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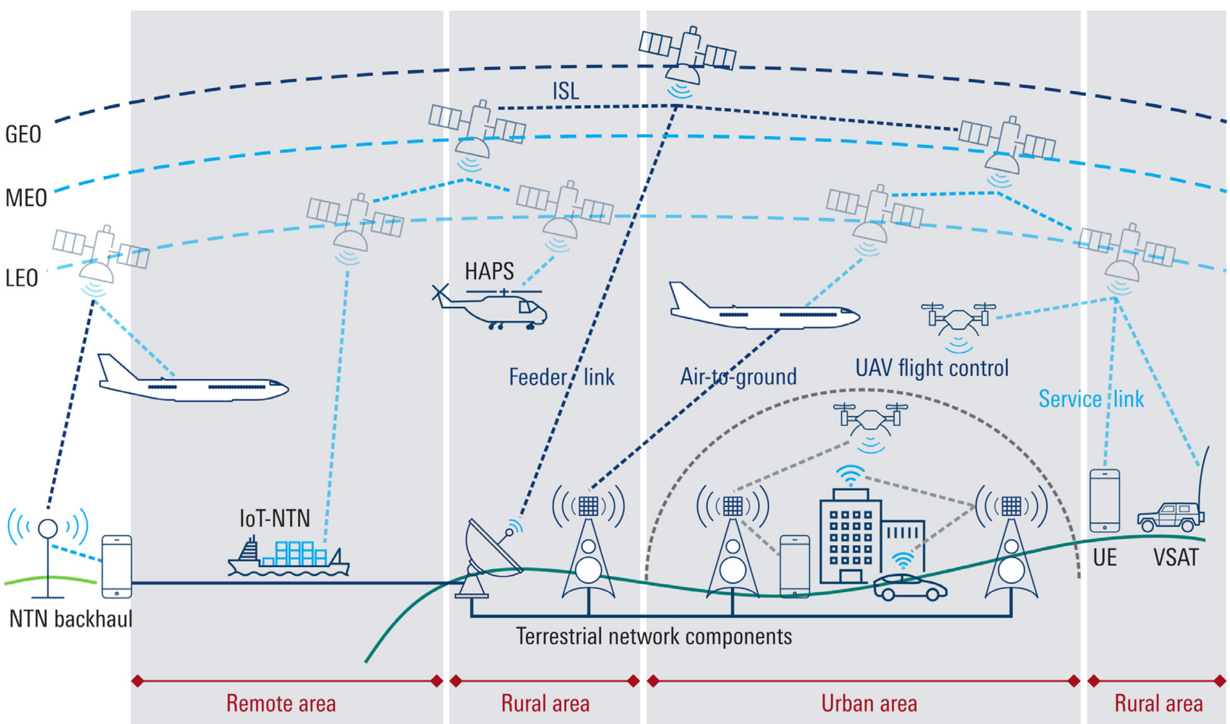
Non-Terrestrial Network Technology from a 3GPP Perspective

In 5G, non-terrestrial networks represent a plethora of connection scenarios from satellite-based communications via airborne stations, considering situations like air-to-ground or flight control of UAVs.

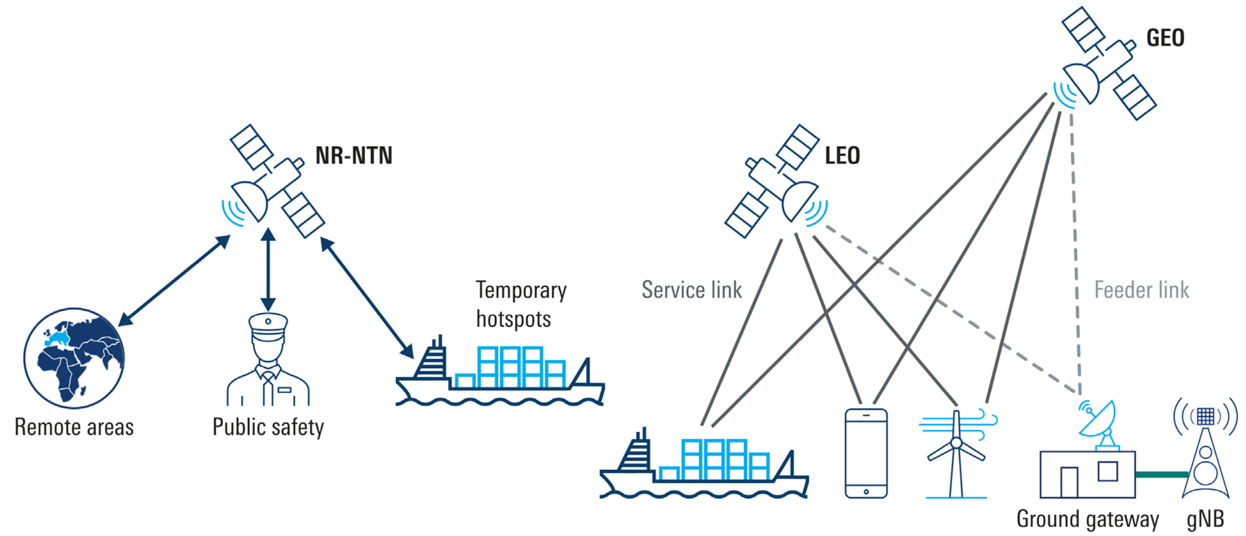
In 5G, non-terrestrial networks come in an array of connection scenarios, from satellite-based communications via airborne stations—e.g., air-to-ground or flight control of unmanned aerial vehicles (UAVs). This article gives a concise technology overview of the different network variations.

These include various satellite-based connectivity scenarios in which satellites differ in flying altitude and coverage area. To incorporate non-terrestrial networks (NTNs), 3GPP launched a Release 15 study [TR 38.811] on channel models and deployment scenarios. After completing this study, 3GPP followed up with a Release 16 study [TR 38.821] on solutions for adapting 5G NR to support NTNs. The main objective of this study is to identify a feature set that enables NTNs within the 5G system while minimizing the impact on the existing 5G system.

Why foster NTN communications? Answer: To fulfill the



1. This image provides a general overview showing connectivity of non-terrestrial networks. (Source: Rohde & Schwarz)



2. Here's a glimpse of how NR-NTNs incorporate non-terrestrial communications within the 5G system. NR-NTN use cases follow 5G eMBB services. (Source: Rohde & Schwarz)

need for ubiquitous connectivity on a global scale. According to market statistics by industrial organizations such as GSMA, in 2020, wireless communications technologies covered more than 80% of the world's population but less than 40% of the Earth's land mass. NTN satellite-based communications can tackle this aspect and focus on worldwide ubiquitous coverage, even in maritime, remote, and polar areas *(Fig. 1)*.

Initial 5G NTN deployments will focus on ubiquitous connectivity and coverage, separating the technology into two facets: NR-NTN and IoT-NTN:

- NR-NTN can be thought of as the enhanced mobile broadband (eMBB) part of 5G enabling satellite-based connectivity, mainly focusing on coverage and outdoor applications.
- IoT-NTN is an extension of IoT technologies such as NB-IoT, LTE-M, or 5G RedCap (also known as 5G NR-Light) in long-term satellite connectivity scenarios.

The latter assumes a best-effort QoS approach with very tolerant requirements concerning delays and data rates. In terms of expected data rates, NTN 5G can't compete with terrestrial 5G, so 5G NTN will complement terrestrial 5G systems and provide connectivity in underserved regions.

NTN Use Cases

With the current evolution of NTNs, two major directions became apparent:

- First, 5G NR enhancements incorporate non-terrestrial communications within the 5G system. NR-NTN use cases follow 5G eMBB services. The technology is described as NR-NTN *(Fig. 2)*.
- Second, the Internet of Things (IoT), or massive machine-type communications (mMTC), is extended by non-terrestrial connectivity, described as IoT-NTN, which differs from NR-NTN by dint of overall lower complexity. The radio link continues with the adaptation of NB-IoT or enhanced machine-type communications (eMTC) for NTN connections, but with reduced device and satellite complexity.

Another characteristic of IoT-NTN is the lack of QoS support. IoT-NTN communications will be established with a best-effort approach, like latency-tolerant applications, but compared to NR-NTN, energy efficiency and power saving play a pivotal role. The [TR 36.763] study proposes both radio-access technologies (RATs)—eMTC and NB-IoT—with equal priority. And, in the first potential deployments, evolved packet-core (EPC) connectivity is the core network in charge. 5G Core may follow at a later deployment phase.

Rel. 17 prioritizes standalone deployment, applying transparent bent-pipe satellite architecture and assuming the user equipment (UE) possesses GNSS capabilities (not simultaneous operation) to pre-compensate time and frequency.[3]

The 3GPP study on next-generation access technology scenarios and requirements found multiple use cases ranging from indoor hotspots to satellite-based 5G system extensions [TR 38.913]. Satellite-based communications aren't new to the ecosystem, and services can be clustered into broadcast satellite services (BSS), fixed satellite services (FSS), and mobile satellite services (MSS).[4]

Fixed satellite services

FSS provides internet and connectivity services to stationary UE, such as very-small-aperture terminals (VSATs). From a business-case perspective, such services have an objective not unlike fixed-line connectivity. The advantage of FSS is its wide coverage and capability to provide connectivity services to underserved or remote areas. An FSS service subset also could be the future deployment of backhaul connectivity of terrestrial 5G radio networks.

Broadcast satellite services

These services correspond to the well-known satellite TV broadcasts (such as DVB-S2). With 3GPP, it's possible to use such systems to broadcast information to either all or a subset of UEs.

Target applications include services like updating software or providing information to regions or UE groups. Another business model includes outsourcing of traffic. If it's relevant to multiple UEs spread over a large coverage area, such broadcast-based systems improve overall system efficiency.

Mobile satellite services

These have the same use cases as the cellular terrestrial networks, but with the advantages of wider coverage and ubiquitous connectivity and disadvantages of potentially lower data rates, longer latency, and targeting for outdoor operations. NTN services complement terrestrial 5G systems. It prioritizes worldwide connectivity and basic service provisioning in a wide coverage area instead of single-user high data rates.

3GPP NTN focuses on more than underserved area coverage. At a higher level, these four use cases are categorized as follows [TR 22.822]:

- **Service continuity** provides RAT coverage where it's unfeasible through terrestrial networks such as in maritime or remote areas. It supports service continuity between land-based 5G access and satellite-based access networks owned by the same operator or by operator agreements.
- **Service ubiquity** is motivated by mission-critical communications (MCX) and aims at permanent system availability. This is particularly evident for public protection disaster relief (PPDR) use cases leading to outage or destruction of terrestrial network architectures. System availability can be resumed and obtained in a short time using NTN connections.
- **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 provide better system efficiency, especially when considering the wide NTN, next-generation Node B (gNB) coverage range.
- **5G system backhaul services** represent situations where end-user devices (UE) are still connected to terrestrial RATs, but the NTN connection serves as a backhaul connection to the core network.

NTN Spectrum Aspects

The most relevant communications aspect is the available frequency spectrum. As it's extremely unlikely that satellites are restricted to one country or region, an international harmonization of frequencies applied to satellite communications is essential. Organizations like the ITU support such coordination initiatives.

Currently, several frequency ranges are being discussed within 3GPP for NTN. Some are in the FR1 legacy spectrum, and some beyond 10 GHz and FR2. The current FR1 bands discussed for NTN are:

- The S-band frequencies from 1980 to 2010 MHz in uplink (UL) direction and from 2170 to 2200 MHz in downlink (DL) direction (Band n256).
- The L-band frequencies from 1525 to 1559 MHz DL together with 1626.5 to 1660.5 MHz for the UL (Band n255).[1]

These frequency ranges have lower path attenuation, and they're already used in legacy communications. Thus, components are available now, but the bands are very crowded, and the usable bandwidth is restricted. Current maximum bandwidth is 20 MHz with up to 40-MHz overall bandwidth envisaged in the future [TR 38.811].

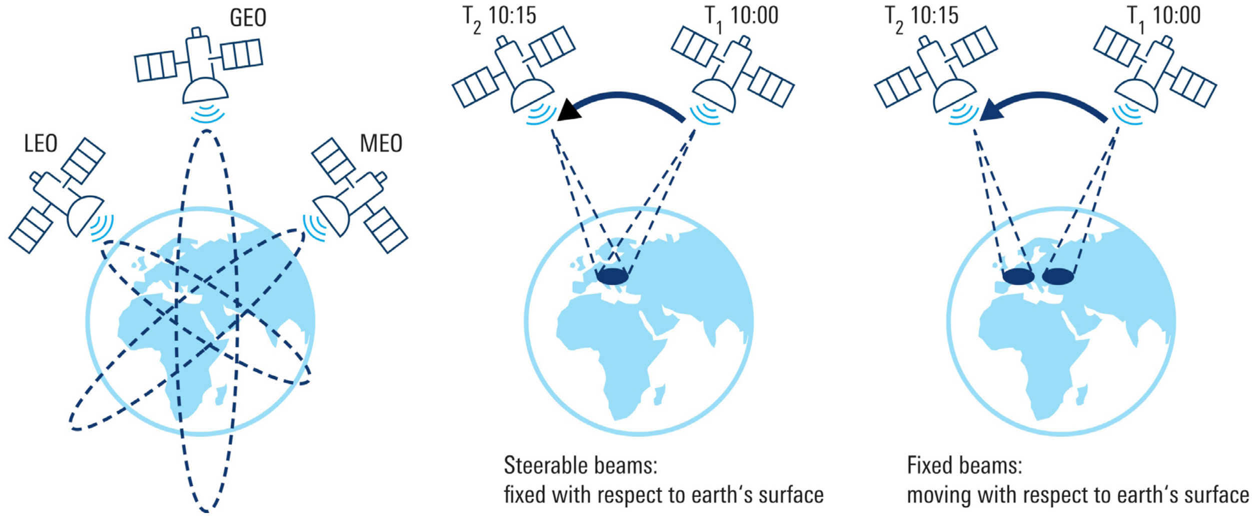
As far as long-term NTN spectrum use is concerned, 3GPP is discussing NR-NTN above 10 GHz. The Ka-band is the highest-priority band with uplinks between 17.7 and 20.2 GHz and downlinks between 27.5 and 30 GHz, based on ITU information regarding satellite communications frequency use.[2] Among current FR2 challenges, one is that some of the discussed bands fall into the spectrum gap between FR1 and FR2 and that NTN frequencies will use FDD duplex mode due to the long roundtrip time.

Like terrestrial communications, coexistence aspects also are relevant for NTN. This is due to RF layer interference leveraged by two facts resulting from the NTN introduction: The cell or beam coverage overranges country and terrestrial cell borders, and the spectrum location either overlaps or is adjacent to existing 5G bands. For such reasons, 3GPP started a study initiative to further investigate coexistence aspects [TR 38.863].

NTN Architecture Aspects

The following architectures are relevant for current and future NTN and satellite constellations:

- **Low-Earth-orbit (LEO)** satellites with an altitude between 500 and 2000 km have a shorter round-trip time (RTT), which is typically less than 30 ms. The size of a LEO satellite also is assumed to be small, typically <1-meter perimeter or even in the range of a dozen centimeters (nanosatellites), with the weight below 500 kg. The assumption is that NTN uses a beamforming mechanism at the satellite station. The typical beam footprint of a LEO satellite ranges between 100 and 1000 km.
- **Medium-Earth-orbit (MEO)** satellites travel at a velocity of about 13,800 km/h and have an orbital period of around six to 12 hours. The beam footprint is like that of LEO constellations.
- **Geostationary-Earth-orbit (GEO)** satellites operate above the equator at an altitude of 35,786 km, resulting



3. For NTN satellite beamforming, two methods are in discussion—moving beams (left) or fixed beams with respect to earth surface (right). (Source: Rohde & Schwarz)

in a notional station keeping its position fixed in terms of elevation and azimuth angle with respect to a given Earth point. The beam-footprint sizes range from about 200 km for narrow beams up to 4000 km in the case of large beam sizes. Due to the larger distance, the RTT of a GEO satellite is about 544 ms.

- **High-altitude platform systems (HAPS)** cover all airborne objects such as airplanes, balloons, helicopters, and drones (UAVs). They operate very flexibly at altitudes from several hundred meters up to about 15 km and have a beam footprint with diameters of just a few kilometers up to 100 km on average. Due to the shorter distance, the RTT isn't unlike that of terrestrial networks. Two satellite beamforming methods are discussed: The beam footprint with respect to earth is either static or moving. As shown in *Figure 3*, there are *steerable beams* and *Earth fixed beams*.

A general characteristic of NTN connections is the addressability of the satellite as we may observe a birth and death situation that is dependent on the elevation angle. In addition, the 5G system extension to incorporate non-terrestrial networks includes adapting to existing 5G system architectures. Especially on the radio access network (RAN), the change from a terrestrial base station to an airborne or spaceborne satellite access station results in some amendments.

NTN architectures need radio access from the terrestrial terminal or UE to the satellite, which is referred to as the service link, and the satellite needs to be connected to a terrestrial gateway, referred to as the feeder link. LEO and GEO satellite constellations have a known or predictable trajectory, which facilitates the routing of the connection to the ground station.

Targeting an NTN-capable RAN deployment, two possible architecture options are discussed within 3GPP: transparent mode and regenerative mode. Release 17 deals primarily with the transparent-mode architecture.

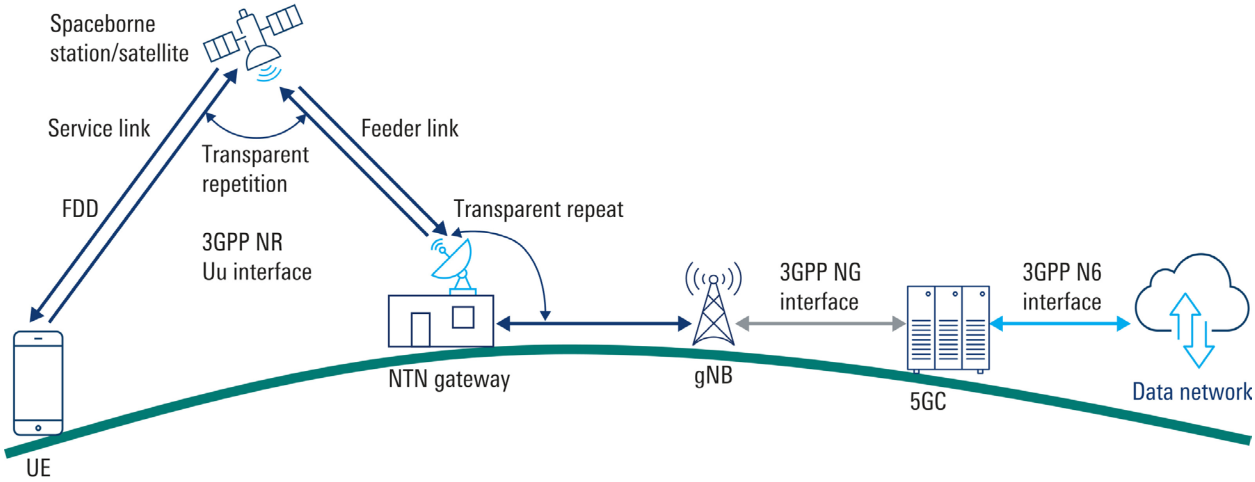
Transparent NTN NG-RAN Architecture

This architecture behaves like a repeater in space (sometimes referred to as the "bent pipe approach") and follows the principle of "what goes up must come down." The major aspect is the disaggregation of the legacy term "base station" into the components of satellite, ground gateway, and terrestrial gNB functions. The satellite functions implement RF filtering, frequency conversion, RF amplification, RF transmission, and reception in uplink as well as downlink direction.

The pivotal characteristic is that the waveform is repeated between the service and feeder link by an unchanged payload. A carrier frequency change is probably applied to avoid interference between the service and feeder links.

This architecture is independent of the radio waveform, so any amendments here don't require changes in the spaceborne station. Disadvantages include noise amplification, as the satellite may not perform any channel equalization or noise cancellation; the vulnerability against jamming attacks; the longer overall RTT as two satellite-earth links are involved; and the lack of inter-satellite link (ISL) connections for traffic steering.

The termination of the 5G NR air interface with respect to the protocol anchor is in the terrestrial gNB function. The gateway function has no explicit task with respect to 5G NR but, of course, an important task with respect to satellite flight control and other tasks. It's probably a parabolic antenna or antenna array with beamforming capabilities to steer the feeder link heading towards the satellite station. The architecture shown in Figure 4 is symbolic—certain deviations are possible. For example, the gateway and the gNB can be incorporated into the same hardware cabinet or the gNB functions are offered to several satellites. Conversely, a satellite is only connected to a single gNB to clarify the protocol termination point.



4. Shown is a symbolic representation of a transparent NTN NG-RAN architecture. In real-world applications, there are possible permutations. (Source: Rohde & Schwarz)

The connection between the UE and the terrestrial gNB includes service 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 first ISL implementations.

Future NTN deployments will include regenerative-mode architectures. The major difference to the transparent payload architecture is that gNB functions are incorporated into the satellite itself for faster scheduling decisions and shorter RTT. The regenerative architecture model raises satellite hardware complexity and computing power and may incorporate multi-access edge-computing (MEC) functionalities to reduce the RTT.

NTN RF Aspects

5G enhancements starting with Release 17 will adapt 5G NR to allow for non-terrestrial network communications. This chapter deals with RF propagation aspects and the resulting challenges, with focus on non-terrestrial propagation aspects compared to well-known channel models or fading profiles in terrestrial propagation conditions.

The great distance between terrestrial UEs and spaceborne stations impacts the link budget by imposing high path attenuation. In addition, this huge distance is responsible for the large time delay or RTT, which also depends on the time and elevation angle.

A paradigm change is afoot: Compared to terrestrial networks, where the term "base station" indicates its stationary nature, satellites travel at a certain velocity, which causes carrier-frequency deviation (Doppler shift). Ionospheric radio-wave propagation is responsible for waveform polarization rotation, known as Faraday rotation

NTN channel modeling

The channel between the TX and RX entity is affected by certain degradations, such as interferences and fading. Large-scale fading mainly depends on the distance between TX and RX and the propagation of the radio wave between them. Small-scale fading is influenced by multipath propagation and Doppler shift of the carrier frequency. It depends on signal bandwidth, relative velocity, scattering, and reflection environments.

With NTN links, there's obstructed and unobstructed propagation. The unobstructed link benefits from a line-of-sight (LOS) dominance in the scattering profile that shows no rich scattering environment, while obstructed links assume nearby scatterers. Note that NTN focuses on outdoor connectivity.

Some marginal differences exist between modeling of terrestrial channels and modeling of NTNs. In the latter case, modeling emulates LOS scenarios with multipath propagation resulting from nearby objects. The angular spread seen by the satellite is almost zero, whereas in terrestrial scenarios, it covers a certain angular range.

Thus, a major difference is that the satellite signal propagation is primarily homogenous except for nearby scattering. 3GPP wants to combine terrestrial fading models [TR 38.901] with satellite channels in a hybrid conceptual architecture

Path attenuation

The long distance between the UE and the satellite will lead to high path attenuation. 3GPP has discussed several link budgets and carried out studies with diverse parameters and simulation results, such as shown in [TR 36.763] or [TR 38.811]. As antenna technology evolves, the objective is to tackle the path loss with highly directive antennas providing high antenna gain.

The composite path loss is based on the following components: basic path loss (mainly as free-space path loss, or FSPL), attenuation due to atmospheric gases, attenuation due to atmospheric scintillation, and building-entry path loss. Typical assumptions are FSPL values of –160 dB (LEO) or –190 dB (GEO), and it's assumed that the UE RX sensitivity will be lower compared to terrestrial networks.

Round-Trip Time and Differential Time Delay

One of the challenges of NR-NTN's low-latency communications is the RTT or long latency due to the large distance between the terrestrial UE and the satellite. Typical one-way latency values range from 30 to 40 ms in LEO constellations and up to 544 ms in GEO constellations.

A detailed analysis of the RTT and latency aspects identifies the following two challenges:

• 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.

• Time-variant latency and varying RTT during the entire connection period due to the nature of an elliptical flight orbit and the changing distance between the UE and the satellite.

The first aspect considers the elliptical beam footprint, but the size of the ellipse depends on the elevation angle. The satellite thus experiences different propagation times among the UEs within the beam footprint.

When considering the second aspect, the UE experiences RTT behavior that varies over time due to the nature of the satellite's orbital trajectory. When the satellite appears at the horizon above the minimum elevation angle, the RTT is largest as the distance between the UE gNB is longest. This impacts the buffer management of the MAC layer and HARQ operation.

Doppler frequency shift

One of the most serious challenges in realizing NTN connections with good end-user QoE is carrier-frequency deviation (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. It depends on the relative velocity between UE and satellite, the carrier frequency, and the angle between the velocity vector and the direction of signal propagation.

Faraday rotation in NTN and polarization aspects

Faraday rotation is visible due to the structure of the atmosphere, indicated by the total amount of electrons. Faraday rotation is introduced to describe the rotation of the polarization resulting from interaction of the electromagnetic wave with the ionized medium in the Earth's magnetic field along the path [TR 38.811].

A possible countermeasure is the use of circular polarization methods. The drawback is that this would either require the UE to apply the same circular polarization to achieve a perfect match or tolerate and accept 3-dB polarization loss in addition to the FSPL.

Summary

3GPP states that with 5G NTN, satellite-based communications should be made possible, but with the lowest impact on 5G. Only technically necessary adaptations will be made.

In the long term, on the path toward 6G, we will leave the cellular behavior of networks behind.[4] Therefore, 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. The three terms "interworking," "integration," and "unification" describe the evolution path from legacy technologies in the satellite and cellular world via 5G NTN and heading up to 6G.

New research areas will be the evolution toward organic networks with cell birth and death behavior, vagabonding network components, and intelligent traffic management. The incorporation of NTN into the 5G system with Release 17 is the advent of a new technology evolution fostering and driving the worldwide proliferation of wireless communications systems. Rohde & Schwarz is accompanying these technology evolutions with expertise in test and measurement and in satellite connectivity.

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Note: All links have been checked and were functional when this document was created.