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

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Abstract—Many organizations recognize non-terrestrial communication (NTC) 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 paper, we review the characteristics and enabling technologies of non-terrestrial systems 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 also evaluate the performance of an NTC scenario in which satellites use millimeter wave (mmWave) frequencies to provide access connectivity to on-the-ground mobile terminals as a function of different networking configurations.

Index Terms—5G; 6G; non-terrestrial communication (NTC); satellites; unmanned aerial vehicles (UAVs).

I. 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 towards 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 technologies 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 [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 communication (NTC) to promote ubiquitous and high-capacity global connectivity [4]. While 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 Unmanned Aerial Vehicles (UAVs), High Altitude Platform Stations (HAPSs), and satellites [5]. Not only can these elements provide on-demand cost-effective coverage in crowded and unserved area, but they can also guarantee trunking, backhauling, support for high-speed mobility, and high-throughput hybrid multiplay services.

The problem of establishing NTC for mobile broadband coverage has just recently attracted the attention of the research community, and very little work exists on such subject. 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 discuss the design trade-offs in this domain. UAVs were also considered as a tool to complement terrestrial connectivity in critical scenarios [7]. The potential of NTC has also been acknowledged in the standard activities. For example, a study item for 3GPP Rel-17 has been approved to improve the use of space platforms in cellular networks, and ETSI is investigating the application of artificial intelligence in the orchestration of terrestrial and non-terrestrial devices.

Nevertheless, despite such earlier investigations, there are still various questions to be answered for proper network design. Along these lines, in this paper we first discuss about how non-terrestrial networks can be deployed to satisfy emerging 6G application requirements. We focus on (i) new architecture advancements in the aerial/space industry, (ii) novel spectrum technologies, e.g., operating in the mmWave and optic bands, (iii) antenna design advancements, and (iv) transport layer developments. Moreover, this is the first contribution shedding light on the research challenges associated to NTC, providing a full-stack perspective with considerations related to spectrum usage, medium access and higher layers, coverage and mobility management constraints. Finally, as a case study, we validate the feasibility of establishing satellite communication at mmWaves to provide access connectivity to terrestrial nodes.

II. NON-TERRESTRIAL COMMUNICATION IN 6G

In this section, we present non-terrestrial deployment scenarios, potential use cases and enabling technologies.

A. General Architecture

Non-terrestrial systems feature (i) a terrestrial terminal, (ii) an aerial/space station, which may operate as a terrestrial base station, (iii) a service link between the terrestrial terminal and the aerial/space station, and (iv) 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 Fig. 1 (left).
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/temporary events, and relay services for terrestrial mobile nodes. On 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 Station (HAPS). HAPSs operate in the stratosphere at an altitude of around 20 km. Thanks to their quick deployment and geographical 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, HAPSs 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 35800 km and, despite the significant signal propagation delay and attenuation experienced at such long distance, can cover very large geographical 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 2000 km and 2000 and 35000 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 have to operate in constellation to maintain service continuity.

B. Use Cases

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

Massive broadband service continuity. Non-terrestrial stations can be deployed to assist existing base stations in providing high-capacity wireless coverage, e.g., 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, e.g., in rural areas or when terrestrial towers are out of service, e.g., 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 towards 3D.

Ubiquitous data broadcasting. The wide geographical coverage and 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 aggregator for Internet of Things (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, e.g., 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 efficiency. Even though non-terrestrial terminals, e.g., UAVs, may consume significant energy for hovering, which is required to maintain the node aloft and enable its mobility, they can be deployed on-demand implementing smart duty cycle control mechanisms, thereby reducing management costs of always-on fixed terrestrial infrastructures. Moreover, non-terrestrial stations like HAPSs and satellites are operated by solar panels which consume limited energy.

C. Enabling Technologies

NTC will be favored by recent technological advancements in the aerial/space industry, as summarized in Table 1 and described in the following paragraphs.

Architecture advancements. Space manufacturers are improving satellite technologies while further reducing the operational costs for satellite launch, deployment, and maintenance.
Nano- 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-factor and more efficient components compared to their silicon counterparts, thereby saving fuel and area on the payload and improving operational efficiency [8]. Additionally, the availability of multi-layered satellite networks, i.e., LEO and GEO constellations, makes it possible to obtain better spatial and temporal coverage.

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 [9]. Furthermore, UAV swarms, combined with HAPSs and satellites, can operate in a multi-layer hierarchical network which enables more accurate processing of data compared to standalone deployments, and to support continuous information broadcasting.

Architecture optimization is also favored by the transition to Software Defined Networking (SDN) [10] which, in combination with 5G network slicing, facilitates deployment and management of Virtualization Network Functions (VNFs) onto the same physical platform. This guarantees improved flexibility, automation, agility through Virtualization Network Functions (VNFs) and management of Virtualization Network Functions (VNFs), thereby raising questions on whether this technology can be used in the non-terrestrial environment. Solutions are being proposed towards the development of new waveforms and modulation and coding schemes that foster broadband NTC at mmWaves [11]. Specifically, impulse-based ultra-wideband (UWB) modulation, where information is encoded depending of the characteristics of the transmitted pulse, has emerged as a viable solution to reduce signal non-linear distortion typically experienced at high frequency. Moreover, cognitive spectrum techniques may realize dynamic spectrum utilization at different frequency 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 [12]. 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 optics link by making use of Turbo and convolutional codes.

**Antenna advancements.** Aerial/space devices can be equipped with reconfigurable phased antennas offering electronic beam-steering to achieve lower power consumption.

### TABLE I: Enabling technologies for non-terrestrial communication.

| Technology                     | Advantage                                                                 |
|-------------------------------|---------------------------------------------------------------------------|
| 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) |
| Flexible payloads             | Dynamic adaptation of beam patterns, frequency, and power allocation      |
| Hybrid payloads               | Better trade-off between performance and payload complexity                |
| Millimeter waves              | Feasibility of ultra-fast connections, antenna gain, spatial isolation and security |
| UWB modulation                | Reduced signal nonlinear distortion by encoding signal based on transmitted pulse |
| Cognitive spectrum            | Reduced interference through dynamic spectrum utilization at different frequency bands |
| Optical communications         | Feasibility of terabits-per-second connections through extreme bandwidth and directivity |
| 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       | Maintenability, scalability, flexibility, robustness to single points of failure |
| Multi-beam architectures      | High spectrum efficiency through spatial diversity                        |
| TCP spoofing                  | Fast TCP full-buffer capacity through TCP acknowledgements               |
| TCP multiplexing              | High performance by splitting TCP session into multiple data flows        |
and reduced size and weight compared to typical mechanical antennas. Metasurface antennas, in particular, exploit artificial materials to realize component miniaturization, improved directivity, low sidelobes and fine beamwidth control, thereby promoting a high degree of flexibility [13]. Future trends in the antenna domain further suggest the employ of inflatable (i.e., made with flexible-membrane materials) and fractal antennas with unique geometrical designs to obtaining 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 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 to implement 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 optics 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.

**Higher-layer advancements.** NTC comes with its own set of challenges compared to standalone terrestrial systems, which might make standard transmission protocols, including congestion control over Transmission Control Protocol (TCP), ineffective. Network operators have therefore developed acceleration techniques that make transport protocols perform better [14]. TCP spoofing, in particular, is used to send false TCP acknowledgements 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.

**III. NON-TERRESTRIAL COMMUNICATION: A CASE STUDY**

Among all the discussed NTC technologies, the use of satellites currently holds great promise as a means to offer intrinsic large-scale broadcasting capability and global coverage in rural/unserved areas. Traditionally, satellite networks have mainly been intended to operate in the sub-6 GHz spectrum. As a case study, following the analysis we presented in our previous work [5], we now assess the feasibility of establishing mmWave communications between terrestrial and satellite terminals to offer high-capacity wireless services. Sec. **II-A** describes the propagation characteristics of the satellite link, while Sec. **II-B** presents some performance results.

**A. Satellite Link at mmWaves**

The mmWave satellite signal undergoes several stages of attenuation, as described by the 3GPP in [15] and summarized in [5] Sec. III.

**Fig. 2:** Shannon capacity vs. $f_c$ and $G_{\text{rx}}$, with $\alpha = 10^\circ$ and for a dense urban scenario.

The path loss indeed increases with the carrier frequency and the propagation distance between the terrestrial and satellite nodes, and is affected by shadow fading and clutter loss, which models the attenuation of the signal caused by surrounding objects. Moreover, in case of Non Line of Sight (NLOS) communication with an indoor terrestrial terminal, an additional building entry loss, whose value depends on the type and location of the building, has also to be considered.

Most importantly, satellite communication at mmWaves is impaired by severe atmospheric absorption, i.e., attenuation due to dry air (oxygen, pressure-induced nitrogen and non-resonant Debye attenuation) and water vapor. At normal atmospheric conditions, atmospheric loss may be as severe as 15 dB/km in correspondence of the oxygen absorption band around 60 GHz. Additionally, Earth-to-satellite propagation is affected by scintillation, which corresponds to rapid fluctuations of the received signal amplitude and phase. For mmWave transmissions, scintillation manifests in the form of tropospheric absorption and is caused by sudden changes in the refractive index due to the variation of temperature, water vapor content, and barometric pressure.

**B. Performance Results**

In our simulation scenario, a terrestrial terminal communicates with a LEO, MEO, or GEO satellite placed at different altitudes $h \in \{300, 10000, 36000\}$ km, respectively. We consider different elevation angles $\alpha \in \{10^\circ, \ldots, 90^\circ\}$, and propagation scenarios. Terrestrial stations are equipped with directional antennas offering a gain $G_{\text{tx}} = 43.2$ dB [15] while, for satellite stations, the gain $G_{\text{rx}}$ is varied to consider different antenna architectures. Satellite communication leverages a bandwidth $W$ that depends on the frequencies $f_c$: 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 $C$, i.e., the maximum achievable data rate, as a function of $h$, $f_c$ and $G_{\text{rx}}$. First, we observe that satellite operations in the bandwidth-constrained below-6 GHz spectrum offer limited capacity (i.e., < 500 Mbps), 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 high frequency, provided that high-gain directional antennas (i.e., $G_{tx} > 50$ dB, as is typical in current satellite antenna technologies) are employed, to cover very long transmission distances. Fig. 3 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, $C$ severely reduces for increasing values of $h$, i.e., transitioning from LEO to GEO satellites. Nevertheless, gigabits-per-second capacities can still be reached if the satellite station forms very sharp beams, with $G_{tx} > 80$ dB, 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 periodic re-alignment of the beams.

The same conclusions can be drawn from Figs. 3 and 4. Additionally, Fig. 3 demonstrates that the system performance decreases at low elevation due to the more severe impact of scintillation absorption, as the signal has to transit longer through the atmosphere. Moreover, Fig. 4 exemplifies that the increased probability of path blockage in the urban scenario may reduce the achievable capacity by more than 60% at high elevation, compared to a rural scenario.

In general, our results acknowledge the feasibility of establishing mmWave connections to interconnect satellites to terrestrial stations at high capacity, even though it is desirable to install large antenna arrays to mitigate the severe path and absorption loss and cover very long communication distances. For a more complete set of results, the interested reader can refer to [5].

IV. NON-TERRESTRIAL COMMUNICATION: OPEN CHALLENGES

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

**Channel modeling.** Even though the 3GPP has specified how to characterize mmWave propagation for the satellite channel [16], 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, channel measurements in the UAV and HAPS scenarios at mmWaves are 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.** 5G NR systems feature a flexible frame structure and numerology, and provide a choice of physical-layer parameters that enable support for use cases with heterogeneous characteristics. In particular, larger sub-carrier spacing should be used to reduce the effect of the Doppler. In the non-terrestrial scenario, however, even the highest available sub-carrier spacing may not be enough to compensate for the very large Doppler shift experienced considering the high speed of aerial/space stations (e.g., around 28000 km/h for LEO satellites). The large Doppler may also cause non-linear distortions in the satellite payload, thus complicating signal reception.

Moreover, non-terrestrial systems feature much larger propagation delays than terrestrial systems (e.g., up to 272.4 ms for GEO satellites). This will likely impact various protocol layers, retransmission mechanisms and response times, especially considering latency- and jitter-constrained wireless services. For example, the large propagation delays in non-terrestrial scenarios create a larger response time for the Adaptive Modulation and Coding (AMC) scheme loop and requires a margin to compensate for the possible outdated Channel Quality Information (CQI), i.e., for channel estimation. Additionally, Time Division Duplexing (TDD), which is frequently considered in terrestrial networks, may be infeasible in non-terrestrial networks since guard times must be proportional to the propagation delay.

**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
TABLE II: Open challenges for non-terrestrial communication.

| 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 installation of dense constellations |
|                         | Wireless coordination among air/spacebornes 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 decrease in resource utilization due to sudden drops in the link quality |
| Architecture technologies| Unclear where to distribute SDN planes                                     |
|                         | Channel dynamics result in different attachment decisions in different periods of time |
|                         | Long RTTs prevent long duration of batteries                              |

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 not relatively static, and typically feature larger cells compared to terrestrial networks. At low elevation angles, this may create a remarkable differential propagation delay between users at the cell edge and those at the center, 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.

Mobility management. When operating at mmWaves to maintain high-capacity connections, directionality is required to achieve sufficient link budget. In this case, fine alignment of the beams has severe implications for the design of control operations, e.g., 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, spacebornes 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. However, the high cost of satellite launches, the limited launching opportunities, and the little orbit control which may result in collision risks can make it difficult to install a sufficiently dense constellation.

Moreover, while in the terrestrial scenario coordination between base stations is possible through fiber connections or via a central entity, coordination among non-terrestrial air/spacebornes has to be implemented wirelessly, thus further complicating constellation management.

Higher-layer design. Current network and transport protocols may show low performance when NTC is involved. First, topology information that is typically exchanged for routing may quickly become obsolete (especially considering unpredictable mobility, e.g., for UAV swarms), and must constantly be refreshed with new information, thus increasing the communication overhead. Second, large RTT results in longer duration of the slow start phase of TCP, during which the sender may take inordinately long before being able to operate at full bandwidth. Third, sudden drops in the link quality, which are common situations in non-terrestrial scenarios, make the sender reduce its transmission rate, thus leading to a drastic decrease in resource utilization.

Architecture technologies. Even though SDN guarantees improved automation for service delivery, it is still unclear where to distribute SDN planes. The choice depends on different factors, e.g., the available processing power capabilities and the achievable transmission rate, which may lead to different network architectures.
Moreover, in case the on-the-ground infrastructure is in visibility of different satellite gateways, it is important to choose the station that maximizes the performance from both a communication and an energy viewpoint. At high frequency, however, the link quality to the space segment may vary significantly, thereby resulting in different attachment decisions at different times.

Furthermore, due to the large distances involved in non-terrestrial operations and the resulting severe path loss experienced, the transmit power has typically to be set as close as possible to the saturation point. This could prevent the long duration of batteries, which is particularly critical in scenarios where aerial devices are used to support IoT applications.

V. Conclusions

Non-terrestrial communication is being investigated as a key component of the 6G framework to support global, ubiquitous and continuous connectivity and overcome the coverage limitations of envisioned 5G networks. In this paper we overviewed recent advancements that will make non-terrestrial communication 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 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.

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