The UE reaction time is the time between a CRC failure detection and the transmission of the NACK message. The gNB reaction time is the time between reception of this NACK and transmission of the retransmission PDU with optionally updated redundancy version (RV).

Figure 38: Round-trip time – definition

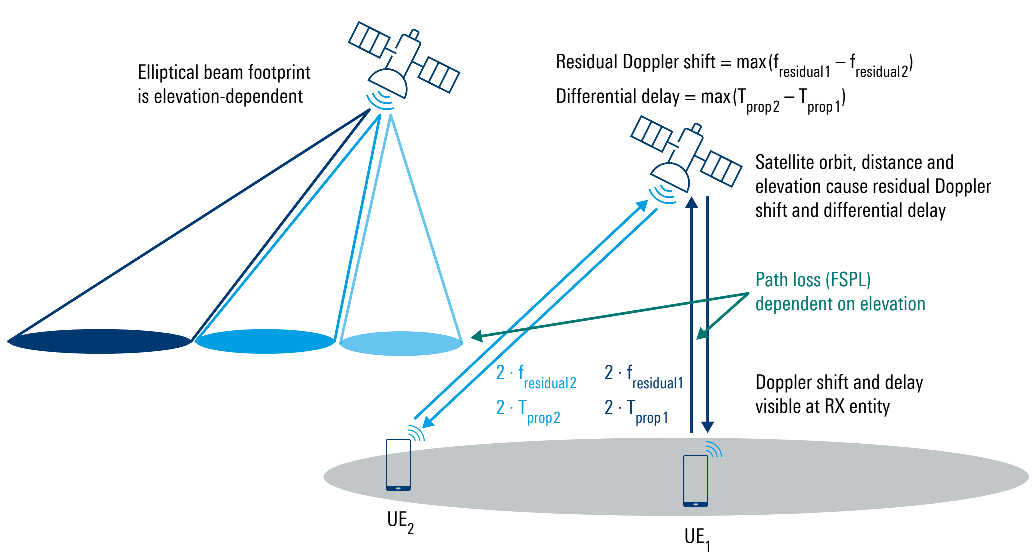


A more detailed analysis of the RTT and latency aspects reveals further challenges:

- Time-variant latency and varying RTT during the entire period of a connection
- Differential delay between the NTN gNB and all UEs in a beam footprint coverage area due to the nature of the elliptical shape and the elevation angle impact

Considering the RTT from the perspective of an NTN gNB, we firstly contemplate the most likely elliptical shape of the beam footprint corresponding to the coverage area or cell size (see Figure 39). This elliptical shape is dependent on the elevation angle or the angle of incursion. As a result, the NTN gNB experiences different propagation times among the UEs. From the satellite perspective, the RTT depends on whether the UE is in the beam center at zero zenith angle or at the nadir position (see UE_1 in Figure 39) or whether the UE is at the beam edge (see UE_2 in Figure 39). The differential RTT or differential delay is defined as the delay difference between the longest delay and the shortest delay.

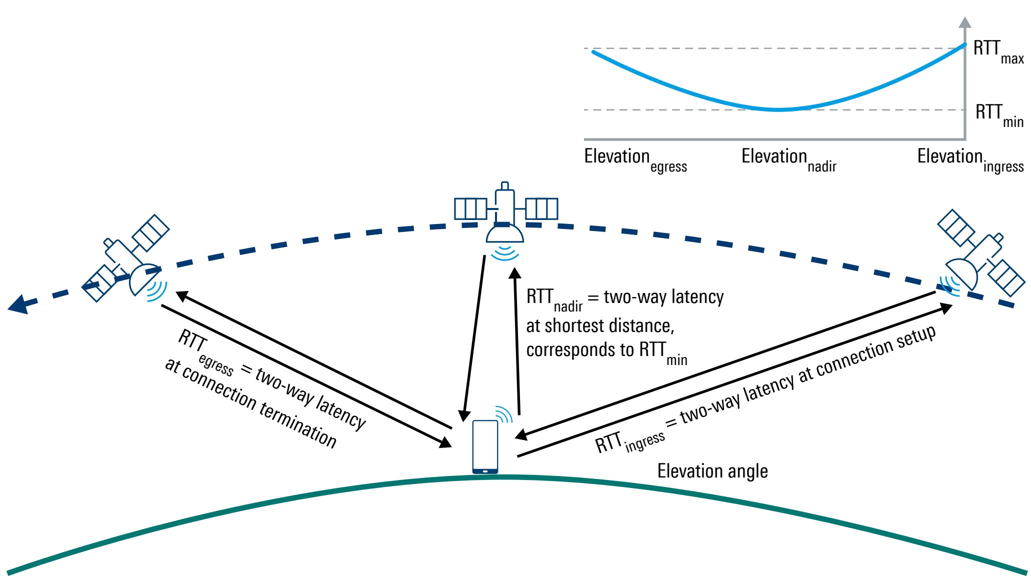
Figure 39: Round-trip time and beam footprint aspects from the perspective of NTN gNB



There is no need to mention that the differential RTT not only depends on the constellation or satellite altitude but also on the beamwidth or beam footprint size. In a GEO satellite simulation, RTT differences of around 16 ms were computed. For a LEO constellation, 3GPP defines a maximum differential delay of approx. 10 ms. The reason for such a limitation that impacts the design is the buffer management implemented at higher layers. Especially at the gNB MAC layer, which needs to align PDUs and forward them to the RLC layer. The MAC layer manages and controls reliability and timing on all active connections with methodologies like HARQ operation. Thus, a thorough buffer management concept should be in operation.

Considering the RTT from the perspective of the UE, we can observe that the RTT is time-variant during the connection period. To avoid misunderstandings, this fact not only relates to the UE perspective, but our assumption is that the gNB compensates the RTT variations with proper timing advance control. The UE experiences a time-variant RTT behavior due to the nature of the orbital trajectory of the satellite. As shown in Figure 40, we assume the maximum RTT occurring at the connection start, which is the case when the LEO satellite appears above the minimum elevation angle at the horizon, described as ingress, and vice versa at the connection termination, described as egress. The shortest RTT should be observed at the nadir position when the LEO satellite is perpendicular to the UE. Overall, we expect parabolic time-variant behavior of the RTT. This has an impact on the buffer management of the MAC layer and on HARQ operation as we encounter orbit constellation variant times between e.g. transmission and re-transmission and between PDUs received during the connection period.

Figure 40: Round-trip time aspects from perspective of UE



4.4 Carrier frequency shift (Doppler frequency shift)

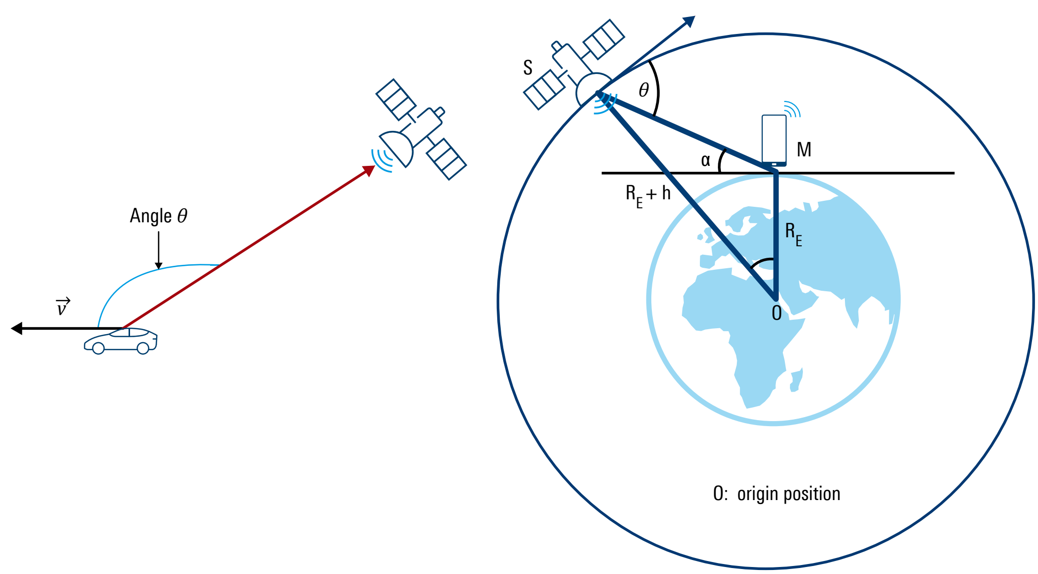
One of the most serious challenges in realizing NTN connections with good end user QoE is the carrier frequency deviation, also known as **Doppler shift**. The paradigm change of a moving base station or satellite in combination with an optional moving UE causes a time-variant Doppler shift across the connection time. This time-variant Doppler shift is also described as the Doppler variation rate or simply **Doppler rate**. Note that here we consider the relative velocity v between the UE and the satellite.

Doppler shift

In a more generic contemplation, one would have to consider the Doppler shift occurring at the satellite as receiver or the Doppler occurring at the UE as receiver. In addition, certain scenarios can be considered [TR 38.811], e.g. GEO or LEO satellite constellations and static UE or UE traveling at higher velocities, e.g. airplanes or so-called generic aerial vehicles (UAV). It is generally assumed that the Doppler shift occurring is calculated based on the velocity v (relative velocity between UE and satellite), the carrier frequency f_c and the angle θ between the velocity vector and the direction of propagation of the signal.

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

Figure 41: Doppler shift, general aspects and definition of angle θ



The Doppler shift Δf is negative when the transmitter is moving away from the receiver and positive when the transmitter is moving towards the receiver.

The delineation in Figure 41 depicts the generic Doppler shift aspects. On the left side, the Doppler is described with respect to the angle θ. In our contemplation, the two velocities of the UE and the satellite are assumed to be relative to the earth, thus they can be cumulated. On the right side of the figure, the system geometry is shown: the satellite S is assumed to travel on a circular orbit with the altitude h, the UE at position M is on the circular orbit described as the surface of the earth with an overall constant earth radius RE and the earth center is at origin position O. For the sake of simplification, we assume the UE to be stationary; if required, any movements of the UE can cumulate with the satellite velocity to result in an updated v_{sat}^*. To allow calculation of the Doppler shift with respect to the elevation angle α, we write the Doppler shift formula in a different way:

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

In the channel models described in [TR 38.811], the elevation angle α is set to 50°. The Doppler shift generally depends on the time evolution of the channel and relates to the cumulated velocity vectors of the UE and satellite and the direction or elevation between TX and RX. In a more generic term, the phase rotation caused by the Doppler shift is calculated with respect to a reference phase at time t_0 as per [TR 38.811].

Figure 42: Phase rotation due to time-variant Doppler shift – general form

Normalized vector pointing in TX or RX direction

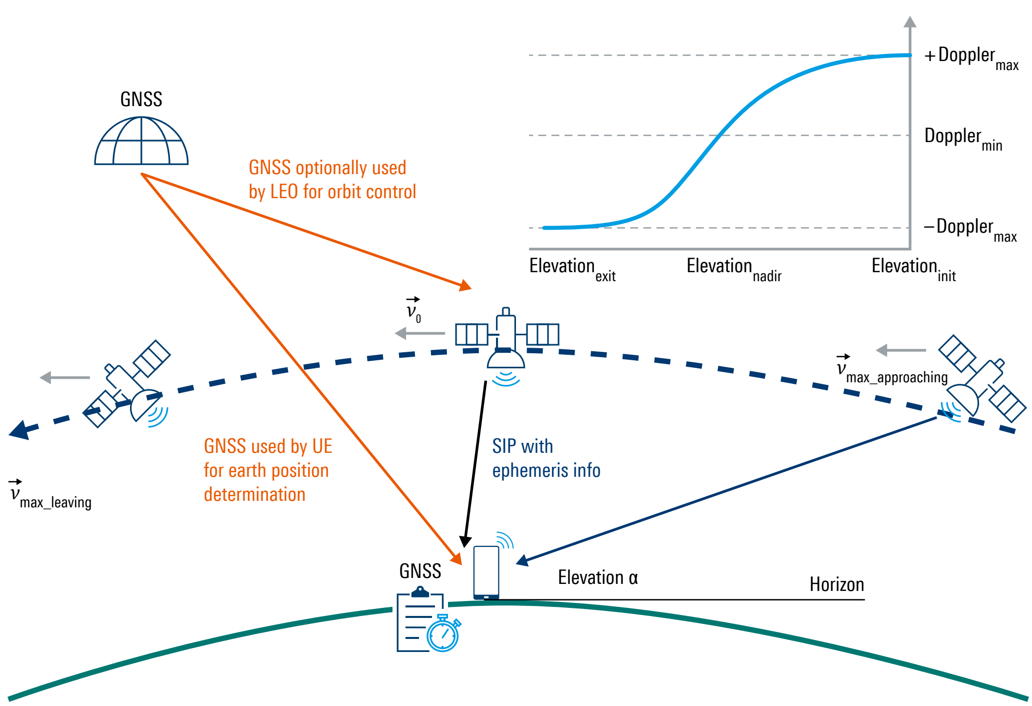
$$\Delta\varphi_{Doppler} = e^{j2\pi \int_{t_0}^{t} \frac{\hat{r}_{RX}^{T}(\tilde{t})\cdot\vec{v}(\tilde{t})}{\lambda_0} d\tilde{t}} \cdot e^{j2\pi \int_{t_0}^{t} \frac{\hat{r}_{TX}^{T}(\tilde{t})\cdot\vec{v}(\tilde{t})}{\lambda_0} d\tilde{t}}$$

Velocity vector of TX and RX

Doppler rate

In NTN, we do not only have to consider the Doppler shift, which represents the carrier frequency deviation occurring at one instance of time, but also the Doppler rate or the Doppler shift variation, because during the connection time, the Doppler shift may vary. In a LEO constellation, the elevation angle α changes over the connection period, and the relative velocity of the satellite changes with respect to the UE. Figure 43 shows such a scenario: the UE detects the LEO satellite when it rises above the minimum elevation angle at the connection ingress and it loses the satellite once it falls below the minimum elevation angle at the egress of the connection. Also, obvious in such a scenario, the relative velocity of the satellite with respect to the UE changes from approaching to leaving, causing a Doppler rate. This applies to both beam footprint scenarios of moving beam or earth-fixed beam (see Figure 14).

Figure 43: Doppler shift rate in a LEO scenario



[TR 38.811] conducted various studies on different Doppler scenarios, e.g. moving train, airplane, static UE, various satellite constellations and frequency carriers. E.g. the Doppler shift simulated at a device emulating a stationary mode with LEO satellite constellation at three different frequencies.

Table 13: Doppler shift parameters expected at three different carrier frequencies

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

As a methodology to compensate the Doppler shift in UL, the UE estimates its location e.g. based on GNSS positioning, and the UE receives system information (SIB) together with satellite ephemeris information. As a result, the UE will then adapt its uplink carrier frequency to adjust the carrier frequency at the satellite receiver in such a way that the Doppler shift impact in uplink direction can be disregarded.

An example algorithm for logic-efficient recursive Doppler rate estimation is provided in [Ref. 33].

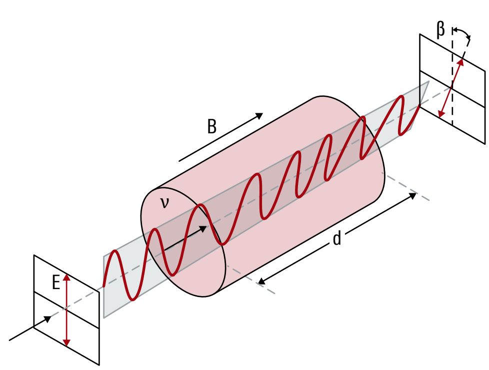
The Doppler shift over the feeder link and any transponder frequency error for both downlink and uplink are assumed to be compensated by the terrestrial gateway and satellite payload without any specification impacts in Release 17.

Not in the scope of 3GPP, but optionally the LEO satellite may use GNSS information as well for orbit management and flight control purposes to support Doppler compensation.

4.5 Faraday rotation in NTN and polarization aspects

Due to the structure of the atmosphere, indicated by the so-called total amount of electrons or total electron count (TEC) an effect is visible that is described by the academic term "Faraday rotation". Faraday rotation is introduced to describe the rotation of the polarization due to the interaction of the electromagnetic wave with the ionized medium in the earth's magnetic field along the path [TR 38.811].

Figure 44: Faraday effect impacting polarization



Faraday rotation above the ionosphere for m^{th} path in the n^{th} cluster

$$F_r = \begin{bmatrix} \cos(\psi_{n,m}) & -\sin(\psi_{n,m}) \\ \sin(\psi_{n,m}) & \cos(\psi_{n,m}) \end{bmatrix}$$

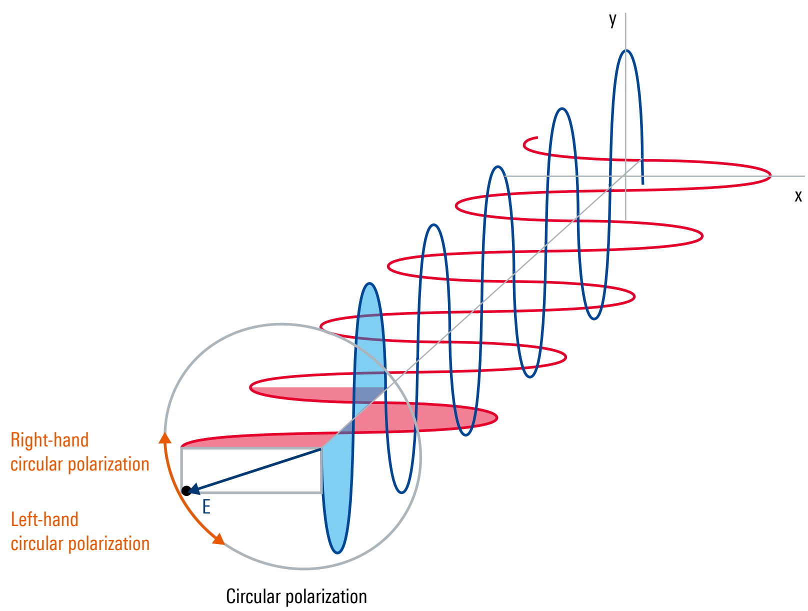
ITU-R P.618-13 suggests: $\psi = \dfrac{108}{f_c^{\,2}}$

In the link-level model, calculation of the channel impulse response parameter should be post-multiplied with F_r for the channel coefficient generation of the m^{th} path in the multipath scenario in the n^{th} cluster when assuming propagation similarities and clustering them. There is an ITU recommendation [ITU-R P.618-13] suggesting a definition of the Faraday rotation ψ depending on the squared carrier frequency f_c.

As a reminder, the term "polarization" describes the orientation of the E-plane of an electromagnetic wave relative to the earth's surface [Ref. 3].

Terrestrial communications often use linear polarization like horizontal and/or vertical polarization. In a simplified model, the geometry of the antennas is quasi-static, i.e. UE and base station antennas are fixed with respect to each other [Ref. 2]. In an NTN situation where a satellite moves at high speed with respect to the fixed earth-bound station (we disregard the UE velocity here as it is inferior to the satellite velocity), linear polarization may lose its alignment. As a countermeasure, circular polarization is often found in space-based applications. The magnitude of the E-field vector is constant, but the direction changes and rotates around the direction of propagation, either in a clockwise or counter-clockwise direction, giving rise to the names **left-hand circular polarization (LHCP)** or **right-hand circular polarization (RHCP)** [Ref. 2].

Figure 45: Circular polarization



One major challenge in designing a TX and RX setup is the possible polarization mismatch. Identical circular polarization between the TX and RX side has no impact as it perfectly matches, but assuming one side uses linear polarization, we face a 3 dB polarization mismatch loss, and if the circular polarization is applied controversarily, the polarization mismatch is close to infinity as LHCP and RHCP are quasi-orthogonal to each other. Proposed is the UE architecture with two RX branches to achieve a combining gain (see chapter 3.3).

Note that NTN is optionally considered to operate in dual-connectivity mode with terrestrial 5G NR, or at least the UEs supporting 5G NTN do need to support terrestrial 5G NR. Even if not simultaneously but at least with respect to their design, they need to support both RATs. The question now is how manufacturers will implement the new circular polarization scheme. One option is to incorporate a new RF frontend design for circular polarization and switch between them or debase the legacy linear polarization and accept a possible polarization loss afterwards.

To support inter-cell interference mitigation or improved frequency re-use mechanisms and avoid such polarization loss, the network will signal the polarization scheme for uplink and downlink. It is left to future studies to establish whether the indication of the polarization extends as far as the granularity of a single SSB index and its respective SSB beam (see [Ref. 1]).

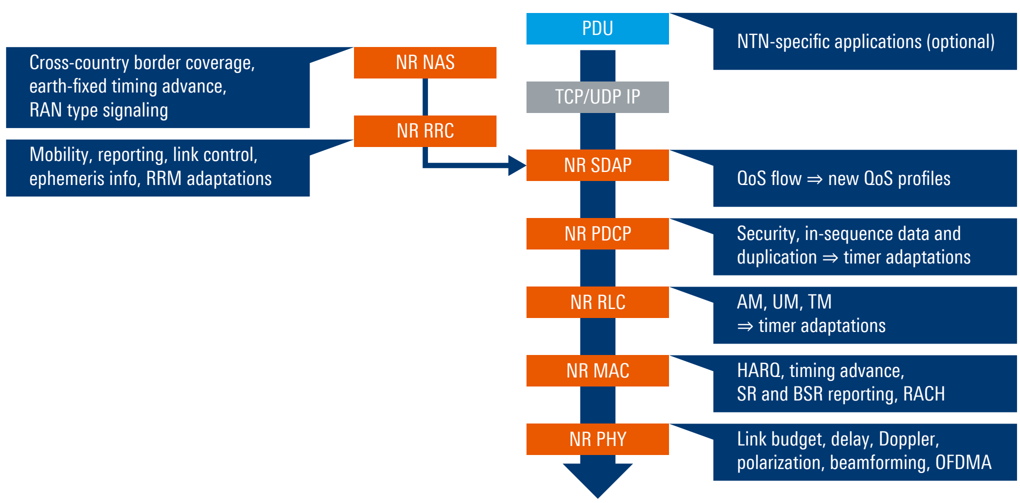
5 NTN PROCEDURES AND PROTOCOL STACK

The introduction of NTN requires an update and amendment of certain procedures to tackle the previously described challenges, e.g. latency, Doppler shift and others. 3GPP conducted several studies to investigate these possible extensions and corrections to the existing 5G NR protocol structure and the existing procedures. The objective of this chapter is to provide an overview of the most relevant procedures with a short presentation of potential countermeasures.

5.1 Protocol stack for 5G NTN

Contemplating the existing protocol structure of 5G and bearing in mind the main objective given by 3GPP to introduce NTN connectivity with the lowest impact on the existing system setup, the discussions conducted in 3GPP resulted in some conclusions on how to amend the protocol structure to enable NTN. The physical layer needs to cope with the new challenges that arise. A potential update of medium access control (MAC), radio link control (RLC), packet data convergence protocol (PDCP) and service data adaptation protocol (SDAP) was studied; see [Ref. 1] for further details on the 5G protocol structure. To optimize the signaling architecture, 3GPP incorporates some adaptations and extensions to the radio resource control and NAS protocol layers. Some of those extensions are described below.

Figure 46: NTN protocol stack



Physical layer

As already discussed, the major impacts of NTN on the physical layer is considered to be the long delays, the Doppler shift, the high path attenuation and the polarization rotation. The physical waveform does not require a specific amendment due to NTN, which is a compromise between complexity, timeline and feasibility. It is decided by 3GPP to maintain OFDMA as the primary waveform because it is in 5G NR, also for NTN connections. There were objections and discussions because with OFDMA there is a high peak-to-average-power ratio (PAPR) and several existing satellite communications decided against OFDM for exactly that reason. Another challenging parameter is the sensitivity of OFDMA to Doppler shifts, thus a pre-adjustment and carrier frequency correction is needed (see chapter 4.4). But with respect to system impact and possible future dual connectivity scenarios between terrestrial and non-terrestrial, the reuse of OFDM for satellite based connectivity will provide advantages as the impact is lowest.

New frequency bands are possible in the 5G system and slight changes like a higher transmit power, circular polarization introduction or sophisticated beamforming methodologies do not require an intensive specification update. 5G NTN will reuse the existing reference signals and physical channel structure.

The flexibility is kept on the physical layer with respect to the spectrum used as NTN may use the FR1 and FR2 range. The complexity increases as the Ka-band discussed for NTN defines an uplink region that is in the gap between FR1 and FR2, or in other words it would then be in a spectrum undefined by 3GPP. This is one reason why FR2 for NTN is postponed. The second reason is the duplex mode FDD applied for NTN. A TDD system needs the definition of a guard period between the TX and RX switch. Due to the long delays in NTN, such a guard period would need to be very long and result in inefficient spectrum use. Consequently, 3GPP decided on FDD for the FR2 frequencies in NTN, which is a novelty as the current FR2 bands are all TDD. The required adaptations of the existing specifications to permit FDD also in FR2 causes a delay in the specification groups and this is another reason why the FR2 bands are not yet considered in Release 17.

With respect to synchronization and initial network acquisition, the currently specified concept using synchronization signals and channels (e.g. the SSB block) stays the same in NTN. It is assumed that the UE will follow the S-criterion, determining the best cell by measuring power (e.g. RSRP) and signal quality (e.g. RSRQ). For cell reselection purposes too, the ephemeris information and the UE location can be considered. The specifications contain the definition for the SSB based RRM measurement timing configuration window known as SMTC, and it is up to the network to update the SMTC configuration of the UE to accommodate the different propagation delays between terrestrial and non-terrestrial cells or to mitigate the relative time change between two SANs. For Release 17, one or more SMTC configurations associated with one frequency can be configured and optionally linked to a set of cells. Different offsets in addition to the legacy SMTC configuration are possible (see also Figure 59).

5G NR already applies adaptive modulation and coding which will remain in NTN with preferred choices of phase-shift key modulations schemes up to the order of 16. UE and satellite support QPSK and 16QAM, optionally 64QAM, can be used. Due to the longer RTT, a possible link quality feedback (e.g. CQI) arrives delayed at the gNB scheduler, but with NTN, the greatest impairment of the SNR is the free space path loss (FSPL), which can be predicted from the constellation geometry. At high satellite velocity and longer packet durations, the path loss may fluctuate, thus, depending on the QoS profile, a more robust MCS scheme is then selected.

Spectral efficiency improvements based on multiple antenna technologies (MIMO) suffer from the dominant LOS and long distance resulting in a delayed rank indicator feedback and it is assumed that NTN MIMO will be left for future enhancements. The absence of scatterers near the satellite antenna tends to make the fading among all the channels between the satellite and UE spatially correlated.

MAC layer

The impact of longer latency affects procedures controlled by the MAC layer. Agreed conclusions are the MAC enhancements for procedures like random access (RACH), power saving or discontinuous reception (DRX), timing advance (TA), scheduling request (SR) and hybrid automatic repeat request (HARQ) [R2-1818511]. A possible elision of HARQ feedback causing an impact on reliability results in the recommendation to tackle reliability issues by a more robust MCS selection and support by higher layers like RLC and PDCP. RACH extensions ensure proper functioning under circumstances resulting from longer delays. Timing advance updates deal with not only the absolute value of the longer RTT but also mitigate affects like time-variant and floating RTT due to the elliptic nature of the beam footprint and satellite motion.

RLC layer

Similar to other protocol layers, the RLC too has to cope with the major challenge of extended RTT. An RLC entity offers the three different transport modes unacknowledged (UM), acknowledged (AM) and transparent mode (TM). With extensive delays, the difficulty is to meet the requirements of the AM, especially as the RLC AM is the default mode for signaling radio bearers. The MAC layer probably operates in HARQ disabled mode and the RLC AM should then ensure reliable data transfer. Note that this may lead to a thorough configuration of the *maxRetxThreshold* parameter that sets the number of maximum retransmissions and bridges between the latency and reliability aspect in the QoS profile. In the acknowledged mode, the RLC layer uses a polling mechanism. The TX entity sends a PDU containing a poll request and starts the timer *t-PollRetransmit*. The RX entity replies with a status report and, in the case of timer expiry, the poll is repeated. The current configurable maximum time of the *t-PollRetransmit* timer is 4000 ms, which is considered to be long enough even for NTN GEO RTT. The flow control of received data units is controlled by the *t-Reassembly* timer, with a maximum of 200 ms. This timer detects a possible loss of RLC PDUs at lower layers. Initial proposals indicate that there is no need for an update as the situation is no different from conventional networks. However, an extension is not precluded. Especially in cases where the HARQ is enabled on the MAC layer, an extension will be beneficial because a running *t-Reassembly* timer also includes HARQ retransmissions. 3GPP working group RAN2 suggests an extension up to 2200 ms for this reassembly timer and to be future proof an additional *t-ReassemblyExt* information element is part of Release 17. This also applies to the *t-statusProhibit* timer whose length of 2400 ms is considered to be long enough, also for NTN. A proposal suggests consideration of a possible extension of the RLC sequence number field, which currently has a maximum length of 18 bits, and extension of the *AM_Window_Size* describing the buffer status. These two values are considered to fulfill the requirements for NTN as well, but future technology evolutions may support larger subcarrier spacings (e.g. 120 kHz) and therefore shorter slot durations as well as methodologies like carrier aggregation or dual connectivity which could then lead to a stalling situation as the buffer will be exceeded [R2-1818512].

PDCP layer

The user plane protocol layer supports data transmission with in-sequence provisioning, discard functions, dispatching, ciphering and duplication. It is assumed that there is no need to update the ciphering function of the PDCP layer due to NTN introduction. Also, the PDCP layer needs to cope with longer RTT and it provides the QoS support in close cooperation with the RLC layer. The PDCP parameter *discardTimer* sets the maximum time before a discard notification is sent to the TX RLC entity and, in the case of extended retransmissions, there is a suggestion to extend this timer as a beneficial amendment. To be future proof, a new information element *discardTimerExt* with length 2000 ms is introduced in Release 17 with the option of future extension. At the RX entity, the *t-Reordering* timer influences the reordering function. The maximum duration of currently 3000 ms is surely sufficient for RLC UM mode, but assuming a larger number of RLC AM retransmissions a probable extension of this timer value could be beneficial. As with the RLC layer, a potential extension of the PDCP sequence number, currently max. 18 bit, and the buffer size given as *Window_Size* would be beneficial to NTN. There is no direct need for such a modification, but future scenarios supporting shorter slot durations with higher subcarrier spacing and carrier aggregation scenarios may profit from such amendments to avoid stalling situations [R2-1818513].

SDAP layer

The SDAP layer is responsible for the mapping between QoS flows and data radio bearers. It is not affected by the large round-trip delays occurring in NTN. As of larger RTT, 3GPP introduces new QoS profiles tolerating such longer delays. For the SDAP, it was found that it is not necessary to introduce any modifications to support NTN [Ref. 10].

Radio resource control layer

With respect to RRC signaling, some adaptations of procedures like idle-mode and connected-mode-related procedures and signaling including system information, registration, paging, use of satellite ephemeris information, location information, measurement configuration, radio resource management (RRM) for scheduling, link adaptation, MCS control and handover procedures all need to be updated. For example, NTN introduction requires a new system information block (e.g. SIB19) that provides information on aspects like ephemeris, common timing advance parameters, validity info for UL synchronization, cell stop info, cell reference location and epoch time. When the UL synchronization info expires, the UE needs to acquire the SIB once again. Mobility between two satellites is supported by RRM procedures. One example is the permission for flexible configuration of RRM-related measurement procedures, like the SMTC windows. Further details will be provided in the following chapters.

NAS signaling

Major impacts on the NAS layer are the extension of cross-border coverage and the resulting PLMN selection process and the incorporation of adaptations that adjust the current NAS signaling, e.g. registration setup to the longer RTT. A major consequence is the definition of a new value **RAT type** that is signaled to the AMF, informing the core network functions about the fact that the UE and the respective service data flow will use an NTN connection and therefore longer RTT needs to be tolerated. Further details will be provided in the following chapters.

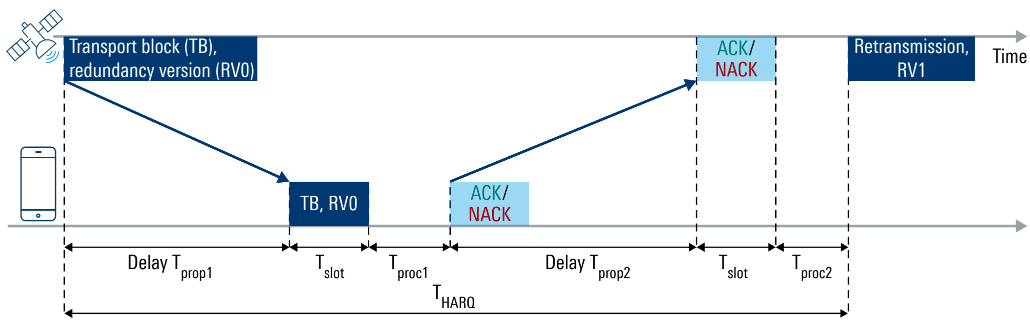
5.2 HARQ

Hybrid automatic repeat request (HARQ) introduced in Release 6 (introduction of HSDPA) supports a reliable connection based on fast acknowledgments and retransmissions with incremental redundancy methodologies like adaptation of the redundancy version. The drawback of such a HARQ process is its stop-and-wait nature: the transmitter needs to wait until a positive acknowledgment is received before it can send the next data packet, otherwise a retransmission occurs [Ref. 1]. To overcome a stall situation, several HARQ processes operate in multi-tasking mode. In 5G NR Release 15, up to 16 HARQ processes operate simultaneously per UE and several timers control behavior such as the periods between RX and acknowledgment and retransmissions. As NTN causes much longer delays, an adaptation of the current HARQ mechanisms is needed and 3GPP discusses three possible adaptations:

- Extending the number of existing HARQ processes to 32 processes
- Disabling HARQ feedback and shifting the retransmission to higher layers, e.g. RLC AM
- Configuration of automatic retransmission, e.g. TTI bundling features

A simple linear increase in the number of HARQ processes is unfeasible due to memory restrictions and the maximum number of possible parallel channels. For example, a GEO constellation with 544 ms RTT would then require such a number of HARQ processes. For a LEO constellation, 3GPP agreed to increase the overall number up to 32 HARQ processes, depending on the UE capability. This entails updating the scheduling message DCI HARQ ID field to a size of 5 bits. As this is optional, the RRC parameter *harq-ProcessNumberSizeDCI* indicates whether the DCI field HARQ process number is extended to 5 bits. To support NTN without excessive requirements with regard to processing power and UE memory, 3GPP agreed to permit the disabling of the HARQ feedback, configurable via RRC parameter *HARQ-feedbackEnabling-disablingperHARQprocess* for each HARQ process. This allows the transmitter to use the HARQ process for successive data transmission without being forced to wait for feedback and causing a stall situation. Optionally, the RRC can enable automatic retransmission of PDUs to improve the reliability of the connection. This blind retransmission which is not related to any feedback is similar to features such as TTI bundling that are already permitted in legacy wireless communications. In summary, the network can choose one of these three scheduling options: Disable, i.e. no HARQ retransmissions, blind retransmissions or extended HARQ feedback. To avoid excessive monitoring of the PDSCH by the UE, such automatic retransmissions are only allowed within a certain time window following the first transmission of a PDSCH PDU. The possible impact on the scheduling mechanism is then a lower target BER for the MCS selection, and the reliability of the connection can also be influenced by the RLC operating in acknowledged mode (AM) and by the process for counting the PDCP layer sequence number [Ref. 10].

Figure 47: HARQ operation aspects with NTN



Constellation	T_{HARQ} max.	No. of HARQ processes	UE side feasibility
Terrestrial	16 ms	16	Rel. 15
LEO	50 ms	50 theoretically, 3GPP agrees to 32	HARQ extension
GEO	600 ms	600 theoretically	For future study

Assumption: 15 kHz SCS and 1 ms slot duration [TR 38.811]

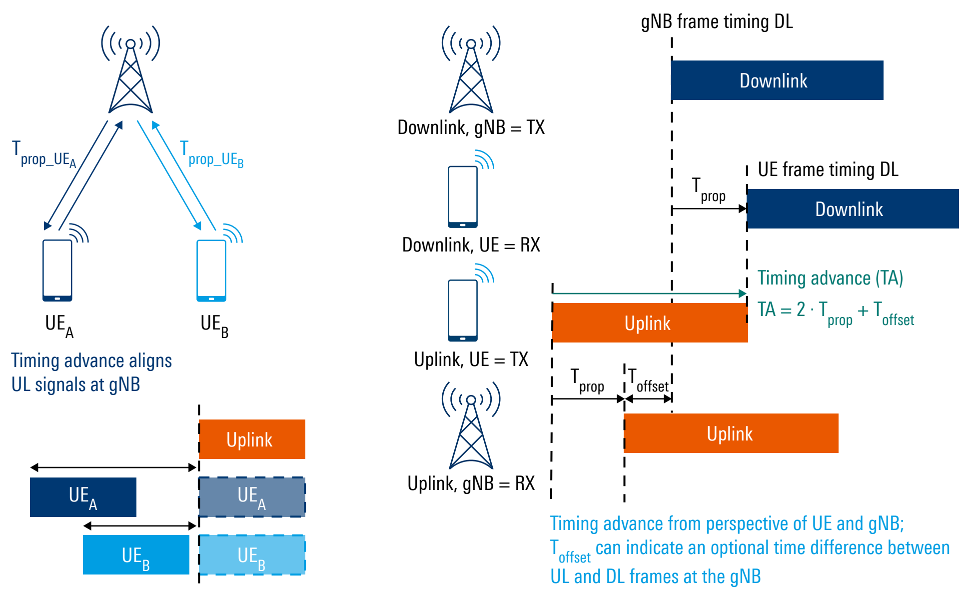
To adjust for longer delays, the response time for HARQ feedback is extended. The PUCCH carrying the HARQ ACK/NACK is deferred by the HARQ timer K_1 and the additional NTN timer K_{offset}. The large RTT requires some updates of HARQ timers in DRX situations; see chapter 5.12 for further details.

Future updates and research topics are e.g. an adaptive HARQ process ID definition and code block group aggregation for reduced acknowledgments [Ref. 30]. In the current standard, a HARQ process consisting of the scheduling of a transport block, the reception process followed by a retransmission is identified by a HARQ process ID number. This ID allows a flexible scheduling of retransmissions in the time domain, but the drawback is that the extension of HARQ processes would require the definition of additional HARQ IDs. Adaptive HARQ is a research topic to incorporate some binding or liaison rules between HARQ process IDs, so that fewer IDs are required when using more HARQ processes. Enhancements with respect to channel coding in the case of long delays lead to the research field of code block group aggregation and reduced acknowledgments. 5G NR supports the separation of a transport block into code blocks and the acknowledgment based on the aggregation of several code blocks. The drawback in the current definition, which focuses on low latency, is the acknowledgment or HARQ related to a single transport block. Research fields are discussing aspects of channel coding across various transport blocks, which will then permit reduced acknowledgment [Ref. 30].

5.3 Timing advance

With the TX timing advance (TA), cellular radio implements a mechanism to compensate for propagation delay and to achieve an in-sync reception of all uplink signal across various UEs. This alignment is initially performed during the connection setup, i.e. the RACH procedure, and later, when a connection is established and ongoing, the MAC layer will maintain this time alignment under its control and update permanently (see [Ref. 1] for general TA aspects). By way of a reminder, the delineation in Figure 48 depicts the purpose of the timing advance and its possible configurations. In the left upper part, a situation is shown where the gNB is confronted with two different propagation delays to UE_A and UE_B and the individual TA values ensure a time alignment of the uplink frames at the receiving gNB. This simplifies the reason why timing advance is needed in cellular networks. The right side of the figure shows that the TA needs to compensate two times the propagation time T_{prop} as it is symmetrical between UL and DL. The sketch additionally indicates an optional value T_{offset}. With this optional configuration parameter, a gNB may apply a time difference as an offset between the DL and UL frames. For example, the NTN parameters K-Mac or $N_{TA,offset}$ described later are such optional configuration parameters.

Figure 48: Timing advance to compensate propagation delays



The introduction of NTN with its long propagation time characteristic requires an amendment of the existing timing advance control procedures. The random access procedure needs to cope with such longer delays to avoid a lost or failed random access attempt as well as the improvement of efficiency with respect to the network capacity. Secondly, during an NTN connection, the system needs to support longer timing advance values to cope with the delays. Certain strategies exist to tackle this issue.

The random access time alignment procedure in terrestrial networks is divided into two steps. First, the UE sends a non-synchronized PRACH signal that presumably arrives with a delay that is two times the propagation delay at the base station antenna. A long guard time as a characteristic of the PRACH preamble defined within the PRACH slot protects against such delays, i.e. using the SIB indication as to which preamble format should be applied, the network indirectly indicates its maximum cell range. As the impact on the existing 5G system should be low, an extension and definition of new PRACH preambles did not come under discussion. In a second step during the random access, the base station measures the delay and controls in its response message (Msg2) the timing advance adjustments [Ref. 1]. The drawback of large delays in NTN situations is that they would require PRACH guard intervals, probably by defining new preamble formats with such long guard times that the entire system would become inefficient. Solutions to cope with longer delays during the random access procedure are an a priori timing advance setting based on the UE-to-satellite distance estimation within the UE and, secondly, the introduction of timer extensions to align the message flow according to such longer delays. An explanation is provided in chapter 5.4.

The second impact is not only the long RTT due to the UE-to-satellite distance, but also the high differential delay (see Figure 39) due to a large beam footprint. These issues require permanent maintenance of the time alignment during a connection, which is similar to terrestrial networks, but this time alignment needs to cope with longer absolute timing advance times. There have been several discussions on the best mechanism to update the timing advance and allow longer times or larger values for TA update. [TR 38.811] discusses the aspect of an alignment between the downlink and uplink at the gNB, which would lead to a large offset between RX and TX at the UE side, as depicted in the upper part of Figure 49. Another proposal discussed a more relaxed time alignment between the uplink and downlink at the gNB side. For example, a gNB could apply a system frame number shift as time offset; see the proposal in Figure 49. These are two mechanisms to deal with the longer absolute delays and allow longer timing advance settings.

In the consideration of TA adjustments, the 5G system needs to cope with the differential timing advance issue, as due to the large beam footprint, the delay between the satellite and various UEs within that footprint is not constant, leading to a need for individual timing advance control per UE. A central aspect of NTN timing advance adaptation is the split into a cell- or beam-specific part and a UE-specific component. The network may select a beam-specific reference point and broadcast the timing advance that should be adjusted for this RTT via SIB as a common value. In Figure 49 below, the common TA calculates as a composite of the delay on the feeder link T_{feed} and the delay of the service link T_{serv_ref} at the reference point:

$$TA_{\text{common}} = 2 \cdot (T_{\text{feed}} + T_{\text{serv\_ref}}) \,/\, \text{c}$$

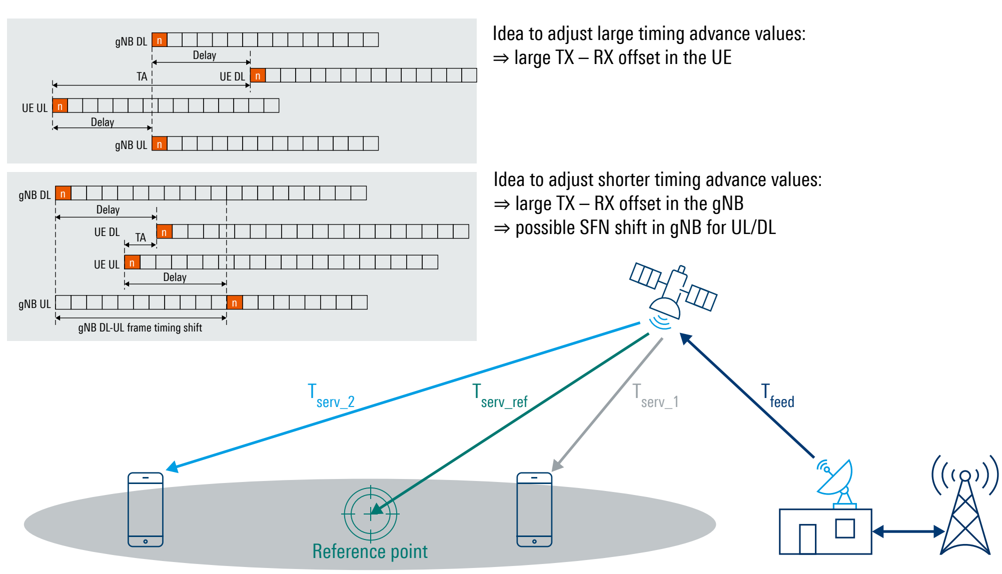
To compensate the differential delay that occurs due to the geometry of the beam footprint, a UE-specific timing advance value can be put into operation.

Such a UE-specific TA can then be computed as the difference between the UE-specific service link delay T_{serv_UE} and the service link delay to the reference point T_{serv_ref}.

$$TA_{\text{specific}} = 2 \cdot (T_{\text{serv\_UE}} - T_{\text{serv\_ref}}) \,/\, \text{c}$$

The residual timing advance is the sum of TA_{common} and $TA_{specific}$.

Figure 49: Timing advance aspects in NTN



The outcome of these discussions are the definitions of the timing advance value being dependent on four major parameters, a UE estimate TA as an a priori approximation, a common TA value used for the entire cell range and a kind of broadcast TA via SIB, a common offset for the TA computation and finally the closed-loop control UE-specific timing advance.

The timing advance applied by an NR-NTN UE in RRC_IDLE/INACTIVE and RRC_CONNECTED is given by [TS 38.213]:

$$T_{\mathrm{TA}} = \left(N_{\mathrm{TA}} + N_{\mathrm{TA,offset}} + N_{\mathrm{TA,adj}}^{\mathrm{common}} + N_{\mathrm{TA,adj}}^{\mathrm{UE}}\right)T_{\mathrm{c}}$$

Where:

N_{TA} is defined as 0 for PRACH and updated based on the TA command field in message 2 during the RACH procedure and MAC control element command (MAC CE TA) during connection.

$N_{\mathrm{TA,adj}}^{\mathrm{UE}}$ is the UE-self-estimated TA to pre-compensate for the service link delay. It is derived from the UEs position estimated via GNSS positioning and the estimated satellite position based on the ephemeris information that the UE has.

$N_{\mathrm{TA,adj}}^{\mathrm{common}}$ is the network-controlled common timing advance, and may include any timing offset considered necessary by the network. It is derived from the higher layer parameters *TACommon*, *TACommonDrift* and *TACommonDriftVariation* if configured, otherwise its value of 0 is supported.

$N_{\mathrm{TA,offset}}$ is a fixed offset already used in the terrestrial 5G network for calculating the timing advance. Its value is signaled by higher layers, depending on the duplex scheme and frequency range. Its purpose is to allow the base station to adjust its transmitter after an uplink frame, especially relevant for TDD networks. The time offset $N_{\mathrm{TA,offset}}$ directly corresponds to the time difference between an uplink and a downlink frame observed at the gNB, e.g. if this value is zero, it means that UL and DL frames are absolutely aligned in the time domain. This value has similar behavior to the parameter K-Mac introduced by 3GPP and explained in chapter 5.5.

Summarizing the timing advance aspects, the NTN UE will pre-compensate the delay (and the Doppler shift) when accessing the network. This is performed in four major steps:

1. The UE determines its terrestrial position, e.g. via GNSS or RAT positioning

2. The satellite provides orbit information, velocity information and common parameters in the SIB broadcast

3. Based on the estimated UE and satellite position, a calculation of the propagation delay is executed by the UE

4. Finally, the UE derives the initial timing advance and frequency shift for initial radio access. Depending on the SIB setting, the UE reports the timing advance during the RACH procedure

5.4 Random access

Long RTT values affect the random access procedure in NTN. We can identify various impacts on both sides, gNB and UE, due to the large delay. On the gNB side, the long RTT may cause some floating RACH window effects and may deteriorate the RACH ambiguity. The UE experiences a longer call setup time and also the contention resolution signaling procedure is affected by this longer RTT.

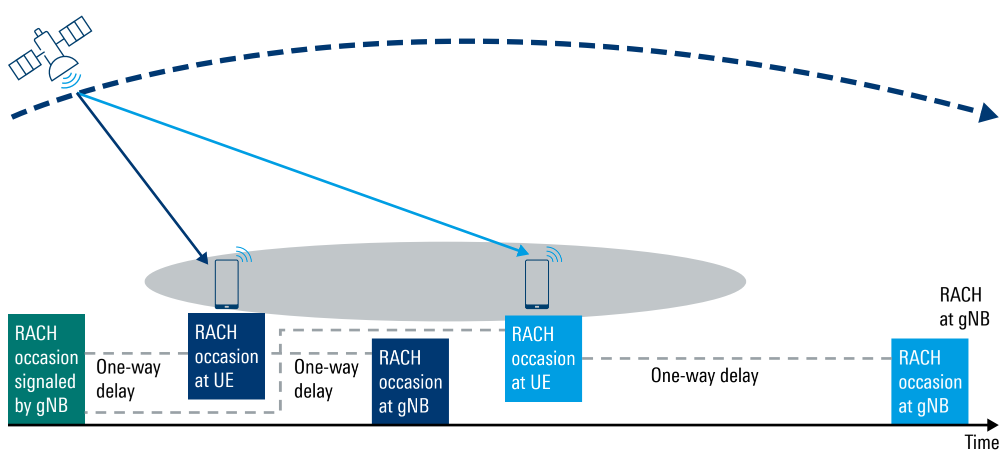
RACH impairments at gNB: Floating RACH window

First, we contemplate the effect occurring on the gNB side visible as a floating RACH time window, i.e. the window where the gNB would expect a PRACH signal reception coming from the UE. Let us take a more detailed look into that topic. The gNB broadcasts these time windows as RACH occasion windows, i.e. aligned to the frame structure, and the gNB indicates the slots and frames when the UE is allowed to send a PRACH sequence [Ref. 1]. Due to the nature of the beam footprint geometry and the relative movements of the satellite with respect to the UE, the reception of such PRACHs at the gNB is dependent on the individual delay. Figure 50 depicts this problem: Two UEs with different delays will create distinct timing differences between the signaled RACH occasion by the gNB and the corresponding reception of the uplink RACH by the gNB.

Figure 50: Differential delay affecting the RACH procedure – gNB perspective

Satellite orbit and shape of beam footprint entail floating RACH windows:

RACH occasion at gNB → RACH occasion at UE → RACH RX at gNB ≠ const



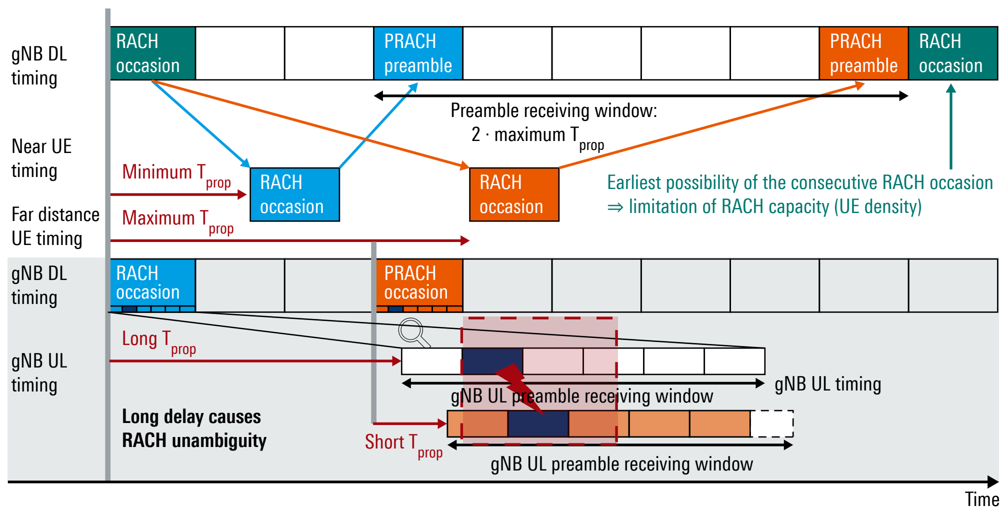
The consequences of and negative impact on the differential delay issues with respect to the gNB are capacity aspects relating to the RACH, as the gNB may need to configure a longer reception window for PRACH. Differential delay experienced by UEs in the same NTN cell causes different arrival times of the preamble at the gNB.

In the current scenario, the network cannot schedule the consecutive RACH occasion before arrival of the last possible PRACH preamble. In other words, the cell size or beam footprint causes a maximum differential delay across the UEs in that coverage area and influences the preamble receive window time at the gNB. Assuming large cell sizes with a high number of UEs, there is a risk of random access collisions and congestion, thus the differential delay aspect plays a pivotal role in the design of NTN deployments.

RACH impairments at gNB: Unambiguity of PRACH occasions

A second aspect depicted in the lower part of Figure 51 is the PRACH ambiguity. A network signals a PRACH occasion which, in simple terms, is a resource pool of various opportunities given to the UE to send random access. There is a direct relationship between the signal sequence preamble used as PRACH and the corresponding PRACH occasion [Ref. 1]. The lower part of the figure indicates the challenge: Assuming a network indicates the PRACH occasion and also assuming there is a large delay, this could cause ambiguity issues between this relationship, the selected PRACH preamble and the corresponding PRACH occasion. The delay is so large that the uplink preamble receive window overlaps with the consecutive PRACH occasion, causing unambiguity.

Figure 51: PRACH ambiguity impact due to long delays

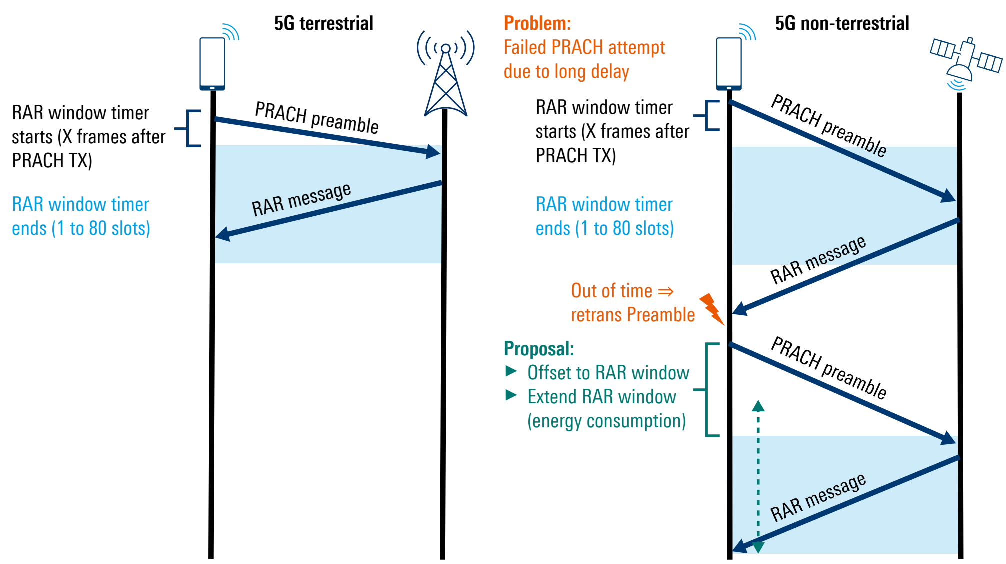


RACH impairments at UE: RACH extension and response timing

With respect to the UE perspective, the impact on the RACH procedure due to the long delays will affect the first step of the random access procedure representing the first connection setup signaling procedure. Let us start with a quick reminder of the random access procedure in 5G (see [Ref. 1] for further details on the RACH procedure): A UE sends the random access preamble (PRACH) in the uplink direction and waits for the random access response (RAR) message (Msg2). The Msg2 response schedules uplink resources enabling the UE to submit the scheduled transmission, known as message 3 (Msg3) that will be answered by the contention resolution message 4 (Msg4) in the downlink direction.

What are the direct impacts on the random access procedure due to the long delay in NTN? After having sent the PRACH preamble, the UE expects the RAR from the gNB within a certain time window. This RAR window is started at a higher layer configured time given by the RRC parameter *msgB-ResponseWindow* and has a preconfigured length. The worst case is that the UE will miss the gNB RAR message due to delayed out-of-window reception because of the long RTT, and it will retransmit the PRACH preamble again. Initial proposals were metrics like a time offset applied to the parameter *ra-ResponseWindow* to defer the start of the RAR response window or to extend its duration by means of a longer *msgB-ResponseWindow*, which then leads to longer PDCCH monitoring affecting the UE power consumption. The specification [TS 38.213] defines the start of the RAR window at the first symbol after additional (T_{TA} + K-Mac) milliseconds, where T_{TA} corresponds to the timing advance and K-Mac is an optional parameter signaled by higher layers (see chapter 5.5).

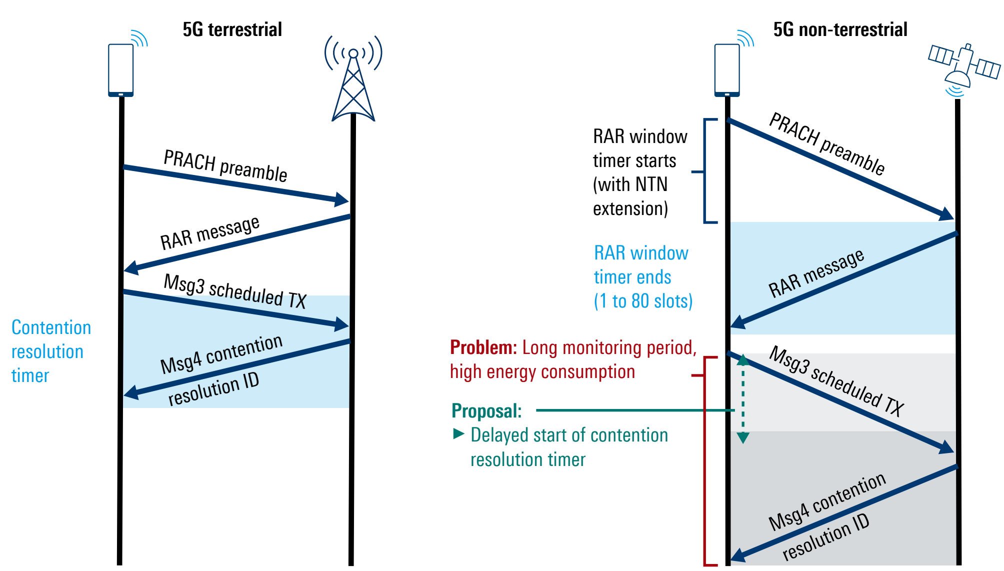
Figure 52: Impact on random access procedure due to long delay; random access response adjustments



RACH impairments at UE: RACH contention resolution

The second impact on the random access procedure, when contemplating the contention resolution based procedure, is that the UE sends an UL message 3 (Msg3) as the response to the RAR and receives as message 4 the contention resolution identity from the network to solve the contention issue. The timer *ra-ContentionResolutionTimer* defines the period where the UE needs to monitor for the contention resolution feedback Msg4. With long RTT values, this timer should either be deferred via an offset or it should be extended, causing a longer monitoring period.

Figure 53: Impact on random access procedure due to long delay; contention resolution response adjustments



Additional RACH aspects in NTN

A minor impact that should be discussed, especially against the background of small data packets, is the optionally preconfigured uplink resource (PUR) that allows the UE to transmit a small PUSCH PDU without previous random access. This feature was introduced to optimize the efficiency, especially in IoT situations with sporadic transmissions of small packets. To ensure reliable communications, the UE will monitor for acknowledgments during a PUR response window. With longer IoT-NTN delays, this response window needs to be extended, which may then cause higher energy consumption. Alternatively, an optional offset timer can be defined to defer this monitoring operation.

Discussion is ongoing with regard to some enhancements of the overall procedure time, e.g. to apply the 2-step RACH procedure instead of the 4-step RACH. This enhancement is also considered for configured grant scheduling and buffer status reporting.

Future NTN deployments investigate adapted random access mechanisms with enhanced Aloha random access procedures. The classic Aloha may suffer from low throughput when a low probability of packet loss is required as RACH collisions may occur. Research is conducted on updated mechanisms like a contention resolution diversity or asynchronous contention resolution diversity; see e.g. [Ref. 34].

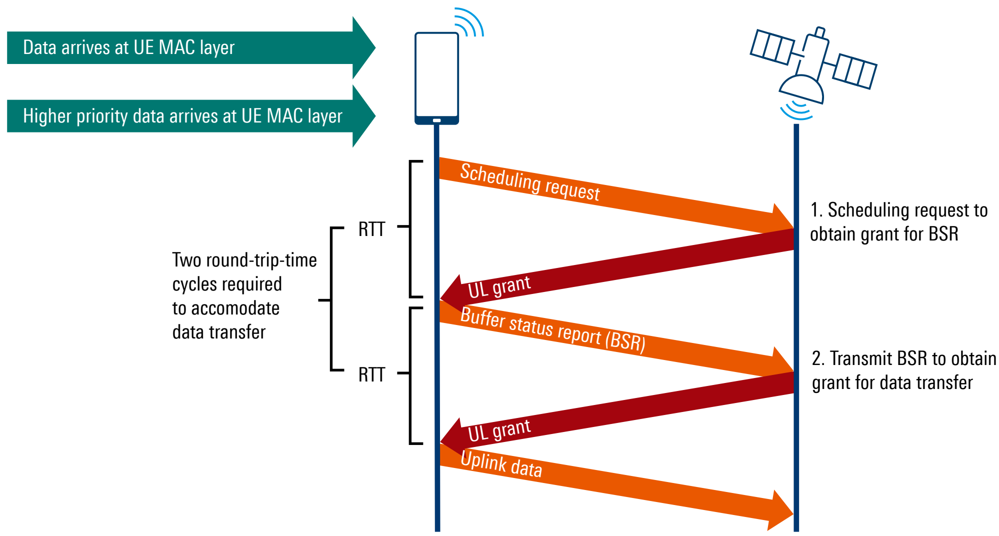
Not part of the current specification work but a potential outlook on future research are new waveforms applied for PRACH. Research activities investigate enhanced PRACH waveforms with better autocorrelation characteristics, optimized PAPR and out-of-band emissions to reduce the amount of PRACH misdetections [Ref. 31].

5.5 Scheduling requests (SR) and buffer status report (BSR)

The MAC layer of the UE needs to request resources on the uplink to transmit as soon as data from the higher layer application is available. If the UE is in idle mode, the UE will use the RACH procedure to initiate a connection. When already in RRC connected mode, the UE can request uplink resources via the transmission of the MAC control element scheduling request. The main objective of the data transfer procedure is to maintain and orchestrate the PDU sessions with related QoS flows. As defined in 5G NR, the MAC layer maps and optionally multiplexes the logical channels from the RLC layer into the MAC PDUs or transport blocks. There are two possible reasons why the UE MAC layer sends a scheduling request (SR) message to request UL resources from the gNB. One reason is new data arriving at the TX MAC entity from higher layer applications. The second reason is data from a higher application with a higher priority arriving at the MAC layer. When an SR is sent, the timer *sr-ProhibitTimer* is started. During the time the prohibit timer is active, no further SR is initiated. The expiration time of *sr-ProhibitTimer* can currently be configured in the range between 1 ms and 128 ms. In the case of extended delays, e.g. a GEO satellite, 128 ms is lower than the RTT and therefore the parameter range has to be extended [R2-1818511]. Other parameters like the scheduling request ID (*schedulingRequestID*) or the maximum number of open scheduling requests (*sr-TransMax*) are considered to be sufficient.

In addition to the possibility of requesting new resources via SR, inband control information that provides status information about potentially pending data is incorporated into the MAC layer. A UE uses the MAC formats as inband signaling to report the pending data amount given as a buffer status report (BSR) and information about the transmit power reserves as the power headroom (PH). With further details, this BSR determines the amount of UL data that is pending on each individual established logical channel [Ref. 1]. With the larger delays of NTN, a potential amendment of the BSR retransmission *retxBSR-Timer* could be beneficial. In summary, the longer RTT will affect the consecutive SR and BSR signaling procedure resulting in an overall longer procedure time.

Figure 54: Scheduling request and buffer status reporting



5.6 Timing relationship enhancements

One required objective aligned with the introduction of NTN into 5G is an update of timing relationships affecting operational procedures of 5G as they are affected by the longer delay. Such as:

- General adaptation of the uplink transmit time, aka timing advance (see chapter 5.5)
- Random-access-related timing behavior (see chapter 5.4)
- Timing with respect to uplink resource scheduling of PUSCH
- Timing with respect to downlink resource scheduling of PDSCH
- Timing corresponding to HARQ feedback (see chapter 5.2)
- Timing aspects with respect to the UE reporting control information
- Timing with respect to reference signals such as CSI-RS that should be considered as the valid reference for measurements and the reporting
- Timing with respect to UE assumptions with respect to channel conditions, e.g. TCI states

There have been multiple discussions within 3GPP on how to tackle the major RTT aspects in a convenient and efficient procedure, allowing some flexibility in deployments. Concisely, the agreements include the definition of a timing offset parameter K_{offset} and additionally the optional deployment for placing an unalignment between DL and UL frames at the gNB. In the latter case, a second time offset K-Mac indicates this unalignment. To counter the differential and time-variant RTT, the timing offsets are indicated cell-specific as the first part and, secondly, its value can be controlled in direct signaling, UE-specific.

Time alignment parameter K_{offset} – cell and UE-specific

Agreement within 3GPP is the introduction of an optional specific parameter K_{offset} consisting of a cell-specific and a UE-specific component. With this configuration, the network can tackle the aspects of the delay and additionally the aspects of differential delay. For example, as shown in Figure 39, the cell-specific offset counters the UE in the nadir direction of the beam footprint and the additional UE-specific offset signaled bilaterally via the MAC layer tackles the optionally occurring differential delay when the UE is located at the beam footprint edge. K_{offset} is computed as the difference between $K_{cell,offset}$ and $K_{UE,offset}$. The parameter $K_{cell,offset}$ is provided by *ServingCellConfigCommon* as part of the system information broadcast within a cell and the parameter $K_{UE,offset}$ further provides an option of adjusting this timer individually via MAC CE elements after initial access.

The timer K_{offset} affects the DCI scheduling of PUSCH, the random access response (RAR) procedure and the HARQ feedback on PUCCH. According to the discussions in 3GPP, it also impacts the CSI reference resource timing and the transmission timing of aperiodic SRS. Its unit is the number of slots for a given subcarrier spacing.

Further discussions are ongoing as to whether the K_{offset} value can be signaled specifically per beam and whether an update of the value after initial access is possible using the MAC CE. For the random access procedure initiated by a PDCCH order received in slot n, the UE determines the next available PRACH occasion in uplink slot n + K_{offset} to transmit the ordered PRACH preamble.

Timing with respect to uplink resource scheduling of PUSCH

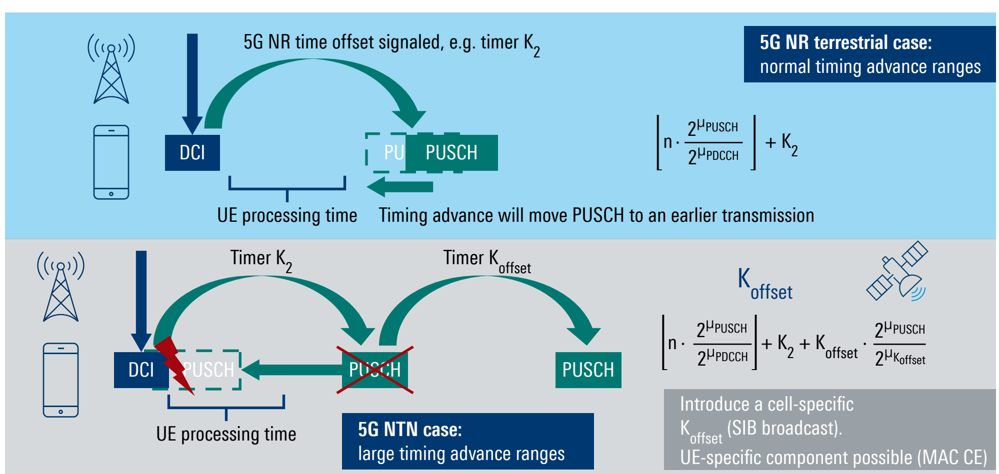
The need for adaptation of PUSCH scheduling timing aspects becomes clear when considering the timing advance correction in long delay scenarios. The upper part of Figure 55 shows the 5G NR scheduling in a terrestrial situation with assumed low delay, and the lower part delineates the aspects when experiencing long delays. The timing advance correction value will shift the TX in the uplink direction towards the RX of the control message DCI. Assuming there is a long delay, the timing advance value has to be large and will probably conflict with the UE minimum processing time.

The specification [TS 38.214] defines the scheduling slot K_s in NTN as:

$$K_s = \left\lfloor n \cdot \frac{2^{\mu_{PUSCH}}}{2^{\mu_{PDCCH}}} \right\rfloor + K_2 + K_{offset} \cdot \frac{2^{\mu_{PUSCH}}}{2^{\mu_{K_{offset}}}}$$

There can be an optional subcarrier spacing configuration $\mu_{K_{offset}}$ signaled, otherwise the term only considers K_{offset} as adaptation of the time domain scheduling.

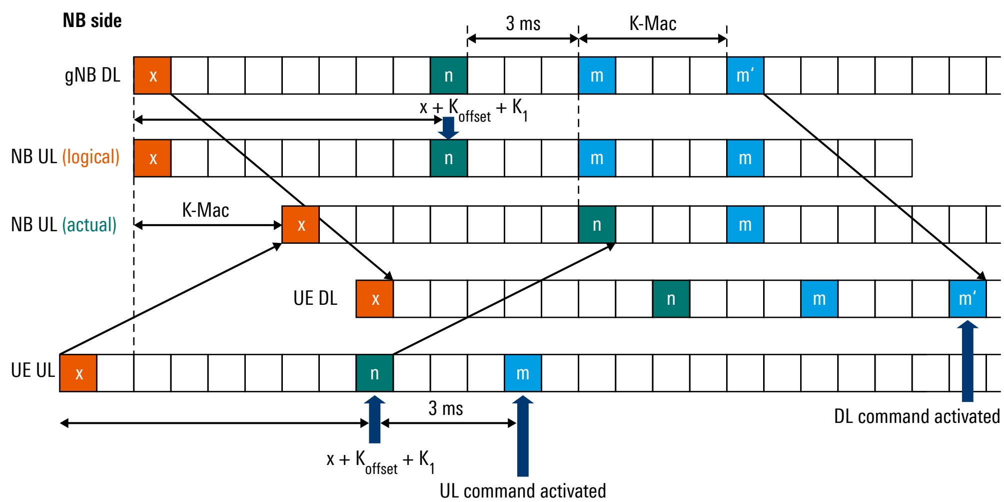
Figure 55: DCI scheduling of PUSCH enhancements to tackle long delays



Time alignment parameter K-Mac to support network UL and DL unalignment

The network can provide the UE with an optional K-Mac value that accounts for the magnitude of unalignment between DL and UL frame timing at the gNB side and is helpful in downlink configuration indicated by a MAC control element command. The timer K-Mac corresponds to a reaction time, i.e. assuming the network sends via MAC CE some commands that should be executed, the UE should react within a certain time. Considering first the situation where uplink and downlink frames are aligned within the gNB, the network sends a MAC CE in slot x and the UE obeys this command in slot m, where m is based on timers K_{offset} and K_1 plus a reaction time of 3 slots. In this situation, the parameter K-Mac is not needed and its value is configured as zero. This situation is depicted in the figure below as the logical gNB UL. To mitigate large delays, the network can decide on an unalignment between UL and DL frames at the gNB, depicted in figure below as the actual gNB UL. In such a situation, the timer K-Mac accounts for the magnitude of this unalignment with a granularity of slots. The UE reacts on the DL command in slot m' where m' is deferred compared to slot m by timer K-Mac. Another situation where the parameter K-Mac is used is uplink power control.

Figure 56: Network UL and DL unalignment K-Mac to counter long delays



UE procedure for reporting control information

To successfully maintain the radio link under obstructive radio conditions, the UE is requested to report control information such as measurement reporting to the network. Typical values are the reference signal received power (RSRP), channel quality indicator (CQI), channel status information (CSI) or rank indicator (RI) to support mechanisms like MCS, beamforming or MIMO. There are marginal corrections or adaptations with 5G NTN due to the longer delay compared to the terrestrial 5G procedures. The UE uses either PUCCH or PUSCH to report control information following the rules described in [TS 38.213]. Optionally, to support longer delay situations, the network can provide the UE with an additional timing adaptation parameter K_{offset}. Assuming the UE is provided with such a parameter, it would transmit the corresponding PUCCH/PUSCH feedback in the slot $n + k + 2^{\mu} \cdot K_{offset}$. Note that, as described before, the K_{offset} may consist of a cell-specific part and a UE-specific part. The UE applies the UE-specific $K_{UE,offset}$ parameter in the slot after slot $k + 3N_{\text{slot}}^{\text{subframe},\mu} + 2^{\mu} \cdot k_{\text{mac}}$, where k_{mac} is provided by higher layers as a K-Mac parameter.

UE procedure for determining physical downlink control channel assignment

The document [TS 38.213] defines procedures and rules enabling the UE to receive the proper control information. With the introduction of NTN, there is no change in the overall concept, i.e. the UE has information about its control and resource sets (CORESET) and also the UE knows about the transmission configuration indication (TCI) like the quasi co-location indication between reference signals. The network may send a MAC control message to update this TCI state information, indicating that the UE needs to apply a certain time instance later. With NTN, this time relationship is now slightly updated. The UE considers the MAC CE activation command applicable in slot $k + 3N_{\text{slot}}^{\text{subframe},\mu} + 2^{\mu} \cdot k_{\text{mac}}$. Where k is the slot where the UE would transmit a PUCCH with HARQ feedback. Enabling longer delay scenarios, the RRC layer can signal a K-Mac parameter to the UE and represent k_{mac} in this definition. The same timing rule applies to the UE determining the path loss value that is applied in computation of the TX power for the consecutive uplink TX.

CSI reference resource definition

Channel state information reference signals (CSI-RS) permit the UE to perform measurements related to channel status information, e.g. RSSI and RSRP, and in particular to support beamforming mechanisms. Clarification is needed to define the unambiguous relation between the CSI-RS in the TX direction and the related CSI report. [TS 38.214] defines this relationship in the time domain: The CSI report in uplink slot n′ uses the CSI resource in slot

$$n - n_{CSI\_ref} - K_{offset} \cdot \frac{2^{\mu_{DL}}}{2^{\mu_{K_{offset}}}}$$

The n_{CSI_ref} corresponds to the minimum measurement time the UE requires to obtain the 5G CSI; a typical value is 4 slots [TS 38.214]. Longer delays in NTN can now be tackled by configuration of the additional timer K_{offset}. With the exponent factor $2^{\mu_{K_{offset}}}$, a different subcarrier spacing between the PDSCH DL and the CSI-RS is possible, allowing a an optional switch between SCSs in a future NTN network configuration. If this adaptation factor is not provided, the term reduces to K_{offset} only, and in a terrestrial-only situation this timer can be set to zero.

Timers relevant for mobility and session management update

One impact onto the 5G core network functions is that to cope with longer delays, certain timers in session management and mobility management need to allow much longer values. An initial agreement is the definition of a new parameter **RAT type** extended by the indication of NTN RAT to the AMF. Consequences are that within the core network functions and NTN UE, extended timers are defined to handle such longer delays.

The study on the 5G architecture enhancements due to NTN [TR 23.737] proposes an update of certain timers belonging to session and mobility management. The extension of the duration of these UE timers is based on the worst-case round-trip time (WCRTT) estimation. The following table is suggested.

Table 14: Session and mobility management timers impacted by NTN

	Timer no.	RTT propagation delay	(Minimum) suggested timer value increase
5GMM UE-side timers			
	T3510	5 RTT	5 WCRTT
	T3517	3 RTT	3 WCRTT
5GMM AMF-side timers			
	no need for changes, AMF determines appropriate values		
5G SM UE-side timers			
	T3580	4 RTT	4 WCRTT
	T3581	1 RTT	1 WCRTT
	T3582	1 RTT	1 WCRTT
5G SM SMF-side timers			
	no need for changes, AMF determines appropriate values		

An extension and amendment of those timers is suggested; see [TS 24.501] for general information on the timers.

- **T3510** registration request timer setting a maximum wait time until the UE considers whether a mobility management context (5GMM) is successfully established or, if the timer expires, has failed. Due to the longer RTT, the message transfer between UE and AMF/SMF takes longer and an extension of this timer within the UE is recommended
- **T3517** service request procedure timer to indicate a 5GMM change from idle to connected mode [Ref. 1]. This timer also affects the overall connection setup procedure and needs to be extended to avoid a connection interruption due to pending service accept responses resulting from a large RTT
- **T3580** PDU session establishment request timer indicating the maximum waiting time until the UE considers whether an initiated PDU session is successfully established or, if the timer expires, has failed
- **T3581** PDU session modification timer indicating the maximum waiting time until the UE considers whether an existing PDU session is modified or, if the timer expires, modification fail indication is output
- **T3582** PDU session release timer indicating the maximum waiting time until the UE considers whether the session is released. The timer is started by the UE when the session release is initiated by the UE. Due to long RTT, an extension of this timer needs to be defined

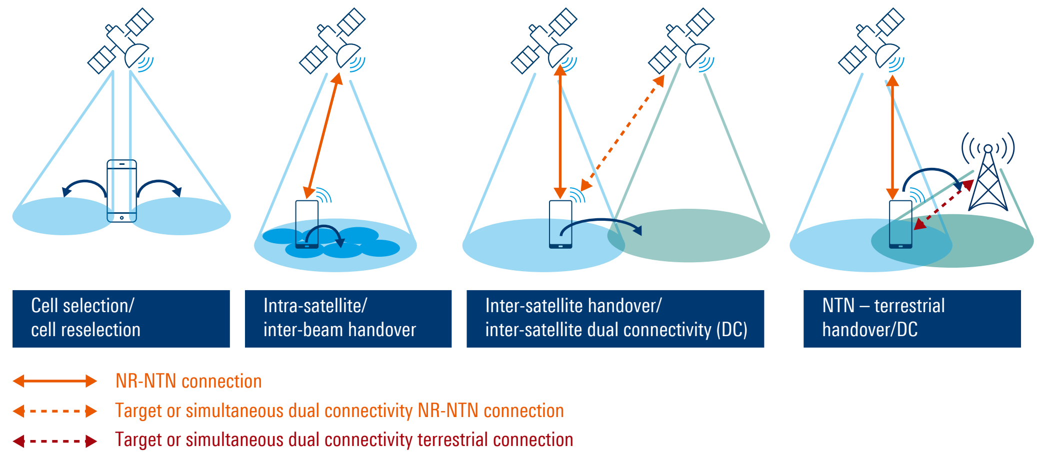
5.7 Mobility scenarios

The incorporation of NTN into the 5G system impacts the current definition of mobility aspects like handover in connected mode or cell reselection in idle mode. An obvious impact is the mobility procedure triggered by movements of the satellite. Owing to its velocity, the satellite moves rapidly with respect to the UE and, secondly, due to the longer RTT the interruption time during the handover may be much longer and may cause recognizable service interruptions. Several mobility procedures need to be considered:

- Mobility procedure while the UE is in idle mode, also known as cell reselection, or in a more general situation also described as PLMN reselection (see chapter 5.11)
- Mobility procedure to handover a connection from one satellite to another satellite, i.e. inter-satellite handover
- Mobility procedure between spaceborne sNB and terrestrial gNB
- Mobility procedure to handover a connection from one beam within a satellite to another beam, i.e. intra-satellite handover
- Reconfiguration procedure to modify allocated radio resources, i.e. change of the bandwidth part (BWP) or frequency channel

The latter corresponds to the general reconfiguration procedures that are possible within 5G. The RRC layer controls the radio link and potentially executes procedures to reconfigure the radio resources. Common examples are the RRC reconfiguration message to schedule another frequency carrier or a BWP change. From a protocol perspective, there is no direct impact on these procedures due to NTN, but the longer RTT may cause some delay in procedure execution.

Figure 57: NTN mobility scenarios



At a first glance, the introduction of NTN does not require new signaling updates of the existing handover or cell reselection procedures, except that the longer RTT may cause some delay or an increase in interruption time. The neighbor cell information broadcast via SIB is probably extended by some ephemeris and orbit information of neighbor satellites. In connected mode, the handover relies on the UE measurement reports sent in the uplink direction. In the case of NTN, the potential risk is that such measurements may either be executed too late or reported delayed due to fast movements of satellites. In summary, the satellite velocity causes issues with respect to satellite visibility and the long RTT causes message transfer delays due to the propagation delay. Consequently, the network may use some additional techniques like predictive handover to anticipate such RRC procedures. On the physical layer, as described, the RSRP determined at the UE is primarily influenced by the FSPL and, consequently, there will not be a huge difference between two RSRPs from two satellites. As a result, the RSRP of neighbor cells may not be the only criterion for RRM mobility procedures.

The mobility scenarios and procedures depend heavily on the deployment of the satellite constellations. In a simplified view, one may assume the knowledge of the orbit information as a supporting parameter for mobility scenarios. One possible LEO constellation effects the coverage of one cell area by means of at least two satellites. As the ephemerides of the satellites are controlled by the satellite operator, it is possible to ensure, thanks to an optimized design of the satellite constellation, that cells are always served by at least one active beam. This implies that during the handover period, a cell shall be visible by at least two satellites at the same time and the handover procedure runs as an RRC reconfiguration procedure to change the serving cell.

The major change in the mobility between two satellites is a change of the trigger concept of the handover. While in terrestrial networks the handover is triggered by the measurement results, e.g. RSRP reported by the UE to the network, NTN may require additional methods. The upper left part of Figure 58 depicts the legacy handover, i.e. when a vehicle based UE travels from one cell coverage into the neighbor cell coverage. In such a situation, we used to speak of **"X-handover"**, with the character "X" representing the fact that the former serving cell RX power level RSRP drops while the new neighbor cell RSRP power increases. Network operators define a handover condition, e.g. the difference between these power levels as the handover trigger criterion. In NTN situations, the handover is needed due to the mobility of the satellite, but the assumption is that both satellites are more or less at the same distance to the UE, thus the power level difference between both signals is marginal.

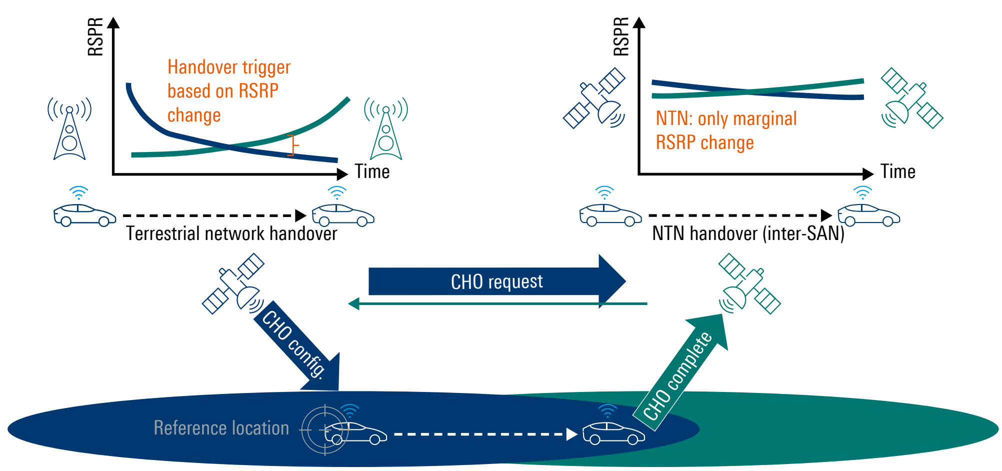
Conditional handover (CHO)

The proposal, supporting handover in NTN, is to apply methods that were defined within 3GPP in the context of the so-called conditional handover. The idea is that the network can configure a certain condition which triggers the handover procedure. [TS 38.300] defines the conditional handover as a mobility procedure executed by the UE when one or more handover execution conditions are met. By way of an example, such potential handover condition criteria can be described as:

- Originally, the conditional handover procedure sets conditions, e.g. a reconfiguration candidate cell receives an offset that is better or worse than a certain threshold (event A3 and A5) in order to permit a kind of autonomy on the UE side and reduce the signaling overhead, especially for UEs with only sporadic mobility scenarios.

- In a NTN situation, such a condition could be the definition of a terrestrial reference point, and the handover condition is fulfilled when the UE's current location deviates by a certain distance, as shown in the lower part of Figure 58. Expectations based on experience with existing LEO satellite constellations assume that such handovers take place roughly every 5 minutes in a NTN connection.

Figure 58: NTN mobility scenarios, conditional handover procedure



Conditional handover (CHO): network configures UE with triggering condition; e.g. distance between UE and reference location

- Related to the reference point trigger, another idea could be the distance between the UE and the satellite. In simple terms, if the distance between UE and satellite exceeds the maximum distance, this is an indicator that the satellite is leaving the visibility range, whereupon a handover trigger is launched.

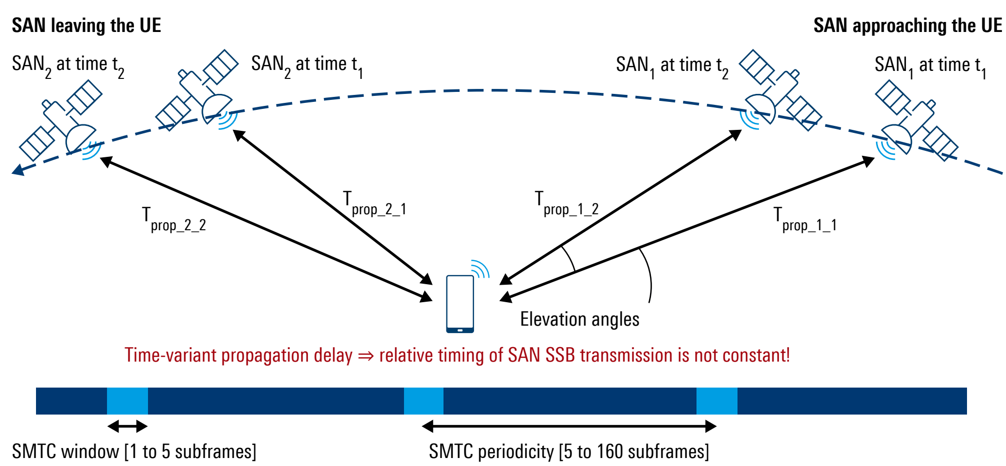
- There are also situations where a region is served by satellite connectivity only for a certain time and the deterministic movements of the LEO satellites allow an anticipated handover trigger. An example is the satellite orbit view from the perspective of the UE as shown in Figure 40. Assuming the UE has a priori information of the satellite orbit, the visibility is determined and the conditional handover can be defined on a timer expiry.

- Similar to the connection time, another condition could be configuration of the elevation angle between the satellite and UE as a criterion.

- Similar to the "distance between UE and satellite" trigger, the signaling of the timing advance value can also trigger a conditional handover.

Mobility scenario – SAN change
One mobility scenario in LEO constellations is the mobility from one satellite access node (SAN) to another and, like in terrestrial networks, the UE needs to acquire the neighbor cell synchronization information, e.g. the SSB signals. 5G NR defines an SSB measurement timing configuration (SMTC) together with a potential measurement gap within a connection, allowing the UE to detect the SSB of a neighbor cell. Such configurations work well for terrestrial networks, where the relative timing of SSBs from the serving and neighbor cell are fixed and the propagation delay only varies due to the UE movements. In a LEO scenario, the propagation delay varies over time due to the satellite movements. When considering a multi-satellite situation in such a mobility scenario, the relative timing of the SSBs also varies over time. In the example in Figure 59, we assume a UE monitoring two satellites. SAN1 approaches the UE and SAN2 leaves the UE. Over time the propagation times change due to the elevation angle and distance change. A static configuration of an SMTC pattern may not be able to handle such a drift in the sense that the SSB of the target cell may eventually be located outside of the SMTC window. This can lead to the UE not being able to detect and measure the target cell synchronization signals. Possible countermeasures are the configuration of multiple and dynamic SMTC windows.

Figure 59: Mobility scenario between two satellites – cell acquisition challenges



To support mobility procedures and in compliance with the transparent mode architecture where the satellite is connected to a non-NTN gNB on the ground, [TS 38.300] defines several control parameters that are supplied by the satellite to the gNB. Such parameters are e.g. information on earth-fixed beams, the cell ID on that beam, the cell's reference location (e.g. the cell's center and range), quasi earth-fixed beams, the time window of the successive switchovers (feeder link, satellite), the identifier and time window of all serving satellites and NTN gateways, the identifier and time window of the serving cell, earth-moving beams, mapping information to fixed geographical areas reported on the NG interface including information about the beam's direction and the motion of the beam's footprint on earth.

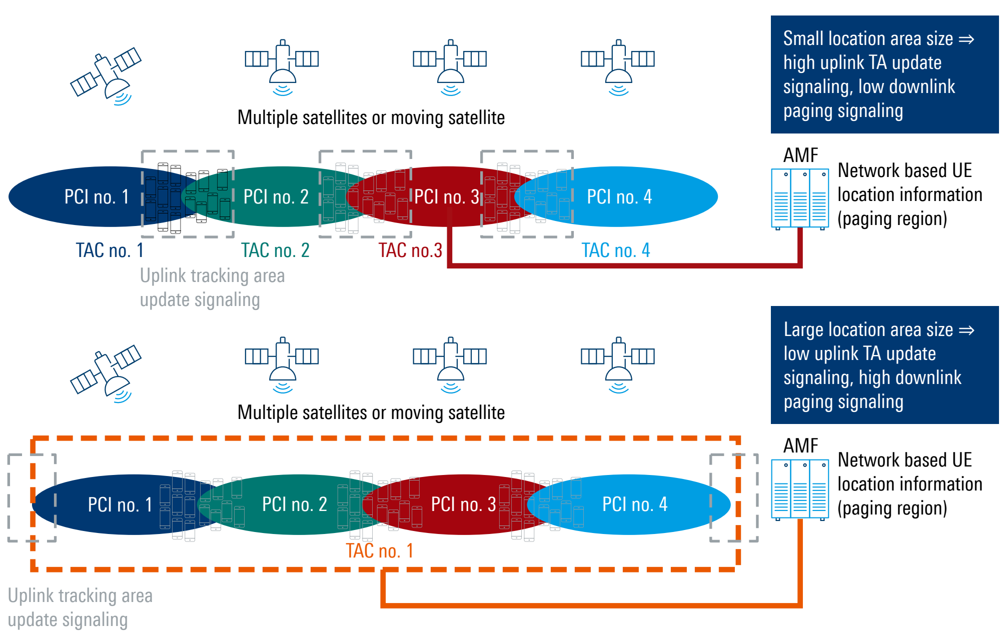
5.8 Measurements and measurement reporting
In general, the introduction of NTN does not result in major changes with respect to measurements performed by the UE and the reporting of these measurements. The primary potential risk is that, due to the long delay, the measurements performed by the UE arrive at the gNB delayed and are therefore obsolete. Or that, due to the mobility of the satellite and the short visibility time of the satellite, the measurement acquisition is exacerbated. Consequently, 3GPP discusses some optimization aspects of the RRM performance. Similar to other procedures, the measurement reporting procedure too may

take advantage of the deterministic orbit information known a priori to the UE. This would allow, for example, the trigger of such measurement reports based on the UE location or based on the relative location of the UE relative to the serving or neighbor satellites. Depending on legal aspects and data sovereignty, the UE may also piggy-back its location information on top of measurement reports sent to the sNB. The combination of the UE location and the orbit information of the satellites would allow anticipation of the upcoming handover. The network may advance the signaling of the measurement window and henceforth compensate the large propagation delay and avoid obsolete reports. Such a measurement window advance can either be signaled via system information broadcast or direct RRC signaling.

5.9 Tracking area updates (TAU)

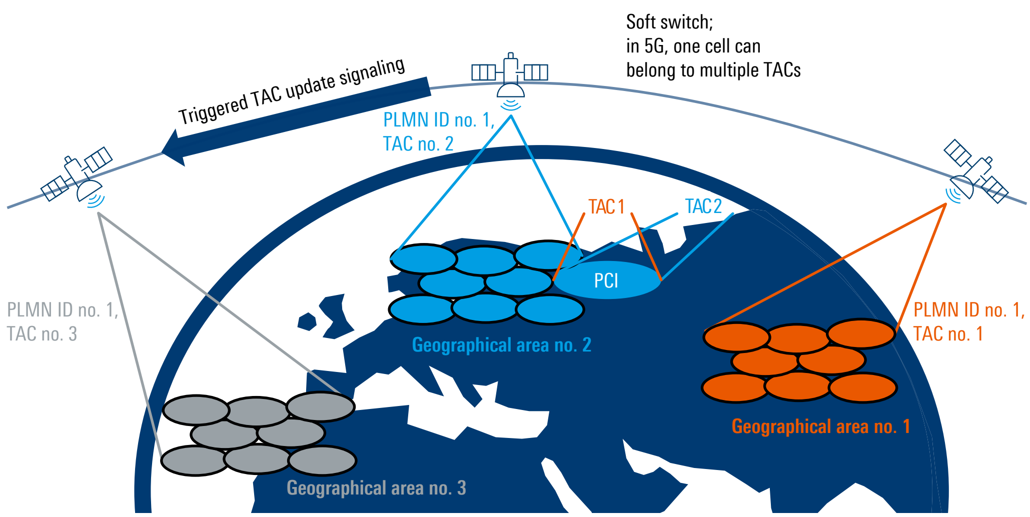
In terrestrial networks, the introduction of a **tracking area (TA)** bridges the gap between the mobility management or location information of the UEs whereabouts stored in the network function AMF versus the UE radio link activity, as this consumes electrical energy. In idle mode, the UE monitors the tracking area code (TAC) within the system information broadcast and sends the NAS message *TRACKING AREA UPDATE* whenever the TAC changes. In contrast, the network uses the paging procedure over the entire tracking area for mobile terminated calls. The delineation in Figure 60 describes this tradeoff between uplink signaling for tracking area updates versus downlink paging for mobile terminated call setup. Assuming a small TA size like in the upper part of the figure, the uplink signaling amount is high and the UE consumes huge amounts of electrical energy, whereas the network has a more accurate knowledge of the UE whereabouts, which reduces the amount of signaling for paging. In the lower part of the figure, the assumption is a large TA size and TA-update-related signaling is low whereas the network paging signaling load is higher. Network operators plan the sizes of tracking areas to minimize the signaling load on both the uplink and downlink sides.

Figure 60: Tracking area sizes versus signaling for TAU and paging



With NTN we observe a paradigm change, as the satellite moves with respect to the earth and consequently a stationary positioned UE, for example, would detect several gNB changes over time and this could result in an overhead of NAS signaling and inefficient power consumption. The consequence in NTN, contrary to terrestrial access networks, is that a potential disconnection exists between geographical cell coverage, phyical cell identity (PCI), tracking area code (TAC) and registration area code (RAC) definitions. This may have some impact on functions that are associated with geographical areas, such as authorization or billing [TR 23.737]. To address this potential issue, the countermeasure introduced in 3GPP is the configuration of an earth-fixed tracking area, i.e. the satellite gNB will adapt the tracking area code broadcasted (see Figure 61). For example, when the satellite flies over Europe, it transmits the European tracking area information and later, when the satellite flies over North America, it sends tracking area information related to North America.

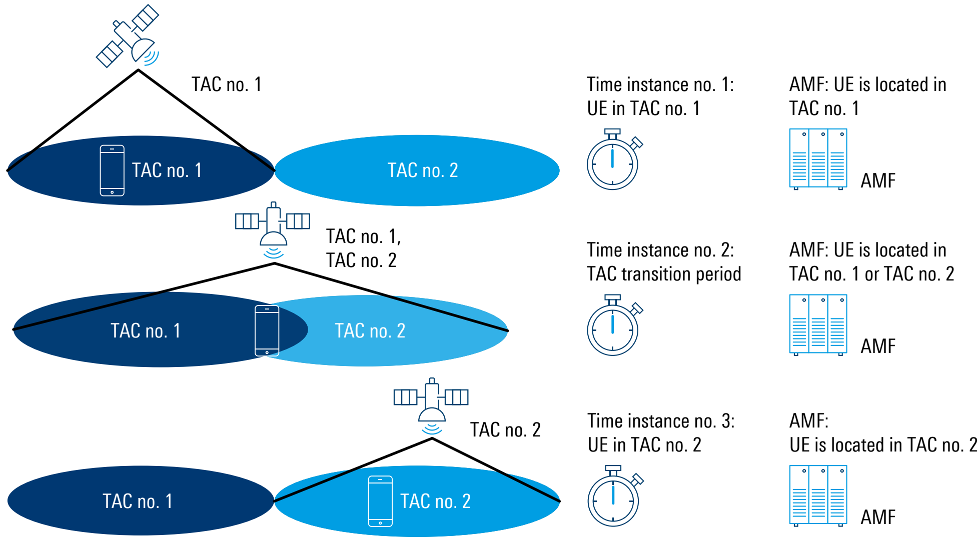
Figure 61: Earth-fixed tracking area code signaling



As today it is possible that one gNB sends different tracking area indices (TAI) via a TAI list and it is therefore possible to group several satellite gNBs into a single TA. This reduces the registration area update signaling by the UE but enlarges the location knowledge area that the network possesses about the UE whereabouts. Consequently, to bridge the gap between extensive uplink TAU signaling and paging, a thorough parameter definition needs to be performed. [TR 23.737] suggests a procedure where the AMF signals a list of registration/tracking areas to the UE when it recognizes that the UE is connected to an NTN RAN. This list of TAs follows the prediction as to which TA will occur next as the ephemeris information about the satellites is known a priori.

Furthermore, the fixed tracking area concept can be divided into hard and soft switch procedures. With the hard switch, the SIB broadcasts a single TAC and the sNB replaces the old TAC with the new one once it trespasses a certain orbital position that would result in a different ground coverage. The disadvantage of such a procedure is the risk of some fluctuation or so-called ping-pong tracking area effects, requiring a potential TAU hysteresis as a countermeasure. With the soft switch procedure, one sNB broadcasts multiple TACs in a SIB list simultaneously. The addition and removal of a TAC to/from the list is coordinated by timers related to the ground coverage. The advantage is more efficient NAS signaling, especially at TAC borders, but at the expense of some potential imbalances with respect to paging coordination. The information in the AMF mobility management about the UE's location is more inaccurate when such a multi-TAC concept is permitted, possibly causing an increase in the complexity of NAS signaling in the network. This paging imbalance aspect is depicted in Figure 62, as the scenarios in the upper and lower part describe the AMF location information of the UE as a single TA while in the middle part, where the network broadcasts two TACs due to sweeping and overlapping tracking areas, the network information is more inaccurate and the paging message to the UE needs to be broadcast over two tracking areas.

Figure 62: Sweeping tracking area code signaling causing paging imbalance



To support tracking area updates, the existing procedures will probably be extended with the addition of time information, e.g. the satellite is only visible for a certain time (see Figure 40). Additionally, to support cell reselection and tracking area update, the satellite may broadcast time-to-live information, i.e. a time estimation of how long the visibility of the satellite may last.

The AMF supports UE mobility (e.g. handovers) and mobile terminated reachability (e.g. paging). The objective is to keep most of the existing policies for cell reselection and TA updates unchanged. With the configuration of earth-fixed tracking areas and also due to the fact that the physical cell identities (PCI) refer to specific geographical areas, the 5GC maintains the location information about the UEs in idle mode. Both TA identifiers and cell identifiers are used in 5GC and the service layer as information about UE location, even in the case of a moving satellite gNB [Ref. 10]. Reminder of a feature already available in 5G: One physical cell ID (PCI) may belong to multiple TACs or even PLMN IDs, originally introduced to support shared networks across operators (e.g. MORAN).

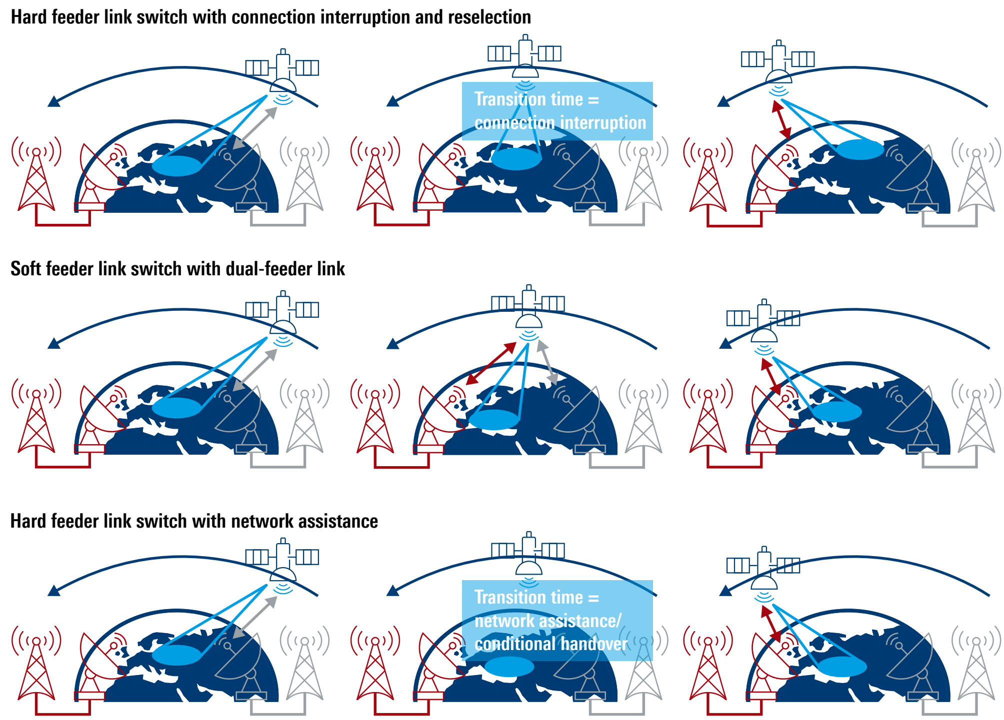
5.10 Feeder link switch

As outlined in the transparent mode architecture description (chapter 3), a satellite is connected via a ground gateway to the non-NTN gNB. The link between the satellite and the ground station is referred to as the feeder link and for reasons such as maintenance, capacity management or traffic offload and due to the movements of the satellite in the case of non-GEO, switching of the feeder link may become necessary. A major challenge is that the feeder link switch may result in transferring multiple established connections for all affected UEs. In addition, a feeder link switch may entail a transition between two gNBs or a change of AMF. Consequently, several procedural steps need to be discussed. The specification distinguishes between a hard and soft feeder link switch, depending on the capabilities of the satellite [TS 38.300].

For a soft feeder link switch, an NTN payload connection is able to cope with more than one gateway during a given period, i.e. a temporary overlap can be ensured during the transition between the feeder links. This requires the capability within the satellite to maintain at least two feeder link connections in parallel [Ref. 30]. Higher layers in the core network architecture are required to tackle duplication and packet loss.

For a hard feeder link switch, an NTN payload connection is established to one gateway at any given time, i.e. a radio link interruption may occur during the transition period between the feeder links. This requires some enhancement of the existing handover procedures and several possibilities exist.

Figure 63: Feeder link switch possibilities



The upper part of Figure 63 shows the hard feeder link switch for a transparent LEO constellation. The assumption shown is the transparent case where the ground stations on earth are connected to different gNBs, i.e. there will be a switch from gNB_1 to gNB_2, resulting in a cell change, even if the beam footprint stays unchanged. This scenario assumes the capability restriction that the satellite can only be served by one feeder link at a time. Based on the assumption of Release 15 NR, the RRC connections for all UEs served by the gNB_1 need to be dropped. The feeder link switch causes an interruption in the connection and most likely also a cell change. After gNB_2 takes over, the UEs may be able to find the reference signals corresponding to gNB_2 and perform initial access to a cell belonging to gNB_2 and re-establish the connection.

The middle part of Figure 63 shows one possible solution to enable service continuity for the soft feeder link switch. At the transition time, the satellite is served by two gateways at least until the time of completion of the feeder link switch. The advantage of this method is of course the seamless service continuity, minimizing the impact on the UEs. A challenging fact, besides the capability requirement for the satellite to support two simultaneous feeder links, is the handling of the cells in cases where both gateways on the ground are connected to different gNBs. One proposal to support such a soft feeder link switch in cases where different gNBs are involved is the idea that the two gNBs may utilize different radio resources of the satellite to ensure both gNBs are visible to the UE (overlapping coverage areas) simultaneously. During the switch period, the future gNB_2 may start transmitting the cell defining SSBs on synchronization raster points that are different from those of the gNB_1. The UE will initiate a handover procedure triggered by RRC control commands from gNB_1 to gNB_2. This could be a blind handover decision commanded by the network without previous measurements and its reporting or the RRC commands a handover assisted with measurement reports. It is also possible and up to the operator deployment to alternatively apply a configuration for a conditional handover (CHO; see chapter 5.7). One example of such a CHO parameterization could be a timer expiry definition to trigger the handover from gNB_1 to gNB_2. Furthermore, the mobility solution based on CHO may also need to mitigate the RSRP dependency. The reason is the fact that the UEs may observe very similar RSRP/RSRQ of the service links provided by the source and target gNBs, because the reference signals are transmitted from the same satellite. One solution may involve network implementation, e.g. setting proper event A5 thresholds for CHO to enable mobility. Event A5 defines that the primary cell becomes worse than absolute threshold 1, and that the neighbor becomes better than another absolute threshold 2. In addition, the CHO criterion configuration relies on radio propagation time instead or in combination with the RSRP/RSRQ radio measurements.

The lower part of Figure 63 shows the hard feeder link switch for transparent LEO constellation. The major difference to the hard feeder link switch presented in the upper part is that here the network will provide assistance information to the UE to reduce the interruption time and support the re-establishment of connections, similar to signaling procedures like network assisted cell change (NACC) in early RAT generations. If it is assumed that only one feeder link connection serving via the same satellite is applicable during the transition, this means that the signal of the serving cell will be not available during the transition period. To provide UE access to the serving cell again, two potential options are proposed:

- The feeder link hard switch procedure based on accurate time control and applying CHO information. The baseline for this procedure is an accurate timing control within the network and an isochronous interruption time. The network is able to predict and rely on the transition period time, i.e. the network knows exactly when, after the signaling from gNB_1 has stopped, the signaling from gNB_2 resumes. With such accuracy and a priori information, the network may configure a CHO procedure with the time information as the trigger condition. Consequently, the UE should not initiate the handover procedure immediately upon receiving the handover command. Instead, the UE should initiate the handover procedure after the target gNB is visible, and thus a handover activation time should be included in the handover command to all connected UEs.

- The feeder link hard switch procedure is based on conditional RRC re-establishment. Considering the large cell size of NTN, it might be a challenge for the gNB initiating the handover to send multiple handover commands to a large number of connected UEs in a short time. This poses the problem that probably some UEs may not be able to perform the handover in time. As a result, radio link failure (RLF) may be detected and then UEs initiate the RRC re-establishment procedure. A negative aspect is that such an RRC re-establishment will involve the RACH procedure and potentially result in a network overload situation. Unfortunately, such a hard handover may take a long time to restore the RRC connection, which may involve RLF detection, cell selection and potential re-establishment failure. Lastly, this may have a negative impact on the overall service continuity. To support the UE and avoid such long interruptions in service continuity, it may be beneficial for the network to provide assistance information (e.g. next cell identity and/or re-establishment conditions) to trigger UE RRC re-establishment instead. Different to methodologies known as network assisted cell change (NACC) where the information about the target cell is sent individually over bilateral RRC control plane connection, in the case of NTN scenarios the assistance information can be sent to UE via SIB instead of dedicated signaling in order to reduce the overall system overhead.

It is of course also possible that both gateways before and after the feeder link switch are connected to the same gNB and that theoretically the cell plus the connection can be kept alive and no handover occurs. This requires a number of details, e.g. exact timing of the downlink channels before and after the link switch, the maintenance of the reference signal configuration and also the gNB needs to keep the security keys unchanged to make this feeder link switch as transparent as possible to the UE.

In contrast, the feeder link switch with a change of gNB may also include a change of core network, i.e. the AMF change and procedures known from roaming such as PLMN handover then need to take place. For the sake of brevity, we will not delve further into these aspects.

5.11 NTN and inter-country mobility management

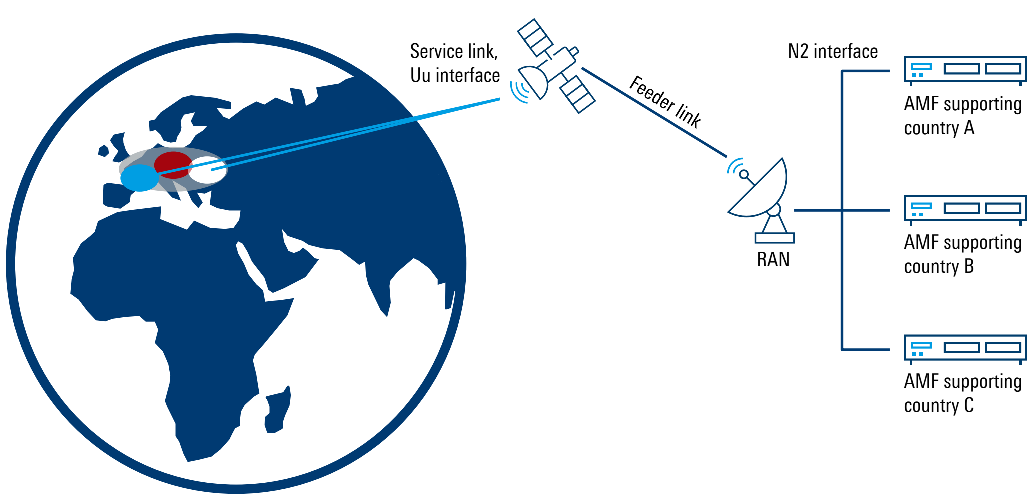
The study conducted by 3GPP to investigate use cases and service scenarios [TS 22.822] outlines the requirement for transborder service continuity. This includes situations where a satellite provides coverage across the border between country A and country B and connects to UEs in either country or, conversely, where a UE resident in country A may select satellite services offered by either satellite services from operator of country A or satellite services from operator of country B. An operator PLMN may have both terrestrial 3GPP access and NTN access. Logically, we understand each of the two RANs and each of the two N2 instances as separate and assume that they handle separate access types (see also Figure 21).

Current terrestrial 5G networks are typically deployed such that they provide radio coverage within a single country only, fulfilling the associated regulatory obligations for that specific country. On the other hand, NTN based networks may cover multiple countries or international regions, e.g. maritime oceans. 3GPP conducts further discussions and investigations on how to comply with legal and regulatory requirements in such transborder situations.

One technology extension is a logical separation between the NTN RAN and the 5GC functions, especially the AMF as mobility management anchor. The AMF may therefore need to verify that the UE is located in an area or country that the AMF is allowed to serve, and the RAN can be connected to different various AMFs (see Figure 64). The verification may be assisted by RAN.

The existing 5G mobility management needs to be extended to deal with access network coverage of the size of a satellite system. Put simply, a single country network of the past needs to be able to cope with worldwide connectivity services of the future. Furthermore, future scenarios where a single PLMN has both satellite and terrestrial 3GPP radio access and mobility of a UE moving between these two access types should be possible [TR 23.737].

Figure 64: NTN and inter-country mobility management



An NTN system architecture should support deployments where a satellite access network is shared between multiple core networks in an architecture that shares 5G multi-operator core networks (MOCN). In this case, the shared satellite RAN broadcasts system information for both PLMNs whose core networks are available. In addition, these PLMNs may also be with different mobile country codes (MCCs) [TR 23.737].

If, when the AMF is selected, the NG-RAN node detects that the UE is in a different country to that served by the AMF, the NG-RAN node implements the **NAS node selection function** behavior specified in [TS 38.410].

For RRC-connected UEs, if the NG-RAN node detects that the UE is in a different country to that served by the AMF, the NG-RAN should perform an NG handover to change to an appropriate AMF.

5.12 NTN UE power saving aspects

Obviously, UE energy consumption is essential for NTN capable devices, especially for IoT-NTN devices. NTN deployment objectives are remote areas and therefore it is likely that frequent recharging of the accumulator or frequent replacement of the battery may not be feasible. Devices may support energy harvesting methods and technologies, but those methodologies are not the focus of this chapter – we will concentrate instead on the radio frontend parts of NTN. At first glance, the power saving technologies introduced in the current RATs prevail and there is no reason for not implementing them (see [Ref. 1]). Mechanisms like discontinuous reception (DRX), power save mode (PSM), wake-up signals (WUS) or extended sleep mode work irrespective of the base station type. The objective of IoT-NTN standardization is to reuse as much as possible from terrestrial networks. An overview of these power saving technologies is provided in [Ref. 37] and [Ref. 1].

Cell acquisition – power saving aspects

A challenging aspect in NTN is the acquisition of the cell because, unlike terrestrial RATs, the NTN station is airborne and, especially in LEO constellations, the satellite is only visible for a short time. When the satellite appears above a certain elevation angle on the horizon, the acquisition of signal (AOS) is possible and, conversely, when the satellite dives below a minimum angle, the loss of signal (LOS) occurs. In addition, it is possible that there is no permanent coverage at a specific earth position. In such situations, the UE would not detect any satellite at all. To leverage cell acquisition, one assumption is that the satellite ephemeris and orbit information is partly known by the UE. Also, the requirement with respect to IoT-NTN devices is the support of GNSS capability to determine their terrestrial position. With such information, the UE may know a priori whether it would be worth starting cell acquisition or better to remain disconnected. Relaxation is to not mandate simultaneous operation of IoT-NTN and GNSS in a UE. This provisioning of ephemeris is essential, e.g. the UE pre-compensates the timing offset resulting from a long delay due to the large distance between the earth and the satellite station, and the UE pre-compensates the frequency offset resulting from a Doppler effect due to satellite mobility. Standardization must carefully take into consideration how much ephemeris information is regarded as necessary because memory size is limited. This is particularly important when contemplating situations where orbit constellations of thousands of LEO satellites need to be stored in the IoT-NTN device.

Tracking area update and cell selection – power saving aspects

Power consumption of the UE is also affected by a certain mobility, one notable example being the tracking area update (TAU) (see Figure 60). With NTN, a certain degree of network mobility is allowed, in particular the cell coverage mobility when contemplating moving beams with respect to the earth surface. A proposal within standardization organizations is the definition of earth-fixed tracking areas and allowing for multiple TACs per SIB, which has a positive influence on UE power consumption (see chapter 5.9).

In the assumption for potential deployments, IoT-NTN complements terrestrial IoT, but it is unlikely that a UE will not be in RRC idle mode simultaneously in NTN and terrestrial cells. To avoid a frequent and excessive number of cell reselections, a potential offset value Q_{offset} can be defined to influence the hysteresis for cell selection and reselection.

DRX in NTN

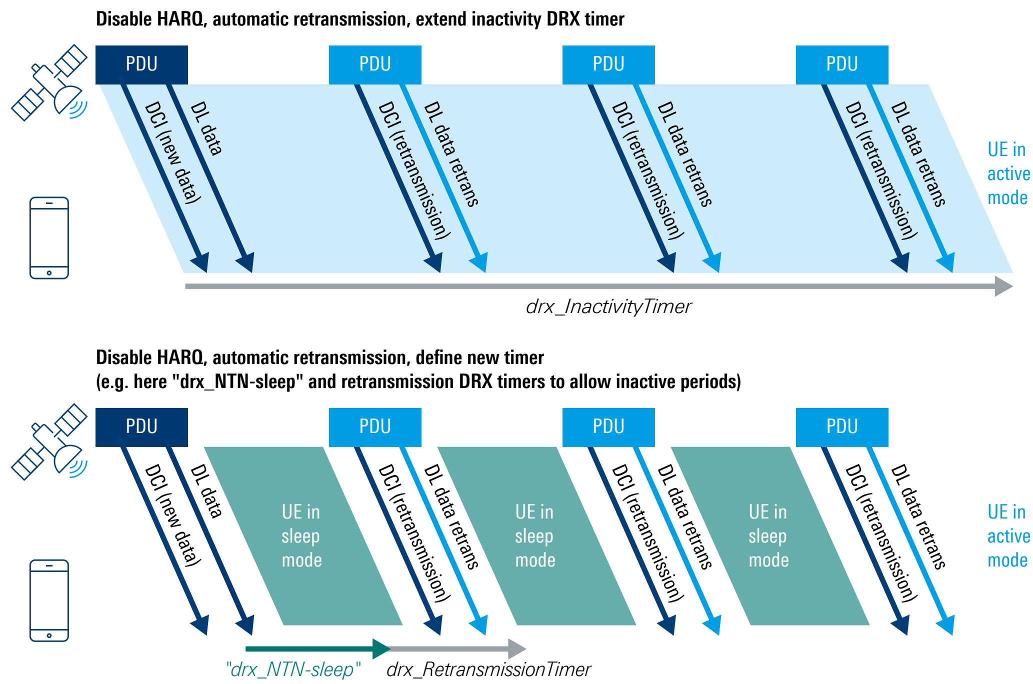
Discontinuous reception (DRX) represents an essential methodology with respect to power saving as it allows the configuration of inactivity times. The existing DRX configuration details continue to apply to NTN, but some adaptations are discussed.

Satellites travel with respect to the UE and do not provide permanent coverage. Assuming a network, configuration of a long DRX time and return of the UE to wake-up mode, it could be likely that the satellite(s) is/are no longer visible and that the UE consumes a great deal of electrical energy for the cell search. To avoid such situations, the UE is provided with ephemeris information and can determine whether there is any probability of detecting a satellite station, and will probably suspend and defer the cell search process.

Power saving aspects are influenced by the assumption that IoT-NTN targets a 1 % activity factor per UE, so it will be in energy saving mode most of the time. Note that like in terrestrial IoT there is no such QoS parameter support – services based on NTN communications are most likely best-effort QoS.

The HARQ process can operate in coordination with DRX for the sake of energy consumption purposes and the long delay mitigation strategy. With NTN, the number of HARQ processes can be extended, the HARQ can be disabled and, to leverage reliable communications, the network can opt for automatic blind retransmission. In combination with DRX procedures, the network would have to adjust the *drx_InactivityTimer*, already defined accordingly for Release 15, in order to make sure that the UE receives the blind retransmissions. The drawback of such an operation is the extended active mode causing higher power consumption. An alternative is the ongoing discussion regarding introduction of a new DRX timer. In the lower part of the example in Figure 65, the timer *drx_NTN-sleep* represents an example name of such a timer operation. The objective is to use this as a kind of NTN-dedicated inactivity period indicator within the *drx_InactivityTimer* period, allowing the UE to enter sleep mode in between consecutive blind retransmissions.

Figure 65: HARQ operation in conjunction with DRX – two examples

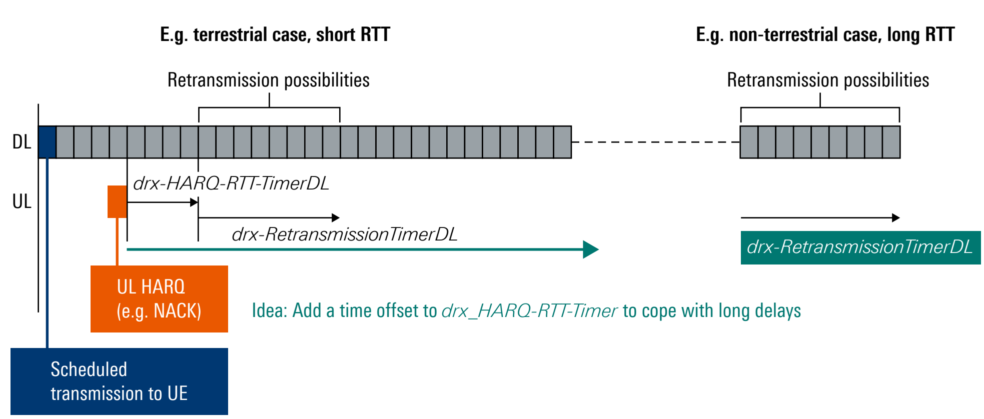


Another challenge occurring due to large RTTs in conjunction with DRX operation is the need to re-adjust the *drx_HARQTimer*. In 5G NR DRX operation, the UE starts this timer after the transmission of a HARQ acknowledgment. The timer defines the minimum time until the next expected retransmission for this specific HARQ process occurs. The *drx_RetransmissionTimer* activates the UEs reception for PDCCH scheduling. The consequence of a large delay is the exceedance of the timer duration by a HARQ retransmission. The countermeasure, as shown in Figure 66, is to introduce an optional offset for this *drx_HARQ_RTT-Timer*. This timer can be set either to zero or to disabled.

A possible extension of the 5G technology could be that the timers for the DRX operation are controlled by MAC control elements (MAC CE) and the RRC layer (see [Ref. 1] for details) and, to facilitate fast activation and deactivation, that possibly the DCI scheduling messages can control these timer behaviors in an NTN network.

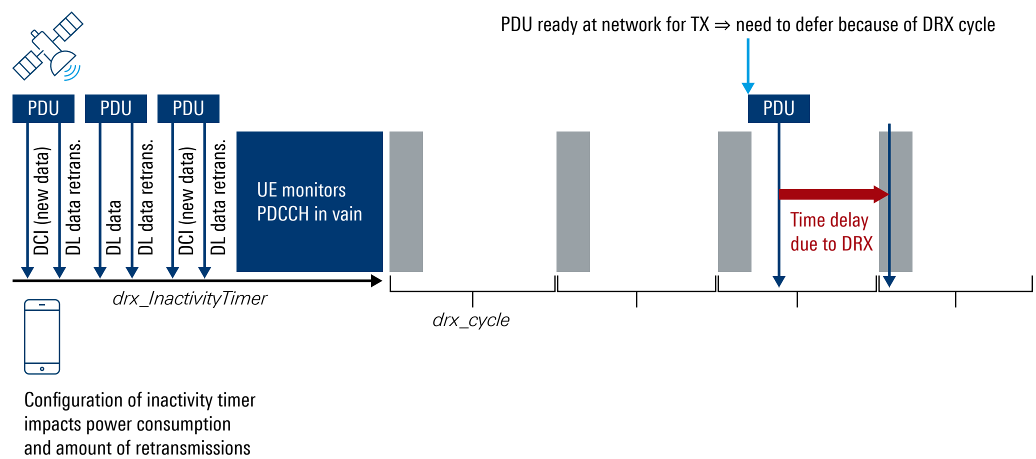
Figure 66: Impact onto existing DRX timers for HARQ and retransmission due to long delay

DRX with DL PDU transmission and NACK



The setting and configuration of the DRX timers is crucial and plays a pivotal role with respect to power saving and the overall impact on the latency experienced in the end-to-end data connection. As of the long delay, the network may configure long or short periods of DRX cycles. The examples provided in Figure 67 show such effects. First, the configuration of the DRX inactivity timer has an impact on the number of blind retransmissions and consecutive data PDUs that could be successfully received in the case of deactivated or reduced HARQ operation. Secondly, a long DRX cycle length offers a beneficial effect on energy consumption but would create an additional delay because, if the network has a PDU ready for transmission, it may defer it because of a running DRX cycle.

Figure 67: Impact on DRX timers due to long delay – two examples



A future prospect supporting power saving modes is the swarm behavior of IoT devices and the configuration of a "collector" UE. 3GPP Release 17 adds a relay mechanism to enhances the sidelink operation originally targeting V2X services. We may now assume that an IoT device that has enhanced energy capability and provides the IoT-NTN connection to the satellite, collects and stores the data of the individual end user IoT devices plus relays the radio link.

6 TECHNOLOGY OUTLOOK, SUMMARY AND CONCLUSION

6.1 NTN within 3GPP Release 18 – outlook beyond Release 18

The 3GPP Release 17 timeline describes a status freeze in summer 2022. Nevertheless, in summer 2021 3GPP started a quest for topics for the upcoming releases and during the December 21 meeting a formal approval of Release 18 work items was issued. As expected, Release 18 will continue with the technology evolution of NTN within 5G systems and several new features will be discussed with regard to their incorporation into 5G NR. While Release 17 is considered as the inception of NTN into 5G and the primary focus is on transparent mode architecture, FR1 frequency ranges and NR-NTN as first service and use case, the upcoming release will work on the extension of NTN functionality. From a use case perspective, the separation of NR-NTN and IoT-NTN will be retained, but Release 18 will work on the incorporation of methodologies to enable satellite based communications also for IoT devices, and enhance the NR-NTN use cases. Objectives aligned with the technology evolution are an increased feeder link capacity, a lower power consumption on the UE side due to enhancements in efficiency, lower costs of the end user terminals, especially the VSAT type UE. On the satellite side, the technology enhancements should enable the deployment of smaller satellites. Certain technology features will be discussed with regard to inclusion of Release18 and beyond.

Frequency extension to FR2 for NTN is a work item to enable frequencies beyond 10 GHz for NTN. This includes the discussion regarding the Ka or Ku-bands as described in chapter 3.2. As before, challenges are the definition of FDD duplex mode in FR2 (FR2 is solely used for TDD) and secondly the definition of the gap between FR1 and FR2 to potentially enable frequencies within the range from 8 GHz to 24 GHz. In addition, frequencies in the Q-, V- and E-bands are potential future candidate frequencies for NTN.

Regenerative mode architecture is a discussion topic to extend the transparent mode by allowing more onboard processing power in the satellite and converting this satellite step by step into an autonomous flying gNB as a long-term objective. Details on the regenerative mode are already described in chapter 3.10.3.

UE supporting NTN without positioning capabilities. While Release 17 assumes a UE capable of NTN connectivity also supporting positioning capabilities, e.g. GNSS, with Release 18 this feature is no longer a must. There is a work item on network-verified UE location allowing the network to either localize the UE or to verify the reported UE location.

NR-NTN and terrestrial NR mobility is a work item to enhance the mobility scenarios by enabling handover between terrestrial and NTN 5G and introducing sophisticated setups like dual connectivity between terrestrial and NTN links.

Coverage enhancements supporting voice over NTN

High altitude platform system (HAPS) support, extending the architecture structure by allowing additional airborne station types besides the satellite type node.

IoT-NTN performance and power consumption enhancements start with the assumption of intermittent delay-tolerant small-packet transmissions as a prioritized use case like in Release 17. Enhancements will include optional HARQ feedback disabling, improved GNSS operation during long connection times and reduced GNSS power consumption in idle periods.

IoT-NTN with a focus on discontinuous coverage enhancements will discuss power saving mechanisms in sparse constellation scenarios, i.e. to avoid energy consumption due to futile satellite or cell search procedures. Also, enhancements for RRC re-establishment procedures in discontinuous coverage situations will be part of the Release 18 work items.

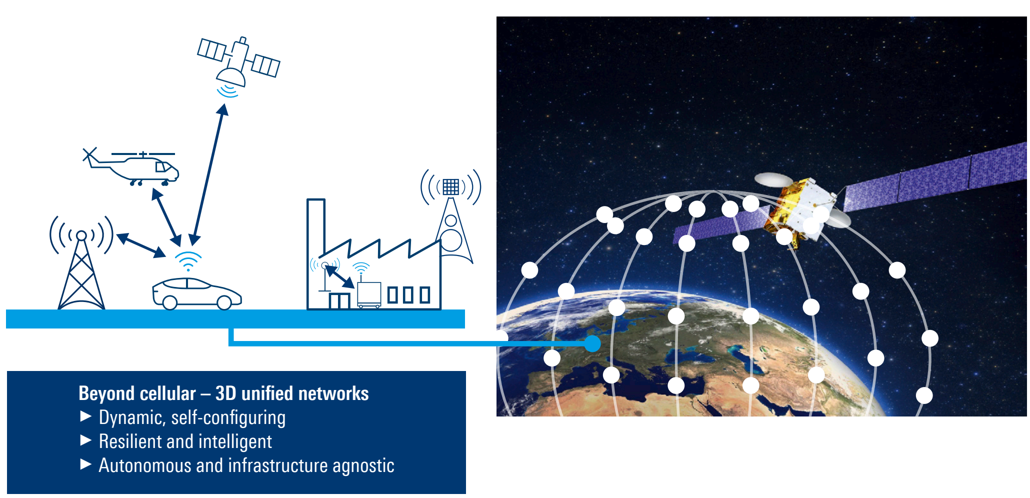
Mobility enhancements for IoT-NTN will adjust some procedures for efficiency reasons. Note that with IoT there are no handover procedures in general, thus, mobility is enhanced by updated RRC re-establishment mechanisms. One idea is, for example, conditional RRC re-establishment where the network and the UE may configure conditions when a connection is assumed to be re-established. The motivation here is to save RACH overhead. For the MTC type of IoT where handover is possible, the idea is to configure similar mobility procedures like NR-NTN as e.g. the location or timing based conditional handover. To bridge between capacity and mobility, the NB-IoT features from Release 17 radio link failure and carrier selection enhancements will probably be adopted for IoT-NTN as well.

IoT-NTN store and forward behavior is a technology that inherits sidelink connectivity originally introduced for vehicle-to-everything (V2X) communications and bridges the gap between satellite addressability and energy consumption. A UE with better power capabilities may offer a data collection service to UEs for which energy consumption is an important consideration, and when a satellite becomes addressable, this UE will forward those data packets to the network.

6.2 Long-term outlook regarding NTN evolution – path towards 6G?

If we summarize the technology evolution with respect to NTN in simple terms, we ascertain that 5G NR is originally designed as a terrestrial based public land mobile network. 3GPP states that with Release 17 5G introduction of NTN, satellite based communication should be made possible, but with minimal impact on 5G, thus only those adaptations will be made that are technically necessary. In the long term, e.g. the path towards 6G, we will move on from the cellular behavior of networks [Ref. 4]. Buzzwords are 3D networks or organic networks. So 6G will consist of dynamic, multiple and intelligent nodes with onboard computing power and multi-access edge computing functionality, interconnected and moving relative to each other. Thus, all platform altitude layers from its inception, ranging from indoor small cells, city macro and high-power high-tower umbrella cells up to low/high altitude platforms culminating in spaceborne LEO and GEO constellations.

Figure 68: Evolution to 3D unified networks



Anticipated 6G technology facets and research activities:

- Network nodes are dynamic, they can enter the network or leave on the fly, coordination between neighbor cells is done automatically

- Network nodes will become autarchic; even without connection to the core network, they can provide communication services. A buzzword talks about resilient networks and digital sovereignty

- Unified networks, i.e. enhancement of network slicing by offering multiple access technologies, i.e. the user service selects the best RAT for specific use cases to obtain optimized QoS

- AI methods incorporated in the network to coordinate inter-node signaling and traffic routing and dynamic network constellations on the one hand. The objective is node autonomy to enable real-time satellite decisions and seamless control. On the other hand, AI methods will be used to route traffic, provide services with best QoS (network slicing using intelligent nodes, i.e. MEC mechanisms)

- Multi-access edge computing (MEC) is much more than just a data cloud. It means onboard computing power, i.e. scheduling decisions, slice selection, QoS profiles negotiation and inter-node coordination

- Enhancements on the random access channel to avoid RACH capacity overloading of a single satellite by introducing non-orthogonal medium access (NOMA) with successive interference cancellation (SIC) methods [Ref. 31]

- Joint communication techniques for spectrum efficiency improvement, applying multiple satellites, e.g. MIMO transmission using two satellites as TX points to overcome the dominant LOS influence and create link de-correlation

- Enhanced and sophisticated methods for spectrum coordination, inter-node signaling procedures for handover and mobility scenarios and agile methods leaving the static architecture of legacy networks

- Security aspects require a redesign because nodes may enter and leave the network and devices possess different shape and form factors. Envisagement of new security concepts on top of the current symmetric authentication mechanism needs to be put into place.

- Architecture evolution of NTN: In Release 17, 3GPP discusses a transparent mode architecture, e.g. the gNB is on the ground and connected via a gateway to the satellite and the satellite provides radio access. Both the feeder and service link are 5G NR. In later releases, the regenerative mode will be introduced, i.e. the satellite has onboard processing and behaves as entire gNB, but is still connected to the ground based core. In the long term, a node will inherit further core network functions and operate independently and autonomously.

- Architecture evolution by connecting UAV based gNBs via satellite backhaul to terrestrial core network functions [Ref. 4]

-

- Holographic radio to control the physical space through intelligent surfaces with the objective of improving spectral efficiency and network capacity

- Free space optical (FSO) or laser based non-RF radio to compensate for atmospheric distortion and to offer ultra-low latency services. Potentially realized as hybrid architecture providing RF and FSO connectivity

6.3 Summary and conclusion

3GPP Release 17 introduction of NTN is assumed to provide a kickstart to the broad satellite mass market applications with several applications. The last decade of progress in telecommunications has been characterized by the rapid proliferation of smart devices providing ubiquitous internet connectivity, important technological advancements like the 5G system with its tremendous flexibility, and the exponential growth in demand for new services. Telecommunication services have advanced from a "nice to have" approach like the first telephone calls, up to the basic necessities and requirements of what modern infrastructure should provide. Governments consider the provision of internet access services as having the same importance level as e.g. nutrition and water supply, energy provision, healthcare and educations systems. As one driving motivation, we therefore observe the requirement for worldwide connectivity all over the globe, in rural or remote areas, local hotspots and even maritime regions. The obvious advantage of satellites is that they allow network coverage in such remote areas or maritime regions with feasible technical complexity and cost attractiveness. The technology evolution within aerospace ecosystems has trailblazed these connectivity use cases. Another aspect worthy of mention is the reduced vulnerability against natural disasters, which improves the resilience, but this comes at the expense of sensitivity to other atmospheric effects e.g. sun storms. Put simply, if satellites play an essential cornerstone in navigation systems (GNSS), the question arises as to why they cannot play an equally essential role in communications as well. This question will be answered by 3GPP Release 17 and later. Satellite based communications will evolve further, starting from a basic service provider with, let's say, best-effort QoS and the main objective being "coverage" all the way to sophisticated methods like vagabonding networks, intelligent ad-hoc backhaul connections and, in the long term, culminating in aspects like organic and cell-free networks. The two ecosystems wireless communications and satellite connectivity will converge and their cooperation will leverage the deployment of satellite services. From a technical perspective, there will be a number of challenges, e.g. the long latency as the large distance between the UE and satellite will always be one characteristic of NTN. There will be countermeasures to mitigate these effects, like the introduction of HAPS, MEC functionality in the satellites and the regenerative architecture, but obviously an NTN connection cannot achieve the same latency as a small-cell indoor scenario. Other technical challenges like the extended timers, the architecture enhancements from transparent to regenerative mode and the frequency adjustment will pose challenges for academic and engineering teams, but progress here is anticipated. It is obvious that NTN inherits unique effects and sometimes provides a technology paradigm change. One notable example is the motion of the "base station" or, better said, satellite, which constitutes a paradigm change in wireless evolution. Research will continue to enhance existing mechanisms for mobility, propagation delay and resource allocation. New research areas will be the evolution to organic networks with cell birth-death behavior, vagabonding network components and intelligent traffic management like sophisticated ISL control across the satellites. So, we understand the incorporation of NTN into the 5G system with Release 17 as being the advent of a new technology evolution fostering and driving the worldwide proliferation of wireless communications systems and Rohde & Schwarz is proud to accompany these technology evolutions with our expertise in test and measurement and satellite connectivity.

7 REFERENCES

[Ref. 1] 5G New Radio Fundamentals procedures, testing aspects, M. Kottkamp, A. Pandey, D. Raddino, A. Roessler, R. Stuhlfauth, Rohde & Schwarz technology book, PW 3642.6376.00, ISBN 978-3-939837-15-2, 5th edition, 2022, www.rohde-schwarz.com/5G-ebook

[Ref. 2] Over-the-air RF conformance measurements on 5G NR devices, H. Mellein, R. Stuhlfauth, Rohde & Schwarz white paper, PD 3609.5897.52, March 2021

[Ref. 3] Antenna Theory, C. A. Balanis, Wiley & Sons Editor, 2005

[Ref. 4] Non-Terrestrial Networks in 5G & Beyond: A Survey, F. Rinaldi, H-L. Määttanen, J. Torsner, S. Pizzi, S. Andreev, A. Iera, Y. Koucheryavy, G. Araniti, IEEE Access, September 2020

[Ref. 5] 3GPP nonterrestrial networks, A. Anttonen, P. Ruuska, M. Kiviranta, VTT Technical Research Centre of Finland, January 2019

[Ref. 6] Short Range Inter-satellite Link for Data Transfer and Ranging using IEEE 802.11n, V. Shah, C. Ritesh Patel, C. Rikin Nayak, International Journal of Computer Applications (0975 – 8887) Volume 164 – No 1, April 2017

[Ref. 7] ITU World radiocommunications conference 2019 (WRC-19), Final acts, 28 October to 22 November 2019, Sharm-El Sheikh

[Ref. 8] Free Space Optical Communication: Challenges and Mitigation Techniques, H. Kaushal, G. Kaddoum, no. January, 2017, pp. 119 to 137

[Ref. 9] HEUMEGA, Independent Trend Analysis on the Topic of Megaconstellations, DLR, June 2021

[Ref. 10] 5G from Space: An Overview of 3GPP Non-Terrestrial Networks, Xingqin Lin, Stefan Rommer, Sebastian Euler, Emre A. Yavuz, Robert S. Karlsson, Ericsson, June 2021

[Ref. 11] 5G Radio Access Network Architecture, The dark side of 5G. S. Sirotkin, Wiley Press 2021, ISBN 978-1-119-55088-4

[Ref. 12] 5G & Non-terrestrial networks, 5G Americas Whitepaper, February 2022

[Ref. 13] Frequency arrangements for implementation of the terrestrial component of International Mobile Telecommunications in the bands identified for IMT in the Radio Regulations, Recommendation ITU-R M.1036-6, October 2019

[Ref. 14] Satellite Communications Systems: Systems, Techniques and Technology, G. Maral, M. Bousquet, Z. Sun, Wiley Editors, April 2020, ISBN 978-1119382089

[Ref. 15] 3GPP R4-2115640 TSG-RAN WG4 Meeting #100-e, August 2021

[Ref. 16] NewSpace terminal testing challenges and considerations, M. Hammond, Rohde & Schwarz white paper, PD 3609.3865.52, June 2019

[Ref. 17] Satellite Communications in the 5G Era, S. K. Sharma, S. Chatzinotas, P. Arapoglou, IET, September 2018, ISBN 978-1-78561-427-9

[Ref. 18] Sat5G project, www.sat5g-project.eu

[Ref. 19] ITU radio regulations, Articles, Edition of 2016

[Ref. 20] Mastering the challenges of NewSpace satellite constellations, T. Willuhn, Rohde&Schwarz white paper, PD 3683.6093.52, February 2022

[Ref. 21] A Dual-Polarized 1024-Element Ku-band SATCOM Transmit Phased-Array with ±70° Scan and 43.5 dBW EIRP, G. Gültepe, S. Zihir, T. Kanar, G. Rebeiz, IEEE MTT-S, 2020

[Ref. 22] 5G's future is hybrid – the non-terrestrial opportunity, white paper, Mobile World Live and Cambridge Consultants, 2021

[Ref. 23] High Altitude Platform Systems – Towers in the Skies, GSMA white paper, version 2.0, February 2022 www.gsma.com/futurenetworks/resources/high-altitude-platform-systems-towers-in-the-skies-version-2-0

[Ref. 24] SpaceX continues Starlink deployment with latest launch, J. Foust, SpaceNews, May 2021, https://spacenews.com/spacex-continues-starlink-deployment-with-latest-launch/

[Ref. 25] London-based global communications company OneWeb raises funding from SoftBank and Hughes to fund its satellite fleet, Silicon Canals, January 2021, https://siliconcanals.com/news/startups/london-oneweb-gets-fund-softbank/

[Ref. 26] Guowang, Renamed China SatNet, Will Be China's Global Broadband Provider, L. Press, CircleID, March 2021, https://circleid.com/posts/20210329-guowang-starlink-will-be-chinas-global-broadband-provider/

[Ref. 27] Dynamic SDN Controller Placement in a LEO Constellation Satellite Network, A. Papa, T. de Cola, P. Vizarreta, M. He, C. Machuca, W. Kellerer, IEEE, 2018

[Ref. 28] Survey on Optimization Methods for LEO-Satellite Based Networks with Applications in Future Autonomous Transportation, K. Celikbilek, Z. Saleem, R. Ferre, J. Praks, E. Lohan, Sensors MDPI, February 2022

[Ref. 29] ITU-R S.1503 recommendation, WRC-97, 2000

[Ref. 30] Signal Processing for High Throughput Satellite Systems: Challenges in New Interference-Limited Scenarios, A. Perez-Neira, M. Vazquez, S. Maleki, M. Shankar, S. Chatzinotas, IEEE Signal Processing Magazine 36, February 2018

[Ref. 31] LEO Small-Satellite Constellations for 5G and Beyond-5G Communications, I. Leyva-Mayorga, B. Soret, M. Röper, D. Wübben, B. Matthiesen, A. Dekorsy, A. Popovski, IEEE Access, October 2020

[Ref. 32] A Technical Comparison of Three Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband, I. del Portillo, B. Cameron, E. Crawley, Acta Astronautica, Vol 159, June 2019

[Ref. 33] A logic-efficient recursive Doppler rate estimation processor for LEO satellites, M. Krondorf, S. Bittner, IEEE 3rd 5G world forum, September 2020

[Ref. 34] Towards the implementation of advanced random access schemes for satellite IoT, M. Krondorf, M. Goblirsch, R. de Gaudenzi, G. Cocco, N. Toptsidis, G. Acar, International journal of satellite communications and networking, November 2019

[Ref. 35] RFIC Silicon based phased arrays and transceivers, G. M. Rebeiz, University of San Diego, IEEE RFIC conference, June 2017

[Ref. 36] Active multi-beam antennas – Testing the drivers for advanced satellite concepts, Rohde&Schwarz webinar, www.rohde-schwarz.com/knowledge-center/webinars/webinar-active-multi-beam-antennas-registration_254213.html

[Ref. 37] Power saving methods for LTE-M and NB-IoT devices, Y. Shi, Rohde & Schwarz white paper, PD 3609.3820.52, June 2019

[Ref. 38] Digital Video Broadcast (DVB) alliance, technical specifications, https://dvb.org/specifications/

Note: All links have been checked and were functional when this document was created. However, we cannot rule out subsequent changes to the links in the reference list.

8 SPECIFICATIONS

TR 23.754, 3GPP TR 23.754	Study on supporting Unmanned Aerial Systems (UAS) connectivity, Identification and tracking (Release 17)
TR 23.737, 3GPP TR 23.737	Study on architecture aspects for using satellite access in 5G (Release 17)
TR 36.763, 3GPP TR 36.763	Study on Narrow-Band Internet of Things (NB-IoT)/enhanced Machine Type Communication (eMTC) support for Non-Terrestrial Networks (NTN) (Release 17)
TR 38.811, 3GPP TR 38.811	Study on New Radio (NR) to support non-terrestrial networks (Release 15), September 2020
TR 38.901, 3GPP TR 38.901	Study on channel model for frequencies from 0.5 to 100 GHz (Release 16), December 2019
TR 38.913, 3GPP TR 38.913	Study on Scenarios and Requirements for Next Generation Access Technologies (Release 16), July 2020
TR 38.821, 3GPP TR 38.821	Solutions for NR to support non-terrestrial networks (NTN) (Release 16), December 2019
TR 38.863, 3GPP TR 38.863	Non-terrestrial networks (NTN) related RF and co-existence aspects (Release 17), January 2022
TR 22.822, 3GPP TR 22.822	Study on using Satellite Access in 5G; Stage 1 (Release 16), May 2018
TS 23.122, 3GPP TS 23.122	Non-Access-Stratum (NAS) functions related to Mobile Station (MS) in idle mode (Release 17), December 2021
TS 24.501, 3GPP TS 24.501	Non-Access-Stratum (NAS) protocol for 5G System (5GS), Stage 3 (Release 16), June 2020
TS 23.501, 3GPP TS 23.501	System architecture for the 5G System (5GS), Stage 2 (Release 17), December 2021
TS 38.300, 3GPP TS 38.300	NR; NR and NG-RAN Overall description, Stage 2 (Release 16), December 2021
TS 38.101, 3GPP TS 38.101	User Equipment (UE) radio transmission and reception (Release 17), December 2021
TS 38.101-5, 3GPP TS 38.101-5	User Equipment (UE) radio transmission and reception, Part 5: Satellite access Radio Frequency (RF) and performance requirements (Release 17), first skeleton draft, March 2022
TS 38.104, 3GPP TS 38.104	Base Station (BS) radio transmission and reception (Release 17), December 2021
TS 38.108, 3GPP TS 38.108	Satellite Access Node radio transmission and reception (Release 17), first draft, January 2022
TS 38.181, 3GPP TS 38.181	NR; Satellite Access Node conformance testing (Release 17), skeleton draft, April 2022
TS 38.213, 3GPP TS 38.213	Physical layer procedures for control (Release 17), December 2021

TS 38.214, 3GPP TS 38.214	Physical layer procedures for data (Release 17), December 2021
TS 38.410, 3GPP TS 38.410	NG-RAN; NG general aspects and principles (Release 16), October 2021
R4-2111460, 3GPP	TSG-RAN WG4 Meeting no. 99, On the Rx Parameters and Rx Testing Setup for NTN gNB, May 2021
R2-1818511, 3GPP	TSG-RAN WG2 Meeting no. 104, Considerations on MAC Timers and on RTD Compensation Offset in Non-Terrestrial Networks (NTN), November 2018
R2-1818512, 3GPP	TSG-RAN WG2 Meeting no. 104, Considerations on RLC Control Loops and Timings in Non-Terrestrial Networks (NTN), November 2018
R2-1818513, 3GPP	TSG-RAN WG2 Meeting no. 104, Considerations on PDCP Control Loops and Timings in Non-Terrestrial Networks (NTN), November 2018
RP-193234, 3GPP	TSG-RAN plenary meeting no. 78, NR-NTN: Spectrum for non terrestrial networks, December 2017
RP-212144, 3GPP	TSG-RAN Meeting no. 93, Study on NR-NTN satellite deployment in bands above 10 GHz (FR2), September 2021
R2-1914195, 3GPP	TSG-RAN WG2, Meeting no. 107bis, Ephemeris data, October 2019
R1-2200780, 3GPP	TSG-RAN WG1 Meeting no. 107bis, Updated RAN1 UE features list for Rel-17 NR after RAN1 #107bis-e, January 2022
R2-2007574, 3GPP	TSG-RAN WG2 Meeting no. 11-e, Considerations on satellite ephemeris, August 2020
ITU-R Recommendation P.2109	Prediction of building entry loss, www.itu.int/rec/R-REC-P.2109-1-201908-I/en
ITU-R Recommendation P.676	Attenuation by atmospheric gases and related effects, www.itu.int/rec/R-REC-P.676
ITU-R Recommendation P.618-13	Propagation data and prediction methods required for the design of Earth-space telecommunication systems, www.itu.int/rec/R-REC-P.618/en
ITU-R Recommendation P.681	Propagation data required for the design systems in the land mobile-satellite service, www.itu.int/rec/R-REC-P.681/en
ITU-R Recommendation M.1036-6	Frequency arrangements for implementation of the terrestrial component of International Mobile Telecommunications (IMT) in the bands identified for IMT in the Radio Regulations, www.itu.int/rec/R-REC-M.1036

Note: All links have been checked and were functional when this document was created. However, we cannot rule out subsequent changes to the links in the reference list.

9 ABBREVIATIONS

Term	Explanation
5G NR	5G New Radio
3GPP	3rd Generation Partnership Program
5GC	5G core network
5GMM	5G mobility management
A	
ACIR	Adjacent channel interference ratio
ACLR	Adjacent channel leakage ratio
AF	Application function
AM	Acknowledged mode
AMF	Access and mobility management function
AoA	Angle of arrival (azimuth)
AoD	Angle of departure (azimuth)
AOS	Acquisition of signal
AsA	Angle spread of arrival (azimuth)
AsD	Angle spread of departure (azimuth)
ATG	Air to ground
ATP	Acquisition, tracking and pointing
B	
BSR	Buffer status report
BSS	Broadcast satellite services
BWP	Bandwidth part
C	
CDL	Clustered delay line
CE	Control element
CL	Clutter loss
CORESET	Control and resource set
CP	Control plane
CPE	Customized premises equipment
CSI	Channel status information
CSI-RS	CSI reference signal
CU	Centralized unit
D	
DC	Dual connectivity
DCI	Downlink control information
DL	Downlink
DRX	Discontinuous reception
DU	Distributed unit
E	
E2E	End to end
ECEF	Earth-centered, earth-fixed
EPS	Evolved packet core (LTE core network)
ESA	European Space Agency
ESA	Electronically steerable phased array antenna
EVM	Error vector magnitude

Term	Explanation
F	
FCC	Federal Communications Commission (US regulator)
FDD	Frequency division duplex
FoM	Figure of merit
FoV	Field of view
FPA	Flat panel antenna array
FSO	Free space optical
FSPL	Free space path loss
FSS	Fixed satellite services
G	
GEO	Geostationary earth orbit
GNSS	Global navigation satellite services
GSCN	Global synchronization channel number
H	
HAPS	High altitude platform system
HARQ	Hybrid automatic repeat request
HPA	High power amplifier
HPHT	High-power high-tower
HTS	High throughput satellite
I	
IAB	Integrated access backhaul
IE	Information element
IMT	International Mobile Telecommunications
IOT	In-orbit testing
IoT	Internet of things
ISL	Inter-satellite link
ITU	International Telecommunication Union
L	
LAPS	Low altitude platform system
LEO	Low earth orbit
LHCP	Left-hand circular polarization
LNA	Low noise amplifier
LOS	Line of sight
M	
MAC	Medium access control
MCG	Master cell group
MCS	Modulation and coding scheme
MCX	Mission critical communications
MEC	Multi-access edge computing
MEO	Medium earth orbit
MIMO	Multiple input multiple output
MNO	Mobile network operator
MOCN	Multi-operator core network
MPP	Multipath propagation
MSS	Mobile satellite services
MTC	Machine type communications
N	
NAS	Non-access stratum
NF	Noise figure
NGSO	Non-geostationary satellite orbits
NLOS	Non line of sight
NR	New Radio
NR-ARFCN	New Radio absolute radio frequency channel number
NSA	Non-standalone
NTN	Non-terrestrial networks

Term	Explanation
O	
O2I	Outdoor to indoor
O-ISL	Optical ISL
O-RAN	Open RAN Alliance (www.o-ran.org)
O-CU	O-RAN centralized unit
O-DU	O-RAN distributed unit
O-RU	O-RAN radio unit
OBP	Onboard processor
OFDMA	Orthogonal frequency division multiple access
OTA	Over-the-air
P	
PAPR	Peak-to-average power ratio
PCF	Policy control function
PCI	Physical cell identity
PDCCH	Physical downlink control channel
PDCP	Packet data convergence protocol
PDSCH	Physical downlink shared channel
PDU	Protocol data unit
PH	Power headroom
PL	Path loss
PLMN	Public land mobile network
PPDR	Public protection and disaster relief
PRACH	Physical random access channel
PSM	Power save mode
PUCCH	Physical uplink control channel
PUR	Preconfigured uplink resource
PUSCH	Physical uplink shared channel
PVT	Position, velocity and time
Q, R	
QoE	Quality of experience
QoS	Quality of service
RAC	Registration area code
RACH	Random access channel
RAN	Radio access network
RAR	Random access response
RAT	Radio access technology
RF	Radio frequency
RF-ISL	Radio frequency ISL
RHCP	Right-hand circular polarization
RLC	Radio link control
RRC	Radio resource control
RRM	Radio resource management
RSRP	Reference signal received power
RSRQ	Reference signal received quality
RSSI	Received signal strength indicator
RTT	Round-trip time
RX	Reception

Term	Explanation
S	
SA	Standalone
SAN	Satellite access node
SCG	Secondary cell group
SCS	Subcarrier spacing
SDAP	Service data adaptation protocol
SDO	Standard developing organization
SF	Shadow fading
SFN	System frame number
SIB	System information block
SMF	Session management function
SMO	Service, maintenance and orchestration
SMTC	SSB-based measurement timing configuration
sNB	Satellite NodeB
SNO	Satellite network operator
SR	Scheduling request
SRI	Satellite radio interface between gateway and satellite
SSB	Synchronization signal and PBCH block
T	
TA	Tracking area
TA	Timing advance
TAC	Tracking area code
TAI	Tracking area index
TAU	Tracking area update
TCI	Transmission configuration indication
TDD	Time division duplex
TDL	Tapped delay line
TLE	Two-line-element
TM	Transparent mode
TM-TC	Telemetry and telecommand
TTI	Transmit time interval
TX	Transmission
U	
UAS	Unmanned aerial system
UAV	Unmanned aerial vehicle
UE	User equipment
UL	Uplink
UM	Unacknowledged mode
UP	User plane
UPF	User plane function
USIM	UMTS subscriber identity module
UxNB	UAV integrated NodeB
V, W	
VSAT	Very small aperture terminals
WCRTT	Worst-case round-trip time
WRC	World radio conference
WUS	Wake-up signal
X, Z	
XPR	Cross-polarization ratio
ZoA	Angle of arrival (zenith)
ZoD	Angle of departure (zenith)
ZsA	Angle spread of arrival (zenith)
ZsD	Angle spread of departure (zenith)

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