Non-Terrestrial Networks: Architecture and Implementation Challenges

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Abstract— **Non-Terrestrial Networks (NTNs) are emerging as a solution to overcome the limitations of terrestrial networks, especially in remote and difficult-to-reach regions where connectivity is limited or absent. NTNs are expected to offer numerous opportunities for next-generation wireless communication systems, paving the way for energy-efficient global connectivity. However, factors such as long delays and variations in propagation compared to terrestrial networks, as well as the high-speed movement of some types of satellites, mean that new challenges will arise, significantly affecting the implementation of this technology. This article aims to address the concept of NTN, their architecture and standardization. Furthermore, it explores the challenges associated with the integration of these networks and proposes solutions to improve their integration and performance.**

Keywords - Non-Terrestrial Networks, 5G Networks, Satellite Communications.

I. INTRODUCTION

NTN utilize aerial and space-based platforms, such as Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) satellites, as well as High Altitude Platform Stations (HAPS), to extend network services beyond the reach of terrestrial infrastructure. The integration of these networks with Fifth Generation (5G) technology marks a significant advance in the search for global connectivity. As the world increasingly relies on continuous digital communication, the ability of NTNs to provide coverage in remote maritime areas, polar regions and disaster-affected zones becomes indispensable. This global coverage is crucial not only for communication, but also for critical applications in sectors such as agriculture and environmental monitoring.

A key advantage of NTNs is the ability to provide connectivity without requiring significant changes to existing devices. This integration is enabled by standardization efforts led by the Third Generation Partnership Project (3GPP) [1], which has been vital in defining the protocols and architectures that allow for interoperability between terrestrial and non-terrestrial networks. This interoperability ensures that devices can switch between networks while maintaining consistent service quality [1]. However, the development of NTNs presents different challenges. Technical issues such as Doppler Shifts, resulting from the relative motion between satellites and ground stations, and significant propagation delays in satellite communication, particularly with GEO satellites, present hurdles that must be addressed. Furthermore, robust handover mechanisms between terrestrial and NTNs are crucial to ensure a seamless user experience as devices move across different coverage areas [2]. The 5G Core (5GC) network plays an essential role in managing these hybrid networks, facilitating the dynamic allocation of network resources to ensure that devices maintain connectivity during the transition between terrestrial and non-terrestrial links.

NTNs play an essential role in the future of telecommunications. Their ability to extend network coverage to the most remote areas of the planet, combined with advances in 5G technology, is considered a key element of the next generation of communications networks. As technology evolves, the challenges associated with NTN will need to be addressed through continued research and development to ensure these networks can deliver on their promise of global connectivity.

This article presents essential factors for professionals and researchers seeking to understand the architecture, standardization requirements, and key technical challenges associated with NTN. In addition, it presents discussions on technological solutions aimed at the efficient integration of these networks into current and next-generation mobile communication systems, promoting advances towards global connectivity.

It is organized as follows. Section II presents work related to what is being published on the topic of NTNs. Section III addresses the standardization of NTNs by 3GPP and the different architectures related to these networks. Section IV presents some challenges considered essential in the study and development of NTNs. Finally, Section V presents the main conclusions of this study.

II. RELATED WORK

As NTNs have become crucial to extending the coverage and capabilities of next-generation communication systems,

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especially in 5G, several studies have highlighted the advantages of integrating NTNs with terrestrial networks, while also identifying several challenges that still need to be addressed.

Recent literature has extensively explored the benefits of NTN integration. Rinaldi et al. [3] highlight the ability of NTNs to provide wide-area coverage, ensure service continuity, and offer scalability, especially in regions where terrestrial networks are economically impractical or geographically challenging, such as maritime, aeronautical, and remote areas. Similarly, Vanelli-Coralli et al. [4] affirm that NTNs can extend 5G services to underserved or unsold areas, improve service reliability, and enhance network scalability. Beyond their ability to cover underserved regions, NTNs are essential to strengthen the resilience of communication networks. In scenarios where terrestrial infrastructure may be compromised, such as during natural disasters or in conflict zones, NTNs can maintain service continuity, as noted by the authors in [3] [4]. This resilience is particularly vital for mission-critical services like emergency response and public safety.

Despite these advantages, several challenges remain. A major issue is the integration between terrestrial and NTN systems. Current architectures, as described by Rinaldi et al. [3], lack full convergence, leading to distinct management and operational frameworks for non-terrestrial and terrestrial components. This fragmentation creates inefficiencies and limits the full potential of NTNs. Vanelli-Coralli et al. [4] further highlight technical challenges, including high propagation delays, Doppler Shifts, and path losses, particularly in satellite-based systems, which hinder synchronization and overall system performance.

Service continuity, particularly for low-latency applications, presents another significant challenge. Rinaldi et al. [3] discuss how NTNs, especially those utilizing GEO and LEO satellites, struggle to meet Ultra-Reliable Low-Latency Communication (URLLC) requirements due to inherent satellite delays. Although NTNs are effective in delivering enhanced Mobile Broadband (eMBB) and massive Machine Type Communication (mMTC) services, their utility in latency-sensitive applications remains limited.

Energy efficiency and cost-effectiveness is another area of concern. NTNs, particularly satellite-based systems, are often associated with higher operational costs compared to terrestrial networks. Efforts to address these challenges include innovations in satellite payload designs, such as regenerative and transparent payloads, that aim to reduce costs while improving service performance. Transparent payloads reduce the complexity of on-board processing, but require more advanced ground infrastructure, whereas regenerative payloads can process signals in space, potentially reducing latency but at a higher operational cost [4].

Spectrum allocation and sharing between NTNs and terrestrial networks also represent a significant challenge. As demand for bandwidth increases, particularly with the proliferation of Internet of Things (IoT) devices and other bandwidth-intensive applications, effective spectrum management becomes increasingly important [3]. Recent research has investigated cognitive radio techniques and spectrum sharing strategies to mitigate interference between terrestrial and non-terrestrial systems, but practical implementation and standardization are still evolving.

In summary, while NTNs offer considerable advantages in enhancing the capabilities of 5G and beyond, several critical challenges remain unresolved. This work seeks to further explore these challenges and propose solutions to enhance the integration and performance of NTNs in next-generation networks.

III. NTN STARDARDIZATION AND ARCHITECTURES

A. 3GPP Releases

NTN emerged within the 3GPP standard, from Release 15 marking an essential moment in the evolution of 5G networks. This release introduced functionalities such as network management for integrating various satellites and airborne platforms, support for IoT in high-latency environments, security mechanisms to protect communications and Quality of Service (QoS) guarantees. These advancements laid the groundwork for NTNs in 5G networks, underscoring the commitment of 3GPP to integrating NTNs into existing infrastructures [5].

In 2018, Release 16 focused on NTN integration through two major studies: New Radio (NR) solutions for NTNs and Satellite Access in 5G. The first one explored how NR networks could be adapted for satellite use, addressing radio wave optimization and latency challenges.

The second study showed how existing interfaces and protocols could be adjusted for interoperability between terrestrial and non-terrestrial networks. These studies significantly expanded the reach of 5G, extending coverage and connectivity into remote or hard-to-reach areas [6].

Release 17 furthered this goal by seamlessly integrating terrestrial and non-terrestrial networks, ensuring smooth handovers and improving mobility management across multiple satellite orbits and constellations. This release also introduced enhanced security features, with new authentication and encryption methods, and optimized power consumption on mobile devices. These developments aimed to strengthen the capabilities of NTN and support a wider range of applications in 5G networks [7].

Releases 18 and 19 continue to evolve the NTNs networks with distinct innovations. Release 18 focuses on the integration of satellites and high-altitude platforms, improving service continuity and user experience, while optimizing satellite data transmission and expanding support for IoT [6]. Release 19 turns its attention to the future, particularly Sixth Generation (6G), enhancing connectivity and integration between NTNs and terrestrial networks. Key highlights include optimizing communications in dynamic environments and applying artificial intelligence and machine learning to real-time spectrum and resource management [8].

Release 19 also emphasizes regulatory and security frameworks, addressing the growing need for reliable communications and expanding NTN capacity for emerging applications like smart cities and autonomous vehicles [9].

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Both releases reflect a continuous focus of 3GPP on the future of mobile communications, with distinct priorities that address evolving technological challenges.

Looking ahead, Release 20 is expected to dive deeper into NTN research, focusing on large-scale communication optimization, managing the increasing number of connected devices, particularly in IoT and smart city environments. Improvements in mobility and service continuity will further refine the user experience in complex scenarios, such as autonomous vehicles. In addition, sustainability and energy efficiency will become areas of focus, with efforts to reduce energy consumption and minimize environmental impact. More robust security protocols will be developed to protect non-terrestrial communications, especially in vulnerable environments. Interoperability with emerging technologies will be a priority, as standards are established to ensure seamless communication between different systems.

Research activities continue to advance, with normative solutions that address the integration of satellite components into 5G architectures [5] [8] [9].

These efforts ensure robust communications in challenging environments. The continued development of NTNs across all 3GPP releases not only enhances 5G capabilities, but also lays the foundation for future generations of mobile communications by integrating advanced technologies and promoting more efficient and sustainable connectivity.

B. *Non-Terrestrial Network Architectures*

In the evolution of Next Generation Radio Access Network (NG-RAN), new interfaces and protocols have been developed to support NTNs. In these architectures, an NTN-based RAN includes onboard satellite network elements (NTN payloads), NTN Gateways (GW) and a ground segment. The gateway interconnects the payload to the terrestrial segment through a feeder link, establishing a bridge between space and terrestrial infrastructure [10].

The terrestrial segment consists of the 5G Core network and a Centralized Intelligence (CI). The latter is responsible for gathering information about the network status and using it to implement the best configurations and optimizing network performance. This model allows the NTN platform to operate as a space mirror or as a gNodeB in space, allowing two architectures for satellite-based NG-RAN: transparent and regenerative, where the gNodeB function can be performed partially or completely through the NTN platform [10].

Based on the location of gNodeB functionalities, it is possible to distinguish three main architectures: transparent, regenerative, and on-board distributed architecture. Furthermore, for each of these architectures, their protocol stacks, both for the User Plane (UP) and the Control Plane (CP), are described, specifying on which element of the non-terrestrial network each protocol function is implemented [11].

1) Transparent Architecture: In the transparent architecture, the gNodeB is located on the ground, therefore after the NTN ground station. The Non-Terrestrial Element (NTE) does not peform onboard processing of the signal. The gNodeB is connected to the core and then the signal is sent to the external Packet Data Network (PDN) [11]. Figure 1 shows the transparent architecture.

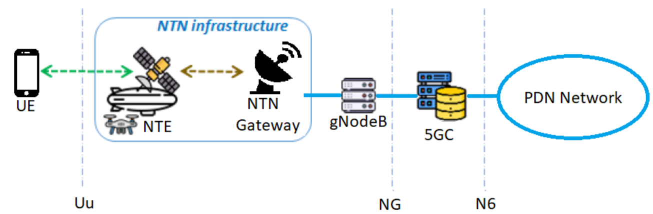

Figure 1. Transparent NTN architecture [11].

2) *Regenerative Architecture*: The gNodeB is embedded in the NTE, thus improving the performance of the NTN. Unlike the transparent architecture, where the Satellite Radio Interface (SRI) on the feeder link is based on 5G-Uu, for regenerative NTN, the SRI is a transport link used to transmit both user data and control from the NTE to the NTN gateway on the ground [11]. Figure 2 shows the regenerative architecture.

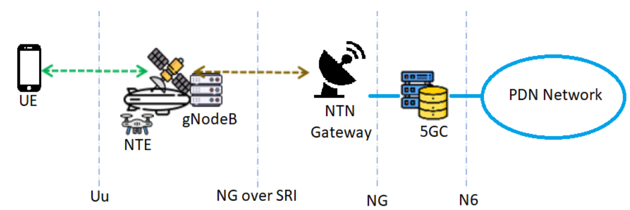

Figure 2. Regenerative NTN architecture [11].

3) *Distributed Architecture*: The distributed embedded architecture uses a functional division of the gNodeB into a Distributed Unit (DU) and Central Unit (CU). The DU is embedded in the NTE, while the CU is on the ground after the NTN gateway. Therefore, the DU split and the CU means separating processing tasks between Central unit on the ground, distributed unit embedded in the satellite, scalability, flexibility and efficient use of resources.

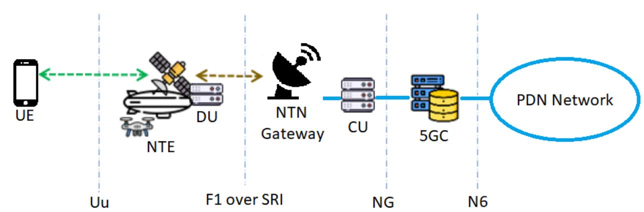

Figure 3. Distributed NTN architecture [11].

To work together, the CU and DU communicate through an interface called F1. This interface is critical to ensure efficient and synchronized operation of the gNodeB. The F1 interface manages communication between the high and low layers, separating the control plane from the user plane. Figure 3 shows the distributed architecture.

IV. CHALLENGES OF THE NTN

Despite the standardization and consolidated structure for the operation of NTN, many challenges still permeate the topic. In the following section, some of these challenges will be presented and what is already thought of as a solution for each, without compromising the efficiency and reliability of network services.

A. NTN Backhaul

One of the biggest challenges of NTN is the backhaul, since the volume of data transmitted in a 5G network is very high and there is great susceptibility around service and power links.

There are two viable scenarios to overcome a system susceptibility situation. In the first scenario, where there is an earth station out of service due to rain or natural disaster, portable base stations can be placed with direct service links connected to the HAPS and these HAPS connected to the base stations corresponding to the power links.

In the second one, it is possible to work with reception diversity when a power link goes out of operation for the same reasons as in the first scenario. Here, it is important to note that the power link integrates NTN with 5G networks [12].

For both scenarios presented, the proposal is to operate in the 38 GHz band to cover a bandwidth of 80 MHz, thus making backhaul data flow viable. To operate in this band, some requirements must be met, such as the correct orientation of the ground station antennas and the HAPS antennas for direct and unobstructed sighting, and also restricting the heights of the HAPS to up to 20 km. Another important factor to be considered is the attenuation due to rain in this 38 GHz band, as shown in Table I. From the table, it is possible to note that for distances compatible with the proposed links of a maximum of 20 km, the attenuation due to rain is around 27 dB/km. The greater the distance, the greater the attenuation, which may make the link unfeasible in some cases.

TABLE I. NTN STUDY ITEMS AND FEATURES BY 3GPP RELEASES

	Distance (km)		
	10	**30**	**50**
Elevation Angle (degrees)	63.4	33.7	21.8
Estimated Rain Attenuation (dB)	26.7	28.8	40.9

To overcome this rain attenuation problem, diversity scenarios can be used in 5G networks combined with Automatic Transmission Power Control (ATPC) and Adaptation Coding and Modulation (ACM) techniques that were created to improve system efficiency [13].

B. Handover

Handover is the process of transferring a device connection between different radio bases in a wireless mobile network when there is a need to improve coverage and signal quality. In NTNs, such as those using satellites and drones, handover becomes even more challenging due to the high mobility of devices, variable latency, and coverage heterogeneity. The constant movement of satellites in relation to Earth, for example, significantly increases the frequency of handovers, requiring robust and efficient mechanisms to guarantee QoS, minimizing interruptions in communication and optimizing the use of network resources. Furthermore, significant latency variations, common in NTN scenarios, further complicate the message exchange process required for handover.

The heterogeneity in coverage in NTN also represents a challenge, demanding advanced solutions so that the connection is stable and continuous, especially in environments with limited or intermittent coverage. To face these challenges, artificial intelligence-based solutions have been explored and are considered promising for improving the handover process in NTNs. Through techniques such as machine learning and deep learning, resources can be optimized in order to estimate channels and make decisions in real time, contributing to a more stable connectivity experience. Recent initiatives have implemented artificial intelligence on satellite network testbeds and promoted the integration of NTNs with 5G terrestrial networks, seeking a more robust and cohesive network infrastructure.

Relevant studies reinforce the importance of NTNs as essential components in future 6G networks. Research such as that in [14] addresses the specific technical challenges of these networks, including high mobility and complexity in resource management, especially for LEO satellites. Another study [15] discusses handover optimizations in NTNs using artificial intelligence and machine learning to improve service continuity and resource management in mobile networks beyond 5G. Furthermore, according to the work in [16], links between satellites and between satellites and Earth suffer from increased latency and limited processing capabilities, making efficiency and the ability to handle handover demand more difficult. Security is also a concern, as NTNs are more susceptible to attacks and compromised devices can be used to disrupt services, making a handover protocol that maintains security even in cases of compromise essential. Finally, conventional handover protocols are ineffective in NTNs as they rely on signal strength indicators that have little variation across satellite coverage areas, requiring handover approaches more adapted to this environment.

Therefore, future research should focus on advances in the integration of artificial intelligence with NTNs, in addition to exploring technologies for latency optimization, interference mitigation, and dynamic spectrum allocation. These innovations are fundamental to ensuring high quality and resilient global connectivity, enabling NTNs to meet the demands of a highly dynamic and critical communications environment.

C. Radio Link Failure

In the case of NTN and NR networks, during a handover, a Radio Link Failure (RLF) can occur due to interference and/or low signal strength, interrupting the connection to the base station, due to signal obstructions resulting from terrain or weather [17], or due to the movement of the satellite. This leads to the discontinuation of the application in use, which represents an impact on user experience [18]. Once an RLF is declared, the User Equipment (UE) begins the RLF recovery procedure. The UE selects the cell and attempts to reestablish the connection with it, a procedure called Access Stratum (AS) recovery. This procedure is successful only if the UE selects a cell from the same gNodeB or from a handover-ready gNodeB. In case of failure, the UE enters an idle state and attempts the Non-Access Stratum (NAS) recovery procedure [19]. The big challenge is dealing with frequent handover situations without resulting in an increase in the number of RLFs, in the case of satellite solutions. In [20], some simulations were carried out taking into account different scenarios of non-terrestrial networks using LEO satellites, and as a result, it is clear that the handover algorithm used in conventional 5G networks fails to provide continuous connectivity in NTN. The big challenge is managing handover delays and unnecessary handovers.

It is observed that the high number of failures is due to a combination of factors, such as the low signal variation between the center and the edge of the cell and the propagation distance greater than the cell size, which prevents device measurements. Another factor is the high downlink interference between adjacent satellite beams, in addition to propagation delays due to long communication distances, which leads to delays in sending control messages and, consequently, increases the handover latency caused by RLF.

D. Reconfigurable Intelligent Surfaces (RIS)

The development of RIS technology represents a fundamental innovation for the advancement of wireless communication in terrestrial and non-terrestrial networks. RIS offers significant benefits, including improved localization and connectivity, as well as improved energy efficiency. Recent research highlights its application in mobile and satellite networks, particularly to improve performance in urban and Non-Line-Of-Sight (NLOS) environments [21].

The integration of RIS technology into various types of networks highlights its potential to address key challenges of next-generation wireless systems. From improving localization in 5G and optimizing resource usage in dense urban areas to extending connectivity through NTNs, RIS offers versatile solutions that are essential to realize the vision of global and energy-efficient 6G connectivity [22].

Despite their favorable benefits, NTNs face several challenges compared to terrestrial networks, such as coverage and signal capacity in various environments, propagation losses in the atmosphere and space, high power consumption, spectrum sharing with terrestrial networks, and security issues.

According to [23], RIS has recently emerged as a promising technology for 6G and beyond. When integrated into NTNs, RIS can revolutionize next-generation connectivity.

RIS consists of a large number of metaelements capable of manipulating the phase, amplitude, and polarization of signals. Specifically, RIS can control signal propagation by reflecting, refracting, and focusing signals on specific locations, effectively improving signal intensity, coverage, and link quality.

RIS-integrated NTNs are expected to provide numerous opportunities for next-generation wireless systems. Recent studies have analyzed their potential in various application domains. Significant results on energy consumption minimization and energy efficiency optimization have been investigated. The achievable gains in terms of sum-rate maximization for RIS-integrated NTNs are high. These systems also intrinsically enhance wireless system security and improve physical layer security in RIS-integrated NTNs. However, a holistic and long-term vision is imperative for the next generation of RIS-integrated NTNs, paving the way to achieve global energy-efficient connectivity enabled by RIS technologies.

Although RIS technology offers transformative potential, several challenges remain for its practical application in NTNs:

1) Hardware Complexity and Calibration: Designing and manufacturing RIS with precise elements can be technically challenging and expensive, particularly for large-scale NTN deployments. Large-scale implementations also require calibration and synchronization among RIS elements to achieve coherent signal manipulation. Ensuring precise and real-time RIS control for signal path optimization can be complex, especially when multiple NTN platforms are involved.

2) Dynamic Channel Conditions: NTN platforms, especially satellite communications, experience dynamic and time-varying channel conditions due to mobility and atmospheric effects. RIS configuration and optimization are based on the acquisition of channel state information, which is critical for continuous connectivity. Efficient algorithms for real-time channel estimation and control are necessary in dynamic NTN environments.

3) AI/ML Integration: Artificial Intelligence and Machine Learning offer significant opportunities to enhance RIS performance in NTNs. By utilizing AI/ML techniques and algorithms, RIS can optimize signal reflection patterns in realtime, adapt to changing network conditions, predict channel variations, and self-optimize based on feedback. RIS driven by AI/ML can dynamically adjust its reflective properties, ensuring optimal signal intensity and quality even in dynamic NTN environments.

V. Conclusions and Future Work

This article presented a synthesis of topics that are widely explored in the literature, including an overview of 3GPP standardization related to the NTN and some possibilities to construct different architectures for this technology. Some challenges are discussed, and some solutions are proposed, focusing on data transmission, handover processes, and emerging technologies, such as RIS. Key issues include the high volume of 5G data causing backhaul challenges, handover difficulties due to device mobility and NTNs variable latency, and the need for robust mechanisms to maintain QoS. To address these, AI based solutions help optimize handover by improving resource allocation and real-time decision-making.

The implementation of RIS technology is emphasized, which can improve connectivity and energy efficiency in NTNs by enhancing signal strength and mitigating interference. RIS technology plays an important role in addressing NTN challenges such as signal coverage, propagation losses, and energy consumption, offering benefits like improved link quality and extended coverage. Challenges include the technical complexities of designing and implementing RIS, dynamic channel conditions in NTN environments, and ensuring security and privacy. Future work should focus on advancing the integration between NTNs and AI-driven mechanisms to improve decision-making in dynamic environments. Key areas include the development of adaptive handover protocols tailored for high-mobility satellite systems, spectrum sharing strategies using machine learning, and secure, resilient architectures for RIS-integrated NTNs. Moreover, there is a growing need to explore edge computing capabilities embedded in satellites to reduce latency and offload processing from terrestrial infrastructure. These directions aim to unlock the full potential of NTNs in enabling autonomous vehicles, smart agriculture, and emergency communications in 6G and beyond.

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