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Non-Terrestrial Networks in 5G & Beyond: A Survey

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ABSTRACT Fifth-generation (5G) telecommunication systems are expected to meet the world market demands of accessing and delivering services anywhere and anytime. The Non-Terrestrial Network (NTN) systems are able to satisfy the requests of anywhere and anytime connections by offering wide-area coverage and ensuring service availability, continuity, and scalability. In this work, we review the 3GPP NTN features and their potential for satisfying the user expectations in 5G & beyond networks. The state of the art, current 3GPP research activities, and open issues are summarized to highlight the importance of NTN over the wireless communication landscape. Future research directions are also identified to assess the role of NTN in 5G and beyond systems.

INDEX TERMS Non-terrestrial network, satellite communication, new radio, 5G system and beyond.

I. INTRODUCTION

The evolution of telecommunication technologies, the ever-increasing demand for new services, and the exponential growth of smart devices fuel the development of Non-Terrestrial Network (NTN) systems as an effective solution to complement terrestrial networks in providing services over uncovered or under-served geographical areas. As defined by the 3rd Generation Partnership Project (3GPP) in [1], an NTN is a network where spaceborne (i.e., GEO, MEO, LEO) or airborne (i.e., UAS and HAPS) vehicles act either as a relay node or as a base station, thus distinguishing *transparent* and *regenerative* satellite architectures.

The uniqueness of NTNs is in their capability to offer wide-area coverage by providing connectivity over the regions that are expensive or difficult to cover with terrestrial networks (i.e., rural areas, vessels, airplanes). Therefore, the NTN represents a coverage extension for the terrestrial network in a world market where the customer needs are changing radically. Indeed, the demand for different services is growing steadily due to the ever-increasing number of devices connected to the Internet.

Ericsson Mobility Report [2] predicts that at the end of 2024 the usage of smartphones will increase up to 45% by consuming more than 21 GB of data per month on average (about 4 times more than the amount consumed in 2018) and generating 95% of the total mobile data traffic. In this context, satisfying all of the user requests and providing the desired Quality of Service (QoS) anytime and anywhere, even when traveling on cruises, high-speed trains, and airplanes, is one of the main challenges for future telecommunication systems.

Not limited to delivering service where it is economically challenging to provide coverage with a terrestrial network, 5G NTN ensures service continuity of Machine-to-Machine (M2M)/Internet of Things (IoT) devices or for people traveling on-board of moving platforms as well as service availability in both critical communications and emerging services (i.e., maritime, aeronautical, railway). Furthermore, 5G NTN is expected to become an efficient solution to enable network scalability owing to the provision of multicast/broadcast resources for the delivery of data to network edges and user terminals [3]. As a result, NTN promises benefits achieved by

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TABLE 1. Comparison of surveys on satellite communications.

Year	Publication	Brief description
2006	Chowdhury *et al.* [4]	The survey on handover schemes in satellite networks focuses on: · classification of handover schemes; · comparison of handover schemes according to certain criteria; · considerations and future research directions on handover management in satellite networks.
2009	Chini *et al.* [5]	The survey on mobile satellite systems focuses on: · network architectures, services, standardization, operational systems, and research issues; · comparison of different mobile satellite systems.
2011	Arapoglou *et al.* [6]	The review on MIMO over satellite networks focuses on: · MIMO-based techniques in terrestrial networks; · MIMO over satellite, satellite channel characteristics, and future research directions.
2016	De Sanctis *et al.* [7]	The survey on satellite communications supporting IoRT focuses on: · satellite-based IoT; · MAC protocols for satellite routed sensor networks; · efficient IPv6 support and heterogeneous network interoperability; · QoS management and group-based communications.
2016	Radhakrishnan *et al.* [8]	The survey on inter-satellite communication for small satellite systems focuses on: · research conducted by the small satellite community; · design parameters for inter-satellite communications; · solutions that enable operations in small satellite systems.
2016	Niephaus *et al.* [9]	The survey on state-of-the-art of satellite and terrestrial network convergence focuses on: · scenarios, technical challenges, and related works concerning the convergence of satellite and terrestrial networks; · functionality to optimize the traffic distribution; · architectures and related adaptations to support the converged satellite and terrestrial networks.
2017	Kaushal *et al.* [10]	The survey on optical communications focuses on: · challenges related to the performance of optical communications in integrated space-ground networks; · techniques to mitigate the side effects of the atmosphere.
2018	Liu *et al.* [11]	The survey on space-air-ground integrated networks focuses on: · state-of-the-art in either space or air networks; · work on both space-ground networks and integrated space-air-ground segments; · network design, resource allocation, open challenges, and future directions in integrated space-air-ground communications.
2019	Burleigh *et al.* [12]	The survey on small satellite communications and networks focuses on: · current evolution of small satellites; · scenarios, applications, advances, and developments in small satellites; · aspects, perspectives, and open challenges of small satellite communications.
2020	Li *et al.* [13]	The survey on physical-layer security in space information networks focuses on: · IoST systems and related challenges; · satellite channel models and secrecy metrics; · research activities on physical security and possible future studies.
Our contributions		This contributions surveys the NTN systems by focusing on: · NTN uses cases and architectures; · satellite network roadmap and role of NTN in cellular communications; · 3GPP research activities, NTN open issues, and future research directions beyond 5G.

revolutionizing the traditional cellular network infrastructure owing to wide-area coverage, scalability, service continuity, and availability.

A. MOTIVATION AND CONTRIBUTIONS

The motivation behind this work stems from the interest shown in satellite networks over the last decade by both industry and academia. It accentuates the added value for 5G networks and becomes essential for two main reasons. The first one is that a satellite connection becomes indispensable where there is no coverage, due to the impossibility of infrastructure (i.e., maritime scenarios), or where there would be a possibility but not the economic convenience. The second reason is related to the security and the resilience of communications, as well as to crisis management. Differently from the terrestrial communications that are potentially subject to service interruptions due to natural disasters or attacks, satellite networks guarantee service continuity in the cases of mission-critical applications, which cannot take the risk of failures.

In past literature, several works reviewed the satellite systems. Table 1 provides a comparison of the existing surveys on satellite communications. The main contributions of this survey are the following:

- review the NTN wireless system and summarize its main features as per the official 3GPP technical reports;

- discuss the state of the art on NTN along the evolutionary path of wireless communications (from 1G to 4G);
- understand the role of NTN within the 5G New Radio (NR) system;
- overview the current 3GPP activities to support NTN as part of the NR technology;
- identify open issues and address future research directions.

B. PAPER ORGANIZATION

The remainder of this text is organized as follows.

- Section II provides a general description of the NTN and its use cases. In particular, subsection II-A introduces two platform classifications (i.e., spaceborne and airborne, which are characterized by different altitude range, orbit type, and beam footprint size) and the main NTN access components (i.e., NTN terminal, NTN gateway, service link, and feeder link). In subsection II-B, the key NTN use cases are listed on the basis of the demanded service type; furthermore, a maritime scenario is illustrated as one of the most important NTN options.
- Section III describes the NTN architectural aspects. In more detail, subsection III-A demonstrates the satellite access architectures where the NTN terminal is served directly by the NTN platform. Alternatively, the NTN terminal and the NTN platform communicate through a relay node in relay-like architectures as highlighted in subsection III-B. In subsection III-C, several alternatives of how the NTN-based NG-RAN can be integrated with the terrestrial NG-RAN are discussed.
- Section IV overviews the role of NTN in cellular communications up to 4G. Specifically, the roadmap of satellite systems is reviewed from the birth of the satellite networks independently from the terrestrial systems and their relation with the 2G technology in subsection IV-A, the integration of satellite networks with the 3G terrestrial system in subsection IV-B, and the growing interest in 4G satellite communication to deliver global connectivity in subsection IV-C.
- Section V outlines the vision of NTN from the 5G perspective (i.e., the introduction of software defined networking and virtualization, network slicing, and edge computing) and summarizes the existing literature concerning security, cognition, NOMA, mobility, Internet of Space Things, and CubeSats.
- Section VI reviews the current research activities conducted by 3GPP by enumerating the NTN features across the study items and highlights the associated 3GPP technical specifications and reports.
- Section VII emphasizes the open issues with respect to mobility management, propagation delay, and radio spectrum. Future research directions are also discussed.
- Section VIII projects the perspectives of satellite communications onto the 6G wireless technology, which may offer extreme flexibility of integrated terrestrial-NTN systems.
- Section IX draws the essential conclusions.

TABLE 2. Abbreviations and acronyms.

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GC	5G Core Network
5G-PPP	5G Public Private Partnership
6G	Sixth Generation
ALJC	Application-Layer Joint Coding
AMC	Adaptive Modulation and Coding
CMS	Conventional Multicast Scheme
CSI	Channel State Information
D2D	Device-to-Device
DCA	Dynamic Channel Allocation
EC	Edge Computing
eMBB	enhanced Mobile Broadband
eMBMS	evolved-Multimedia Broadcast/Multicast Service
eNB	evolved-NodeB (4G base station)
ESA	European Space Agency
FeMBMS	Further enhanced-Multimedia Broadcast/Multicast Service
FSS	Fixed Satellite System
GEO	Geostationary Earth Orbiting
GMS	GEO Mobile Radio
gNB	next generation-NodeB (5G base station)
gNB-CU	gNB Central Unit
gNB-DU	gNB Distributed Unit
GoS	Grade of Service
GSM	Global System for Mobile Communication
HAPS	High Altitude Platform Systems
HARQ	Hybrid Automatic Repeat Request
HMAA	Home Mobile Agent Anchor
HTC	Holographic Type Communication
HTS	High Throughput Satellite
ICT	Information and Communication Technology
IMR	Intermediate Module Repeater
INI	Inter-Numerology Interference
IoRT	Internet of Remote Things
IoST	Internet of Space Things
IoT	Internet of Things
IoV	Internet of Vehicles
ISL	Inter-Satellite Link
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LEO	Low Earth Orbiting
LIS	Large Intelligence Surface
LMAA	Local Mobile Agent Anchor
LoS	Line-of-Sight
LTE	Long-Term Evolution
M2M	Machine-to-Machine
MBMS	Multimedia Broadcast/Multicast Service
MCS	Modulation and Coding Scheme
MEO	Medium Earth Orbiting
mMTC	massive Machine Type Communication
MSS	Mobile Satellite System
NB	NodeB (3G base station)
NFV	Network Function Virtualization
NGSO	Non-Geostationary Orbit
NG-RAN	Next-Generation Radio Access Network
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NTN	Non-Terrestrial Network
OFDM	Orthogonal Frequency-Division Multiplexing
OMS	Opportunistic Multicast Scheme
QH	Queuing of Handover
QoS	Quality of Service
SAGIN	Satellite-Air-Ground Integrated Network
S-DMB	Satellite – Digital Multimedia Broadcasting
SDN	Software Defined Networking
SRI	Satellite Radio Interface
S-UMTS	Satellite – Universal Mobile Telecommunications System
SW-CDMA	Satellite Wideband Code Division Multiple Access
UAS	Unmanned Aircraft System
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-Reliable Low Latency Communication
VAC	Virtual Agent Cluster
W-CDMA	Wideband Code Division Multiple Access

TABLE 3. Types of NTN Platforms [1].

Platforms	Altitude Range	Orbit	Beam Footprint Size
GEO satellite	35786 km	Fixed position in terms of elevation/azimuth w.r.t. a given point on Earth	200 - 3500 km
MEO satellite	7000 - 25000 km	Circular around Earth	100 - 1000 km
LEO satellite	300 - 1500 km	Circular around Earth	100 - 1000 km
UAS platform	8 - 50 km (20 km for HAP)	Fixed position in terms of elevation/azimuth w.r.t. a given point on Earth	5 - 200 km

To facilitate the understanding of the employed terminology, the main acronyms and abbreviations used throughout this work are collected in Table 2.

II. NON-TERRESTRIAL NETWORKS

A. NTN GENERAL DESCRIPTION

An NTN may have different deployment options according to the type of the NTN platform involved, as listed in Table 3. The NTN platforms are grouped into two main categories: spaceborne and airborne. The classification of *spaceborne* platforms typically depends on three main parameters, such as altitude, beam footprint[1] size, and orbit.

Spaceborne platforms can be differentiated as:

- *Geostationary Earth Orbiting (GEO)* has a circular and equatorial orbit around Earth at 35786 km altitude and the orbital period is equal to the Earth rotation period. The GEO appears fixed in the sky to the ground observers. GEO beam footprint size ranges from 200 to 3500 km.
- *Medium Earth Orbiting (MEO)* has a circular orbit around Earth, at an altitude varying from 7000 to 25000 km. MEO beam footprint size ranges from 100 to 1000 km.
- *Low Earth Orbiting (LEO)* has a circular orbit around Earth, at an altitude between 300 to 1500 km. LEO beam footprint size ranges from 100 to 1000 km.

LEO and MEO are also known as Non-GEO (NGSO) satellites for their motion around Earth with a lower period than the Earth rotation time; in fact, it varies from 1.5 to 10 hours.

The *airborne* category encompasses Unmanned Aircraft Systems (UAS) platforms, which are typically placed at an altitude between 8 and 50 km and include High Altitude Platform Systems (HAPS) at 20 km altitude. Similar to the GEO satellite, the UAS position can be kept fixed in the sky w.r.t. a given point on the ground. UAS beam footprint size ranges from 5 to 200 km.

Spaceborne and airborne platforms may belong to two different configurations distinguished according to the carried payload. Indeed, NTN platforms implement either transparent or regenerative payload. The *transparent* or bent-pipe payload configuration foresees that only radio frequency filtering, frequency conversion, and amplification are done on-board the satellite (or UAS platform). Conversely, in the *regenerative* payload configuration, the NTN platform effectively implements all the gNB functions on board. A detailed description of the NTN architectures is provided in Section III.

In addition to space/airborne platforms, the NTN access is featured by the following components:

- *NTN terminal* refers to either the 3GPP User Equipment (UE) or a specific satellite terminal. Very small aperture terminals operate in the radio frequency of Ka-band (i.e., 30 GHz in the uplink and 20 GHz in the downlink), whereas handheld terminals operate in the radio frequency of S-band (i.e., 2 GHz).
- *NTN gateway* is a logical node connecting the NTN platform with the 5G core network.
- *Service link* is the radio link between the NTN terminal and the NTN platform.
- *Feeder link* is the radio link between the NTN gateway and the NTN platform.

B. 5G NTN USE CASES

The NTNs are expected to play an important role in 5G & beyond systems by covering different verticals, including transport, eHealth, energy, automotive, public safety, and many others (see Fig. 1). 5G NTN use cases may be divided into three categories: *service continuity* to provide NTN access where this is infeasible through terrestrial networks; *service ubiquity* to improve the NTN availability in cases of disasters that lead to a temporary outage or destruction of a terrestrial network; and *service scalability* to offload traffic from the terrestrial networks, also during the busy hours [15].

In the 5G & beyond context, the NTN supports all three usage scenarios defined by the International Telecommunication Union (ITU) [16], which are Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC), and Ultra-Reliable and Low Latency Communications (URLLC). Since providing URLLC services may be a challenging task due to the satellite propagation delays and stringent URLLC requirements of reliability, availability, and latency, NTN mainly considers the eMBB and mMTC as the main 5G service enablers for the definition of the use cases [3].

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[1] The beam footprint [3] has an elliptical shape and it may be either moving over Earth with the NTN platform on its orbit or remain Earth-fixed if beam pointing mechanisms are applied to compensate for the NTN platform motion.

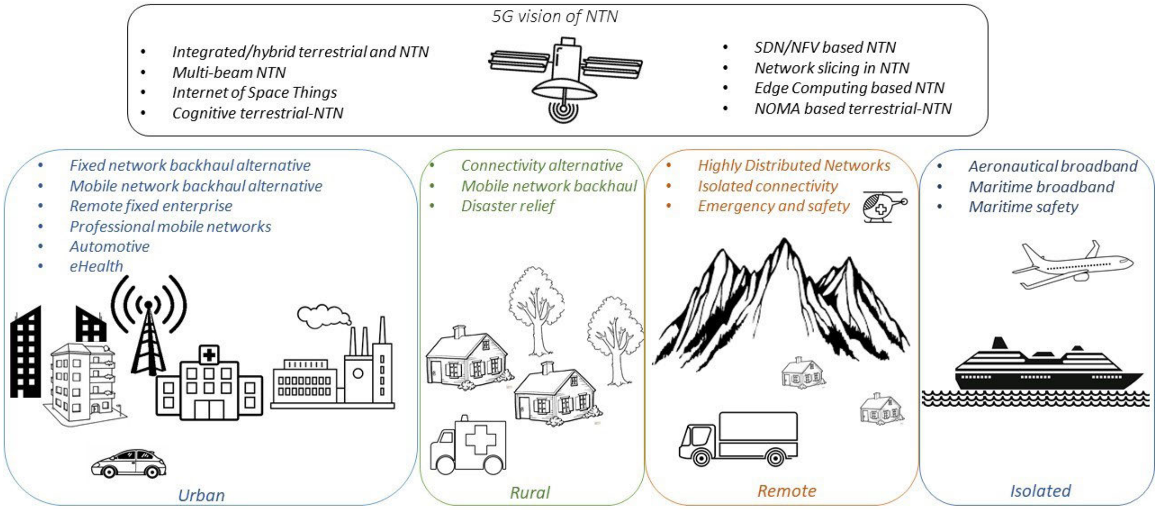


FIGURE 1. 5G NTN use cases.

As for eMBB services, NTN aims to provide broadband connectivity in un/under-served areas and on moving platforms (i.e., vessels and aircrafts), as well as to offer network resilience by combining terrestrial and NTN systems. Furthermore, NTN is also exploited to offload the terrestrial networks by making a broadcast channel available to deliver broadcast/multicast contents or wide/local area public safety messages to handheld or vehicle-mounted UEs across home premises or on-board of moving platforms.

As for mMTC, NTN supports connectivity for both wide and local area IoT services. In the case of a wide-area IoT service, the connectivity between the IoT devices and the NTN platform is provided, as well as the service continuity, through satellites and terrestrial gNBs for telematics applications (i.e., automotive and road transport, energy, agriculture). In the case of a local area IoT service, NTN provides connectivity between the mobile core network and the gNBs serving IoT devices by gathering information belonging to the groups of sensors deployed under the coverage of one or more cells.

Therefore, the NTN is relevant for 5G NR systems because it aims to offer benefits over urban and rural areas in terms of the 5G targeted performance (i.e., experienced data rate and reliability), as well as to provide connectivity in un-/under-served areas for both users and mMTC devices.

Among the key use cases, NTN also represents an attractive solution for the *maritime scenario* [17]. Ensuring in-sea coverage is infeasible via a terrestrial network because it is expensive and introduces capacity limits. Hence, NTN may be useful to facilitate communications within the maritime industry by managing the maritime space and providing seamless sea traffic services to devices and users in collaboration with seaborne platforms. NTN may also be exploited for sending notifications (i.e., to inform vessels of the location of a vessel in danger) and emergency requests (i.e., maritime accidents) to improve maritime safety [18].

III. NTN ARCHITECTURES

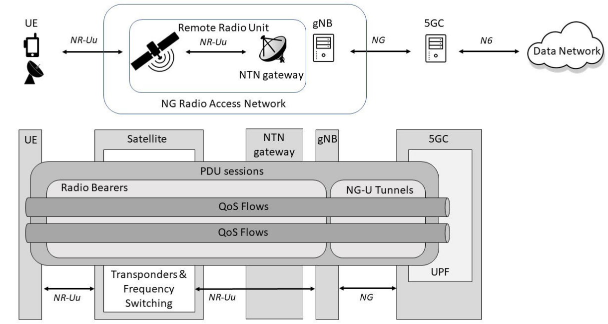
In Next-Generation Radio Access Network (NG-RAN), new interfaces and protocols are being added to support NTNs. An NTN platform may act as a space mirror or gNB in the sky. Consequently, two satellite-based NG-RAN architectures are possible: *transparent* and *regenerative*. In the latter case, the NTN platform may implement partial or full gNB functionality depending on whether the gNB functional split (i.e., the gNB comprises central and distributed units [14]) is considered or not.

Another classification of the NTN architectures can be made based on the type of access [1]. Hence, in the *satellite access architecture* the NTN terminal is directly served by the NTN platform, whereas in the *relay-like architecture* the NTN terminal and the NTN platform communicate with each other via a relay node.

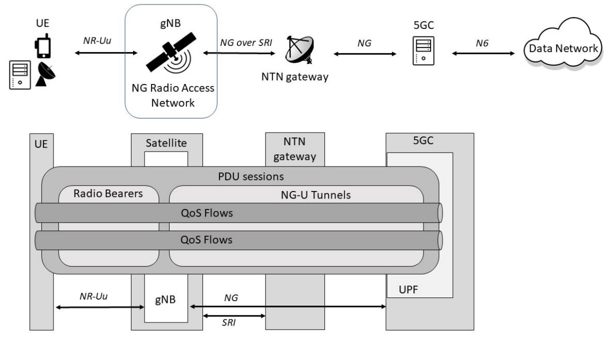
A. SATELLITE ACCESS ARCHITECTURES

Fig. 2(a) displays the transparent satellite-based architecture where the NTN platform relays the NR signal from the NTN gateway to the NTN terminal and vice versa. The Satellite Radio Interface (SRI) on the feeder link is the same as the radio interface on the service link (i.e., NR-Uu). The NTN gateway can forward the NR signal of the NR-Uu interface to the gNB. One or more transparent satellites may be connected to the same gNB on the ground.

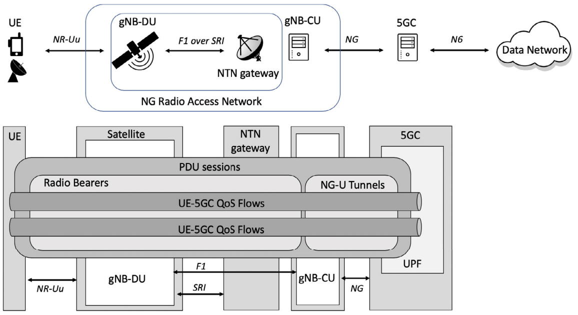
Fig. 2(b) demonstrates the regenerative satellite-based architecture where the NTN platform has on-board processing capabilities to generate/receive the NR signal to/from the NTN terminal. The NR-Uu interface is on the service link between the NTN terminal and the NTN platform. The radio interface between the NTN platform and the 5G Core Network (5GC) is NG, which is over SRI in the air path between the NTN platform and the NTN-gateway. Inter-Satellite Links (ISLs) are transport links between the NTN platforms.



(a) Transparent payload-based satellite

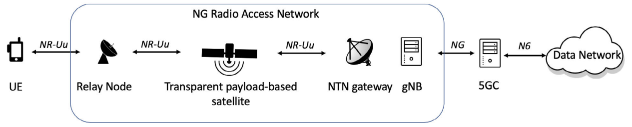


(b) Regenerative payload-based satellite

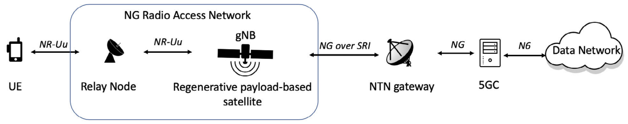


(c) Regenerative satellite-based gNB-DU

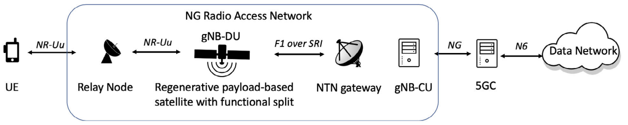
FIGURE 2. **Satellite access architectures.**



(a) Transparent payload-based satellite



(b) Regenerative payload-based satellite



(c) Regenerative satellite-based gNB-DU

FIGURE 3. **Relay-like architectures.**

As specified in the NG-RAN [14] architecture description, a gNB consists of a gNB central unit (gNB-CU) and one or more gNB distributed units (gNB-DU). Fig. 2(c) shows a “5G NR friendly” NTN architecture based on the regenerative satellite. The gNB-CU on the ground is connected via the F1 interface over SRI to the NTN platform, which acts as a gNB-DU. The NR-Uu is the radio interface between the NTN terminal and the gNB-DU on-board satellite, whereas the NG interface connects the gNB-CU on the ground to the 5GC. gNB-DU on-board different NTN platforms may be connected to the same gNB-CU on the ground.

B. RELAY-LIKE ARCHITECTURES

In Fig. 3(a), the access network forwards the NR signal to the NTN terminal through a relay node, which receives it from the transparent payload-based satellite. In Fig. 3(b) and Fig.3(c), the regenerative payload-based satellite includes full and part of the gNB, respectively. The relay node forwards the NR signal received from the regenerative payload-based satellite (see Fig. 3(b)) with the gNB functional split (see Fig. 3(c)), to the NTN terminal. For further study, Integrated Access and Backhaul (IAB) architectures are described in [19], which relay the access traffic when both access and backhaul links are considered.

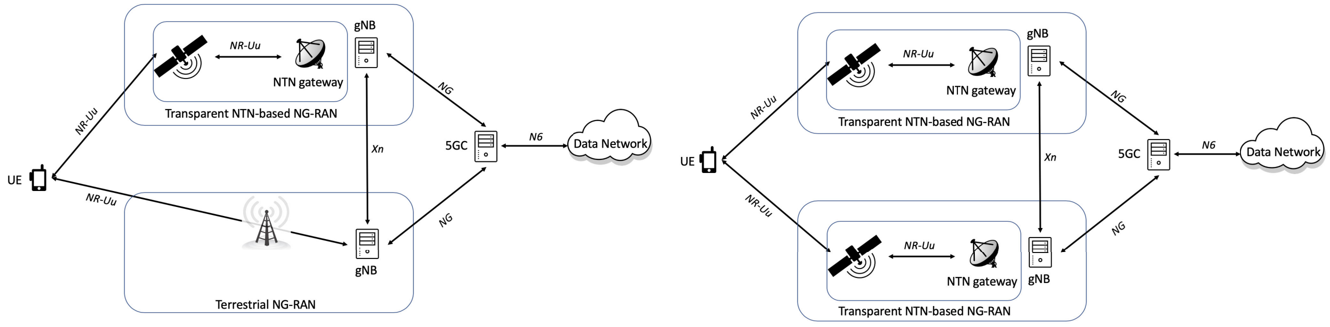
C. SERVICE CONTINUITY & MULTI-CONNECTIVITY

The integration of NTNs and terrestrial networks is essential to guarantee service continuity and scalability in 5G and beyond systems. An integrated terrestrial-NTN system may offer benefits in urban and rural areas in terms of the 5G performance targets (i.e., experienced data rate and reliability), guarantee connectivity among dense crowds (such as concerts, stadiums, city centers, and shopping malls) and for users traveling in high-speed trains, in airplanes, and on-board of cruises.

However, 5G systems support service continuity not only between terrestrial NG-RAN and NTN NG-RAN, but also between two NTN NG-RANs. 3GPP’s TR 38.821 [1] studies the feature of multi-connectivity to allow simultaneous access to both the NTN and terrestrial NG-RANs or two NTN NG-RANs. Therefore, the architectures supporting multi-connectivity are described below.

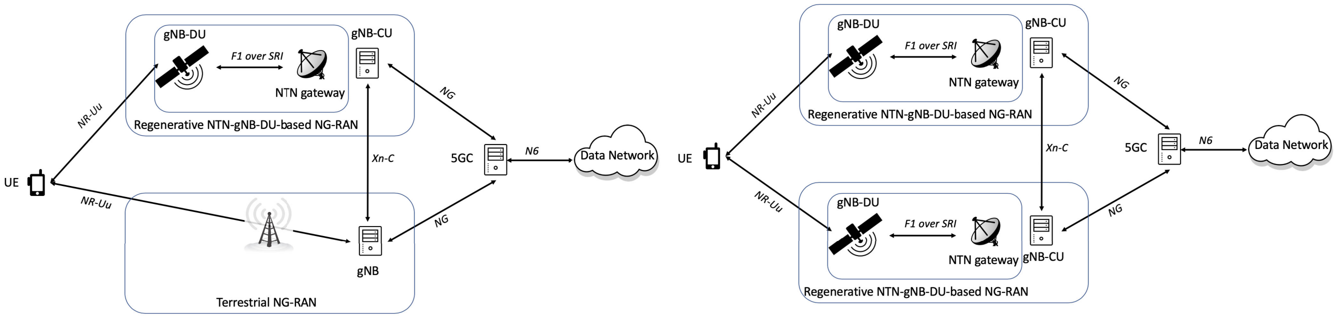
In Fig. 4(a), the ground terminal is connected simultaneously to the 5GC via both transparent NTN-based NG-RAN and terrestrial NG-RAN. The NTN gateway is located in the Public Land Mobile Network (PLMN) area of the terrestrial NG-RAN.

Fig. 4(b) refers to the combination of two transparent NTN-based NG-RANs consisting of either GEO or LEO, or a combination of both. This scenario may be followed to provide services to the UEs in un-served areas. In particular, LEO is employed to deliver delay-sensitive traffic since it is being characterized by lower propagation delay than GEO. The latter is used to provide additional bandwidth and, consequently, higher throughput.



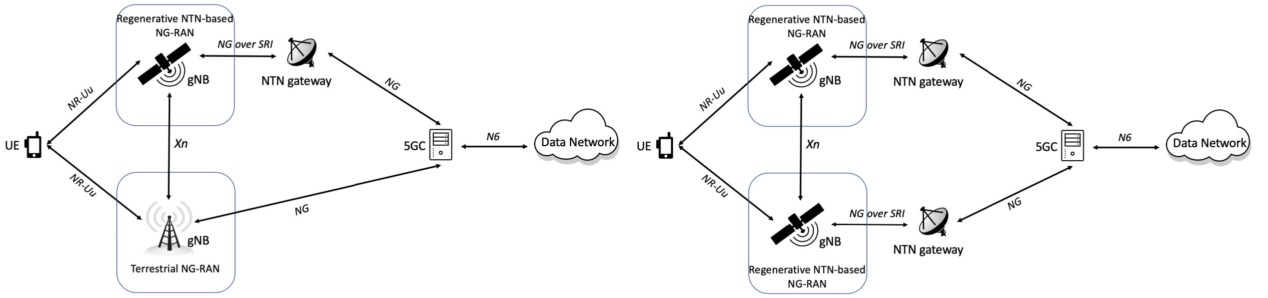
(a) A transparent NTN-based NG-RAN and a terrestrial NG-RAN

(b) Two transparent NTN-based RANs



(c) A regenerative NTN-gNB-DU-based NG-RAN and a terrestrial NG-RAN

(d) Two regenerative NTN-gNB-DU-based RANs



(e) A regenerative NTN-based NG-RAN and a terrestrial NG-RAN

(f) Two regenerative NTN-based RANs

FIGURE 4. **Architectures supporting multi-connectivity.**

Fig. 4(c) demonstrates the combination of a regenerative NTN-gNB-DU-based NG-RAN and a terrestrial NG-RAN. The functional split is applied in this type of architecture; hence, the NTN platform represents a distributed unit of the gNB and the related central unit is on the ground. This scenario may be followed to provide services to the UEs in under-served areas. Multi-connectivity can also involve two regenerative NTN-gNB-DU-based NG-RANs (see Fig. 4(d)).

Fig. 4(f) considers the combination of two regenerative NTN-based NG-RANs consisting of either GEO or LEO, or a combination of them both being interconnected with ISLs. Differently from the previous case, in this type of the architecture, the NTN platform performs all the gNB tasks (i.e., the functional split is not applied). Multi-connectivity can also involve regenerative NTN-based NG-RAN and terrestrial NG-RAN (see Fig. 4(e)).

IV. ROLE OF NON-TERRESTRIAL NETWORKS IN CELLULAR COMMUNICATIONS

A. SATELLITE NETWORK ROADMAP

Satellite networks were born independently from terrestrial systems because of the different nature of satellite communications in terms of the covered distances, utilized radio spectrum, design, costs, applications, and targets. Satellite systems were initially intended to provide first-generation (1G) analog services, such as in voice and other low data rate applications, primarily in maritime scenarios (i.e., INMARSAT).

In the early ‘90s with the second-generation (2G) technology, satellite communications were exploited to deliver aeronautical services to people traveling on aircrafts as well as to provide coverage in certain land areas. Meanwhile, NGSO satellite constellations (e.g., Iridium and Globalstar) gained the attention of the research community due to their ability to provide global satellite coverage. However, it was found to be expensive to compete with GEO and cellular networks.

Further, the so-called Super GEO satellites succeeded above all in niche areas (sea and aeronautics) where a terrestrial network is expensive to deploy [20], whereas *little*, *big*, and *super* LEO satellites with their key issues (i.e., spectrum allocation and regulatory aspects) are considered to be a part of the satellite personal communication networks [21].

As satellites are typically proprietary solutions, the integration between satellite and terrestrial networks is difficult. However, several aspects (i.e., higher costs, limited coverage, and weak exploitation of satellite features) inspired the thinking to combine satellite and cellular networks first by supporting Global System for Mobile Communications (GSM) [22] via satellite through GEO Mobile Radio (GMR) air interface. Then, an integration of satellites with terrestrial networks aimed to support the emerging third-generation (3G) wireless system, also known as Universal Mobile Telecommunications System (UMTS) [23].

B. SATELLITES IN 3G UMTS SYSTEMS

Satellite network operators decided to collaborate rather than compete with the cellular network operators. Hence, new features (i.e., location update, handover) were added to the UMTS specification to render the satellite air interface fully compatible with the terrestrial UMTS networks. This fostered the commercial roll-outs of the 3G technology owing to the rapid delivery of UMTS services through the satellites.

UMTS represented the first step toward the convergence of mobile and broadband systems by offering services to groups of users (i.e., Multimedia Broadcast Multicast Service – MBMS [24]). Indeed, the 3G UMTS technology is characterized by the need to provide MBMS services to the users located inside and outside the terrestrial coverage via the 3G cellular network or Satellite-Digital Multimedia Broadcasting (S-DMB) [5]. Therefore, ITU initiated the IMT-2000 standardization framework and defined the UMTS technology as a 3G global wireless system operating in the frequency band of 2 GHz. Further on, the satellite system was considered complementary to the terrestrial network in providing services for international roaming as well as in serving sparsely populated areas to reach ubiquitous coverage [25].

Several EU activities [26], such as INSURED, NEWTEST, SECOMS, SINUS, and TOMAS, were directed to study the air interface, mobile terminals, and applications of the satellite component in UMTS (S-UMTS). Researchers were hence driven to propose the integration of terrestrial and satellite networks for a more efficient 3G system. For example, in [27], technologies such as Intelligent Network [28], Mobile-IP [29], and dual-mode mobile terminals have been at the foundation of a possible S-UMTS architecture. Further, the ever-increasing demand for group-oriented services by the UEs on-board of vehicles, aircrafts, ships, and trains led to new network solutions for MBMS delivery via satellite.

In [30], a new integrated satellite-terrestrial UMTS (S/T-UMTS) architecture has been considered for the extension of cellular network coverage, to provision urban and indoor coverage with the introduction of the Intermediate Module Repeater (IMR). This allowed for a tight cooperation between satellite and terrestrial network operators in providing low-cost MBMS services. A Radio Resource Management (RRM) strategy has been proposed to support both data streaming and push & store services by accounting for the QoS and Grade of Service (GoS) [30]. An RRM scheme for the delivery of MBMS services has also been discussed in [31] by considering satellite system requirements. Another RRM technique has been studied in [32] where an RRM analysis has been conducted for a dynamic channel allocation (DCA) technique with queuing of handover (QH) requests by exploiting a grid for traffic prediction and by considering a realistic mobility model.

With the integration of satellites into the 3G terrestrial networks, user terminals were designed to operate in dual-mode to enable service continuity from one network to another (i.e., inter-segment handover) whenever necessary. For example, the SINUS project aimed at designing an inter-segment handover algorithm, which has been described in [33]. In [34], a new vertical handoff decision algorithm has been designed for integrated UMTS and LEO satellite networks by taking into account the performance in terms of QoS and handover costs. When a handover takes place between the LEOs of a constellation, it can belong to either of the three categories: *(i)* spot-beam handover occurring between the neighboring spot-beams of a satellite, *(ii)* satellite handover that features the transfer of an existing connection from one satellite to another, and *(iii)* ISL handover where ISL links are exploited to reroute the connection when inter-plane ISLs – connecting the satellites located at different orbital heights – are switched off temporarily. In [4], handover schemes for LEO satellite networks have been reviewed.

Since the satellite system was first considered as an integral part of the 3G wireless network, there were many technological and physical aspects (i.e., propagation delay, Doppler effect, satellite diversity) to be investigated for efficient satellite-terrestrial interworking. In [35], the Satellite Wideband Code Division Multiplexing Access (SW-CDMA) air interface – driven by the European Space Agency (ESA) to integrate satellites into the 3G UMTS global network by minimizing the difference with the WCDMA air interface [36] – has been deeply analyzed in terms of the physical-layer performance and the LEO-constellation system capacity has been evaluated. Channel variations due to the environment (i.e., Rice factor) have been taken into consideration in [37] to propose a novel adaptive modulation and coding technique, which better accommodates mobile satellite communication systems.

Over the UMTS time, HAPS [38] started representing a valid alternative to satellites for the introduced advantages, such as rapid deployment, broad coverage, low upgrade cost, high flexibility, and low propagation delay. In fact, they were considered quasi-stationary as well as taller than a cellular antenna and lower than a satellite. In [39], a feasibility study has been carried out to integrate HAPS with the terrestrial UMTS system by analyzing the impact in terms of interference. Further, requirements for full compatibility with the UMTS specifications have been studied. Moreover, mindful of the importance of HAPS in supporting the MBMS service over 3G and beyond systems, HAPS capabilities and limitations have been investigated in [40].

Therefore, satellites saw a steady development in terms of the supported functionalities. Initially, satellites had a basic feature to relay or forward signals and carry transparent-based (or bent-pipe) payload. Over time, they progressed to feature on-board processing or regenerative-based payload, while the NGSO satellite constellations inter-connected through ISLs were revised with an emphasis on the design costs reduction as compared to the first NGSO satellites – to achieve lower propagation delays than with GEO satellites.

C. SATELLITES IN 4G SYSTEMS

The Long-Term Evolution (LTE) system [41] was designed to support IP-based traffic as well as to achieve lower latency, higher data rate, and better spectrum efficiency than UMTS. The 4G technology represents a convergence of different access networks (i.e., cellular and satellite networks) and supports global roaming as one of its main targets. Since the terrestrial network infrastructure may be occasionally infeasible (i.e., economically, due to impossibility of installation) across many scenarios (i.e., maritime, aeronautical, disaster relief, military, and others), the satellite technology gained considerable attention of researchers in the 4G era.

The Mobile Satellite Systems (MSS) [5] provided satellite communication services to mobile users and represented an attractive way to provide coverage at lower costs in places that are not (well) reachable by the cellular network. Differently from the Fixed Satellite Systems (FSS) being affected by atmospheric attenuation, MSS suffers from non-Line-of-Sight (non-LoS) propagation attenuation, known as multipath propagation, due to obstacles (e.g., buildings, trees) and to their irregularities (e.g., foliage).

The integration of satellite and terrestrial access technologies can help overcome the non-LoS degradation through either *integrated networks* or *hybrid networks*. The integrated approach foresees that the terrestrial network can be considered as an alternative communication system to the satellite network. In [42], a layered approach for integrating the satellite and the terrestrial networks has been assessed in terms of services, radio access technologies, and protocol layers. Unlike in [42], where a multi-layered architecture has been proposed to enable satellite communications over various layers (i.e., HAPS, LEO, MEO, GEO) through inter- or intra-satellite links, in [43] an ultra-dense configuration of only LEO satellites has been integrated with the terrestrial network and an optimization model has been proposed to offload the terrestrial data traffic for maximizing the LEO-based backhaul capacity.

The hybrid network adopts terrestrial gap fillers for retransmitting the satellite signal in non-LoS conditions, supplies the return link (from the terminal to the satellite) with the terrestrial system, and extends the satellite coverage in indoor or urban areas with local evolved-NodeBs (eNBs or LTE base stations) and vice versa. In [44], a hybrid satellite-terrestrial network architecture has been proposed for broadcast and two-way missions. For the former, satellite and terrestrial relays operate in Single-Frequency mode. For the latter, satellite and terrestrial eNBs manage the spectrum so as to reduce interference between the satellite beams and the terrestrial network cells.

Further, communication in rural and scattered suburban areas is handled by the satellite segment, whereas in urban and dense suburban scenarios transmissions are handled by the ground component. The satellite is connected to the 4G core network through a gateway, which is able to handle its integration into a hybrid network. Conversely, the ground component is composed of terrestrial relays to forward the traffic to the terminal and the eNBs that manage the two-way communication and the return link.

The 4G terrestrial network can take advantage of cooperative communication between the users (i.e., Device-to-Device communication) to improve the QoS of edge nodes and to favor the out-of-coverage communication. Cooperation among the devices is also exploited in 4G satellite networks, thus raising several issues, such as synchronization, bandwidth allocation, and selection of forwarding and relaying devices [45]. In [46], two cooperation schemes, namely, Decode-Forward and Amplify-Forward, have been analyzed with the aim to determine, which solution can offer better data forwarding capabilities from the satellite to the mobile terminal, even when the latter moves into the areas that are unreachable from the satellite.

Further, 4G technology fuels the ever-increasing demand for real-time video services and, consequently, raises issues of link adaptation and radio resource management. Among the link adaptation procedures, Adaptive Modulation and Coding (AMC) has the aim to select the Modulation and Coding Scheme (MCS) on the basis of the channel conditions of a single user or a group of users (i.e., multicast).

In the case of a multicast scenario, manifold AMC solutions can be implemented. The conservative approach, named Conservative Multicast Scheme (CMS), adapts the MCS of the entire user set according to the lowest channel quality experienced in the multicast group (i.e., the most robust modulation). The opportunistic approach, named Opportunistic Multicast Scheme (OMS), serves only a set of users in a given Transmission Time Interval (TTI) to maximize the overall throughput. Another approach is known as Subgrouping: it splits the multicast group into smaller subgroups with the aim of optimizing a given objective function (i.e, user satisfaction or system Aggregate Data Rate). In [47], a novel radio resource allocation scheme combined the Multicast Subgrouping [48] with the Application-Layer Joint Coding (ALJC) technique [49] to enhance the performance of the multicast transmissions over satellite evolved-MBMS (eMBMS) networks.

Radio spectrum management issues become essential not only due to the increased demand for eMBMS [50], but also due to the satellite architecture features that progress from single-beam to multi-beam. Multi-Spot Beam Satellites are based on the frequency re-use principle, which is well-known for terrestrial communications. According to the frequency re-use factor, the available spectrum is split such that the adjacent spot-beams do not utilize the same set of radio resources to avoid inter-beam interference.

In [51], a dynamic bandwidth allocation technique has been proposed to reduce the difference between the available system capacity of all spot-beams and the total traffic demand as well as achieve fairness among spot-beams with different traffic demands. In [52], the authors have proposed a radio resource allocation scheme for an integrated satellite/terrestrial system with the aim to optimize the spectral efficiency, increase the system capacity, and minimize the interference between the terrestrial and the satellite components, since terrestrial multi-cells re-use satellite resources.

In [53] and [54], two mathematical frameworks have been developed to handle the problem of inter-beam and inter-satellite interference in multi-beam satellite systems. In [53], a mathematical study of an advance precoding scheme has been completed by taking into account the information about the route and the distribution of users as well as their Channel State Information (CSI). In [54], the precoding task has been solved as a k-means-based clustering problem.

The integration of different radio access networks (i.e., satellite and terrestrial) to achieve global connectivity poses several challenges due to the heterogeneity in access technologies, network architectures, and protocols as well as the demand for dissimilar types of services [55]. Not limited to radio resource management, one of the key issues is mobility and, hence, handover procedures. Handover may belong to *intra-* or *inter-system* types. The former may occur either between the beams generated by the same satellite (i.e., intra-satellite handover) or between two satellites (i.e., inter-satellite handover). The latter may occur between the satellite radio access network and the terrestrial system and vice versa (i.e., vertical handover).

From past literature, it follows that inter-system handover has attracted much interest in the research community. In [56], a handover procedure subdivided into initialization and execution phases has been analyzed for integrated satellite-terrestrial mobile systems, and then a mathematical model has been presented for assessing inter-system handover. In [57], a buffering scheme has been proposed prior to handover to compensate for service interruptions during inter-system handover, whereas in [58], protocols for mobility management have been designed to select the best network in the case of inter-system handover according to certain decision metrics (i.e., costs, network conditions, power consumption, system performance, and user activity).

V. NON-TERRESTRIAL NETWORKS IN 5G SYSTEMS

Until a couple of decades ago, the satellite and terrestrial networks were considered to be independent and were developing separately from each other. From the current-generation wireless technology (i.e., 5G) onward, these two networks are viewed from a different perspective. The 3GPP standardization has already completed the first 5G NR specifications and progressed on solutions to support the NTN in 5G NR systems [59]. In addition, several projects like SAT5G [60], as part of the H2020 5G PPP initiative [61], targeted to propose cost-effective solutions to provide 5G connectivity everywhere and to create new opportunities in the 5G world market.

Service continuity is one of the key requirements to be ensured when the 5G NTN NG-RAN is integrated with the 5G NR terrestrial RAN or with another 5G NTN NG-RAN [1]. The requirement of service continuity between the two NG-RANs means that the specification support should enable a seamless handover between the systems without a service interruption as well as a fluent IDLE mode UE operation for optimal network selection.

The NTN segment, when combined with the terrestrial network, plays an essential role to achieve global coverage owing to boosting capacity (as a result of high-frequency reuse and precoding techniques) and ensuring service continuity even when traveling.[2] In [62], architectural and technical issues have been discussed for 5G systems including the NTN, whereas in [63] the effect of NTN integration into the mobile systems has been assessed through an experimental comparison in terms of the Key Performance Indicators (KPIs).

The integration of terrestrial and non-terrestrial networks is thus considered to be an attractive solution for 5G technology development. In the past couple of years, multiple research works have investigated a combination of two radio access networks. The authors in [11] were the first to provide a review on Space-Air-Ground Integrated Networks (SAGIN), where the system performance has been improved by exploiting deep learning methods for traffic balancing purposes [64].

In [65], a new perspective on integrated systems has been presented by discussing Software Defined Space-Terrestrial Integrated Networks based on Software Defined Networking (SDN) [66], which separates the control plane from the data plane. In [67], the integration of non-terrestrial and terrestrial networks has been simplified by introducing a new architecture that combines SDN and Network Function Virtualization (NFV) [68], which implements specific hardware functionalities via software.

Security is one of the essential concerns in NTN communications. Several works in the literature tackled this issue in integrated NTN-terrestrial networks, wherein cognitive radio

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[2] It is worth noting that satellite links are reliable only in outdoor conditions. In indoor conditions, the satellite access network is not used directly by the devices due to higher pathloss and, therefore, the satellite signal needs to be amplified by mounting terminals on-board aircrafts/vessels/trains. Indoor conditions are considered only for HAPS, since they are closer to Earth and, hence, the pathloss is lower than in the satellite networks [3].

is introduced to improve the spectrum utilization when the NTN and the cellular network share the same bandwidth. The authors in [69] investigated the physical layer security and proposed a stochastic beamforming approach. Multi-antenna terrestrial base stations were employed as a source of green interference to enhance the security of NTN communications in [70], [71], and [72].

In [73], a cooperative secure transmission beamforming scheme has been designed to assess the communications security in NTN-terrestrial systems and the secrecy rate has been maximized under the power and transmission quality constraints. In [74], the secrecy performance has been analyzed while considering the connectivity in a multi-antenna NTN with terrestrial recipients (i.e., downlink direction) via multiple cooperative relays and in the presence of several eavesdroppers. In [75], different adaptive transmission schemes have been addressed to analytically obtain the expression for the achievable channel capacity in hybrid NTN-terrestrial relay networks.

A joint opportunistic relay selection scheme has been proposed in [76] to enhance the system protection against attacks. Three typical attack approaches have been described in [77] to illustrate possible threats to the NTN security. Unlike previous works where cooperation has been adopted for cognitive NTN-terrestrial networks, in [78] a non-cooperative game with limited information exchange was constructed to address the power control problem in the case of spectrum sharing between the NTN and the terrestrial network.

Further, the performance of cognitive NTN-terrestrial systems has been investigated in [79] via the outage analysis given the interference temperature constraints and in [80] by analytically deriving the outage probability and the ergodic capacity. This latter parameter has also been formulated in [81], where different full cooperative relay protocols (i.e., amplify-forward and decode-forward) were considered, whereas in [82] the system performance has been assessed through a partial relay selection scheme.

The 5G wireless technology features non-orthogonal multiple access (NOMA) among its radio access techniques. Unlike the traditional OMA techniques where one user is being served on each orthogonal carrier, NOMA enables more than one user being served on each orthogonal carrier [83]. In the literature, several works investigated both the NTN and the integrated NTN-terrestrial networks based on NOMA techniques. A survey on multi-satellite cooperative transmission systems has been offered in [84], where multi-satellite relay transmission systems based on NOMA have also been addressed.

In [85], the achievable ergodic capacity has been formulated for a NOMA-uplink NTN, whereas in [86] both the ergodic capacity and the outage probability have been investigated for a hybrid NTN-terrestrial relay network with the cooperative NOMA scheme in the downlink direction. Also in [87], the authors analyzed the outage probability and derived it in the closed form. Since terrestrial and NTN systems interfere while the two downlink channels reuse the same bandwidth, the respective capacity has been computed for a NOMA-based terrestrial-NTN system in [88], whereas an optimization design has been proposed in [89] for NTN multicast communications that share the mmWave spectrum with terrestrial communications by exploiting the NOMA techniques.

On a related matter, GEO High Throughput Satellite (HTS) and LEO satellite mega-constellations are expected to become the focus of attention for both telecommunication operators and researchers. Indeed, GEO HTSs achieving very high data rates facilitate the provision of eMBB services in further enhanced MBMS (FeMBMS) mode [90], whereas LEOs support extremely low-latency 5G services (i.e., URLLC) under low propagation delay of LEO transmissions. Therefore, GEO and NGSO satellites may be exploited either over standalone or non-standalone radio access combined with terrestrial cellular systems.

In [91], a standalone GEO satellite NG-RAN has been addressed to deliver multi-layer video services in the forthcoming 5G NR deployments by following a novel RRM strategy for efficient resource allocation that provides several multimedia video flows. Further, in [92], path-based network coding has been proposed for achieving better reliability and time-efficient distribution of traffic in NTN-terrestrial mobile systems. A standalone LEO NG-RAN has been considered for 5G mMTC services in [93], where an uplink scheduling technique has been outlined to make the differential Doppler shift tolerable by the MTC devices.

However, the integration of LEO satellites with the 5G technology is not straightforward because of the challenging LEO features, such as Doppler effect, high-speed mobility around Earth, and smaller coverage area than for the GEO satellite. These factors lead to the construction of LEO constellations for providing global coverage. In [94], an enabling network architecture with dense LEO constellations has been designed to offer enhanced reliability and flexibility in integrated NTN-terrestrial systems.

In a constellation, LEOs are interconnected via ISL and, owing to the on-board processing capabilities of a regenerative payload-based LEO, data transmissions may occur directly between the LEO satellites. In [95], analytical models have been coined for determining the probabilities of call blocking and handover failure in a constellation of regenerative payload-based LEOs. In the case of transparent payload-based LEO, data traffic needs to be routed to the terrestrial network, thus entailing vertical handover situations.

To ensure connection transfers without harmful interruptions over the heterogeneous wireless access technologies, seamless handover becomes a challenging matter. In [96], a strategy based on positioning has been considered to minimize the delay and to manage the inter-satellite handover in satellite communications (when a handover occurs, the nearest satellite is selected as the access satellite), whereas in [97] stochastic and deterministic optimization problems have been constructed to support handover

TABLE 4. Classification of research work by common topics for different wireless technologies.

Topic	Motivation		
	3G – UMTS	4G – LTE	5G – NR
Integrated NTN-Terrestrial Networks	Integration of satellites with terrestrial networks is indispensable to reach ubiquitous coverage. The idea of a global wireless system was born during the 3G times and characterized all subsequent wireless technologies up to the present day. Therefore, researchers considered it as an attractive research topic.		
	[30] - [39] - [40]	[42] - [43] - [44]	[62] - [63] - [11] - [94]
Radio Resource Management	RRM is relevant to offer tight cooperation between satellite and terrestrial networks. Researchers focused on devising efficient radio resource allocation methods to reduce all interference types as well as on proposing effective link adaptation procedures to provide real-time video services.		
	[31] - [32] - [37]	[47] - [48] - [51] - [52] - [53] - [54]	[91] - [92] - [93]
Mobility Management	Mobility management is essential to offer service continuity by achieving seamless handover over heterogeneous wireless access networks. Hence, researchers investigated new procedures for rapid inter-system handover to avoid service interruptions and optimize network selection.		
	[33] - [34] - [4]	[55] - [56] - [57] - [58]	[95] - [96] - [97]

in heterogeneous aeronautical networks with an SDN controller.

Not limited to the exponential growth of demand for high data-rate services, the 5G is characterized by a very large number of inter-connected devices. The communications among a swarm of heterogeneous devices (i.e., the Internet of Things) pave the way for a new paradigm named the Internet-of-Space Things (IoST) to efficiently incorporate the IoT concept into the space access networks. The IoST vision has been introduced in [98] to offer global connectivity by overcoming the terrestrial base station limitations [99] with low-cost and flexible solutions by combining SDN and NFV paradigms.

Indeed, NTNs support broadcast/multicast IoT communications, Internet of Remote Things (IoRT) [100] applications, and Internet of Vehicles (IoV) [101] even across rural and remote areas (i.e., beyond the terrestrial coverage). Further, the important results achieved by the microelectronics and microsystems industries open a new direction for adopting smaller and more powerful satellites for the forthcoming 5G satellite era [12]. CubeSats, which originally aimed for university and research purposes [102], have been addressed over the years [103], [104]. They are now seen as a revolutionary solution to realize a global IoST network for small payload sizes, low costs (i.e., design, construction, launch, readiness for use), and high scalability [105].

In addition to SDN and NFV [106]–[108], 5G supports Network Slicing [109] and Edge Computing (EC) [110]. The former ensures better scalability, higher availability, and the overall resource optimization owing to the provision of specific network capabilities and characteristics with a logical network customized based on, i.e., service requirements. The latter shifts computing and storage resources closer to the user, thus supporting lower latency. These two concepts were also adopted for 5G satellite networks in [111], [112], and [113].

In [111], 5GsatEC has been proposed as a 5G satellite edge computing framework, wherein a hardware platform optimizes resources (i.e., computing, storage, network) for different services and users, whereas a software framework is built on a 5G satellite edge computing service architecture based on microservices (i.e., system, basic, and user services). In [112], edge computing has been introduced to support space-based cloud-fog satellite network slices, while edge computing nodes have been added into the computing architecture of a satellite network to reduce the delay in different slices. In [113], the authors studied an integration of CubeSats into multi-tenant scenarios by designing an SDN/NFV IoT platform based on EC that includes CubeSat constellations.

In summary, 5G technology envisions the involvement of NTN as a means to extend terrestrial coverage and help provision for advanced services whenever and wherever the traditional cellular network is overloaded or not available. Table 4 classifies the related literature by a common subject matter (integrated NTN-terrestrial networks, RRM and mobility management, etc.) under different wireless technologies. Further, Table 5 summarizes the research works by open research topics in the 5G & beyond fields. Finally, Table 6 briefly describes the main contributions of past publications on NTN and satellite communications.

VI. CURRENT 3GPP RESEARCH ACTIVITIES

Activities on NTN inside the 3GPP RAN and System Aspects (SA) Technical Specification Groups (TSGs) started in 2017 under Release 15 and are still ongoing.

TABLE 5. Summary of past works on NTN by open research topics in 5G & beyond.

Topic	Description
Cognitive Radio	Cognitive radio is an enabling technology for 5G & beyond communications. Researchers focused on new cognitive radio techniques to handle massive access to the NTN and spectrum sharing in integrated NTN-terrestrial networks through the allocation of limited radio resources in a flexible manner. **References:** [78] - [79] - [80] - [81] - [82] - [133]
Security	Data security is one of the main requirements in 5G & beyond systems. Researchers proposed methods to preserve data integrity from data-tampering attacks by third-party eavesdroppers. Security is often interconnected with cognitive radio to improve the spectrum usage. **References:** [69] - [70] - [71] - [72] - [73] - [74] - [75] - [76] - [77]
NOMA	NOMA revolutionized the traditional OMA techniques, since more than one user can then be served on each orthogonal carrier. Researchers investigated the advantages introduced by NOMA over integrated NTN-terrestrial networks. **References:** [84] - [85] - [86] - [87] - [88] - [89]
IoST	The concept of inter-communication among a large number of heterogeneous IoT devices has been extended to space. Researchers were primarily interested in CubeSats to realize a global IoST network with low cost and high flexibility. **References:** [98] - [99] - [12] - [102] - [103] - [104] - [105]
SDN and NFV	5G features SDN to separate the control plane from the data plane, while NFV is used to implement hardware capabilities via software. Researchers considered an emerging perspective of hybrid NTN-terrestrial networks that incorporate SDN and NFV paradigms. **References:** [106] - [107] - [108]
Network Slicing and Edge Computing	5G employs Network Slicing to provide specific network characteristics where logical networks are customized, while Edge Computing is utilized to move computing and storage resources closer to the user. Researchers integrated the two concepts with space networks to offer better scalability and lower latency. **References:** [110] - [111] - [112]

A RAN-level 3GPP study on NTN NR was completed in December 2019 and the normative work started in August 2020 for Release 17. Conversely, the SA work depends on the progress in RAN groups and may proceed further after the normative RAN-level work progresses. Table 7 lists the features and study items on NTN as investigated by the 3GPP from Release 15 to Release 17. In particular, each 3GPP feature or study item is associated with the *lead body* (i.e., 'R' for RAN aspects and 'S' for system aspects). The *completion* field indicates when the 3GPP feature or study item was completed or is expected to be completed.

3GPP technical reports and specifications related to NTN are as follows:

- TR 38.811 [3] defines the NTN deployment scenarios and the related system parameters (i.e., architecture, altitude, orbit, among others), adapts the 3GPP channel models for NTN, describes the deployment scenarios, and identifies the key impact areas for the NR interface.
- TR 38.821 [1] studies a set of necessary features/adaptations enabling the operation of the NR protocol in NTNs with a focus on satellite access. An access network based on UAS and including HAPS may be considered as a special case of non-terrestrial access with lower delay/Doppler value and variation rate. The objectives of this work are the consolidation of potential impacts on the physical layer and definition of the related solutions, performance assessment of 5G NR in selected deployment scenarios (LEO satellite access, GEO satellite access) through link-level and system-level simulations, solutions for 5G NR related to Layer 2 and 3, and solutions for the RAN architecture and the related interface protocols.
- TR 22.822 [15] supports service continuity between the terrestrial NG-RAN and the NTN-based NG-RAN owned by the same operator or subject to an agreement between operators. This TR aims at identifying the use cases for the delivery of services when considering the integration of NTN-based access components into the 5G system and, consequently, new services and requirements (i.e., setup, configuration, maintenance, and regulation).
- TS 22.261 [114] describes the service and operational requirements for a 5G system, which includes UE, NG-RAN, and 5G core network components.
- TR 23.737 [115] identifies the impact areas of satellite integration into the 5G system when considering the use cases of the TR 22.822 [15]. It finds solutions to adapt the 5G system for three use cases (i.e., roaming

TABLE 6. **Brief description of published research papers on NTN and satellite communications.**

Ref.	Short summary of the proposal	Year
[30]	Integrated S/T-UMTS architecture and RRM strategy to support data streaming and push & store services.	2004
[31]	RRM scheme to deliver MBMS services by considering satellite system requirements.	2004
[32]	RRM analysis of a dynamic channel allocation technique with queuing of handover requests.	1998
[39]	Feasibility study in terms of interference to integrate HAPS with Terrestrial UMTS system.	2003
[40]	On the importance of HAPS to support MBMS services in 3G and beyond systems.	2005
[42]	Layered approach to integrate services, radio access technologies, and protocols in satellite-terrestrial networks.	2005
[47]	Radio resource allocation scheme combining multicast subgrouping and ALJC techniques.	2018
[54]	Application of k-means-based clustering to solve the precoding problem in multi-beam satellite systems.	2017
[55]	Survey on benefits and challenges of integrated satellite-terrestrial networks.	2004
[58]	Mobility management protocols to select the best network under inter-system handover.	2007
[62]	Discussion on architectural and technical issues of 5G systems.	2019
[63]	Analysis of NTN integration effects in mobile systems.	2019
[69]	Physical layer security and stochastic beamforming approach.	2018
[70]	Multi-antenna base station to enhance secure transmissions in satellite networks.	2016
[71]	Resource allocation for cooperative beamforming and artificial noise in secure satellite-terrestrial networks.	2018
[72]	Secure multicast transmission design for cognitive satellite-terrestrial systems.	2019
[73]	Cooperative secure transmission beamforming scheme maximizing the secrecy rate in terrestrial-NTN systems.	2018
[74]	Analysis of secrecy performance of communication between multi-antenna NTN and terrestrial recipients.	2019
[75]	Adaptive transmission schemes for hybrid NTN-terrestrial relay networks.	2019
[76]	Joint opportunistic relay selection to enhance system protection against attacks.	2018
[77]	Description of typical attack approaches to enhance security in NTN.	2019
[78]	Non-cooperative game for spectrum sharing between NTN and terrestrial networks.	2019
[79]	Outage analysis in a cognitive NTN-terrestrial network.	2017
[80]	Outage probability and ergodic capacity derivation for a cognitive NTN-terrestrial network	2019
[81]	Full cooperative relay protocols to characterize the ergodic capacity.	2017
[84]	Survey on multi-satellite cooperative transmission systems based on NOMA.	2018
[85]	Ergodic capacity formulation for NOMA-based uplink NTN systems.	2019
[86]	Ergodic capacity and outage probability for a hybrid NTN-terrestrial relay network with cooperative NOMA scheme.	2019
[87]	Analysis and derivation of a closed-form expression for outage probability.	2019
[88]	Capacity computation for a NOMA-based terrestrial-NTN system.	2017
[89]	Optimization of NTN multicast communications sharing spectrum with terrestrial communications.	2019
[92]	Path-based network coding to improve reliability in NTN-terrestrial mobile systems.	2019
[93]	Standalone LEO NG-RAN and uplink scheduling technique to handle Doppler shift in 5G mMTC scenarios.	2019
[94]	Network architecture with a dense LEO constellation for reliable and flexible integrated NTN-terrestrial systems.	2019
[95]	Analytical models to determine call blocking and handover failure probabilities in a LEO constellation.	2018
[97]	Stochastic and deterministic optimization problems to support handover in heterogeneous aeronautical networks.	2019
[98]	Introduction of the Internet of Space Things.	2019
[99]	SDN and NFV as low-cost and flexible solutions to provide global connectivity.	2017
[100]	Introduction of the Internet of Remote Things in satellite communications.	2016
[101]	Computation offloading mechanism for 5G Satellite-ground IoV systems.	2019
[102]	CubeSats as cost-effective science and technology platforms.	2011
[105]	Realization of global IoST networks with CubeSats.	2019
[106]	Introduction of softwarized networking and virtualization into satellite networks.	2015
[111]	Edge computing framework over 5G satellite architecture.	2019
[133]	Single-Frequency Multi-Beam Transmission of eMBMS services over 5G NR multi-beam NTN systems.	2020

between terrestrial and NTN systems, 5G Fixed Backhaul between NTN-based NG-RAN and 5G Core, and resolution of issues related to NG-RAN and 5GC).

- TR 28.808 [116] identifies the key issues associated with the business roles, services, and management and orchestration in a 5G network with integrated satellite components. It studies the associated solutions, aims at minimizing the complexity of satellite integration into the existing business models, as well as considers the management and orchestration aspects of the current 5G networks.

In [59] and [118], adaptation of 5G NR for satellite communications was considered based on the Release 15 of NR specifications. The work in [59] focused on physical layer and user plane aspects, while [118] described the challenges related to the connected mode and idle mode mobility as well as captured the NR specific network architecture aspects in both GEO- and NGSO-based NTN systems.

Longer delay associated especially with GEO deployments poses challenges for the random access procedure as well as hampers all the RRC procedures. For example, delay causes considerable data transmission interruptions during

TABLE 7. List of 3GPP Features and Study Items on NTN.

Release	Lead Body	Feature and Study Item	Completion
15	R1	Study on NR to support Non-Terrestrial Networks	2018-06-15
16	R3	Study on solutions for NR to support Non-Terrestrial Networks	2019-12-15
	S1	Integration of satellite access in 5G	2018-06-06
17	S2	Study on architecture aspects for using satellite access in 5G	2020-06-25
	S5	Study on management and orchestration aspects with integrated satellite components in a 5G network	2020-06-12 (65%)
	R1	Study on NB-IoT/eMTC support for Non-Terrestrial Networks	exp. 2021-06-15
	S2	Integration of satellite components into the 5G architecture	exp. 2020-09-12
	R2	Solutions for NR to support Non-Terrestrial Networks	exp. 2021-12-15

handovers. Moreover, as HARQ retransmissions add up to the delay, it has been proposed to disable HARQ in certain cases. All user plane protocols require adjustments due to longer propagation delays. Furthermore, both timing and frequency corrections are needed, especially for the UL transmissions, so that the gNB receives the UL transmissions in the exact time/frequency resources allocated for a given UE.

For LEO satellite systems, the movement of a satellite, and thus the beam footprint at low orbit, bring new issues to be addressed. For example, in terrestrial systems, all network identities are assumed to remain fixed in geographical areas. Hence, a gNB covers and serves a fixed geographical region, while in LEO systems the cells (i.e., beam footprint) move over the ground. In both LTE and NR, the UE in IDLE mode reads from system information, under which tracking area it is located. If the current tracking area code is different from the tracking area code that the UE is registered with, it needs to perform a tracking area update and inform the network about its new tracking area. In the case of an incoming call, the network pages the UE at the tracking area, which the UE has last indicated.

Further, as the LEO satellite orbits Earth, its connected ground node needs to be switched from time to time. For the regenerative LEO, this implies that the gNB changes the ground connection. For the transparent LEO, this means that the geographical area covered by the gNB on the ground is altered. When the feeder link switches, enhancements to the network signaling as well as to the signaling toward the UE are required.

VII. OPEN ISSUES AND FUTURE DIRECTIONS

In this section, we discuss the main open issues and pave the way to future research directions. In particular, we focus on the management of mobility, propagation delay, and radio resources. Table 8 summarizes some of the open questions discussed in the following subsections.

A. MOBILITY MANAGEMENT

NGSO satellites are characterized by shorter propagation delays and higher data rates than GEO satellites. Hence, they are considered to be an effective solution to enhance the 5G terrestrial networks. However, the motion of both the NGSO satellites around Earth and the UEs in a given region yields a time-varying NGSO channel. The dynamic nature of NGSO satellite links has an important implication on handover and paging procedures. As shown in Fig. 5, handover can belong to one of the following categories:

- *Intra-satellite handover* occurs between satellite beams. In the case of NGSO satellites, frequent intra-satellite handovers are related to high speeds of the beam footprint on the ground.
- *Inter-satellite handover* occurs between satellites and is essentially related to the limited geographical coverage of NGSO satellites.
- *Inter-access network handover*, also known as vertical handover, occurs either between satellites belonging to different access networks or from the NGSO satellite to the gNB (or vice versa) in integrated terrestrial-NTN systems.

TABLE 8. Open issues in NTN.

Feature	Effect	Impact	Issues & Directions
· NGSO satellite motion	· Cell pattern motion	· Handover · Paging	· *Mobility management*: new solutions for frequent handover mechanisms in NGSO satellite networks. · *Tracking area management*: new methods to provide exact information on UE Tracking Areas during Initial Registration and UE locations during Registration Update and Paging.
· NTN platform altitude, orbit, and motion · NTN gateway position and elevation · NTN terminal position, antenna type, and motion	· Propagation delay · Varying NTN channel	· Channel estimation · Scheduling	· *Delay-CSI-MCS management*: new techniques to select transmission parameters (i.e., MCS) to ensure that UE may perceive satisfactory service quality and reliably decode transmitted data despite rapid channel fluctuations and long propagation delays. · *Ephemeris data management*: new solutions to efficiently provide and update the UE with the required ephemeris data, which may be substantial.
· NGSO satellite motion · NTN gateway position and elevation	· Connection drops between NGSO satellite and NTN gateway	· Feeder link switch-over	· *Feeder-link management*: enhancements to both network signaling and signaling to the UE are needed to efficiently perform a seamless feeder link switch-over.
· New available frequency bands · Scalable NR numerology · Hybrid/integrated NTN-terrestrial networks · Multi-beam HTS	· Interference · Non-null side lobes of beam radiation patterns	· Resource allocation	· *RRM and interference management*: new approaches for allocating radio resources to avoid inter-RAN interference (e.g., between two RANs of an integrated/hybrid NTN-terrestrial network), intra-NTN inter-beam interference (e.g., among beams of the HTS), and inter-NTN interference (e.g., among satellites of the NTN). Further, novel methods of radio spectrum utilization are demanded to manage the availability of new 5G frequency bands and the introduction of scalable NR numerologies to avoid inter-numerology interference.

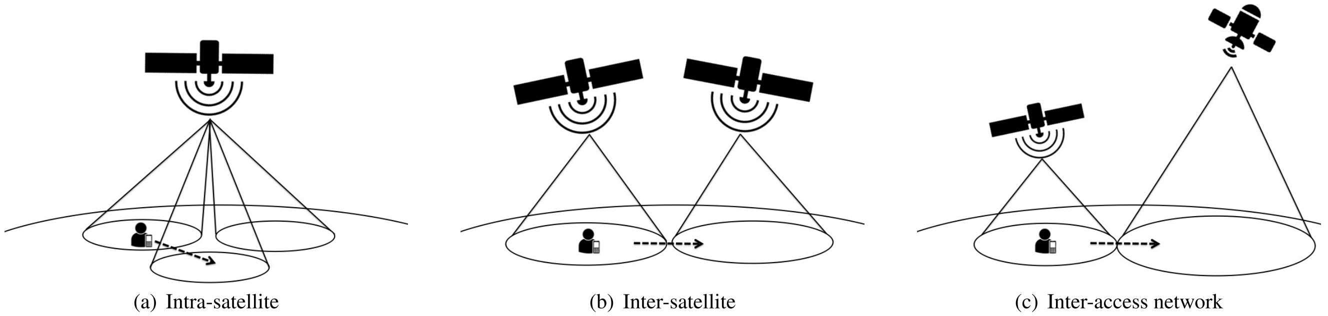
(a) Intra-satellite (b) Inter-satellite (c) Inter-access network

FIGURE 5. Types of handover.

The paging issue is primarily related to the tracking area management [1]. The tracking area is the satellite coverage area; it can be fixed (for both GEO and NGSO satellites) or moving (for NGSO satellites). The moving tracking area incurs high paging loads that are difficult to manage by the network. Indeed, the NGSO beam footprints do not correspond to the terrestrial cells on the ground. As a consequence, the NGSO satellite-based RAN is not able to provide the exact information on the UE tracking area during the initial registration. Furthermore, the UE cannot always establish its location for Registration Update and Paging procedures.

In recent years, several research works addressed mobility management. One of the main objectives was to coin handover solutions over LEO satellite networks, since handovers frequently occur because of the LEO features, i.e., LEOs are positioned at low altitudes, provide a limited coverage, and rapidly move around Earth. In [119], the authors modeled the handover process and proposed a strategy for inter-beam satellite handover based on the potential game for mobile terminals to minimize the number of handovers, balance the LEO constellation load, and reduce the handover time.

In [120], the authors introduced a virtual agent cluster (VAC) to manage handovers and construct the home mobile-agent-anchor (HMAA) and the local mobile-agent-anchor (LMAA) to let users share their location information. To avoid handover failures, the authors in [121] formulated a novel method of handover prediction based on the UE velocity that is non-negligible in LEO satellite networks. In [122], three algorithms have been designated to consider the handover time, the route update frequency, and the relay satellite configuration in global navigation satellite systems.

None of the works in past literature considered the 5G NR. Future studies might integrate the NR technology with the NTN to improve compatibility with 5G NR terrestrial networks. New procedures to support dual-connectivity and novel mechanisms for vertical handovers might be proposed to improve global network coverage, service continuity, and seamless mobility in hybrid/integrated terrestrial and NTN systems. Further, solutions for UE geolocation are required to determine the belonging beam (satellite), the beam (satellite) belonging time, and the next-to-switch beam (satellite) to simplify handover and paging procedures.

B. PROPAGATION DELAY MANAGEMENT

The propagation delay has a profound impact on the system performance in non-terrestrial communications and can be considered as one of the main challenges for URLLC applications and critical communications (i.e., public safety). The propagation delay is defined as the latency either from the NTN gateway to the NTN terminal via space/airborne platform (i.e., transparent payload) or from the space/airborne platform to the NTN terminal (i.e., regenerative payload). Furthermore, the propagation delay depends on the NTN platform altitude, the NTN gateway position and elevation angle, and the NTN terminal position [3]. It can also be distinguished as follows:

- *One-way propagation delay* considers the time needed by the information to travel from the NTN gateway to the NTN terminal through the NTN platform (in the case of the transparent payload-based satellite) or from the NTN platform to the NTN terminal (in the case of the regenerative payload-based satellite).
- *Two-way propagation delay*, also known as Round Trip Time (RTT), takes into account the time required by the information to travel from the NTN gateway to the NTN terminal through the NTN platform and back (in the case of the transparent payload-based satellite) or from the NTN platform to the NTN terminal and back (in the case of the regenerative payload-based satellite).

Furthermore, the propagation delay is a crucial parameter to be considered during the choice of transmission parameters (i.e., MCS). In NGSO satellite-based communications, the UE radio channel is characterized by rapid fluctuations over time; hence, after the propagation time has elapsed, the UE may no longer be able to decode the received data or can perceive an undesired QoS.

In recent literature, several works considered imperfect channel estimation over satellite networks. In [123], the authors quantitatively evaluated the effect of imperfect CSI in terms of the outage probability and ergodic capacity in a cognitive satellite-terrestrial network. In [124], the authors considered the CSI imperfections to formulate a closed-form expression for the outage probability in a hybrid satellite-terrestrial relay network based on NOMA. To allow for data transmissions over multi-way satellite relaying systems, the authors in [125] formulated a novel method of channel estimation.

The NTN channel is modeled by considering relative movements of both the NTN platform and the UE, NTN altitude and orbit, UE antenna type, atmospheric conditions, presence or absence of obstacles (i.e., building, foliage, mountains), deployment scenario, and frequency bands. In future research activities, it might be essential to investigate the ways how these factors lead to changes in the user channel as well as how to cope with abrupt channel variations by considering propagation delay to ensure service continuity.

C. RADIO RESOURCE MANAGEMENT

Radio resource management is one of the major considerations in 5G NR technology. Hence, efficient radio resource allocation is essential to avoid the following:

- *Intra-NTN inter-beam interference.* The success of HTS is driven by the multi-spot-beam technology that leads to improved capacity. However, efficient frequency reuse is required to avoid interference between the adjacent beams.
- *Inter-NTN interference.* In the case of heterogeneous NTN systems, when an NGSO satellite enters the LoS conditions with the GEO satellite, dynamic RRM techniques aid in coping with mitigating interference between the GEO and the NGSOs inside the GEO LoS cone.
- *Inter radio access network interference.* The integration of NTNs with terrestrial systems may be exploited in many 5G scenarios to extend cellular coverage or to offload terrestrial traffic. In the latter case, radio resources need to be allocated to limit the interference between the GEO (or NGSO) and the gNBs.

In recent years, researchers mostly investigated techniques to mitigate inter-beam interference in multi-spot-beam based HTS. In several works, precoding strategies have been introduced to reduce the interference at the NTN receivers due to non-null beam side lobes. Multicast precoding approaches have been summarized in [126]. Among them, multicast multigroup problem in frame-based multi-beam NTN has been considered in [127], where a low-complexity precoder has been proposed. In [128], the authors maximized the satellite system throughput by solving an optimization frame-based precoding problem.

In [54], two solutions based on k-means clustering algorithm have been formulated to group users in the same cluster according to their similarity in terms of the Euclidean distance and their channel coefficients. A mathematical framework for the throughput maximization facilitated the user clustering in [129], whereas in [130] multicast precoding problem has been solved with a novel geographical scheduling scheme. Recent research results on radio resource management were reported in [131], [132], and [133].

In [131], a new genetic algorithm considered the propagation effects, interference among beams, and atmospheric attenuation. In [132], a novel power resource allocation scheme has been proposed and a mathematical model has been constructed for ensuring the trade-off between the transmit power and the beam directivity. In [133], the authors introduced an emerging RRM technique, named Single-Frequency Multi-Beam Transmission (SF-MBT), to simultaneously deliver eMBB services into the dedicated Beam Areas over 5G NR multi-beam NTN systems.

The availability of new frequency bands (i.e., mmWave) and the introduction of scalable 5G NR numerology [134] led to additional challenges in the management of the radio spectrum for NTN systems. Indeed, different numerologies (i.e., different subcarrier spacings) may coexist over a given frequency band, thus generating novel types of interference, known as inter-numerology interference (INI) [135]. In recent literature, several works analyzed the INI factors that impact the overall performance [136]. INI cancellation methods for 5G NR multi-numerology terrestrial systems were also investigated [137].

5G NR over NTN is expected to be introduced in 3GPP Release 17 by following the outcomes of the preceding study items [138]. Release 17 is also planned to include a study item on NB-IoT for NTN [139]. Therefore, the research community might address the issue of INI mitigation in multi-numerology NTN systems for 5G and beyond technologies. Future research activities can focus on new solutions to boost the capacity by limiting inter-beam interference in multi-spot-beam satellite systems. Finally, novel radio resource allocation techniques might be required to handle the transmission of several services and to cope with inter radio access network interference in hybrid/integrated terrestrial-NTN systems.

VIII. TOWARD 6G SATELLITE COMMUNICATIONS

ITU has already started work on Network 2030 [140] with the aim to merge digital and real worlds across all dimensions. In addition to the 5G macro-categories (i.e., eMBB, mMTC, and URLLC), emerging 6G applications may include the following:

- *Holographic Type Communications (HTC)* require very high bandwidths to achieve excellent quality of hologram data transmitted from remote sites.
- *Multi-Sense Networks* involve not only acoustic, optical, and tactile senses but also the sense of smell and taste for fully immersive experience.
- *Time Engineered Applications*, such as industrial automation, autonomous systems, and massive sensor networks, where the time factor is extremely important for real-time response.
- *Critical Infrastructure*, where critical safety operations are essential in emergency areas.

Space communications can thus become a promising enabling feature not only for 5G but also for the future 6G wireless technology. Indeed, the integration of spaceborne and airborne platforms with terrestrial networks may achieve even more success in 6G [141], [142]. Among the NTN platforms, drones might be primarily exploited to complement the terrestrial coverage by providing connectivity to hotspot areas and in scenarios with weak terrestrial signal. Further, NGSO satellites have the potential to support drones and terrestrial gNBs in backhauling and coverage extension.

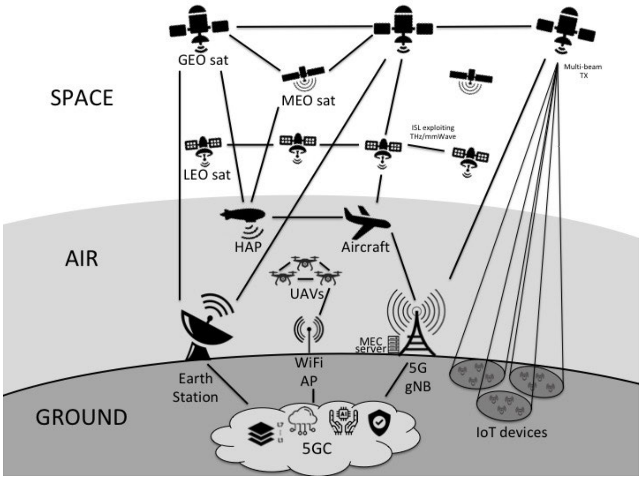

FIGURE 6. Role of NTNs in 5G and beyond.

Integrated NTN-terrestrial networks can benefit from wide-area coverage, predominant LoS, as well as low-loss and high-throughput transmissions. 6G-enabled NTN may also adopt new technologies, such as laser-mmWave, optical, and holographic type communications, photonics-based cognitive radio, machine learning, and Artificial Intelligence, all to achieve further enhanced low-latency and high-reliability during space-Earth transmissions [143]. A future vision of satellite communications might embrace the following 6G enabling features:

- *Holographic radio* to control the physical space owing to Large Intelligence Surface (LIS) [144] by improving spectral efficiency and network capacity.
- *Non-Radio Frequency* to compensate for wavelength distortion due to atmospheric phenomena as well as to offer ultra-low latency and high reliability.
- *Artificial Intelligence* for real-time satellite decisions and seamless satellite control to achieve high-level autonomous operations.

In 6G wireless, NTN communications may become essential to ensure extreme flexibility and integration of terrestrial and satellite networks. Here, the 6G NTN is expected to support emerging critical use cases (i.e., disaster prediction) and achieve global connectivity with seamless network access in maritime and mountainous scenarios. To offer a more systematic view on space communications, Table 9 surveys the role of NTN over the technological eras, from 1G satellites to how satellite networks may evolve in the future toward 6G. Finally, Fig. 6 illustrates the vision of NTN in 5G and beyond technologies.

TABLE 9. Vision of satellite communications from 1G to 6G.

Technology	Novelty	Description
1G	· Voice · Low data-rate applications	Satellite systems are considered independently from terrestrial systems due to their features (i.e., covered distance, exploited radio spectrum, design, cost, applications, and targets).
2G	· Aeronautical and maritime services	Satellite coverage is limited to areas unreachable by terrestrial networks. Therefore, satellites remain proprietary and in competition with traditional cellular networks.
3G	· Broadband and multimedia services	3G technology makes the first step toward the convergence of satellite and terrestrial networks (i.e., satellite air interface is fully compatible with terrestrial UMTS network infrastructure).
4G	· Hybrid/integrated satellite-terrestrial networks ·HTS	Satellite communications are considered indispensable for achieving global roaming where terrestrial network infrastructure is impossible to be installed or is economically expensive.
5G	· SDN/NFV based NTN-terrestrial networks · IoST · Cognitive NTN-terrestrial networks · NOMA based NTN-terrestrial systems	Integration of NTNs with terrestrial networks is a means to provide connectivity anywhere and anytime. To achieve this goal, the following requirements need to be provided: · *multi-connectivity* allows users to be served by two or more different RANs simultaneously (i.e., NTN and terrestrial network); · *service continuity* ensures smooth handover between different RANs.
6G	· NTN based on holographic radio · NTN based on non-radio frequencies (i.e., optical) · Satellite communications based on Artificial Intelligence.	Space-aerial-terrestrial networks may achieve further success in 6G. Drones can be exploited as base stations to provide connectivity in hotspots and remote areas, and may be supported by NGSO satellites in backhauling and coverage extension. Since several features are to be introduced in 6G, satellite communications might be revolutionized with holographic radio, non-radio frequency, and Artificial Intelligence.

IX. CONCLUSIONS

The last decade of progress in telecommunications has been characterized by the rapid proliferation of smart devices, the important technological advancements, and the exponential growth of demand for new services. These developments fueled the interest of both ICT operators and researchers in the NTN systems as a means to provide ubiquitous services by achieving global network coverage. The relevance of NTN across their two design options (i.e., standalone satellite vs. integrated terrestrial and non-terrestrial architecture) is expected to raise further in beyond-5G ecosystem.

The objective of this work is to provide a holistic overview of the NTN evolution in connection to cellular communications – initially from 1G to 4G – by investigating the central research topics, such as the integration of non-terrestrial and terrestrial networks, the radio resource allocation, and the mobility. This study also highlights the importance of NTN in 5G technology by further focusing on its role toward 6G, and contributes a summary of the current 3GPP research activities in supporting the NTN as part of the 5G NR technology.

Notably, the NTN demonstrates certain unique effects due to its individual characteristics, i.e., long propagation delay, motion of NGSO satellites, and many others. In due course, this work finally elaborates on the main open issues (mobility, propagation delay, and radio resource allocation) with the purpose of understanding future attractive research directions.

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