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Role and Evolution of Non-Terrestrial Networks towards 6G systems

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ABSTRACT Today, the worldwide economy and society are already taking advantage of the first deployments of 5G networks. However, the challenges that will be posed by 2030 networks on the infrastructure, technologies, and performance requirements call for a further leap in mobile communications. To this aim, evolutions of the 5G concepts in 5G-Advanced, and rethinking of future Radio Access Technologies, *i.e.*, 6G which is expected to be the next revolution in the mobile ecosystem, are already being addressed by the scientific and industrial communities. In this framework, as demonstrated by 3GPP Rel. 17 specifications, Non-Terrestrial Networks (NTN) are expected to play a vital role in near and long term mobile communications, based on the joint optimisation of the terrestrial and non-terrestrial components in a unified 3D architecture. In this paper, we extensively discuss the 3GPP normative activities for 5G (Rel. 17), 5G-Advanced (Rel. 18 onward), and 6G (Rel. 20+) in terms of enabling features, architectures and interfaces, and protocols. Then, we explore the evolution of the 5G services towards 5G-Advanced and 6G NTN applications. Finally, we discuss the evolution to 6G network infrastructures with respect to the main performance requirements.

INDEX TERMS Non-Terrestrial Network, 5G-Advanced, 6G, Architecture, 3GPP, Satellite Communications, 3D Infrastructure, Service Requirements, Applications

I. INTRODUCTION

5G networks are already being deployed, with global benefits for the economy and the society. At the end of 2023, 81% of the European population and 96% in the US is covered by 5G networks and, at global level, there are approximately 950 millions subscribers, [1]. The successful deployment of key functionalities, such as end-to-end network slicing and the intensification of the Radio Access Network (RAN) virtualisation, allowed 5G to rapidly develop in the past years, with a major impact in modern life and in the way societies operate in economy, industry, education, entertainment, and logistics & travel. Despite the massive benefits and enhancements already brought by 5G communications,it has been observed that 5G is still neither completely meeting the expected quality for the general public and the industry nor fully addressing the Digital Divide between rural and urban areas. Thus, to fully unleash their potential, 5G-Advanced systems are being defined; moreover, the exploration of uncharted areas that would be part of a future sixth generation technology has already begun, [2]–[4]. It is generally expected that sixth generation (6G) mobile communication systems will emerge around 2030. In early 2018, the International Telecommunication Union Radiocommunication sector (ITU-R) embarked on a programme to study and develop “IMT-2030” (International Mobile Telecommunications 2030), setting the stage for the

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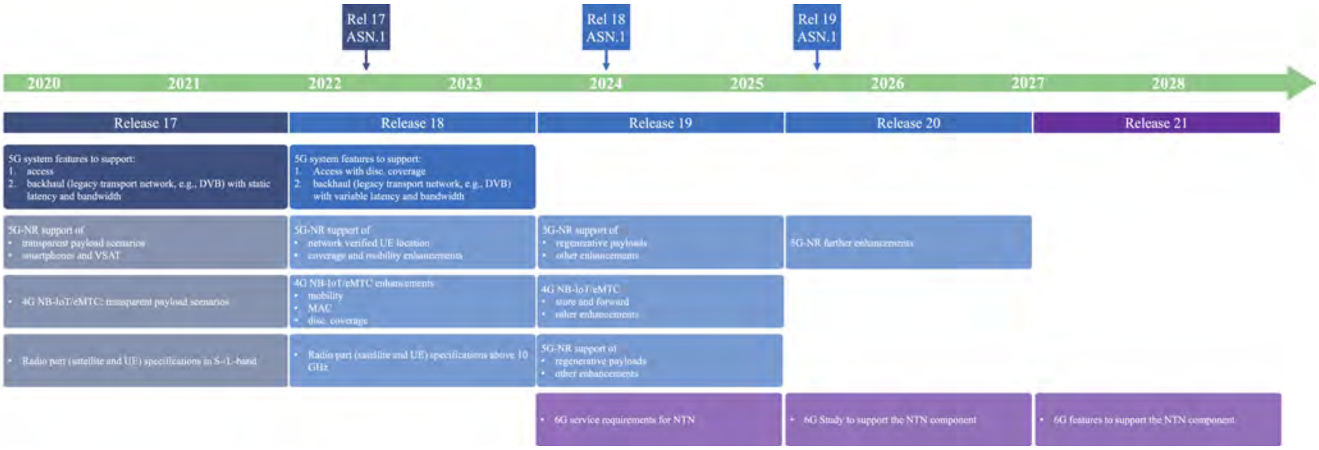


FIGURE 1. 3GPP NTN standardization schedule (including tentative scope for Release 19 and beyond): Work/Study items on NTN.

6G research activities that have since emerged across the world. Between 2018 and 2020, the ITU Telecommunication standardisation sector (ITU-T) Focus Group on Technologies for Network 2030 (FG-NET-2030), established to study the capabilities of networks for 2030 and beyond, developed a preliminary set of target services for IMT-2030, [5]. In 2021, ITU-R Working Party 5D (WP 5D), in charge of the overall radio system aspects of the terrestrial component of IMT systems, started the definition of the IMT-2030 vision, [6].

Future 6G systems are expected to finally achieve the ambitious objective of a fully connected and programmable world, built on the convergence of the physical, human, and digital domains by means of, [7]: i) *Digital Twins* of the systems, leading to the virtualisation of a physical process, product, or service, and allowing to act upon it through tightly synchronised sensors and actuators; ii) *Connected Intelligence*, in which trusted Artificial Intelligence (AI) functions will manage the virtual representations and the global network infrastructure; and iii) *Immersive Communications*, in which Tactile/Haptic Internet, high-resolution images and videos, and other sensory data will be exchanged with high throughput and low latency to provide a fully immersive experience to remote users.

In this framework, it is globally recognised that a non-terrestrial component will play a fundamental role in the unified 6G network infrastructure, [2]–[27]. During the last years, Satellite Communications (SatCom) indeed witnessed a renovated interest, also thanks (but not limited) to the massive industrial efforts to deploy mega-constellations in Low Earth Orbit (LEO), *e.g.*, Amazon Kuiper, OneWeb, and SpaceX Starlink, [26]. The first global mobile-communication standard incorporating a non-terrestrial component by specifying the features enabling the 5G system to support Non-Terrestrial Networks (NTN) appeared in the 3rd Generation Partnership Project (3GPP) Release 17, for which the core part was completed in September 2022 by freezing radio protocol specifications (ASN.1), and the performace part was completed in March 2023, [9]–[13]; these specifications build on the outcomes of the study phase for NTN, performed in Rel. 15 and 16, [28], [29]. This joint effort between stakeholders of both satellite and mobile industries enables the integration of SatCom in the 3GPP ecosystem, with a two-fold benefit: i) the achievement of a truly global service continuity and resiliency, based on the integration of NTN and Terrestrial Networks (TN); and ii) the possibility for SatCom industries to reduce the costs through economy of scale. Moreover, it shall be noticed that, before NTN, there was no inter-operable standard for SatCom; thus, the inclusion of the non-terrestrial component in 3GPP can also yield huge benefits for SatCom industries thanks to the exploitation at the ground segment of equipment coming from different providers. The NTN specifications are also supported by vertical stakeholders (including Public Safety, transportation, automotive, etc.) calling for: i) the seamless combination of satellite and mobile systems; and ii) the support of all 5G features across the access technologies.

As shown in Figure 1, 5G systems with integrated NTN based access are still evolving in 3GPP Rel. 18, for which radio protocol specifications (ASN.1) will be frozen by June 2024, [30]. Further, the content of Release 19 has been defined in December 2023 aiming at freezing the radio protocol specifications (ASN.1) by December 2025. As discussed in this paper, Rel. 19 will introduce several enhancing features for 5G-Advanced NTN, thus paving the way towards 6G technologies. Moreover, to extend the capabilities and enhance the end-user experience compared to 5G, a significant innovation breakthrough in technologies and architectures is needed to prepare for the next generation of mobile communications, 6G, in which the terrestrial and non-terrestrial components will be jointly optimised, rather than integrated. From a standardisation point of view, 6G will start to be discussed in 3GPP in Q2 2024 within the System and System Aspects (SA) Technical Specification Group (TSG).

In addition to the technical standardisation, it is worthwhile mentioning that ITU-R recently concluded the World Radiocommunication Conference 2023 (WRC-23), in which

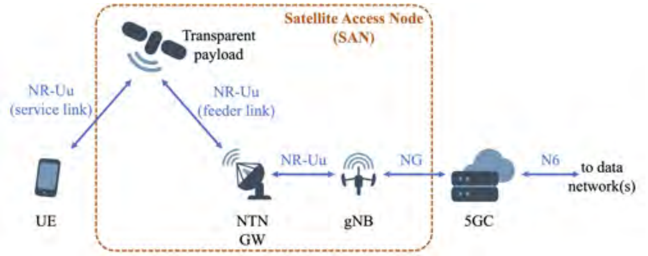


FIGURE 2. NR NTN system based on transparent payload.

several important decisions were approved for terrestrial and non-terrestrial spectrum allocations; moreover, the preliminary action items for the next WRCs (2027 and 2031) have also been approved.

A. PAPER CONTRIBUTION AND ORGANISATION

In this paper, we: i) report an extensive review of the normative work performed within 3GPP Rel. 17 to introduce the NTN component in the 5G ecosystem, including architectures and protocol aspects; ii) provide an overview of the standardisation activities related to the definition of 5G-Advanced and discuss the 6G vision and future system architecture for a unified network infrastructure; iii) extensively discuss the services and applications for 5G via NTN, their enhancement in 5G-Advanced, and the foreseen new capabilities in 6G; iv) discuss the key target requirements that can be expected for 6G communications, both for the unified infrastructure and for the NTN component; and v) report the outcomes of the WRC-2023 for NTN spectrum allocations.

The remainder of this paper is organised as follows: i) Section II reports the normative work in Rel. 17 (5G) and Rel. 18 to 20 (5G-Advanced), including key features, architectures and interfaces, and protocols; ii) in Section III, we introduce the envisioned role of the NTN component in 6G networks; iii) Section IV provides an extensive discussion on the use cases and applications for 5G, 5G-Advanced, and 6G via NTN; iv) Section V reports the key target requirements for 5G, 5G-Advanced, and 6G communications; v) Section VI shows an extensive review of current and planned NTN broadband and IoT service providers; vi) Section VII reports the outcomes of the ITU-R WRC-23 and the planned activities for WRC-27 and WRC-31; vii) finally, Section VIII concludes this work.

II. NORMATIVE WORK FOR 5G AND 5G-ADVANCED

The 3GPP NTN standard has been developed aiming at supporting three general reference scenarios, defined based on the target terminal type, operating band, and platform orbit, [28], [29]. These are outlined in Table 1, where we can distinguish between satellite access networks operating in:

- Frequency Range 1 (FR1), *i.e.*, below 6 GHz, which provide: i) direct wideband connectivity to outdoor handheld terminals and/or car/drone mounted devices, via the 5G NR standard; and ii) direct narrowband connectivity to outdoor Internet of Things (IoT) devices, via the 4G Narrowband IoT (NB-IoT)/enhanced Machine Type Communication (eMTC) standard;
- Frequency Range 2 (FR2), *i.e.*, above 10 GHz, providing indirect broadband connectivity to local access networks via Very Small Aperture Terminals (VSAT) installed on building rooftops or Earth Station In Motion (ESIM) terminals on moving platforms (vehicle, train, vessel, or airplane).

Below, we first report the main features introduced in Rel. 17 to support the NTN component. Then, we discuss the studies that, building on these outcomes, are driving the definition of 5G-Advanced NTN within Rel. 18, 19, and 20. Figure 1 shows the standardisation schedule from Rel. 17 to Rel. 21.

A. NTN FEATURES IN REL. 17: 5G

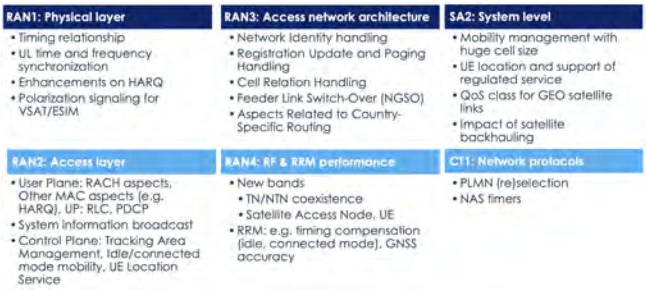
Starting from Rel. 17, three main satellite network solutions have been integrated in the 5G ecosystem, [10]: i) an NR-based satellite access network, in which the non-terrestrial nodes are connected to the 5GC and support the NR access technology; ii) a Long Term Evolution (LTE) based satellite access network, in which the non-terrestrial nodes are connected to the 4G Evolved Packet Core network (EPC) through NB-IoT and eMTC radio access; and iii) satellite backhaul, with a transport network over satellite providing connectivity between the 5GC and the gNB(s), which can be based on 3GPP or non-3GPP radio protocols. Focusing on the NR-based satellite access, the system architecture is based on a transparent payload and an NTN gateway (GW), as shown in Figure 2. The gNB is connected to the User Plane Function (UPF) and Access and Mobility Function (AMF) in the 5G Core network (5GC) for the User Plane (UP) and Control Plane (CP), respectively, through a terrestrial link implementing the NG Air Interface, [31]. Since the NTN payload is transparent and, thus, all radio protocols are terminated at the on-ground gNB, both the feeder and the user links are implemented via the NR-Uu Air Interface. While a single gNB is shown, it is worthwhile mentioning that: i) multiple NTN payloads can be be connected to a single gNB; ii) multiple gNBs can be connected to a single NTN payload.

In essence, the NTN transparent payload acts as a Radio Frequency (RF) repeater, thus forwarding the radio protocols received from the User Equipment (UE) to the gNB and *vice versa*. The service link can be implemented based on: i) Earth-fixed beams, with on-ground beams continuously covering the same geographical area for the entire time, as with Geostationary Earth Orbit (GEO) satellites; ii) Quasi-Earth-fixed beams, in which the beams cover the same area for a period limited to the NTN node visibility, as for LEO satellites with steerable beams; or iii) Earth-moving beams, in which the beams are non-steerable and continuously cover the area below the NTN payload, moving on the Earth's surface along the NTN node movement on its orbit.

The NTN standardisation activities first took into account the peculiar characteristics of satellite networks and channels, such as large time varying Round Trip Delay (RTD),

TABLE 1. Targeted system scenarios defined in the 3GPP NTN standard.

	Direct connectivity (FR1)		**Indirect connectivity (FR2)**
Targeted terminals	IoT devices	handheld (smartphones) and car/drone mounted devices	VSAT and/or ESIM
Service	Narrowband (hundreds of kbps)	Wideband (few Mbps)	Broadband (hundreds of Mbps)
Orbit	GSO and NGSO	NGSO	GSO and NGSO
3GPP Radio Interface	4G NB-IoT/eMTC	5G NR	5G NR
Market	Professional: utilities and agriculture	Consumer Professional: automotive, Public Safety, utilities, agriculture, Defense	Professional: telco (*e.g.*, backhaul), IPTV, SNG, transportation, Public Safety, Defense



RAN1: Physical layer
- Timing relationship
- UL time and frequency synchronization
- Enhancements on HARQ
- Polarization signaling for VSAT/ESIM

RAN3: Access network architecture
- Network Identity handling
- Registration Update and Paging Handling
- Cell Relation Handling
- Feeder Link Switch-Over (NGSO)
- Aspects Related to Country-Specific Routing

SA2: System level
- Mobility management with huge cell size
- UE location and support of regulated service
- QoS class for GEO satellite links
- Impact of satellite backhauling

RAN2: Access layer
- User Plane: RACH aspects, Other MAC aspects (e.g. HARQ), UP: RLC, PDCP
- System information broadcast
- Control Plane: Tracking Area Management, Idle/connected mode mobility, UE Location Service

RAN4: RF & RRM performance
- New bands
  - TN/NTN coexistence
  - Satellite Access Node, UE
- RRM: e.g. timing compensation (idle, connected mode), GNSS accuracy

CT1: Network protocols
- PLMN (re)selection
- NAS timers

FIGURE 3. 3GPP NR-NTN specifications impact.

Doppler effect, and moving cells, identifying the new technological challenges compared to legacy terrestrial systems, [28]. Building on the outcomes of this preliminary assessment, the potential NTN architectures and the challenges, together with the proposed solutions, related to Layer 1 (*e.g.*, PHY/MAC procedures), radio protocols (*e.g.*, mobility and tracking area management), and architectures and interfaces were identified, [29]. The introduced adaptations were aimed at exploiting the NTN links based on SoA space technologies and industrial assets, [9]–[13]. Figure 3 summarises the main enhancements included in Rel. 17 grouped per 3GPP Technical Specification Group (TSG) Working Group (WG). Among them, the following ones are worth to be explored:

- The long propagation delay and Doppler shift impact on the Physical (PHY), Medium Access Control (MAC), and Radio Link Control (RLC) layers related to the uplink timing control, Random Access (RA), Adaptive Coding and Modulation (ACM), and Hybrid Automatic Repeat reQuest (HARQ) procedures. To mitigate such impacts, timing and frequency compensation solutions have been introduced, which exploit the ephemeris information broadcasted by the network and the location estimated by the UEs, equipped with Global Navigation Satellite System (GNSS) capabilities. Thus, to acquire the uplink synchronisation (*i.e.*, in the RA and while connected), the NTN UEs autonomously pre-compensate the Timing Advance (TA) and the Doppler shift. In particular, the TA is computed by considering a UE-specific part (corresponding to the RTD on service link, calculated by the UE based on its GNSS derived position and ephemeris information indicated by the network) and a common part (calculated by the UE using higher layer common TA parameters indicated by the network). Once the UE is in connected mode, it continuously adjusts these parameters based on the ephemeris and valid GNSS information; when such information is not available or reliable, the UE is not allowed to communicate with the gNB until they have been re-acquired. It shall be mentioned that, while the pre-compensation of the instantaneous Doppler shift on the service link is performed by the UE, its management on the feeder link is left to network implementation. Once the synchronisation has been achieved by the UE, the RA procedure can be performed; in this context, enhancements have been included to adjust the reception windows and to resolve the contention/preamble ambiguity. It is worthwhile highlighting that the adjustments on the timing of these procedures also tackle the impact of the large on-ground cells generated by the NTN payload, since they are also related to the differential delays and Doppler shifts in the cell. Finally, to mitigate the impact of HARQ stalling, this procedure can be disabled and/or the number of parallel processes can be increased.
- Mobility management procedures have been adapted so as to take into account the generation of large moving on-ground cells. For UEs in *idle/inactive state*, new measurement rules for the re-selection of the cell supported by location and timing information provided via the System Information Block (SIB) have been introduced in [32]: i) location-assisted cell re-selection is based on the distance between the considered user and the reference cell location, *i.e.*, either the serving cell and/or the neighbouring one; ii) the timing information refers to the time instant in which the serving cell is going to not serve the geographical area anymore. When the UE is in *connected state*, a new location-based measurement event has been introduced to trigger the reporting of the location information at the UE. In addition, conditions upon which the UE can initiate a Conditional Hand-Over (CHO) to a candidate cell have been identified, which include Radio Resource Management (RRM) measurement-based, time-based, and location-based triggers. With respect to handover procedures on the feeder link, new solutions have been

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TABLE 2. NTN operating bands and duplexing mode as per Rel. 17.

Band	UL (UE-to-SAN)	DL (SAN-to-UE)	Duplexing
n256	1980-2010 MHz	2170-2200 MHz	FDD
n255	1626.5-1660.5 MHz	1525-1559 MHz	FDD

introduced in particular for Non-Geosynchronous Orbit (NGSO) systems that shall modify the serving GW due to the platform movement. The feeder link handover is a procedure at Transport Network Layer in which both soft and hard solutions are possible. With respect to the UE location information, it is worthwhile highlighting that, upon a network request and after the security has been established in connected mode, the UE can report a *coarse* location estimation, *i.e.*, the most significant bits in the GNSS coordinates such that an accuracy of approximately 2 km is achieved.

In addition to the above, the RF performance of the payload on the service link have been characterised in L and S bands based on adjacent channel coexistence studies between NTN and TN, [33]. Table 2 reports the NTN bands and the duplexing mode; it shall be mentioned that band n256 is adjacent to the terrestrial NR bands n1 (Frequency Division Duplexing, FDD) and n34 (Time Division Duplexing, TDD) and band n255 is not adjacent to terrestrial bands. In terms of duplexing, it shall be noticed that NTN operates in FDD, due to the large propagation delays that might pose challenges for TDD; however, TDD might be evaluated for LEO or High Altitude Platform Systems (HAPS). TR 38.863 captures the NTN RF requirements in FR1 for the UEs supporting Satellite Access Nodes (SAN) as per TS 38.101-5, [34], and TS 38.108, [35]; a SAN includes the on-ground non-NTN infrastructure gNB functions, the GW, the feeder link, and the RF functions of the NTN payload. In terms of RF performance, it is worthwhile highlighting that: i) an NTN-enabled UE shall satisfy the same requirements as a legacy terrestrial UE; and ii) the SAN shall satisfy less stringent requirements compared to those for TN. Finally, the RF requirements were also defined for HAPS, [36], which is considered as a wide-area base station without additional modifications, allowed to operate in band n1 (1920-1980 MHz on the downlink and 2110-2170 MHz on the uplink). Thus, the UEs already support them without modifications.

Furthermore, new Quality of Service (QoS) indicators (5QI) have been introduced to support the extended latency over satellite access and backhaul, [10].

B. NTN FEATURES IN REL. 18-20: 5G-ADVANCED

While Rel. 17 provided the first global standard incorporating the NTN component into mobile communications, activities are already on-going to define the specifications for NTN in 5G-Advanced systems, *i.e.*, Rel. 18 and 19.

Table 3 reports the list of current Study Items (SI) and Work Items (WI) for Rel. 18. Further enhancements for the NG-RAN based NTN are being developed considering: i) both GSO and NGSO deployments; ii) the evaluation of Earth-fixed tracking areas with fixed or moving cells in NGSO systems; iii) FDD operation for users equipped with GNSS capabilities; iv) VSAT devices, both fixed and on moving platforms, and commercial handheld terminals operating in FR1; and iv) for VSAT only, the support above 10 GHz. Based on these work assumptions, for enhanced Mobile Broadband (eMBB) services via NR-NTN, the SA TSGs are assessing the feasibility of network-based UE location determination and specifying the system enhancements to support discontinuous coverage. Within RAN TSGs, the main focus is currently devoted to: i) coverage enhancements; ii) the deployment of VSAT, fixed and on ESIM, above 10 GHz; iii) NTN-TN and NTN-NTN mobility and service continuity aspects; and iv) network-based UE location. For massive Machine Type Communications (mMTC), the reference standards are the 4G NB-IoT and eMTC. However, for the sake of completeness, it is worth highlighting that the main focus is related to addressing the remaining issues from Rel. 17, supporting discontinuous coverage, and define mobility enhancements.

With respect to Rel. 19, one SI under SA1 recently started on “Study on satellite access - Phase 3” (FS_5GSAT_Ph3). Moreover, preliminary studies at SA level were captured in TR 22.865, [37]. The objectives of this recent SI are to: i) provide support with intermittent/temporary NTN connectivity (*e.g.*, NGSO) for delay-tolerant communications, *e.g.*, serve the UEs in scenarios where there is not a simultaneous feeder link connection to the ground segment; ii) support UEs without GNSS capabilities, which poses challenges related to the location-based procedures outlined in Rel. 17; iii) define positioning enhancements, by performing a gap analysis on the existing requirements in TN and identifying relevant technical and regulatory requirements; and iv) introducing communications between UEs covered by the same satellite. The content of Rel. 19 has been approved in the 3GPP plenary meeting held in December 2023. In particular, the new WI on “Non-Terrestrial Networks (NTN) for NR Phase 3” (NR_NTN_Ph3) defines the objectives for futher NTN enhancements in Rel. 19, [38]:

- Offer an optimised performance to the users, in particular for handheld terminals (including smartphones with a -5.5 dBi antenna gain) on the downlink taking into account NTN deployment constraints, such as payload power limitation, large on-ground footprints, and limited feeder link bandwidth. To this aim, both link and system level analyses will be performed. For the former, the aim si that of improving the link margin of selected PHY channels to accommodate a reduction of the Effective Isotropic Radiated Power (EIRP) in FR1; in addition, a link margin improvement for some PHY channels (such as PDSCH and PDCCH) can be considered without impacting the design of the synchronisation block. As for the latter, the solution might be that of supporting dynamic and flexible power sharing

TABLE 3. NTN Study and Work Items in 3GPP Rel. 18 with TSG lead.

Item	Lead	Title
(WI) NR_NTN-enh	RAN2	Enhancements to Solutions for NR to support non-terrestrial networks (NTN)
(WI) IOT_NTN-enh	RAN2	Enhancements to Solutions for NB-IoT & eMTC to support non-terrestrial networks (NTN)
(WI) 5GSATB	SA1	5G system with satellite backhaul
(SI) FS_5GSAT_Sec	SA3	Study on Security Aspects of Satellite Access
(SI) FS_NR_NTN_netw_verif_UE_loc	RP	Study on requirements and use cases for network verified UE location for NTN in NR
(SI) FS_IOT_NTN	SA5	Study on Management Aspects of IoT NTN Enhancements
(SI) FS_5GET	SA1	Guidelines for extra-territorial 5G Systems (5GS)
(SI) FS_5GSAT_Ph2	SA2	5GC enhancement for satellite access Phase 2
(SI) FS_5GSATB	SA2	Study on satellite backhauling

between beams or different beam pattern/size across the satellite footprint, for both FR1 and FR2. In addition, Beam Hopping (BH) solutions will be addressed, as not all of the NTN beams will be simultaneously active at the nominal EIRP due to on-board power and feeder link bandwidth limitations.

- Offer an optimised capacity performance on the uplink by means of multiplexing techniques. In this case, specifically for LEO systems, a large number of UEs int he coverage area shall successfully send their data while covered by the NTN node, which implies a rapid access to and release of the NTN resources. In this context, it shall be noticed that the spectrum resources might be limited in particular for early NTN deployments. Moreover, some UEs might require more resources, based on their specfic traffic patterns; thus, further granularity for the resource multiplexing might be needed to better tailor the resource allocation to the traffic demand. It nmight also be possible to allocate more resources on a case-by-case basis to the UEs to better support Voice over NR (VoNR) and Voice over IP (VoIP) in coverage-limited scenarios.
- Support NTN architectures with regenerative payloads. NTN architectures with 5G system functions on-board the NTN node provide new options and enhanced flexibility compared to the legacy Rel. 17-18 system based on transparent payloads, inluding benefits in RRM handling and optimisation, as well as the coordination among different gNBs thanks to Inter-Satellite Links (ISLs). Moreover, such feature is needed to support real-time connectivity between two UEs and between the 5GC and the UE via the space segment with/without ISLs. In this context, the specifications for an on-board gNB will be reported in TS 38.300; these will include all the necessary enhancements for intra- and inter-gNB mobility, in particular to support the Xn interface over ISLs or feeder links.
- Introduce Reduced Capability (RedCap) UEs for FR1 NTN. In fact, RF and RRM requirements were defined for RedCap UEs for terrestrial systems in Rel. 17-18, but global coverage would clearly benefit from RedCap devices. The support of RedCap devices (for instance handheld or IoT terminals) operating in FR1 for NTN would offer enhanced service capabilities compared to IoT-NTN while maintaining a limited terminalc complexity. The following analyses will be performed: i) for full duplex FDD RedCap and enhanced RedCap (eRedCap) UEs, define the RF and RRM requirements; and ii) for half duplex RedCap and eRedCap, define whether essential modifications are needed for their support.
- Support Multicast Broadcast Services (MBS), which represent an important added value for NR NTN thanks to its extended coverage compared to terrestrial infrastructures. In some scenarios, it might be expected that the service area is smaller than a typical cell and, thus, enhancements are needed to notify the service area of the broadcast service.

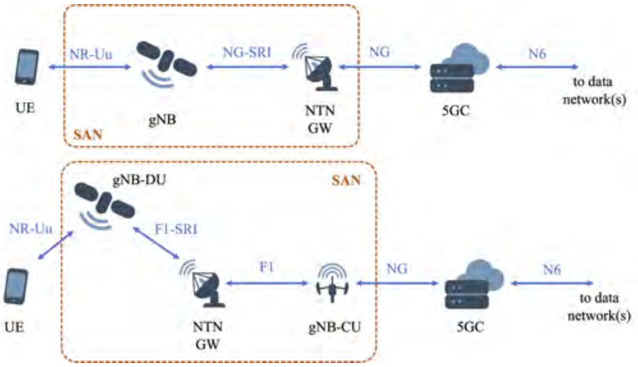

FIGURE 4. NR NTN system based on regenerative payload with (above) and without (below) functional split.

The main assumptions for the Rel. 19 enhancements are in line with those already considered for Rel. 18, *i.e.*: i) GSO/NGSO deployments; ii) Earth-fixed tracking areas with Earth-fixed/-moving NGSO cells; iii) FDD mode; and iv) UEs equipped with GNSS capabilities. In addition, both Type 1 (electronic steering antenna) and type 2 (mechanical steering antenna) terminals are considered. The compatibility for HAPS and Air-to-Ground (ATG) systems is considered as

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FIGURE 5. NR NTN system based on regenerative payload with an on-board IAB-Donor.

FIGURE 6. NR NTN system based on TN-NTN DC: transparent (above) and regenerative (below) payloads.

implicit with the enhancements now being designed, or in any case with a limited impact on specifications.

Figure 4 shows the NTN system with regenerative payloads; differently from the Rel. 17 transparent case, the NR-Uu protocols are terminated on-board and, thus, this Air Interface is only present on the service link. As for the feeder link: i) without functional split, the logical NG interface can be implemented by means of any Satellite Radio Interface (SRI), *e.g.*, DVB-S2X or DVB-RCS2, and the GW basically acts as a Transport Network Layer node; ii) with functional split, the feeder link shall support the connection between the on-board Distributed Unit (gNB-DU) and the on-ground Centralised Unit (gNB-CU) by implementing the logical F1 interface over SRI. Notably, the implementation of regenerative payloads can significantly reduce the over-the-air latency, by terminating all NR-Uu protocols on-board. However, it also increases the system complexity and cost. It shall also be mentioned that the F1 interface is persistent, *i.e.*, it cannot be re-activated on-demand. Thus, in NGSO scenarios, proper solutions shall be identified, as also reported in the above list of studies. Based on the Rel. 19 agreements at the RAN Plenary in December 2023, for the moment being the standardisation effort will focus on deployment scenarios with the full gNB on-board, as this case is expected to be the less impactful in terms of NR-NTN specifications.

In addition to regenerative payloads in Rel. 19, it can be expected that the evolution of NTN in Rel. 20 and beyond will introduce further improvements and architectural enhancements by supporting Integrated Access and Backhaul (IAB) nodes, Multi-Connectivty (MC), and the support of High Power UE (HPUE). With IAB nodes, the UEs do not directly connect to the gNB. This network element was introduced in Rel. 16 as a flexible solution for multi-hop backhauling and to address dense deployment scenarios, minimising the impact on the core network; the IAB architecture is scalable and the only limitation to the number of hops is given by the network performance, [39], [40]. In general, an IAB-Donor acts as a gNB and its DUs can manage other IAB nodes; each IAB-DU is connected to one or more IAB-nodes through the NR-Uu (UP) and F1 (CP) interfaces, which pose the same challenges as in the previous architectures. Figure 5 shows an example of indirect access in NTN with an on-boad IAB-Donor node. One of the advantages of on-board IAB nodes/Donor is that both direct access to the UEs and backhaul connectivity to other IAB nodes can be provided.

FIGURE 7. NR NTN system based on NTN-NTN DC: full gNB (above) and gNB-DU (below) payloads.

The implementation of simultaneous Protocol Data Unit (PDU) sessions in MC for a UE over terrestrial and NTN-based RAN was studied in Rel. 17, but not included in the specifications. In 5G-Advanced, these aspects will be further addressed. Combined operations between TN and NTN, *e.g.*, setting up one NTN and one TN connection in parallel, is not precluded, but it might be challenging due to the significantly different link characteristics, which pose harsh constraints, *e.g.*, on the UP flow control. Current NTN specifications do not support Non-Standalone (NSA) with TN: even Multi Radio Dual Connectivity (MR-DC) and NR-to-NR Dual Connectivity (NR-NR DC) would be challenging. Thus, currently, NSA-based aspects (such as Xn mobility between NTN gNBs and terrestrial gNBs, MR-DC, secondary Radio Access Technology data volume reporting, traces, etc.) have been de-prioritised in 3GPP. Several Xn specifications are not expected to require explicit modifications to the 3GPP specifications for NTN; thus, such support is left for vendor implementation. It is expected the NG-based mobility should work to transition between NTN and TN. Moreover, It is also foreseen that NTN can interact with 5G, 4G, or even 3G terrestrial networks via legacy inter-RAT procedures.

Figures 6 and 7 depict an example of DC with TN-NTN and NTN-NTN access, respectively. As mentioned above, with TN-NTN DC the complexity is extremely challenging due to the need for proper synchronisation and alignment of the transmissions over two very different channels and RATs. In both cases, the Xn interface over SRI is needed to tightly coordinate the master and secondary gNBs. Moreover, the RAN might flexibly select either the NTN or the TN gNB as master node, with the other acting as secondary gNB.

Further enhancements for 5G-Advanced NTN systems will be defined in Rel. 20. The identification of these topics in 3GPP is still to be initiated, as the activities are focusing on the finalisation of Rel. 18 and the beginning of Re. 19 studies.

III. 6G NTN VISION

The specifications in Rel. 17 provide a solid ground for the inclusion of the NTN component in the 3GPP ecosystem, further enhanced in 5G-Advanced; in this context, the studies are on-going in Rel. 18 and the next steps for Rel. 19 have been identified, while Rel. 20 has not yet been addressed. However, on the road to 6G systems, new technologies and capabilities shall be introduced. As shown in Figure 1, 6G specifications are expected from Rel. 20 in terms of service requirements and required adaptations for the NTN component, while only from Rel. 21 the actual specifications will be defined. Thus, below we report a vision of the key elements and the architecture of 6G NTN. It shall be noticed that the proposed vision is based on past and current standardisation and research activities in the framework of international funded projects and 3GPP/ITU-R discussions, but it might evolve based on the global technical discussions.

Taking into account preliminary analyses on the expectations for future 6G infrastructures and networks, it is widely recognised that the unification of the terrestrial and non-terrestrial components will be fundamental, [2], [7], [18], [19], [41]–[44]. In this context, before 5G systems, the TN and NTN components were independently optimised, with a difficult *a posteriori* integration. This paradigm has changed with the advent of 5G NTN, where the objective has been that of optimising the TN and integrating the NTN component with a minimum impact on the UE, RAN, and 5GC while supporting a large range of satellite deployment scenarios, [9]. However, only with 6G the TN and NTN components will be jointly optimised, with native satellite access, in the unified 3D Multi-Dimensional Multi-Layer Multi-Band architecture (MD-ML-MB NTN) shown in Figure 8, [18]. It is worthwhile highlighting that such unified infrastructure is recognised as the future 6G system by both Mobile Network Operators (MNOs) and Satellite Network Operators (SNOs), who are collaborating also in 3GPP to this aim. This will clearly require the definition and design of the Air Interface specifications and the related technologies for the joint TN-NTN optimisation. As such, there will be the need to further improve the flexibility and reconfigurability of the overall system in order to accomodate the different TN/NTN node and channel characteristics. In addition, new business models will be required for both MNOs and SNOs. Such aspects are out of the scope of this work.

The envisioned driving factors for future 6G NTN are:

- *Capacity*: The NTN infrastructure shall be able to adapt the overall capacity of the space segment to its demand, which can be highly dynamic across the service area. When multiple terminals request the same content, broadcast/multicast services for a certain threshold of content bandwidth and service can be envisaged. The use of caching at the network edges could be an advantage for non-real-time traffic. This also requires to adapt the feeder and inter-node links capacity.
- *Sustainability*: The NTN design shall tackle: i) the operation and disposal (*e.g.*, de-orbiting) strategy of the space/aerial segment based on multiple flying nodes to prevent space junks, in-orbit collisions, and impacts on astronomical observations; ii) the carbon footprint minimisation (including the energy consumption) of the network infrastructure, especially the on-ground nodes and terminals; and iii) the compliance with requirements on users' exposure to Electro Magnetic Fields (EMF).
- *Resiliency*: Network resiliency is a key requirement as 6G systems will be the cornerstone of the digital economy. The NTN component is subject to different natural and man-made disasters compared to TNs and, thus, it can improve the overall resiliency by doubling the routing possibilities to support the traffic flow. In addition, in the MD-ML-MB infrastructure, different routing possibilities to support the traffic can be optimised contributing to further increase the system resiliency.
- *Security*: The support of logical slices, each used or operated by different operators, requires high security to prevent eavesdropping and to ensure the traffic integrity. In addition, the integration of the 6G network component in the cloud also requires novel security architectures to protect the storage/computing of data on-board the different flying network nodes, interconnected via temporary wireless links to form a dynamic topology.
- *Reliability*: It shall be possible to guarantee high reliability of the transmission of data in a given time slot by means of further coverage enhancement and/or retransmission techniques such as repetition, interleaving, or power/coding dynamic adaptation.
- *Design to usage*: It is essential to also take into account installation and operational constraints in the design of the terminals served via NTN. The network infrastructure shall be designed to accommodate constraints such as form factor, energy consumption, and usage conditions. Being able to serve directly smartphones in light indoor conditions (*i.e.*, *first wall*) should be considered, although this may imply a reduced QoS. For the automotive and drone markets, the size and form factor of the terminals shall be adapted to the mounting constraints. Finally, fixed terminals shall be designed for self-installation on building rooftops.
- *Co-existence*: Given the global spectrum scarcity, it is necessary to design the NTN component able to co-exist with TNs. Currently, it is not possible to operate TN and NTN over the same frequency in same geographical area in FR1. It would be up to regional/state level regulators to decide on whether a specific spectrum/band shall be used for the TN or NTN network. Cross-border coordination is mandatory, since NTN can cover areas that span different countries. For frequencies above 24 Ghz

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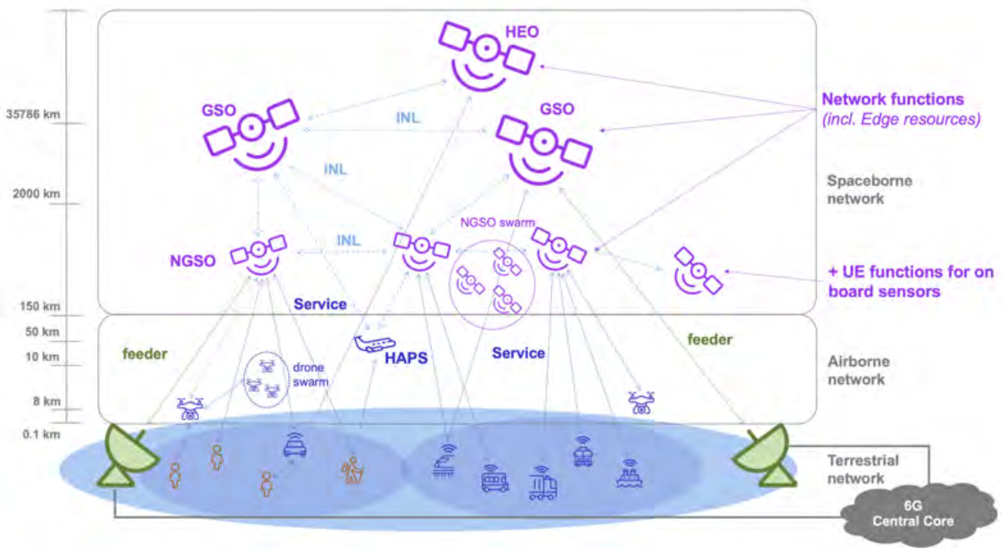

FIGURE 8. Vision of the MD-ML-MB architecture for 6G NTN systems, [18].

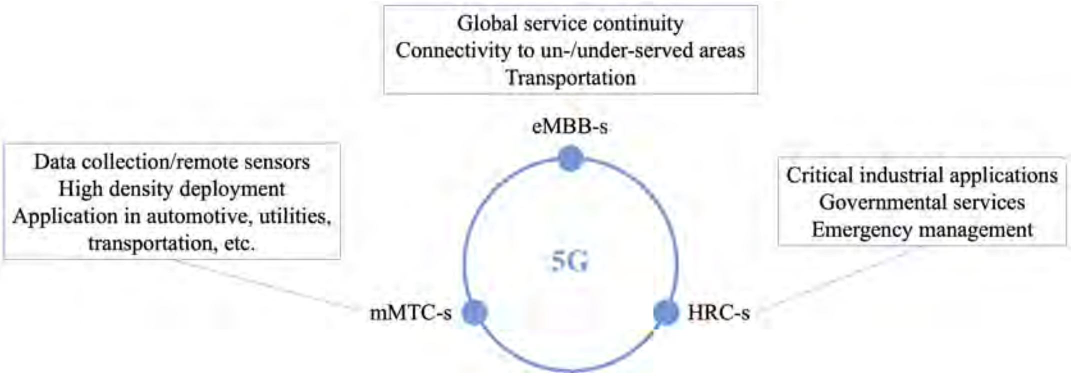

FIGURE 9. 5G NTN use cases based on ITU-R and 3GPP vision for satellite systems.

(FR2), co-existence with some limitations is possible, but it needs further studies. Even if technically possible, studies on the coexistence with adjacent services should be performed by regional regulators. In 3GPP, RAN4 will run coexistence studies on adjacent channels only (NTN-TN and NTN-NTN).

- *Network reconfigurability*: Thanks to edge computing and storage resources on each network node, it will be possible to configure the NTN component to support a given service by optimising the parameters impacting the service, *e.g.*, response delay, bandwidth across the involved wireless links, and/or energy consumption at ground and terminal level.
- *Seamless response time*: In NTN, lower orbits allow to serve the users with a lower latency. Such reduced latency is critical for time-sensitive interactive applications, *e.g.*, gaming and trading, but also internet access. Typically, this deeply penalises GEO networks, for which the RTD exceeds 500 ms. In such context, combining access networks based on GEO nodes with those based on LEO nodes can be beneficial. It allows to benefit from the low latency of LEO systems and from the large bandwidth that may be provided by GEO satellites. This will allow to support a wide range of services characterised by different latency requirements, *e.g.*, eMBB and ultra-Reliable and Low Latency Communications (uRLLC). In this context, it shall be noticed that NTN encompasses both space-borne and air-born nodes. Thus, low latencies might be achieved via NTN as well (for instance, an NTN node at 100 km or 300 km would lead to an over-the-air latency of approximately 0.33 or 1 ms). The actual feasibility will clearly depend on the specific service (*i.e.*, its latency requirements) and system architecture.

It shall be mentioned that the features and technologies listed above will require extensive demonstration and validation before manufacturing and launching the payloads. It might be expected that the envisioned technologies will be available in orbit from 2030, but this will also depend on the manufacturers' business plans, and not just on regulation and standardisation decisions. Providing technical details or preliminary evaluations for the envisioned features is out of the scope of this vision manuscript.

IV. APPLICATIONS AND USE CASES

In this Section, we discuss the services that can be provided via NTN for 5G and 5G-Advanced. Then, we elaborate on the potential services that can be supported in the 6G framework with the support of a non-terrestrial component.

A. 5G NTN

A set of use cases for 5G NTN was initially identified in 3GPP TR 22.822, [45]. Notably, NTN can bring an added value to complement terrestrial RANs for: i) *service continuity*, complementing the 5G services in under-/un-served areas and resolving the "0G" issue, *i.e.*, Digital Divide; ii) *service ubiquity*, improving the service reliability and availability where the TN is unavailable due to natural disasters or man-made attacks, which partially or completely destroyed the terrestrial infrastructure; and iii) *service scalability*, by means of the larger coverage area reached by the NTN elements, which can efficiently provide broadcast and multicast services, as well as off-load traffic from the TN during the peak hours. In addition, ITU-R defined new satellite-based use cases and requirements in Report M.2514, [46], inspired by the use cases identified for terrestrial 5G in [6]. Based on the 3GPP and ITU-R discussions, Figure 9 shows the potential use cases for 5G NTN, including: eMBB via satellite (eMBB-s), mMTC via satellite (mMTC-s), and High Reliability Communications via satellite (HRC-s).

The category of eMBB-s services mainly consists of mass market consumers and enterprise connectivity. In this case, the NTN component aims at complementing the 5G services, supporting high data rate applications in rural and remote areas, *e.g.*, air and maritime environments, and, eventually, in sub-urban areas. The provision of connectivity to ESIM terminals, supporting connectivity at high velocity, is required to meet the requirements for the transport vertical market. However, eMBB-s is not limited to handheld, and it also targets fixed terminals. In particular, 5G aims at addressing global converge with fixed access services (the so called Fixed/Mobile Convergence), justified by the dual role of Mobile Network Operators (MNO) and fixed telcos providers. Benefits clearly appear to make infrastructures and technologies common and fully shared. The topic of convergence between wireline and wireless connectivity has been addressed in Rel. 16, [47]. The eMBB-s services are the natural evolution of the massive usage of 4G for broadband access and, thus, they represented a priority over the other categories due to shorter time-to-market targets.

With respect to mMTC-s, there are many applications that can be provided to IoT/mMTC users by exploiting a NTN RAN. Among these, we can identify:

- *Global NB-IoT/mMTC coverage*, in which the aim is guaranteeing continuous coverage for NB-IoT and mMTC devices for any type of data transfer to/from a central server. This objective can be achieved by deploying a (mega-)constellation of satellites at low orbits. However, even at low orbit, non-delay critical communications shall be considered due to the larger RTD via NTN. As mentioned above, IoT/mMTC terminals on moving platforms can experience a lack of connectivity and, thus, the NTN infrastructure could guarantee global coverage. To allow the service provider to not interrupt its service, the NTN network can either directly provide the service in its coverage area or complement the terrestrial network(s) by means of roaming agreements with the SNO. In this scenario, the 5G system shall be able to select the optimal RAN to provide the required service, when both terrestrial and airborne/spaceborne access are possible.
- *Smart good tracking*, in which the NTN infrastructure through one or more SNOs can guarantee the global and continuous tracking on a moving platform (ship, train, flight, truck) carrying specific goods. The boxes or containers might be equipped with sensors providing: i) the location, as a mandatory parameter; ii) an optional set of data to remotely monitor the assets' status (*e.g.*, temperature). For instance, a cargo flight can be connected to a TN when parked or when taxiing to/from the runway, while relying on NTN during the flight. A similar concept applies to the maritime case, with ships connected to the TN when in a harbour or close to the coast and to the NTN when off-shore. In general, to monitor the assets' status, either each box is equipped with a UE directly connecting to the MNO/SNO or an IAB node collects information from all sensors and reports them through the MNO/SNO.

The HRC-s category covers all scenarios with specific requirements for availability and reliability. Among these, the following are worth to be mentioned:

- *Governmental services*, which mainly cover services and applications under governmental organisations for, *e.g.*, border and event surveillance, traffic management, secure communications, etc.
- *Emergency management*, referring to scenarios in which a natural or man-made disaster fully/partially destroyed the RAN. Notably, guaranteeing a communication infrastructure to the first responders in the area is fundamental to coordinate the search and rescue operations, reporting the emergency evolution to the control center. In such conditions, LEO satellites, HAPS, or drones can promptly provide a communication infrastructure with a limited latency to the first responders; in addition, with a lower priority compared to search and rescue, connectivity can be also provided to the population in the area. In terms of connectivity, the requirements might be heterogeneous, ranging from few hundreds of kbps (*e.g.*, location reports and messaging) to a few tens of Mbps (*e.g.*, Augmented Reality helmets providing live feeds to the control center). A possible network

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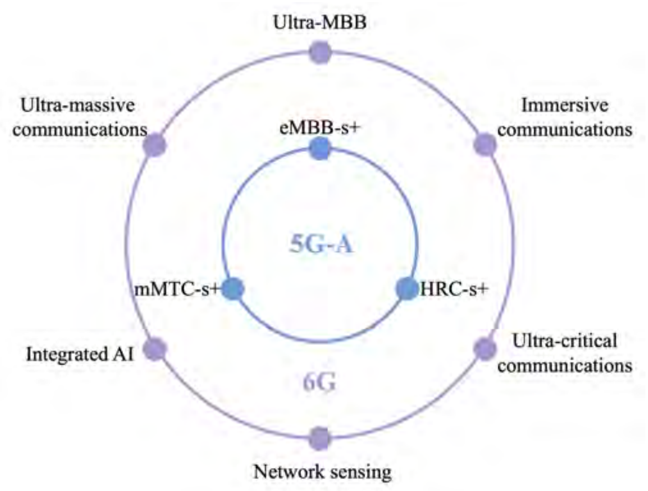

FIGURE 10. Envisioned 5G-Advanced and 6G NTN use cases.

deployment would be that of having drones acting as Access Points (AP) to the network and LEO satellites providing backhaul connectivity to the core network by means of ISLs, if needed. The network would be temporary and, thus, Software Defined Network (SDN) capabilities would be beneficial to optimise coverage, resource allocation (*e.g.*, by exploiting active antennas and beamforming or Multi-Connectivity), and routing in the constellation.

- *Remote control/monitoring of critical infrastructures*, where NTN can provide the communication infrastructure to: i) remote monitoring and control, through HAPS and LEO nodes, of non-time-critical operations, with moderate requirements in terms of capacity and low latency; ii) continuous or on-demand upload (data analytics) and/or download (sensor data for remote analysis), involving large amount of data and no specific restriction on latency; iii) video surveillance with High Definition (HD) video transmission, requiring large capacity and low latency; and iv) on-demand requests of information from the remote control center to the on-site personnel, with variable capacity requirements but no time criticality. To this aim, the 5G system shall support potentially large uplink/downlink data rates via satellite, guarantee a large service availability and reliability, and guarantee a high level of reconfigurability so as to tailor the communication parameters to the different latency and capacity requirements.

B. 5G-ADVANCED NTN

In the framework of 3GPP NTN, it is not expected to introduce novel services for 5G-Advanced. However, the evolution in the technologies, architectures, and techniques will positively impact the 5G applications from a performance perspective; this will lead to improved eMBB-s (eMBB-S+), mMTC-s (mMTC-s+), and HRC-s (HRC-s+) services via satellite, as shown in Figure 10. It is also worthwhile highlighting that 3GPP, since Rel. 14, introduced new features to enable MNOs to provide Multicast and Broadcast Services (MBS) over standardised interfaces. In this framework, characterised by an ever increasing capacity request (*e.g.*, to provide Ultra HD broadcasting), NTN can indeed be beneficial to provide MBS in unserved areas and serve users with the required QoS when the MNO is saturating due to the large traffic requests. Notably, this type of scenario is not only related to the distribution of TV content, but to any type of digital data to be distributed over large geographical areas.

C. 6G NTN

The definition of the first requirements and scenarios for 6G systems is still in its infancy. However, it is expected that such systems will both enhance the 5G and 5G-Advanced use cases (eMBB-s+, mMTC-s+, and HRC-s+) and introduce novel applications for new technologies and capabilities. It shall be noticed that the potential use cases discussed below refer to the unified 3D MD-ML-MB system architecture in which the terrestrial and non-terrestrial components shall be jointly optimised and tailored to provide the required service with the desired QoS. Referring to Figure 10, the 6G use cases can be grouped into the following usage scenarios:

- *Ultra-MBB*, which is the natural evolution of eMBB-s+, aiming at delivering tens of Gbps on-demand and improving the consistency of the users' Quality of Experience (QoE) anywhere. The increased capacity and efficiency will address the human-centric use cases for access to multimedia content, services, and data.
- *Immersive communications*, covering all use cases in which the users will virtually experience fully immersive communications, also including interactions with machine interfaces. Typical use cases might include Holographic Communications (HC) and Augmented/Virtual (AR/VR). In the next decade, network advancements are expected to enable fully immersive user experiences. A key component of the immersive nature of user experience is the transmission of 3D holographic images from one/multiple sources to one/multiple endpoints in an interactive manner. There are a variety of user-device oriented technologies, such as AR/VR via head-mounted display (HMD) devices. However, fully immersive and interactive 3D HC will be a challenge even for future networks. In general, these scenarios have common characteristics with Ultra-MBB services; however, some use cases might require high reliability and low latency as well, for responsive and accurate interactions, *e.g.*, in industrial applications.
- *Ultra-massive communications*, which, extending the mMTC-s+ use cases, is a key enabler for several applications, such as tracking, monitoring and control, and environment sensing for the future *smart world*, *i.e.*, smart cities, agriculture, transportation, logistics, etc. Depending on the specific application, the requirements in terms of data rate, security, and reliability can be quite

diverse, while guaranteeing a connection density further increased compared to 5G.

- *Ultra-critical communications*, including all services with stringent requirements on latency, availability, and reliability. Typical applications can be Tactile/Haptic Internet, remote surgery, and remote industrial management. Tactile Internet is the evolution of IoT, encompassing human-to-machine and machine-to-machine interaction with a variety of real-time interactive control systems applicable to industrial, societal, and business use cases. It adds a new dimension to human-to-machine interactions by enabling transmission of human touch and haptic sensations. This enables humans and machines to interact with their environment, while on the move and within a certain physical range over which communication takes place. Tactile Internet may also revolutionise machine to machine interactions by building upon the next industrial revolution, with the addition of human interactions into the mix. If developed properly, the promise of this combination will be nothing short of revolutionary for how humans learn and work using the Internet. Remote robotic surgery is an example of Tactile Internet, with visual feeds provided using real-time HC streaming technology with adjustments based on whether the surgeon is wearing a HMD device or interacting with a hologram. Real-time feedback (audio, visual/haptic, patient diagnostic) is transmitted back to the surgeon throughout the surgery process. In industrial applications, remote control is enabled using tactile sensors providing kinaesthetic feedback from the machine to the operator. Tactile feedback is augmented with real-time audio-visual information, possibly using holography/VR technologies.
- *Network sensing*, which is one of the two usages denoted as *beyond communications* by ITU-R, [6]. The integration of communication and sensing will play a fundamental role in achieving the envisioned 6G 3D network. Sensing-assisted communications allow to exploit the 6G wireless systems more effectively and realise wide-area multi-dimensional sensing. It will provide beyond-communication spatial-temporal services, such as an increased environmental awareness, imaging, mapping, advanced localisation, tracking and posture/gesture recognition. More specifically, in a 6G NTN network, sensing-assisted communications will enhance the RRM efficiency, *e.g.*, to optimise the resource allocation and use by considering the users' movement trajectories and environmental changes, improve the beam management algorithms, or enhance the network energy efficiency.
- *Integrated AI*, another *beyond communications* scenario in which distributed and integrated AI computation is supported. Today, AI is already impacting every aspect of business and society and it is expected that it will also shape how future communication networks will evolve. Many of the potential 6G use cases assume AI-native services, enabled through a distributed edge architecture with integrated communication and computing capabilities, agnostic to licensed/unlicensed spectrum. Typical applications include, but are not limited to, training and inference for image recognition, creation and prediction through Digital Twins, collaborative robots/cobots for complex tasks, network-assisted automated driving, network 3D ML-MD-MB orchestration, predictions through Digital Twins, as well as intelligent interaction to quickly transfer knowledge and accumulate skills for human and machines. Notably, this category is characterised by large capacity, low latency (for critical applications as in the automotive vertical), and high reliability.

It is worthwhile highlighting that the above services are a vision of what might be provided by unified non-terrestrial/terrestrial 6G networks. During the next years, some use cases not listed above might clearly emerge, even becoming main drivers for the definition of the envisioned ML-MD-MB 6G infrastructure.

V. PERFORMANCE REQUIREMENTS

Similarly to the evolution from 4G to 5G, it is expected that 6G networks will provide significantly improved performance and capabilities. Such Key Performance Indicators (KPIs) will be coupled with the various services described above to identify which of them are more relevant on an application basis. As already mentioned, the definition of the 6G requirements is still on-going; however, in Figure 11 we report a list of potential KPIs, including those provided by 5G systems. With respect to 5G-Advanced, it shall be noticed that there is no explicit definition of their KPIs, nor there will be. It is however expected that they will provide a first performance enhancement before the next technology leap that will be introduced with 6G communications.

In addition to the well-known KPIs reported in Figure 11, it can be expected that new indicators will be required to properly assess the network performance in the new use cases and applications identified in Section IV, [6]:

- *Sensing capability*, to take into account all sensing-related performance, *e.g.*, speed, angle, direction, range, and location.
- *AI capabilities*, to measure the ability of the network element(s) and/or infrastructure to support all AI-related operations, such as data collection, data analysis and preparation, model training and testing.
- *Security and resilience*, to identify the capability of the network element(s) and/or infrastructure to guarantee the information integrity/confidentiality and its robustness to natural disasters or man-made attacks.
- *Sustainability*, to assess the capability of the overall network infrastructure in reducing/limiting the environmental impact.
- *Interface interoperability*, to provide an indication of the flexibility and openness of the different interfaces between the network elements (or within the same network

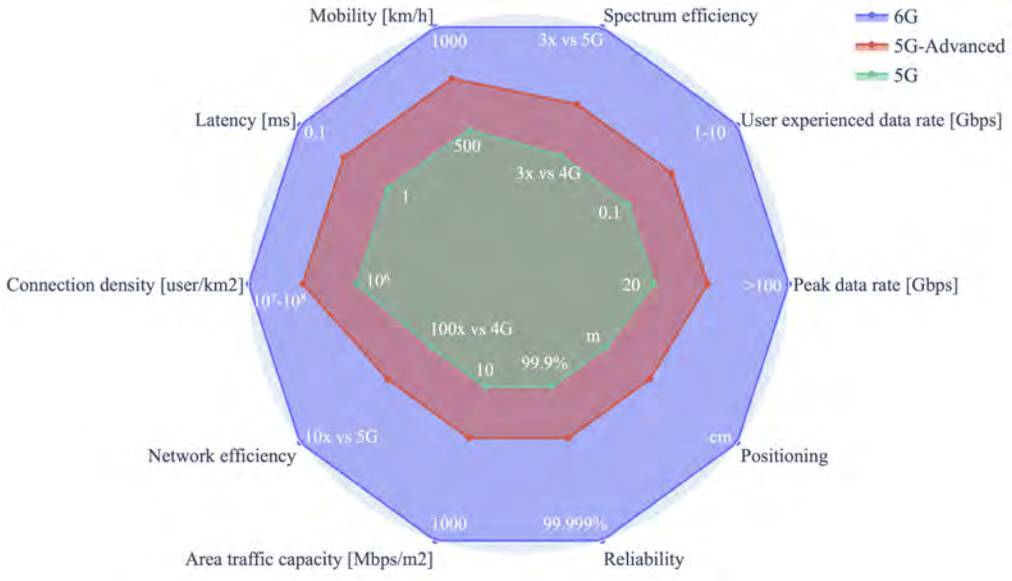

FIGURE 11. Enhancement of key capabilities from 5G to 6G.

TABLE 4. Target performance requirements for 5G-Advanced and 6G NTN. (*HH: handheld.*)

Deployment		Experienced data rate (DL/UL) [Mbps]	Latency (UP/CP) [ms]	Reliability	Posit. error [m]	Posit. acquisition [s]	Speed [km/h]	Connect. density [UE/km^2]
5G-Advanced	HH outdoor	1/0.1	GEO <600/40 MEO <180/40 LEO <50/40	99.99%	<1	<2	3	[100]
	HH outdoor Public Safety	5/5		99.999%	<1	<1	100	[50]
	Mobile platforms and building-mounted VSAT	50/25		99.99%	<1	<2	250	[100]
6G	HH light indoor	1/0.1 (emergency)		99.999%	<0.1	<1	N/A	[100]
	HH outdoor	20/2		99.999%	<0.1	<1	3	[50]
	Vehicle or drone mounted	80/40 (FR1) 300/150 (FR2)		99.999%	<0.1	<1	1000	[100]

element), aiming at a fully seamless inter-system plug-and-play solution.

In addition, it shall be mentioned that other KPIs current being discussed include the waveform efficiency, in terms of the operating point compared to the saturation power, and the coverage, to quantify the capability to provide a given QoS/QoE in the desired service area.

The envisioned KPIs for 6G systems call for the unified 3D ML-MD-MB network architecture introduced in Section III, as neither the terrestrial nor the non-terrestrial components alone will be able to satisfy such challenging objectives. Focusing on the role of NTN in 5G-Advanced and 5G systems, taking into account both the 3GPP normative activities and the industrial interests, the following use cases are deemed to be the most relevant in the medium/long term:

- 5G-Advanced: i) handheld outdoor terminals, for pedestrian users and Public Safety services; ii) VSAT on mobile platforms or building mounted.
- 6G: i) handheld terminals, outdoor or light indoor (first wall) conditions; ii) vehicle/drone mounted terminals.

Table 4 reports the target performance for the above mentioned deployment scenarios. Two important remarks are worthwhile on the identified requirements. First, the values of connection density are in square brackets to highlight that their definition is still on-going and, thus, they shall not be considered as finalised. One critical point is that, depending on the on-ground beam size and the target service area, the number of users to be served by the NTN component might be excessive for both current and near-future payloads. In this framework, the connection density shall be considered as a parameter to be assessed, rather than a target to be achieved. Second, in terms of deployment scenarios involving mobile platforms, the main objective in 5G-Advanced is to enhance NTN to enable platform-mounted IAB nodes. This feature would allow to embark access points on-board the transportation systems, providing backhaul connectivity to the 5GC. Moving to 6G systems, specific installation constraints on car or drones, *e.g.*, volume, shape, form factor, shall be taken into account when designing the connectivity characteristics. It shall be noticed that the values discussed here for 6G NTN

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TABLE 5. Broadband service providers via NTN.

Operator	System (deployed)	Spectrum	Operational	Services
SpaceX Starlink	12000+ (3580)	Ku-band	Yes	Broadband
OneWeb	648 (542)	Ku-band	TBD	Broadband
Kuiper	3236 (0)	Ku-band	est. 2024	Broadband
Galaxy Space	1000 (7)	Q/V-band	TBD	Broadband
Boeing	147 NGSO (1)	V-band	TBD	TBD
Inmarsat	14 GEO (14)	TBD	TBD	Broadband to IoT
Telesat	188 (2)	C/Ku/Ka-band	TBD	Broadband
Echostar	10 GEO (10)	S/Ku/Ka-band	Yes	Broadband
HughesNet	3 GEO (2)	Ka-band	Yes	Broadband
Viasat	4 GEO (4)	Ka-band	Yes	Broadband

systems are based on the expected evolution from 5G/5G-Advanced and on the on-going discussions in the regulation and standardisation fora, which involves some of the authors of this manuscript. As such, they will need to be extensively validated by means of both numerical simulations and Proof of Concepts.

VI. CURRENT AND PLANNED SERVICE PROVIDERS

Today, broadband services are already offered by several NTN operators with proprietary technology, using VSAT/dish antennas as user equipment for the reception of broadband capacity in Ka-/Ku-band. As previously highlighted, most of the focus in early NTN deployments is on the use of GEO and LEO satellites, with the most common approach for GEO satellites to be used for fixed broadband and IoT (*i.e.*, for non-delay-critical services), whereas LEO systems are more attractive for their low delay and better link budget. The main broadband NTN providers are summarised in Table 5; they offer communication services to fixed user devices.

In the ever-evolving landscape of Satellite Communications and NTN, a triumvirate of LEO constellations has emerged as the vanguard of technological innovation. Starlink, OneWeb, and Kuiper, each with their unique aspirations and designs, spearhead the race towards a new era of global connectivity:

- Starlink: At the forefront of LEO constellations, Starlink has etched its name as the preeminent operator with a deployment of an impressive 3580 satellites. The primary mission of Starlink is to bridge the Digital Divide, with a particular emphasis on delivering fixed broadband services to rural areas at global level. In the vast expanse of North America, Starlink achieves commendable throughputs, averaging between 50-100 Mbps on the downlink and approximately 10 Mbps on the uplink. This is made possible through a sophisticated 23-inch diameter dish antenna. Moreover, Starlink goes beyond the ordinary, offering premium services with enhanced throughput, facilitated by a different dish antenna. One of the standout features of Starlink's infrastructure is the mobility of its dish antenna; such mobility is not just enabling seamless roaming capabilities, but it also extends its services to remote entities such as ships and planes. As of today, Starlink has woven a web of connectivity, serving regions spanning the United States, Canada, Australia, New Zealand, Europe, South America, and selected countries in Africa and Asia.
- OneWeb: In the realm of LEO constellations, OneWeb presents a vision of connectivity that extends beyond residential markets. With plans for a constellation comprising 648 LEO satellites, of which 542 were already operational in January 2023, OneWeb's focus lies primarily on catering to businesses and governmental entities. This strategic approach positions OneWeb as a key player in providing broadband services tailored to the unique needs and demands of businesses and government organizations. As the constellation continues to expand, OneWeb aims at redefining global connectivity for enterprises and public institutions.
- Kuiper: Kuiper, the brainchild of Amazon, has set its sights on deploying a formidable LEO satellite system, encompassing 3236 satellites orbiting at an altitude of around 600 km. What sets Kuiper apart is not only its scale, but also its commitment to diverse customer needs, evident in its recently disclosed terminal designs. These innovative terminal designs include a standard customer terminal measuring 11 inches square and 1-inch thick, promising speeds up to 400 Mbps. In addition, an ultra-compact, cost-effective 7-inch square model offers speeds up to 100 Mbps, targeting residential customers and fulfilling the needs of government and enterprise customers with ground mobility and IoT requirements. Lastly, a high-bandwidth design measuring 19 by 30 inches delivers speeds of 1 Gbps, catering to enterprise, government, and telecom applications.

The use of NTN technology has also numerous potential use cases for IoT applications, which can be served from both LEO or GEO satellites, particularly in remote and hard-to-reach areas. For example, precision agriculture systems can leverage real-time data from sensors placed on unmanned aerial vehicles to optimize crop yields and reduce resource waste. Similarly, remote monitoring and control of critical

TABLE 6. IoT/D2D service providers via NTN.

Operator	System (deployed)	Spectrum	Technology	Operational	Services
Dedicated providers					
Starlink SpaceX	2016 LEO (0)	MNO spectrum, 2 GHz MSS	Pre-Rel. 17	2024	messaging voice broadband
AST SpaceMobile	243 LEO (1)	MNO spectrum	Pre-Rel. 17	2024	messaging voice broadband
Lynk	5000 LEO (3)	MNO spectrum	Pre-Rel. 17	2023	messaging low-data rate
Sateliot	250 LEO (1)	2 GHz MSS	Rel. 17 NB-IoT	TBD	NB-IoT
Iridium	66 LEO	L-band	Proprietary	Yes	messaging low-data rate
Orbcomm	31 LEO	137-150 MHz	Proprietary	Yes	assets tracking
GlobalStar	24 LEO	L/S-band	Proprietary	Yes	assets tracking
Ligado	1 GEO	L-band	Rel. 17 NB-IoT	TBD	NB-IoT
Partnerships					
T-Mobile/SpaceX	2016 LEO (0)	MNO spectrum	Pre-Rel. 17	2024	messaging data, voice, video
AT&T/AST	243 LEO (0)	MNO spectrum	Pre-Rel. 17	2024	messaging data, voice, video
Vodafone/AST	100 LEO (0)	MNO spectrum	Pre-Rel. 17	2024	messaging data, voice, video
Verizon/Kuiper	3236 LEO (0)	Ka-band	Proprietary	TBD	ground sites backhaul (LTE and 5G)
Apple/GlobalStar	24 LEO	L/S-band	Proprietary	2022	emergency messaging
MediaTek/Skylo/Bullitt	6 GEO (Inmarsat)	L-band	3GPP NTN	2023	messaging
Skylo/Ligado/Viasat	1 GEO (Ligado)	L-band	3GPP NTN	2023	NB-IoT messaging low-data rate

infrastructures, such as oil rigs, wind turbines, and mining sites, can be made more efficient and secure with the help of NTN-enabled sensors and actuators. Direct-to-Device (D2D) services are also emerging, offering emergency and messaging services with the promise to evolve to higher speeds over LEO networks. With a 3GPP-based NTN solution in Rel. 17 using the sub-2Ghz band spectrum, it is possible to achieve tens of megabits per second speed in the downlink (although this peak speed will be shared among all users in a given cell), as well as a round trip delay in the range of a few tens of milliseconds. With 3GPP Rel. 18, additional spectrum in Ka-band will offer much higher speeds, in the order of hundreds of Mbps, to non-handheld devices using small dish antennas, similar to that offered by SpaceX Starlink. Practical speeds will vary depending on device capability, spectrum utilized, load and antenna sizes. Furthermore, NTN can be used for disaster response and recovery operations by providing reliable and resilient communication links in areas affected by natural disasters. In any of these scenarios the remarkable outcome of satellite D2D is the expansion of coverage for current and future consumer cell phones in hard-to-reach and remote or rural areas, to an extent a terrestrial network cannot achieve.

The main providers for IoT and D2D as of the first half of 2023 are listed in Table 6. Dedicated providers (owners of satellite constellations) are grouped separately from partnerships, but most partnerships rely on at least one dedicated provider. Some of the newer constellation owners (*e.g.*, Starlink, AST SpaceMobile) have not secured their own North American spectrum yet, but plan to initially offer their services through partnerships with MNOs. Emergent dedicated providers seek high numbers of LEO satellites to offer latencies and speeds comparable to those of terrestrial networks. The satellite's ability to reach nearly any point on ground will allow dedicated providers to exploit the market for global NB-IoT, and simultaneously offer limited capabilities to smartphones. Roaming agreements with MNOs can help realising this vision for global connectivity while remaining cost-efficient, thanks to the reduced launch cost. Finally, it is worthwhile mentioning that a partnership between Qualcomm and Iridium for 66 LEO satellites providing messaging services via proprietary technologies was concluded in November 2023.

VII. ITU-R SPECTRUM ALLOCATIONS

During the WRC-23 held in November/December 2023, ITU-R, supported by worldwide delegates, defined all aspects related to the use of spectrum for the next years and drafted the Agenda Items (AIs) for further studies to be addressed in WRC-27 and WRC-31, [48], [49].

In general, important decisions have been taken involving satellite communications and, more in general, NTN, which

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allowed to progress on several fundamental aspects, including, *e.g.*: i) possible new allocations for Mobile Satellite Service (MSS) for direct connectivity between NTN nodes and to end users; ii) L-/S-band allocations for HAPS as IMT base stations (HIBS), also establishing the regulations for their use; and iii) new allocations for provide high-speed Broaband Satellite Service (BSS) to aircraft via NGSO platforms. In addition, there were critical discussions on a proposal to review the Equivalent Power Flux Density (EPFD) limits designed to avoid/limit harmful interference between satellites at different orbits. This proposal was mainly supported by several mega-constellation players that recently entered the NTN market, while SNOs owning GEO platforms were reluctant due to the potential disruption of a stable regulatory environment. The final ITU-R decision reports that EPFD studies shall be performed in the next four years and discussed at WRC-27.

Below, we report the list of the main NTN-related AIs and the corresponding decisions at WRC-23:

- *To consider the use of HIBS in the mobile service in certain frequency bands below 2.7 GHz already identified for IMT, on a global or regional level*. It was agreed that, in all bands, HIBSs have been identified on a non-protection basis, while for the protection of IMT and fixed services, regional groups agreed on the required PFD masks. Moreover, it was agreed to define a HIBS as a *HAPS as an IMT base station operating between 18 km and 25 km*. In terms of allocations, it was agreed that HIBSs can operate: i) in the 698-960 MHz band (or portions of it) in Regions 1 and 2, with reception-only operations in the 694-728 MHz, 830-835 MHz, 805.3-806.9 MHz bands; and ii) in frequency bands 1710-1980 MHz, 2010-2025 MHz, and 2110-2170 MHz in Regions 1 and 3, and bands 1710-1980 MHz and 2110-2160 MHz in Region 2. Bands 1710-1785 MHz in Regions 1 and 2, and band 1710-1815 MHz in Region 3, are limited to reception, while the band 2110-2170 MHz is limited to transmission.
- *To harmonize the use of the frequency band 12.75-13.25 GHz (Earth-to-space) by Earth stations on aircraft and vessels communicating with geostationary space stations in the Fixed Satellite Service (FSS) globally*. It was agreed that the 12.75-13.25 GHz (Earth-to-space) frequency band can be used by Earth Stations In Motion (ESIM), limited to aircraft and vessels, that communicate with FSS GSO satellites.
- *To study and develop technical, operational, and regulatory measures, as appropriate, to facilitate the use of the frequency bands 17.7-18.6 GHz, 18.8-19.3 GHz, and 19.7-20.2 GHz (space-to-Earth) and 27.5-29.1 GHz and 29.5-30 GHz (Earth-to-space) by NGSO FSS ESIM, while ensuring due protection of existing services in those frequency bands*. The responsibility of administrations in case of harmful interference, the minimum requirements for ESIM, and the interference management procedures have been agreed and will be detailed in the updated Radio Regulations (RR) to be published by ITU-R.
- *To determine and carry out the appropriate regulatory actions for the provision of ISLs in specific frequency bands, or portions thereof, by adding an inter-satellite service allocation where appropriate*. It was agreed to enable ISLs operations in Ka-band, in particular in bands 18.1-18.6 GHz, 18.8-20.2 GHz, and 27.5-30.0 GHz. This use is limited to space research, space operations, and/or Earth exploration satellites, but also to the transmission of data originating from industrial and medical activities in space. Frequency bands 18.1-18.6 GHz, 18.8-20.2 GHz, 27.5-29.1 GHz, and 29.5 GHz are limited for ISLs between NGSO satellites or between NGSO and GSO satellites; finally, band 29.1-29.5 GHz is limited for ISLs between NGSO and GSO satellites.
- *To consider a new primary allocation to the FSS in the space-to-Earth direction in the frequency band 17.3-17.7 GHz in Region 2, while protecting existing primary services in the band*. It was agreed that the following frequency bands can be used by NGSO FSS subject to coordination with other NGSO FSS satellites: i) 12.5-12.75 GHz (space-to-Earth) in Region 1; ii) 10.95-11.2 GHz (space-to-Earth), 11.45-11.7 GHz (space-to-Earth), 11.7-12.2 GHz (space-to-Earth), 13.75-14.5 GHz (Earth-to-space), 17.3- 17.7 GHz (space-to-Earth) in Region 2; and iii) 12.2-12.75 GHz (space-to-Earth) in Region 3. In addition, in all regions the following bands have also been allocated: 17.8-18.6 GHz (space-to-Earth), 19.7-20.2 GHz (space-to-Earth), 27.5-28.6 GHz (Earth-to-space), 29.5-30 GHz (Earth-to-space). Finally, it was agreed that, in Region 2, the use of FSS in 17.3-17.8 GHz shall not cause harmful interference nor claim protection from the assignments to BSSs operating in conformity with ITU-R regulations.

In addition to the above decisions, also a preliminary list of studies to be performed for WRC-27 and WRC-31 has been defined. In general, based on the identified studies, it can be observed that there is a significant and increasing interest in Q-/V-band systems, high-speed broadband services via NGSO satellites, and enhancing the flexibility and resources of ISLs to manage the massive constellations currently being deployed. More specifically, for WRC-27: i) studies and regulatory measures on the use of 47.2-50.2 GHz and 50.4-51.4 GHz (Earth-to-space) for aeronautical and maritime ESIMs communicating with space stations in the FSS with GSO and NGSO; ii) possible revisions of sharing conditions in the frequency band 13.75-14 GHz to allow the use of uplink FSS earth stations with smaller antenna sizes; iii) studies relating to the use of 51.4-52.4 GHz by gateway earth stations transmitting to NGSO satellites; iv) possible new primary allocations to the FSS (space-to-Earth) in 17.3-17.7 GHz and BSS (space-to-Earth) in the frequency band 17.3-17.8 GHz in Region 3, and to consider PFD limits to be applied in Regions

1 and 3 to NGSO satellites in 17.3-17.7 GHz; v) technical and regulatory measures for fixed-satellite service satellite networks/systems in 37.5-42.5 GHz (space-to-Earth), 42.5-43.5 GHz (Earth-to-space), 47.2-50.2 GHz (Earth-to-space) and 50.4-51.4 GHz (Earth-to-space) for equitable access to these frequency bands; vi) technical and operational issues, and regulatory provisions, for space-to-space links among NGSO and GSO satellites in 1518-1544 MHz, 1545-1559 MHz, 1610-1645.5 MHz, 1646.5-1660 MHz, 1670-1675 MHz, and 2483.5-2500 MHz allocated to the mobile-satellite service); vii) possible allocations and regulatory actions on MSS in the 1427-1432 MHz (space- to-Earth), 1645.5-1646.5 MHz (space-to-Earth and Earth-to-space), 1880-1920 MHz (space-to-Earth and Earth-to-space), and 2010-2025 MHz (space-to-Earth and Earth-to-space) bands required for the future development of low-data-rate MSS NGSO; and viii) possible new allocations to the MSS for direct connectivity between space stations and IMT user equipment to complement terrestrial IMT network coverage.

With respect to WRC-31, despite the list of AIs will be defined during WRC-27, the following topics have preliminarily been identified: i) aeronautical and maritime ESIMs communicating with NGSO in 12.75-13.25 GHz; and ii) ISL allocations in 3700-4200 MHz and 5925-6425 MHz, and associated regulatory provisions, to enable links between NGSO and GSO satellites.

VIII. CONCLUSIONS

In this paper, we provided an extensive overview of the normative activities for 3GPP NTN, spanning from the consolidated Rel. 17 specifications to the on-going activities for 5G-Advanced (up to Rel. 20) and the expected studies that will target 6G (Rel. 21+). In this context, we also discussed the envisioned 3D Multi-Layer Multi-Orbit Multi-Band architecture for future 6G, providing a full and harmonised unification of the terrestrial and non-terrestrial network infrastructures. Current 5G services via satellite, eMBB-s, mMTC-s, and HRC-s have been discussed and a vision on their enhancement in 5G-Advanced and novel services in 6G systems has been detailed. In 6G, a significant breakthrough in technologies and architectures will lead to the creation of a fully connected world around the following concepts: i) digital twinning of systems, with sensors and actuators that can tightly synchronise the domains to achieve digital twins of cities, factories, or even our bodies; ii) connected intelligence, with the network serving as the key infrastructure with trusted AI functions managing virtual representations in the digital domain; and iii) immersive communications, where high-resolution visual/spatial, tactile/haptic, and other sensory data can be exchanged with high throughput and low latency to create an immersive experience of being somewhere else. In addition, we extensively discussed the target KPIs for 5G-Advanced and 6G, both in terms of the global 6G network and for the NTN component. In this respect, it is worthwhile highlighting that, in addition to the enhancements on legacy KPIs, new ones shall be introduced to properly assess the 6G capabilities, *i.e.*, sensing, native AI, security and resilience, sustainability, interface interoperability. To provide a complete and extensive view of the status and plans for NTN systems, we finally discussed the broadband, D2D, and IoT providers via NTN and the most relevant decisions for NTN from the ITU-R WRC-23, as well as the preliminary action items for WRC-27 and WRC-31.

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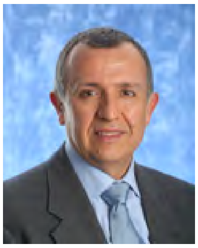

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