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A Tutorial on Non-Terrestrial Networks: Towards Global and Ubiquitous 6G Connectivity

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Contents

A Tutorial on Non-Terrestrial Networks: Towards Global and Ubiquitous 6G Connectivity

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ABSTRACT

The International Mobile Telecommunications (IMT)-2030 framework recently adopted by the International Telecommunication Union Radiocommunication Sector (ITU-R) envisions 6G networks to deliver intelligent, seamless connectiv-

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Muhammad Ali Jamshed, Aryan Kaushik, Sanaullah Manzoor, Muhammad Zeeshan Shakir, Jaehyup Seong, Mesut Toka, Wonjae Shin and Malte Schellmann (2025), "A Tutorial on Non-Terrestrial Networks: Towards Global and Ubiquitous 6G Connectivity", Foundations and Trends® in Networking: Vol. 14, No. 3, pp 160–253. DOI: 10.1561/1300000072.

ity that supports reliable, sustainable, and resilient communications. To achieve this vision, Non-Terrestrial Networks (NTN) represent a significant advancement by extending connectivity beyond the Earth's surface. These networks integrate advanced communication technologies that go beyond conventional terrestrial infrastructure, enabling comprehensive global connectivity across domains such as the Internet, Internet of Things (IoT), navigation, disaster recovery, remote access, Earth observation, and even scientific initiatives like interplanetary communication.

Recent developments in the 3$^{\text{rd}}$ Generation Partnership Project (3GPP) Releases 17-19, particularly within the Radio Access Network (RAN)4 working group addressing satellite and cellular spectrum sharing and RAN2 enhancing New Radio (NR)/IoT for NTN, highlight the critical role NTN is set to play in the evolution of 6G standards. The integration of advanced signal processing, edge and cloud computing, and Deep Reinforcement Learning (DRL) for Low Earth Orbit (LEO) satellites and aerial platforms, such as Uncrewed Aerial Vehicles (UAV) and high-, medium-, and low-altitude platform stations, has revolutionized the convergence of space, aerial, and Terrestrial Networks (TN). Artificial Intelligence (AI)-powered deployments for NTN and NTN-IoT, combined with Next Generation Multiple Access (NGMA) technologies, have dramatically reshaped global connectivity.

This monograph provides a comprehensive exploration of emerging NTN-based 6G wireless networks, covering vision, alignment with 5G-Advanced and 6G standards, key principles, trends, challenges, real-world applications, and novel problem solving frameworks. It examines essential enabling technologies like AI for NTN (LEO satellites and aerial platforms), DRL, edge computing for NTN, AI for NTN trajectory optimization, Reconfigurable Intelligent Surfaces (RIS)-enhanced NTN, and robust Multiple-Input-Multiple-

Output (MIMO) beamforming. Furthermore, it addresses interference management through NGMA, including Rate-Splitting Multiple Access (RSMA) for NTN, and the use of aerial platforms for access, relay, and fronthaul/backhaul connectivity.

Keywords: Non-Terrestrial Networks (NTN), 3$^{\text{rd}}$ Generation Partnership Project (3GPP), Artificial Intelligence (AI), Reconfigurable Intelligent Surfaces (RIS), Next Generation Multiple Access (NGMA).

1

Roadmap to 6G and Role of NTN: Why NTN is Vital for the Evolution of 6G Networks?

In a world where 2.9 billion people remain without internet access, addressing the digital divide has never been more critical. This disparity is particularly pronounced among certain demographics; in ten countries across Africa, Asia, and South America, women are 30-50% less likely to use the Internet than men. Although cell technology is the most widely used communication system, it faces significant challenges, especially in rural areas, even in developed countries. Non-terrestrial networks (NTN) offer a promising solution to these challenges, introducing new ways to connect the unconnected and enhance global communication [59], [65], [76].

NTN refer to wireless communication systems operating above the Earth's surface, utilizing satellites in low earth orbit (LEO), medium-earth orbit (MEO), and geostationary equatorial orbit (GEO), as well as high altitude platform stations (HAPS) and uncrewed aerial vehicles (UAV) [48], [144], [205]. These elements are crucial to achieve uninterrupted coverage and extend connectivity to remote areas lacking traditional terrestrial network (TN) access. Currently, devices are classified into those connected to TN and those connected to satellites [10], [75]. This means that users who need satellite connections must use an additional device in conjunction with their smartphone. However, in an integrated system, all mobile devices will integrate both terrestrial and satellite access. As technology progresses, satellites are expected to function as base station (BS). NTN plays a crucial role in expanding global connectivity, supporting various industries, and advancing technological capabilities. Therefore, the interconnection and inter-operation between NTN and TN are of significant importance [21], [42].

6G is expected to offer significantly superior connectivity compared to earlier generations, featuring higher data rates, reduced latency, and improved reliability. NTN could supplement terrestrial 6G infrastructure by extending coverage to remote and under-served areas, where deploying traditional TN is challenging or economically impractical [74], [77], [164], [198]. Within a 6G ecosystem, these NTN will operate alongside TN to provide seamless connectivity across various geographical regions, supporting initiatives such as the United Nations' 17 sustainable development goals (SDG). The integration of NTN within 6G networks will facilitate a wide range of new applications and use cases, many of which are extensions of current 5G applications, but have been limited by the performance constraints of existing networks. An illustration of the convergence and coexistence of NTN and TN is shown in Figure 1.1.

1.1 NTN Standardization in 3GPP

The 3$^{\text{rd}}$ Generation Partnership Project (3GPP) is the global standardization body of cellular radio systems and their core networks. It was constituted in 1998 by seven telecommunication standard development organizations, aiming to develop the 3G mobile standards in an internationally aligned format to leverage creation of a standards eco-system that would facilitate global scale and create an enduring platform for its future evolution. Thanks to its success, it continued its standardization work to date, while keeping its original name – even though we are far beyond the 3rd Generation radio standard by now, peeking towards 6G.

The work in 3GPP is structured into three technical specification groups (TSGs), which are defined as:

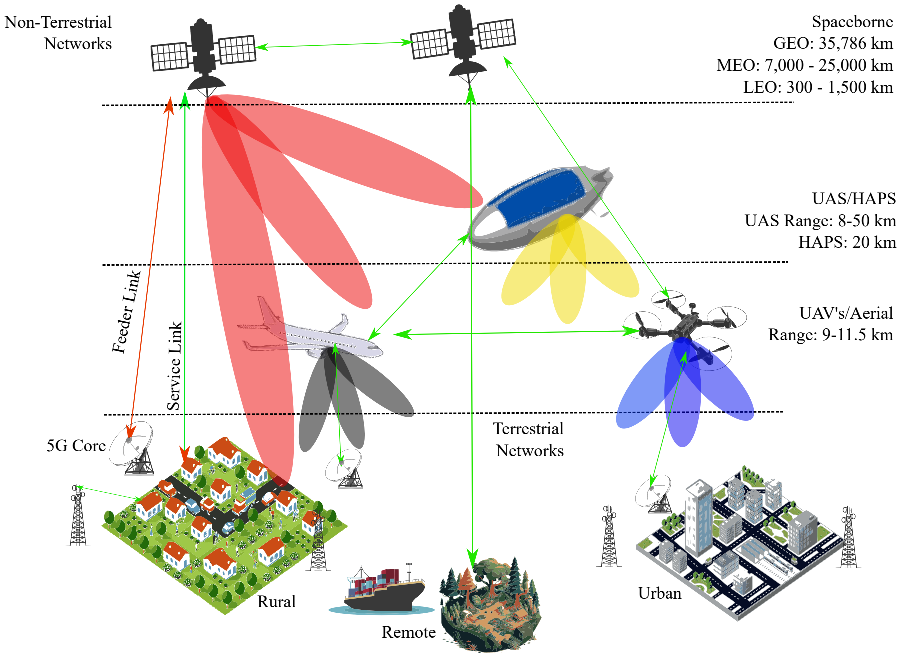


Figure 1.1: An illustration of convergence/co-existence of NTN and TN.

- Radio access network (RAN)
- Service and System Aspects (SA)
- Core network and terminals (CT)

Each of the TSGs is sub-structured into working groups (WGs), where each WG focuses on a different level of the network or system, respectively, and they are simply numbered serially (i.e., RAN1 to RAN5 and SA1 to SA5). The work in the WGs is carried out in so-called study items (SI) and work items (WI), where a SI constitutes preparatory and pre-evaluation work for topics and aspects that are aimed to be covered by future releases of the standard. The outcome of a SI is summarized in a technical report (TR), labeled with a specific 5-digit number in a 2-level format, e.g. 22.822. If a common consensus is reached to follow-up the work from the SI, typically a WI follows, where at the end a technical specification (TS) is published carrying its own 5-digit number.

The outcome of the standardization work is published in so-called Releases, where a Release provides a full functional description of the features and processes characterizing the cellular radio system and its core network. A Release consists of several TSs, which specify the normative requirements for the cellular radio system and are issued by the corresponding TSGs. A specific SI or WI, respectively, is usually defined for the duration of the working phase of a particular Release; hence, a SI and a WI referring to the same topic will typically be in subsequent Releases – though they may even appear in the same Release if the duration of the SI in particular is defined significantly shorter than the duration of the Release's working phase.

The complete roadmap of NTN integration into the 3GPP cellular radio system from its beginning up to date is comprehensively described in [139], and will be summarized here in sufficient detail. Figure 1.2 provides a brief overview of the three most recent Releases of 3GPP focusing on the integration of NTN and TN. First considerations on NTN integration started in 3GPP Release 14 already, where the main driving factors were:

- Coverage extensions to areas with poor or without cellular coverage.
- Services supported more efficiently by satellites, such as multicast/broadcast.
- Provision of a backup network in disaster zones with damaged cellular network.
- Higher resiliency of NTN.
- Cost reduction through a unified radio interface for TN and NTN.

1.1.1 Release 15

Release 15 was the first to standardize the normative requirements for 5G new radio (NR), which was initially focusing on TN and various architectural options. The stage 1 TS 22.261 included a requirement for 5G to support multiple access technologies, stipulating that the 5G

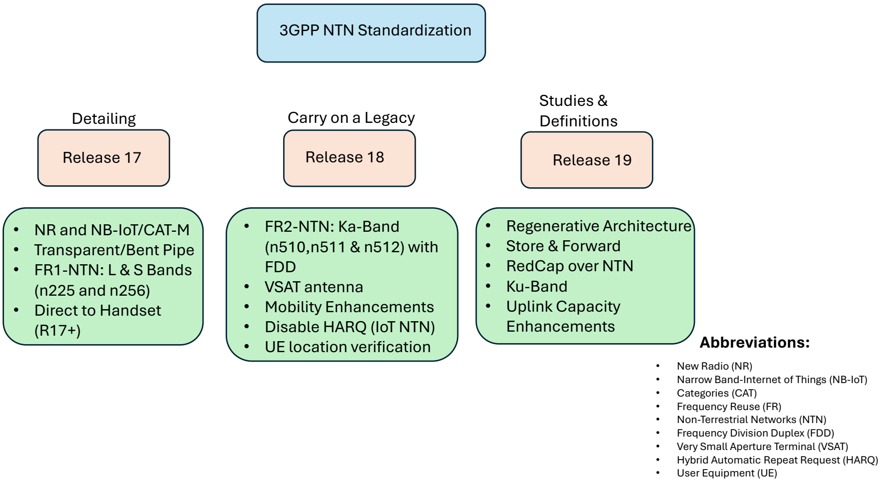


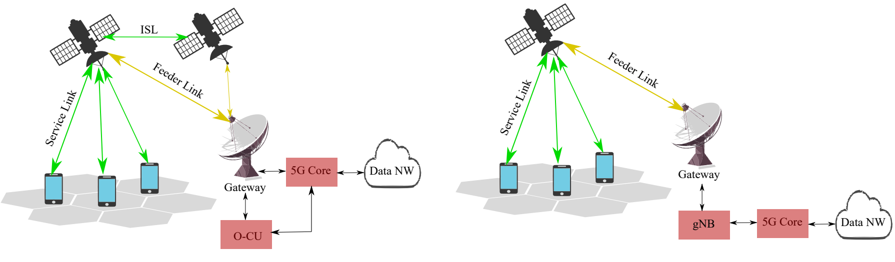
Figure 1.2: An illustration of 3GPP timeline indicating the start of NTN incorporation and future perspective.

system should be able to support mobility between supported access networks. However, due to time constraints, the standardization of satellite support was not included in Release 15. Despite this omission, TSG RAN initiated a SI entitled "Study on NR to Support NTN". This study focused on several key areas:

- NTN use cases for enhanced mobile broadband (eMBB) and massive machine type communication (mMTC) service.
- Adapting the 3GPP channel model from Release 14 to accommodate NTN.
- Providing a detailed description of deployment scenarios for NTN while analyzing the necessary modifications to support satellite or HAPS operations in NR.

The results of this SI were summarized in TR 38.811. For eMBB, NTN use cases involve providing broadband connectivity to cells or relay nodes in under-served regions, in conjunction with terrestrial wireless or wireline access, though with limited user throughput. It also encompasses establishing broadband connections between the core network and cells in isolated areas, which is especially valuable for public safety applications. In addition, it facilitates the broadband connectivity between the core network and cells on moving platforms. For mMTC, NTN aims to ensure global connectivity between internet of things (IoT) devices and the NTN and to provide connectivity to a BS that serves IoT devices within a local area network (LAN).

The 3GPP adopted the common terms for characterizing the two main NTN architectures: Regenerative and transparent payload, as illustrated in Figure 1.3 and explained below.



Regenerative

Transparent (Bent Pipe)

Figure 1.3: Transparent versus Regenerative payload.

Transparent payload A spaceborne or airborne platform that lacks on-board processing capabilities modifies the frequency carrier of the incoming uplink radio frequency (RF) signal, then filters and amplifies it before re-transmitting it on the downlink. In essence, this platform functions as an analog RF repeater.

Regenerative payload A spaceborne or airborne platform that handles RF filtering, frequency conversion, and amplification, along with on-board processing tasks, essentially operates as a BS.

1.1.2 Release 16

In Release 16, TSG RAN and SA initiated one new SI each. The SI led by SA1, entitled "Study on using satellite access in 5G," analyzed 12 concrete use cases for using satellite access in NR, which were summarized in TR 22.822. This SI assessed their conditions, impacts, interactions with existing services and features, and potential stage 1 requirements. These requirements included roaming between TN and satellite networks, broadcast and multicast with a satellite overlay, IoT via satellite networks, temporary use of satellite components, optimal routing or steering over satellites, satellite transborder service continuity, global satellite overlay, indirect connections through a 5G satellite access network, 5G fixed backhaul between NR and the 5G core, 5G moving platform backhaul, 5G to premises, and satellite connections of remote service centers to offshore wind farms.

The RAN3 led SI focused on solutions for NR to support NTN, including support of NTN-TN service continuity and multi-connectivity scenarios for NTN-TN or for two NTN in parallel, which lead to TR 38.821. This SI built upon the key impacts identified in Release 15, examining the implications for RAN protocols and architecture in greater depth and beginning to assess possible solutions. The investigation concentrated on satellite access via transparent GEO and LEO satellite networks, with HAPS-based access being considered a special case of NTN due to its lower Doppler and variation rates. The usage scenarios included pedestrians and users in vehicles, such as high-speed trains or airplanes. Reference scenarios evaluated included GEO and LEO satellites with both steering and moving beams, for both transparent and regenerative payloads. The RAN3 working group advised that the normative work should prioritize GEO-based satellite access with transparent payloads and LEO-based satellite access with either transparent or regenerative payloads. The outcome of both SIs yield proposals for the normative work to focus on with corresponding recommendations.

1.1.3 Release 17

Release 17 was the first release with normative requirements for NTN in 3GPP specifications [150]. In this release, the corresponding activities have also started to support narrow band-IoT (NB-IoT) and enhanced machine type communication (eMTC) type of devices via NTN in 4G long term evolution (LTE).

The Release 17 WI "Stage 1 of 5GSAT" led by SA1 translated the findings from the corresponding Release 16 SI into stage 1 requirements, which were captured in TS 22.261. These requirements include the following: The 5G system must support service continuity between TN and satellite networks owned by the same or different operators with agreements and must facilitate roaming. User equipment (UE) with satellite access should support optimized network selection and re-selection to public land mobile networks (PLMN) with satellite access based on home operator policy, and must support mobility across various access networks. UE must be able to provide or assist in providing their location to the 5G network, and the system must determine a UE location to provide services according to regulatory requirements. There must be support for low power mobile IoT communications and satellite links between the RAN and core network, accommodating satellite backhaul latencies. Support for meshed connectivity between satellites with inter-satellite link (ISL) is required, as well as the selection of communication links based on quality of service (QoS) fulfillment.

The SA2 led WI focused on the integration of satellite components in the 5G architecture, resulting in the three specifications documents TS 23.501 (System architecture for the 5G system), TS 23.502 (procedures for the 5G system) and TS 23.501 (Policy and charging control framework for the 5G system).

TSG RAN led WI "Solutions for NR to support NTN", where the purpose was to adapt the basic features of 5G NR to match the characteristics of the satellite channel. The focus was solely on the transparent architecture, and it was assumed that the UE are global navigation satellite system (GNSS) capable, allowing them to obtain precise position information. As operating bands for satellite communication in the frequency range FR1 (i.e., 410 MHz – 7125 MHz), the frequency division duplexing (FDD) bands n255 (L-band), operating the uplink at 1626 - 1660 MHz and the downlink at 1525 - 1659 MHz, and n256 (S-band), operating the uplink at 1980 - 2010 MHz and the downlink at 2170 - 2200 MHz, have been introduced. For HAPS, it was concluded that the FDD band n1 (uplink: 1920 - 1980 MHz, downlink: 2110 - 2170 MHz) can be applied, allowing NR UEs as defined by TS 38.101-1 to support HAPS without any additional changes.

New solutions and extensions of existing protocols proposed by the WI to support NTN operations cover several areas. Among those are enhancements in timing, synchronization, and hybrid automatic repeat request (HARQ) to cover long round trip delay; mobility management to ensure seamless handovers between NTN and terrestrial networks, utilizing satellite ephemeris and common parameters for the Timing Advance (TA); switchover procedures for the service link (i.e., between the UE and the NTN node) and the feeder link (i.e., between the ground station and the NTN node).

1.1.4 Release 18

In Release 18, the RAN-led SI entitled "Study on self-evaluation towards the submission of the International Mobile Telecommunications (IMT)-2020 submission of the 3GPP satellite radio interface technology" evaluated the NR functionalities of Release 17 that facilitate 5G via satellite, as well as the corresponding LTE-based solutions for NB-IoT. In this SI, three different usage scenarios were considered for the analysis in a rural environment:

- eMBB-s (Enhanced Mobile Broadband - satellite),
- HRC-s (High Reliability Communications - satellite),
- mMTC-s (Massive Machine Type Communications – satellite).

Furthermore, SI "Study on requirements and use cases for network verified UE location for NTN in NR" pointed out the need for network-based methods to verify the reported UE location within large NTN cells, taking into account regulatory mandates for public alerts, emergency communications, and legal interception. Network-based verification with an accuracy of 5-10 km was mandated, prompting normative work in Release 18.

The operation bands for satellite communication have been extended by the new FDD band n254, which operates the uplink at 1610 - 1626 MHz (L-band) and the downlink at 2484 - 2500 MHz (S-band), while the maximum channel bandwidth supported for NR NTN in FR1 has been extended to 30 MHz. Moreover, the WI "NR NTN enhancements" led by RAN2 aimed to enhance features from earlier releases, such as coverage enhancements as well as improved NR uplink coverage by enabling repetitions in the control channel and bundling reference signals for channel estimation. It also defined Rx/Tx time measurements for network verified UE location and introduced enhancements for NTN-TN and NTN-NTN mobility and service continuity, such as broadcasting geographical TN areas with frequency information, improved conditional handover triggers, and satellite switch with re-sync. Furthermore, NR-NTN operation in the above 10 GHz bands (targeting frequency range FR2) was considered, resulting in the introduction of FDD bands n510, n511, n512 in the Ka band, operating uplink in the 17 - 20 GHz range and downlink in 27 - 30 GHz range, with Rx/Tx requirements for very small aperture terminal (VSAT) UE types and radio resource management (RRM) for electronically/mechanically-steered beam UEs.

In TSG SA, several new SIs were started. Among those, the SI “Study on 5G core enhancement for satellite access phase 2” focused on handling mobility management and optimizing power savings under conditions of intermittent coverage, while the SI “Study on security aspects of satellite access” explored security and privacy issues related to mobility management and power conservation amid discontinuous coverage. The SI “Study on support of satellite backhauling in 5G system” concentrated on the use of satellite backhaul for mission critical scenarios with HRC-s enabled by satellite edge computing and local data switch – which requires a regenerative payload for its realization. The WIs driven by TSG SA focused on satellite backhauling in 5G systems, where the results were captured in TS 22.261 and TS 23.501 - 503.

1.1.5 Release 19

In current Release 19, TSG RAN leads the WI “NTN for IoT phase 3”, which aims to achieve several objectives for 2025. The link is improved by supporting additional satellite payload parameters for satellite constellations operating in FR1-NTN and FR2-NTN, improving the uplink capacity and throughput of FR1-NTN by using overlaid repetitions based on orthogonal cover codes (OCC), signaling the intended service area of a broadcast service via NR NTN, and supporting for the first time in a WI regenerative payloads, featuring 5G system functions on the NTN node. Furthermore, the support of reduced capability (RedCap) devices (e.g., handheld or IoT) for NR NTN operating in FR1-NTN will be specified.

TSG SA is leading several SIs in Release 19. The SI “Study on Satellite Access - Phase 3” focuses on use cases and requirements to further improve the 5G system by satellite. Key subjects to be investigated are store and forward (S&F) satellite operation for delay tolerant communication services (enabling services for discontinuous satellite coverage), direct UE-satellite-UE communication without using any feeder link to route the communication signal through a ground station (yielding significantly reduced communication delays), GNSS-independent operation (to enable satellite access to UEs without GNSS receiver/no access to GNSS services), and positioning enhancements for satellite access (3GPP based methods for satellite-only access). The normative part of this work will be done in a corresponding WI (starting at a later stage), and results will be captured in TS 22.261.

Further SIs led by TSG SA are as follows: An SI on integration of satellite components in the 5G architecture focuses on regenerative payloads, S&F satellite operation and UE-satellite-UE communication. An SI on management aspects of NTN investigates management capabilities to support new network architectures or functions for satellite regenerative payloads, considering various satellite constellations. Another SI delves into security aspects of 5G satellite access, and finally, an SI focusing on application enablement will explore application layer solutions for satellite access. Last but not least, a workplan to support the Ku-band (downlink: 10.7 - 12.75 GHz, uplink: 12.75 - 13.25 GHz or 13.75 - 14.5 GHz) has been agreed.

1.2 NTN Evolution

NTN, particularly through direct-to-mobile (D2M) technology, leverage satellites to provide cellular connectivity directly to standard mobile devices. This approach offers several significant advantages. Firstly, it allows users to utilize their existing devices, ensuring accessibility without the need for additional specialized equipment. This can be transformative in disaster scenarios, where traditional infrastructure might be compromised. For instance, SMS has proven to offer the best performance-to-resource ratio in emergencies, and with NTN, SMS and other essential services can reach even the most remote areas reliably.

Beyond emergency communication, NTN unlocks vast opportunities for the IoT on a global scale. Remote sensors, powered by NTN connectivity, can monitor a plethora of environmental and infrastructural parameters in real-time. For example, earthquake warning systems can benefit immensely from NTN, where sensors deployed in seismically active but isolated regions can relay crucial data instantaneously, providing timely alerts that can save lives and mitigate damage. This capability is not limited to natural disaster monitoring; agricultural sectors in rural areas can also utilize IoT devices to optimize farming practices, from soil moisture sensors to weather monitoring stations, thereby enhancing productivity and sustainability [60], [71].

Furthermore, NTN benefits extend beyond technological advancements and emergency response. In regions with low internet penetration, NTN can serve as a catalyst for social and economic empowerment – particularly among women. By providing reliable internet access to remote and under-served areas, NTN can facilitate education, healthcare, and entrepreneurial opportunities. Women, who are currently underrepresented among the internet users from a global perspective, can gain access to online resources, educational tools, and networks that were previously out of reach for them, thereby promoting gender equality and fostering inclusive development.

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