

Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities

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ABSTRACT

Many organizations recognize non-terrestrial networks (NTNs) as a key component to provide cost-effective and high-capacity connectivity in future 6th generation (6G) wireless networks. Despite this premise, there are still many questions to be answered for proper network design, including those associated to latency and coverage constraints. In this article, after reviewing research activities on NTNs, we present the characteristics and enabling technologies of NTNs in the 6G landscape and shed light on the challenges in the field that are still open for future research. As a case study, we evaluate the performance of an NTN scenario in which aerial/space vehicles use millimeter wave (mmWave) frequencies to provide access connectivity to on-the-ground mobile terminals as a function of different networking configurations.

INTRODUCTION

While network operators have already started deploying commercial 5th generation (5G) cellular networks, the research community is discussing use cases, requirements, and enabling technologies toward 6th generation (6G) systems [1]. Among other challenges, current networks fall short of providing adequate broadband coverage to rural regions [2]. Moreover, even in the most technologically advanced countries, existing cellular infrastructures may lack the level of reliability, availability, and responsiveness requested by future wireless applications, and show vulnerability to natural disasters. Connectivity outages during natural disasters, in particular, may slow down or impede appropriate reaction, create significant damage to business and property, and even loss of lives.

One solution to increase network resiliency would be to densify cellular sites, which however involves prohibitive deployment and operational expenditures for network operators and requires high-capacity backhaul connections [2, 3]. Moreover, network deployment in rural areas (i.e., the most under-connected areas) is further complicated by the varying degree of terrain that may be encountered when installing cables or fibers between cellular stations. Network densification will also inevitably lead to an energy crunch with serious economic and environmental concerns.

To address these issues, 6G research is currently focusing on the development of non-terrestrial networks (NTNs) to promote ubiquitous and high-capacity global connectivity [4]. While

previous wireless generation networks have been traditionally designed to provide connectivity for a quasi bi-dimensional space, 6G envisions a three-dimensional (3D) heterogeneous architecture in which terrestrial infrastructures are complemented by non-terrestrial stations including Aerial Vehicles (UAVs), High Altitude Platforms (HAPs), and satellites [5]. Not only can these elements provide on-demand cost-effective coverage in crowded and unserved areas, but they can also guarantee trunking, backhauling, support for high-speed mobility, and high-throughput hybrid multiplay services. Notably, the potential of NTNs has been acknowledged in the standard activities. A work item for 3GPP Rel-17 has indeed been approved in December 2019 to define and evaluate solutions in the field of NTNs for NR, with a priority on satellite access. Study items have also been identified for Rel-18 and Rel-19, thus acknowledging long-term research within the timeframe of 6G.

Research studies on NTN are not only limited to 3GPP reports. For instance, Babich *et al.* presented a novel network architecture for an integrated nanosatellite-5G system operating in the millimeter wave (mmWave) domain [6], while in our previous work [5] we identified the most promising configuration(s) for satellite networking and discussed some design trade-offs in this domain. UAVs were also considered as a tool to complement terrestrial connectivity in critical scenarios [7]. Additionally, there currently exist several case studies of NTN deployments in different countries, in addition to efforts by international foundations and initiatives [2].

Nevertheless, despite such earlier investigations, there are still several questions to be answered for proper network design. In particular, while some prior work typically focuses on stand-alone aerial/space architectures, a formalization of the challenges and opportunities pertaining to a multi-layered network, in which heterogeneous non-terrestrial stations co-operate at different altitudes in an integrated fashion, has not yet been provided. Some other articles, for example [8], review how to improve the protocol stack design in a space-air-ground integrated network, but do not thoroughly explore the most recent technological advancements to achieve performance optimization. Moreover, a complete description of NTN enabling technological solutions and future research directions is currently scattered in several technical reports, which makes them confusing and tiresome to follow without the proper background.

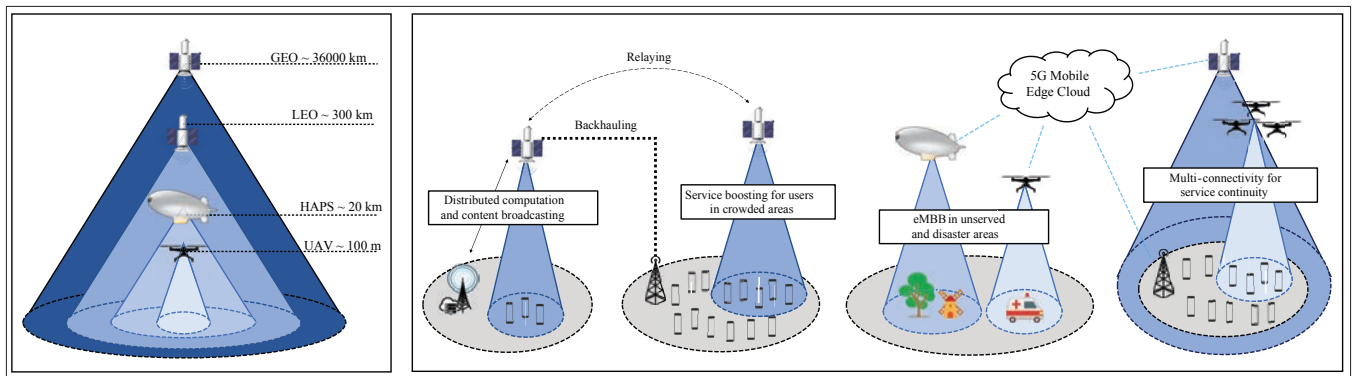


FIGURE 1. Non-terrestrial stations (left) and use cases enabled by the integration of terrestrial and non-terrestrial networks (right).

This article addresses these challenges by formalizing how NTN can be practically deployed to satisfy emerging 6G application requirements. We focus on:

- New architecture advancements in the aerial/space industry
- Novel spectrum technologies, for example, operating in the mmWave and optical bands
- Antenna design advancements
- Transport layer developments.

Moreover, we shed light on the research challenges associated to NTN, providing a full-stack perspective with considerations related to spectrum usage, medium access and higher layers, coverage and mobility management constraints, thus stimulating further research on this topic. Finally, as a case study, we validate the feasibility of establishing non-terrestrial communication at mmWaves to provide access connectivity to terrestrial nodes.

NON-TERRESTRIAL NETWORKS IN 6G

NTNs refer to (segments of) networks operating through an air/spaceborne vehicle for communication. While the possibility to integrate satellite technologies to provide access connectivity on the ground was first introduced by 3GPP in Rel-15, more recent activities have been promoted for Rel-16 and Rel-17 to define deployment scenarios and parameters, and identify key potential impacts in NR [9]. Specifications may also continue with enhancements in Rel-18 and Rel-19.

Based on this introduction, in the following section we describe a typical non-terrestrial architecture. Following that we present potential use cases and related deployment scenarios.

GENERAL ARCHITECTURE

Non-terrestrial systems feature:

- A terrestrial terminal
- An aerial/space station, which may operate similarly to a terrestrial base station
- A service link between the terrestrial terminal and the aerial/space station
- A gateway that connects the non-terrestrial access network to the core network through a feeder link.

Different types of stations can be considered, as depicted in the left part of Fig. 1.

Unmanned Aerial Vehicle (UAV): UAVs fly at low altitudes (e.g., a few hundred meters), and thanks to their flexibility, have recently gained increasing attention to provide broadband wide-

scale wireless connectivity during disasters or temporary events, and relay services for terrestrial mobile nodes. On the one hand, UAVs can be deployed on-demand, thereby promoting energy efficiency compared to always-on fixed terrestrial infrastructures. On the other hand, UAVs incur high propulsion energy consumption to maintain and support their movement, thereby posing severe power management constraints.

High Altitude Platform (HAP): HAPs operate in the stratosphere at an altitude of around 20 km. Thanks to their quick deployment and geographic coverage of hundreds of kilometers, these elements are indeed being considered to support ultra-flexible deployment and cost-effective wireless services, without the prohibitive costs of terrestrial infrastructures. However, HAPs may suffer from the need for refueling and challenges related to stabilization in the air.

Satellites: Satellite stations can be classified according to their orbit characteristics. Geostationary Earth Orbit (GEO) satellites orbit on the Earth's equatorial plane at an altitude of about 35,800 km and, despite the significant signal propagation delay and attenuation experienced at such long distance, can cover very large geographic areas and are continuously visible from terrestrial terminals. Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites, instead, orbit at an altitude between 200 and 2,000 km and 2,000 and 35,000 km, respectively, and guarantee better signal strength and lower propagation delay compared to GEO systems. However, these satellites are non-stationary relative to the Earth's surface and must operate in a constellation to maintain service continuity. The 3GPP is promoting different NTN architectures depending on the degree of integration among the different air/spaceborne elements [9]. Specifically, the 3GPP envisions:

- A *transparent* satellite-based Radio Access Network (RAN) architecture in which the satellite repeats the user's signal from the feeder link to the service link and vice versa
- A *regenerative* satellite-based RAN architecture in which the satellite payload implements regeneration of the signals received from the Earth, while also providing inter-satellite connectivity
- A *multi-connectivity* architecture involving two transparent RANs (either GEO or LEO or a combination thereof), where integration of terrestrial and non-terrestrial access is also supported.

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

TABLE 1. Enabling technologies for non-terrestrial networks.

USE CASES

For many years, non-terrestrial devices have been considered to support services like home delivery, meteorology, video surveillance, television broadcasting, remote sensing, and navigation. However, recent technological developments in the aerial/space industry have opened the way toward integration between terrestrial and non-terrestrial technologies to enable more advanced use cases, as illustrated in the right part of Fig 1 and summarized below.

Communication Resilience and Service Continuity: Non-terrestrial stations can be deployed to assist existing base stations in providing high-capacity wireless coverage, for example, in hot-spot areas or when terrestrial infrastructures are overloaded. Non-terrestrial elements can also provide a secondary backup route to preserve the connection when the primary path is unavailable, for example, in rural areas or oceans, or when terrestrial towers are out of service, for example, after natural disasters. Additionally, these elements can provide on-demand extra capacity to cell-edge users, the most resource-constrained network entities, thereby promoting fairness in the network. Finally, aerial platforms can host Mobile Edge Cloud (MEC) functionalities to offer on-the-ground terminals additional computing and storage capabilities, thereby evolving coverage toward 3D. Even though the limited energy support from battery may render the MEC environment challenging, machine-learning-assisted migration and technologies for renewable energy production/harvesting and storage are studied to minimize power consumption [10].

Global Satellite Overlay: When the distance between two terrestrial infrastructures increases, inter-site connectivity through optical fiber may become too expensive. A constellation of satellites, where each spacecraft is interconnected with other neighboring spacecrafts via inter-satellite links, can then provide high-capacity access connectivity to on-the-ground devices by relaying the user's signals through an overlay space mesh network.

Ubiquitous Internet of Things (IoT) Broadcasting: The wide geographical coverage and the inherent broadcast nature of aerial/space platforms make it possible to convey multimedia and

entertainment contents to a very large number of user equipments, including in-motion terminals that cannot benefit from terrestrial coverage like planes or vessels. UAVs and satellites can also play the role of moving aggregators for IoT traffic, thereby offering global continuity of service for applications that rely on sensors.

Advanced Backhauling: Non-terrestrial terminals can serve on-the-ground backhaul requests wirelessly, for example, for locations where no wired backhaul solutions are available, thereby saving terrestrial resources for the access traffic and avoiding the costs of traditional fiber-like deployments. Satellites and other aerial platforms can also complement the terrestrial backhaul in dense regions with high peak traffic demands, thus achieving load balancing.

Energy-Efficient Hybrid Multiplay: Air/spaceborne platforms have the ability to provide high-speed connectivity while promoting energy efficiency. On one side, aerial platforms like UAVs, while consuming significant energy for hovering, can be deployed on demand implementing smart duty cycle control mechanisms, thereby reducing management costs of always-on fixed terrestrial infrastructures. On the other side, space platforms like satellites can be operated by solar panels which provide efficient, clean, and renewable energy compared to traditional energy sources powering terrestrial devices.

NON-TERRESTRIAL NETWORKS: ENABLING TECHNOLOGIES

The evolution of NTN will be favored by recent technological advancements in the aerial/space industry, as summarized in Table 1 and described in the following subsections. We focus on the innovations that do not currently fall within the scope of early 5G standard activities but could flourish in 6G.

ARCHITECTURE ADVANCEMENTS

Space manufacturers are improving satellite technologies while further reducing the operational costs for satellite launch, deployment, and maintenance. Nano-satellites and pico-satellites in the LEO orbits, in particular, are emerging as game-changing innovations thanks to their

reduced component costs, and low communication latency and energy consumption. Moreover, the adoption of the Gallium Nitride (GaN) technologies on satellites allows the use of smaller form factors and more efficient components compared to their silicon counterparts, thereby saving fuel and area on the payload and improving operational efficiency [11]. Today, the commercialization of GaN products is restricted to military applications, with most 5G devices utilizing silicon wafer substrates, but their adoption in commercial networks may still be realized for 6G. Additionally, the availability of multi-layered satellite networks, for example, LEO and GEO constellations, makes it possible to obtain better spatial/temporal coverage. Nevertheless, a real integration between terrestrial and non-terrestrial networks still seems far in the future, and standardization activities are scheduled within the timeframe of 6G.

UAV technology has also improved recently. Solid-state lithium batteries, in particular, make it possible for UAVs to work twice as long compared to today's aerial devices, and are being considered as a safer and more efficient alternative compared to standard lithium-ion batteries. Furthermore, UAV swarms, combined with HAPs and satellites, can operate together to support more robust information broadcasting compared to a standalone deployment by adding redundancy against single points of failure in the path.

Architecture optimization is also favored by the transition to Software Defined Networking (SDN) [12] which, in combination with network slicing, facilitates the deployment and management of Virtualization Network Functions (VNFs) onto the same physical platform. Furthering a trend already started in 5G, 6G will contribute to the design of a disaggregated architecture that can operate in view of the competitive nature of the non-terrestrial environment to guarantee improved flexibility, automation, and agility in the delivery of services to terrestrial terminals. Satellite payloads can be realized in software to flexibly adapt beam patterns, frequency, and power allocation, and react to the dynamics foreseen in future wireless traffic. Moreover, hybrid payload implementations, in which the burden of signal processing is split between the on-the-ground gateway and the non-terrestrial station, have been recently studied to achieve better trade-offs between performance and payload complexity.

SPECTRUM ADVANCEMENTS

Non-terrestrial devices have typically been operated in the legacy frequency bands below 6 GHz which, however, may not satisfy the boldest data rate requirements of future beyond-5G services. Capacity issues can be solved by transitioning to high-frequency communications in the mmWave and optical bands, where the huge bandwidths available may offer the opportunity of ultra-fast connections. However, while the adoption of the mmWave spectrum is being successful in the 5G market for both cellular and vehicular networks, it is still unclear whether this technology can be used in the non-terrestrial environment. Solutions are being proposed toward the development of new waveforms and modulation

Programmable environments enabled by metasurfaces and intelligent structures are another revolutionary element of the 6G ecosystem to realize antenna component miniaturization, improved directivity, low sidelobes and fine beamwidth control.

schemes, for example, impulse-based ultra-wide-band (UWB) modulation where information is encoded depending of the characteristics of the transmitted pulse, as a viable approach to reduce the non-linear signal distortion typically experienced at high frequencies [13]. Moreover, cognitive spectrum techniques may enable dynamic spectrum utilization in different bands, while minimizing interference.

Optical wireless technology can also be used in the feeder link to achieve aggregate capacity in the order of terabits-per-second [14]. Optical transceivers, in fact, leverage higher bandwidth and directivity compared to radio-frequency systems and consume much less power and mass. In this context, atmospheric perturbations and interference from sunlight can be mitigated by wavefront correctors and deformable mirrors, which compensate the signal distortion after propagating through the atmosphere, and advanced modulation schemes. Error control coding also improves the performance of the optical link by making use of Turbo and convolutional codes. Nevertheless, despite this potential, standardization bodies have not yet considered inclusion of optical solutions in the NTN standard, and will be targeting beyond-5G use cases.

ANTENNA ADVANCEMENTS

Aerial/space devices can be equipped with reconfigurable phased antennas offering electronic beam-steering to achieve lower power consumption and reduced size and weight compared to typical mechanical antennas. Programmable environments enabled by metasurfaces and intelligent structures are another revolutionary element of the 6G ecosystem to realize antenna component miniaturization, improved directivity, low sidelobes and fine beamwidth control [15]. Future trends in the antenna domain further suggest the use of inflatable (i.e., made with flexible-membrane materials) and fractal antennas with unique geometrical designs to obtain high directivity in dynamic scenarios. Additionally, UAVs and/or nano-satellites (e.g., in the LEO orbit) can be deployed in swarms to obtain a distributed coherent antenna array to realize extremely narrowbeam transmissions. Such a solution offers maintainability and scalability, as elements can be easily arranged without affecting system operations, and robustness to single points of failure.

Advanced antenna solutions allow the implementation of multi-beam architectures that send information to different spots on the ground through a plurality of beams, thereby maximizing spectrum efficiency through spatial diversity. The multi-beam approach is further favored by operations in the mmWave and optical domains, where the wavelength is so small that it becomes practical to build large antenna arrays in a small space while maximizing antenna gains through beamforming.

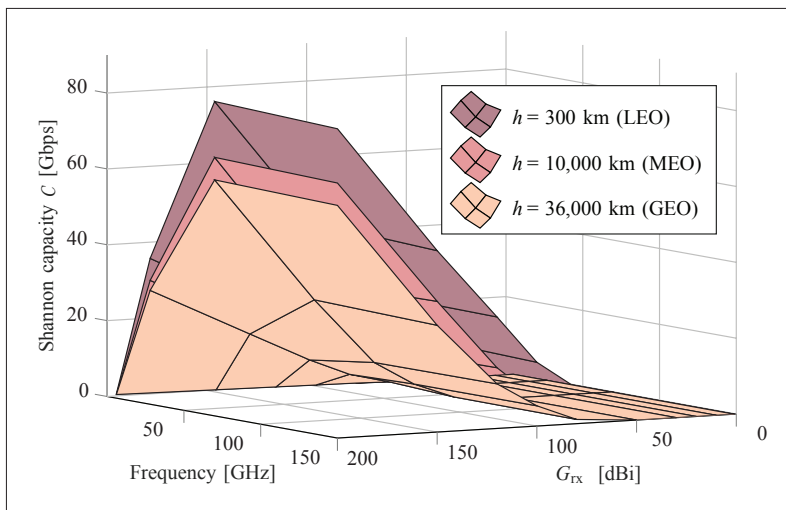


FIGURE 2. Shannon capacity vs. h , f_c , and G_{TX} , with $\alpha = 10^\circ$ and for a dense urban scenario.

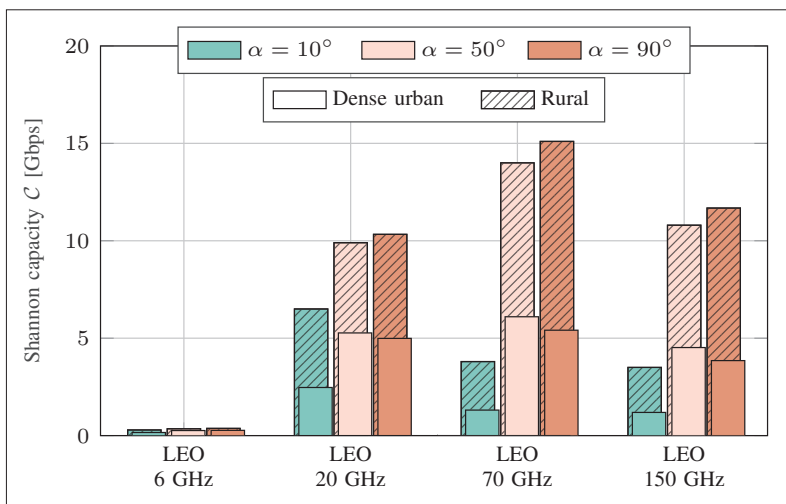


FIGURE 3. Shannon capacity vs. α for an LEO-GND scenario with $h = 300$ km, with antenna-gain-to-noise-temperature $G_{rx}/T = 15.9$ dBi/K [9]. Dense urban (rural) scenario for plain (striped) bars.

HIGHER-LAYER ADVANCEMENTS

NTNs come with their own set of challenges compared to standalone terrestrial systems, which might make standard transmission protocols, including congestion control over Transmission Control Protocol (TCP), less effective. Network operators have therefore developed acceleration techniques that make transport protocols perform better. TCP spoofing, in particular, is used to send false TCP Acknowledgments to terrestrial terminals from a spoofing entity (or software) nearby, as if they were sent from the aerial/space station, thereby making it possible for the TCP control mechanism to quickly reach the maximum supported rate. TCP multiplexing is another solution that converts a single TCP session into multiple data flows, each of which can adjust its TCP parameters to match the characteristics of the non-terrestrial connection.

NON-TERRESTRIAL NETWORKS: A CASE STUDY

As a case study, in this section we assess the feasibility of establishing mmWave communications between terrestrial and satellite terminals, possi-

bly through hybrid integration of multiple aerial/space layers. This choice was driven by the fact that the use of satellites operating in the mmWave bands, among all the technologies discussed earlier, currently represents one of the most promising innovations (as already successfully demonstrated in the cellular and vehicular fields) to offer high-capacity broadcasting capability in NTN.

In our simulations, a terrestrial terminal communicates with a satellite placed at different altitudes h , and we consider different elevation angles $\alpha \in \{10^\circ, \dots, 90^\circ\}$ and propagation scenarios. The channel is modeled as described by the 3GPP in [9] and summarized in [5, Sec. III]: specifically, the signal undergoes several stages of attenuation due to atmospheric gases and scintillation. Terrestrial stations are equipped with directional antennas offering a gain $G_{TX} = 39.7$ dBi [9] while, for satellite stations, the gain G_{rx} is varied to consider different antenna architectures. Satellite communication leverages a bandwidth W that depends on the carrier frequency f_c : we set $W = 20$ MHz for $f_c \leq 6$ GHz, $W = 800$ MHz for $6 < f_c \leq 60$ GHz, and $W = 2$ GHz for $f_c > 60$ GHz.

In Fig. 2 we plot the Shannon capacity \mathcal{C} , which represents a commonly accepted metric to facilitate accurate benchmarking of wireless networks, as a function of h , f_c and G_{rx} . First, we observe that satellite operations in the bandwidth-constrained below-6 GHz spectrum offer limited capacity (i.e., < 500 Mb/s), which might be insufficient to satisfy the most demanding beyond-5G use cases. The performance can be improved by considering mmWave transmissions, thanks to the massive bandwidth available at higher frequencies, provided that high-gain directional antennas (i.e., $G_{rx} > 50$ dB, as is typical in current satellite antenna technologies) are employed, to cover very long transmission distances. Figure 2 also makes the case that further increasing f_c beyond 70 GHz would decrease the Shannon capacity due to the increasingly harsh impact of atmospheric absorption in the higher mmWave spectrum.

As expected, \mathcal{C} severely reduces for increasing values of h , that is, transitioning from LEO to GEO satellites. Nevertheless, gigabits-per-second capacities can still be reached if the satellite station forms very sharp beams, thereby boosting the performance through massive beamforming. This is practically feasible since GEO satellites are stationary relative to the Earth's surface and do not require beam re-alignment.

Similar conclusions can be drawn from Fig. 3, where we observe that the system performance decreases at low elevation due to the more severe impact of scintillation absorption (which is caused by sudden changes in the refractive index due to the variation of temperature, water vapor content, and barometric pressure), as the signal has to transit longer through the atmosphere. Moreover, Fig. 3 exemplifies that the increased probability of path blockage in the urban scenario may reduce the achievable capacity by more than 60 percent at high elevation, compared to a rural scenario.

Despite these promising results, better wireless coverage can be provided when a standalone space layer is assisted by HAPs operating in the stratosphere, as already discussed above. A performance comparison between a standalone LEO

scenario (LEO-GND) and a multi-layered scenario (LEO-HAP-GND) in which a HAP bridges the LEO communications toward the ground is plotted in Fig. 4. It appears clear that the intermediate HAP offers improved capacity by amplifying the signal from the upstream satellite before forwarding it to the ground, while ensuring a quicker deployment and lower costs compared to spaceborne stations. The benefits are particularly evident when $h = 1,200$ km and $\alpha = 10^\circ$, that is, when the resulting longer propagation distance from the LEO satellite may deteriorate the signal quality below detectable levels on the ground, with a performance boost of +250 percent.

NON-TERRESTRIAL NETWORKS: OPEN CHALLENGES

Despite current standardization efforts toward the development of NTN, there remain several open issues for proper protocol design which call for long-term research, as highlighted below and summarized in Table 2.

Channel Modeling: Even though the 3GPP has specified how to characterize mmWave propagation for the satellite channel [9], it is currently not investigating second order statistics (including therefore correlation in both space and time), nor the impact of Doppler, fading, and multipath components, which is critical at high frequencies. Moreover, a general and accurate model of a fully-layered space-air-ground channel is still lacking.

Spectrum Co-Existence: As non-terrestrial systems move into the mmWave bands, where other systems have been operating for many years (e.g., satellites offering weather forecasting services), consideration needs to be given to the co-existence among different networks. The main challenge is the development of flexible spectrum sharing techniques that maintain adequate isolation among different communications while ensuring reasonable licensing costs.

PHY Procedures: In the non-terrestrial case even the highest available sub-carrier spacing

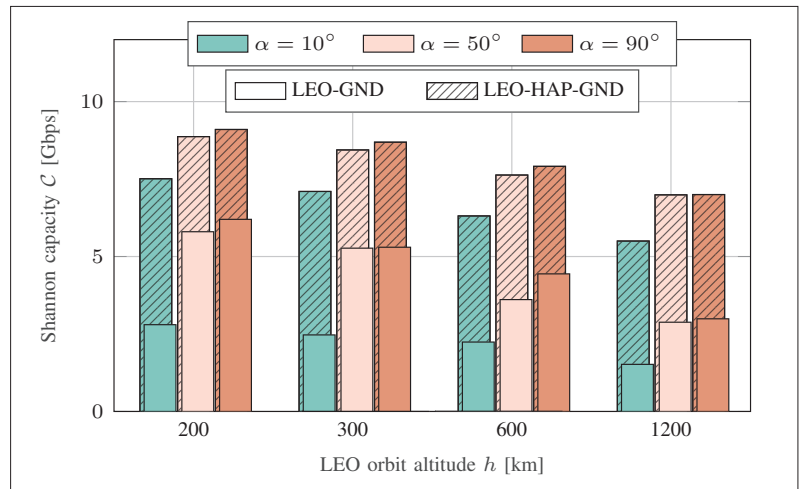


FIGURE 4. Shannon capacity vs. α and h for a dense urban scenario at $f_c = 20$ GHz. We compare an LEO-GND (plain bars) and a multi-layered LEO-HAP-GND scenario (striped bars) in which a HAP deployed at 20 km acts as a relay.

in the frame structure may not be enough to compensate for the large Doppler experienced considering the high speed of aerial/space stations. Moreover, the large propagation delays in NTN may create a larger response time for the Adaptive Modulation and Coding (AMC) scheme loop and requires a margin to compensate for the possible outdated control signals exchanged during channel estimation. Notably, in an integrated terrestrial/non-terrestrial framework, different network elements on the end-to-end communication path may process the information at different rates, thus contributing to the overall communication delay. Additionally, Time Division Duplexing (TDD), which is frequently considered in terrestrial networks since guard times must be proportional to the propagation delay.

Open challenge	Explanation
Channel Modeling	Missing adequate characterization of mmWave second order statistics, Doppler, fading, multipath
Spectrum co-existence	Spectrum sharing is required to provide isolation among different non-terrestrial services
PHY procedures	Design of flexible numerology to compensate for large Doppler shift Non-linear payload distortions may complicate signal reception Large RTTs increase the response time for ACM scheme Large RTTs make it infeasible to operate in TDD
HARQ	Large RTTs may exceed the maximum possible number of HARQ processes
Synchronization	Large non-terrestrial station's footprint creates a differential propagation delay among users in the cell
Initial access	Channel dynamics may result in obsolete channel estimates
Mobility management	Directionality complicates user tracking, handover, and radio link failure recovery
Constellation management	Non-terrestrial stations may need to serve a very large number of users Constellation of non-terrestrial stations is necessary to maintain ubiquitous service continuity High cost of satellite launches complicates deployment of dense constellations Wireless coordination among air/spaceborne vehicles complicates constellation management
Higher-layer design	Channel dynamics result in obsolete topology information Large RTTs result in longer duration of the slow start phase of TCP Channel dynamics result in decreased resource utilization due to sudden drops in the link quality
Architecture technologies	Unclear where to distribute SDN planes Long RTTs prevent long duration of batteries Design of central authority making secure network/communication decisions

TABLE 2. Open challenges for non-terrestrial networks.

An integrated space-air-ground architecture should envision the existence of a trusted central authority making secure network topology and communication decisions to prevent malicious nodes from being selected as a gateway.

HARQ: The long Round Trip Time (RTT) experienced in non-terrestrial networks may exceed the maximum possible number of Hybrid Automatic Repeat reQuest (HARQ) processes that are typically supported in 5G NR systems. In this regard, simply increasing the number of processes may not be feasible due to memory restrictions at the mobile terminal's side. Long RTTs also require large transmission buffers, and potentially limit the number of retransmissions allowed for each transmission.

Synchronization: Non-terrestrial systems are fast-moving, and typically feature larger cells compared to terrestrial networks. At low elevation angles, this may create a very large differential propagation delay between users at the cell edge and those at the center (up to 10 ms for GEO satellites [9]), thereby raising synchronization issues.

Initial Access and Channel Estimation: Initial access makes on-the-ground terminals establish a physical connection with a non-terrestrial station by detecting synchronization signals. This is particularly challenging in non-terrestrial applications, where the channel may vary quickly over time, as the initial estimate may rapidly become obsolete. Also, in space-ground integrated networks, each intermediate node tends to associate to a gateway based on its own unilateral benefit, neglecting the potential disadvantages on the whole network performance.

Mobility Management: When operating at mmWaves to maintain high-capacity connections, directionality is required in order to achieve sufficient link budget. In this case, fine alignment of the beams has severe implications for the design of control operations, for example, user tracking, handover, and radio link failure recovery. These challenges are particularly critical in the non-terrestrial domain, where the very high speed of aerial/space platforms could result in loss of beam alignment before a data exchange is completed. The increased Doppler encountered at high speed could also make the channel non-reciprocal, thus impairing the feedback over a broadcast channel.

Constellation Management: A non-terrestrial station has a larger footprint than a terrestrial cell and is required to serve a larger number of on-the-ground terminals. This may result in saturation of the available bandwidth, with strong implications for latency and throughput performance. Additionally, air/spaceborne vehicles move rapidly relative to the Earth's surface and may create regions where coverage is not continuously provided. A constellation is thus necessary to maintain ubiquitous service continuity. When configuring multiple satellites that move in different orbits to operate in an integrated fashion, however, constellation management is hindered by handovers and load balancing among the different layers. Moreover, while in the terrestrial scenario coordination between base stations is possible through fiber connections or via a cen-

tral entity, coordination among non-terrestrial air/spaceborne stations has to be implemented wirelessly, thus further complicating constellation management.

Higher-Layer Design: Current network/transport protocols may show low performance when NTN is involved. First, topology information may quickly become obsolete (especially considering unpredictable mobility, for example, for UAV swarms) and must constantly be refreshed, thus increasing the communication overhead. Second, a large RTT results in a longer duration of the slow start phase of TCP, during which the sender may take inordinately long before operating at full bandwidth. Third, sudden drops in the link quality, which may be common in NTNs, make the sender reduce its transmission rate, thus leading to a drastic decrease in resource utilization. Finally, when a multi-layered integrated network is considered, different network devices may support different (and sometimes conflicting) communication protocols, thus complicating network management.

Architecture Technologies: It is still unclear where to distribute SDN planes for proper service delivery; the choice depends on different factors, like the available processing capabilities or the achievable transmission rate. Furthermore, due to the large distances involved in non-terrestrial operations and the resulting severe path loss experienced, the transmit power is typically to be set as close as possible to the saturation point. This could reduce the duration of batteries, which is particularly critical in scenarios where aerial devices are used to support IoT applications. Finally, an integrated space-air-ground architecture should envision the existence of a trusted central authority making secure network topology and communication decisions to prevent malicious nodes from being selected as a gateway.

CONCLUSIONS

Non-terrestrial networks are being investigated as a key component of the 6G framework to support global, ubiquitous and continuous connectivity, and to overcome the coverage limitations of envisioned 5G networks. In this article we overviewed recent advancements that will make non-terrestrial networks a reality, including the development of new aerial/space architectures, and innovative spectrum and antenna technologies. As a case study, we demonstrated that the mmWave frequencies can be used to establish high-capacity connections between on-the-ground terminals and satellite/HAP gateways, provided that sharp beams are formed. Despite such promises, we also summarized current open challenges for the deployment of non-terrestrial networks, thereby stimulating further research in this domain. Most importantly, our future studies will be dedicated to exploring the relationship between capacity performance and energy efficiency in the non-terrestrial ecosystem.

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