IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 23, 2022, accepted March 16, 2022, date of publication March 25, 2022, date of current version April 5, 2022.

*Digital Object Identifier 10.1109/ACCESS.2022.3162243*

# LEO Satellites in 5G and Beyond Networks: A Review From a Standardization Perspective

**TASNEEM DARWISH[1], (Senior Member, IEEE), GUNES KARABULUT KURT[2], (Senior Member, IEEE), HALIM YANIKOMEROGLU[1], (Fellow, IEEE), MICHEL BELLEMARE[3], AND GUILLAUME LAMONTAGNE[3]**

[1]Department of Systems and Computer Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada
[2]Poly-Grames Research Center, Department of Electrical Engineering, Polytechnique Montréal, Montréal, QC H3T 1J4, Canada
[3]Division of Satellite Systems, MDA Space, Sainte-Anne-de-Bellevue, QC H9X 3R2, Canada

Corresponding author: Tasneem Darwish (tasneemdarwish@sce.carleton.ca)

This work was supported in part by MDA Space, and in part by Mitacs Canada.

**ABSTRACT** Low Earth Orbit (LEO) Satellite Network (SatNet) with their mega-constellations are expected to play a key role in providing ubiquitous Internet and communications services in the future. LEO SatNets will provide wide-area coverage and support service availability, continuity, and scalability. To support the integration of SatNets and terrestrial Fifth Generation (5G) networks and beyond, the satellite communication industry has become increasingly involved with the 3rd Generation Partnership Project (3GPP) standardization activities for 5G. In this work, we review the 3GPP standardization activities for the integration of SatNets in 5G and beyond. The 3GPP use cases of SatNets are highlighted and potential requirements to realize them are summarized as well. The impacted areas of New Radio (NR) are discussed with some potential solutions. The foreseen requirements for the management and orchestration of SatNets within 5G are described. Future standardization directions are discussed to support the full integration of SatNets in Sixth Generation (6G) with the goal of ubiquitous global connectivity.

**INDEX TERMS** LEO satellites, satellite networks, 3GPP standards, 3GPP use cases.

## ABBREVIATIONS

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project. |
| 5G | Fifth Generation. |
| 5G | PPP 5G Infrastructure Public Private Partnership. |
| 5G+ | Fifth Generation and Beyond. |
| 6G | Sixth Generation. |
| ACM | Automatic Coding and Modulation. |
| AEEC | Airlines Electronic Engineering Committee. |
| AI | Artificial Intelligence. |
| ARQ | Automatic Repeat Request. |
| BSS | Broadcast Satellite Service. |
| CA | Carrier Aggregation. |
| CCSDS | Consultative Committee for Space Data Systems. |
| CP-OFDM | Cyclic Prefix - Orthogonal Frequency Division Multiplexing. |
| CT | Core Network and Terminals. |
| DC | Dual-Connectivity. |
| DL | Downlink. |
| ECC | Electronic Communication Committee. |
| eMBB | Enhanced Mobile Broadband. |
| ENI | Experiential Networked Intelligence. |
| ESIM | Embedded SIM. |
| ETSI | European Telecommunications Standards Institute. |
| FDD | Frequency Division Duplex. |
| FSS | Fixed Satellite Service. |
| GEO | Geosynchronous Earth Orbit. |
| gNB | 3GPP 5G Next Generation Base station. |
| gNB-CU | gNB Centralized Unit. |
| gNB-DU | gNB Distributed Unit. |
| HAPSs | High Altitude Platform Systems. |
| HARQ | Hybrid Automatic Repeat Request. |
| HEO | Highly Eccentric Orbiting. |
| IAB | Integrated Access Backhaul. |
| IETF | Internet Engineering Task Force. |
| IIoT | Industrial Internet of Things. |
| INGR | International Network Generation Roadmap. |

The associate editor coordinating the review of this manuscript and approving it for publication was Shagufta Henna.

| | |
|---|---|
| IoT | Internet of Things. |
| IP | Internet Protocol. |
| ISG | Industry Specification Group. |
| ISL | Inter-Satellite Links. |
| ITU | International Telecommunication Union. |
| LEO | Low Earth Orbit. |
| M2M | Machine-to-Machine. |
| MANO | Management and Orchestration. |
| MDT | Minimization of Drive Test. |
| MEC | Mobile Edge Computing. |
| MEO | Medium Earth Orbit. |
| MIMO | Multiple-Input Multiple-Output. |
| MIPv6 | Mobile Internet Protocol version 6. |
| ML | Machine Learning. |
| MPTCP | Multi-Path TCP. |
| MR-MC | Multi-Radio/Multi-Connectivity. |
| MSS | Mobile Satellite Service. |
| mWT | Millimeter Wave Transmission. |
| NFV | Network Function Virtualization. |
| NGSO | Non-Geostationary Orbiting. |
| NICT | National Institute of Information and Communication Technology. |
| NIN | Non-IP Networking. |
| NR | New Radio. |
| NR-Uu | New Radio Uplink Unicast. |
| NTN | Non-Terrestrial Network. |
| OSM | Open Source MANO. |
| PAPR | Peak-to-Average Power Ratio. |
| PMIPv6 | Proxy Mobile Internet Protocol version 6. |
| PRACH | Physical Random Access Channel. |
| PT-RS | Phase Tracking Reference Signal. |
| QoE | Quality of Experience. |
| QoS | Quality-of-Service. |
| RAN | Radio Access Network. |
| RAR | Random Access Response. |
| RAT | Radio Access Technology. |
| RIS | Reconfigurable Intelligent Surfaces. |
| RLC | Radio Link Control. |
| RTT | Round Trip Time. |
| SA | Service and System Aspects. |
| SatNet | Satellite Network. |
| SCTP | Stream Control Transmission Protocol. |
| SDN | Software Defined Network. |
| SEN | Self-Evolving Network. |
| SI | Study Item. |
| SNR | Signal-to-Noise Ratio. |
| SONs | Self-Organizing Networks. |
| SPS | Semi-Persistent Scheduling. |
| TA | Tracking Area. |
| TCP | Transmission Control Protocol. |
| TDD | Time Division Duplex. |
| TSG | Technical Specification Group. |
| TTI | Transmission Time Interval. |
| UAV | Unmanned Aerial Vehicle. |
| UDP | User Datagram Protocol. |
| UE | User Equipment. |
| UL | Uplink. |
| URLLC | Ultra-Reliable Low-Latency Communication. |
| VNF | Virtualized Network Function. |
| VSATs | Very Small Aperture Terminals. |
| WI | Work Item. |
| WLAN | Wireless Local Area Network. |
| WRC | World Radio Conference. |
| XR | Extended Reality. |

## I. INTRODUCTION

The exponential growth of the number of connected smart devices, the ever-increasing demand for new services with stringent Quality-of-Service (QoS) requirements, and the need for continuous connectivity everywhere are creating difficult-to-meet challenges for the terrestrial telecommunication sector. Ericsson Mobility Report [1] estimated that there will be 3.5 billion 5G subscriptions by the end of 2026. Moreover, smart cities, intelligent transportation systems, and automated industrial sites will involve billions of sensors and devices that will create a huge traffic load on terrestrial communication networks and that will require continuous coverage with efficient mobility support. In this context, satisfying all user requests and providing the desired QoS anytime and anywhere—even when traveling on cruises, high-speed trains, and airplanes—are two of the main challenges for future telecommunication systems.

Satellite communication networks consist of spaceborne platforms which include Geosynchronous Earth Orbit (GEO) satellites, Medium Earth Orbit (MEO) satellites, and LEO satellites. During the past few years, a growing interest is witnessed in broadband provisioned by LEO satellite networks (SatNets) with large satellite constellations (e.g., Kuiper, Starlink, OneWeb, and Lightspeed). With their capacity to form networks among satellites, LEO SatNets will play a significant role in future integrated networks. This new satellite architecture will revolutionize traditional communication networks with its promising benefits of service continuity, wide-area coverage, and availability for critical communications and emerging applications (e.g., Internet of Things (IoT) devices/Machine-to-Machine (M2M), and intelligent transportation systems), and enabling network scalability.

In the history of telecommunications, satellites and terrestrial networks have always been considered two independent ecosystems, and their standardization efforts have proceeded independently of each other. To benefit from the market potential of integrating satellite networks into the 5G ecosystem, the satellite communication industry showed a growing participation in the 3GPP standardization work for 5G.

Mainly, 3GPP covers cellular telecommunications technologies, including radio access, core network, and service capabilities, which provide a complete system description for mobile communication systems. 3GPP unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), which produce the reports and global technical specifications that define 3GPP technologies. Besides its main role in 5G, 3GPP is a leading standardization body that addresses the aspects related to the integration of satellites access in 5G networks. Therefore, in this review, we focus on 3GPP standardization activities that aim to integrate satellite access in 5G networks.

3GPP classifies satellites as part of the Non-Terrestrial Network (NTN), which is considered as a complement to the terrestrial networks. As defined by 3GPP, an NTN is a network where spaceborne platforms (i.e., GEO, MEO, LEO satellites) or airborne platforms (i.e., High Altitude Platform Systems (HAPSs) [2]) act either as a relay node or as a base station. However, satellites have been the focus of 3GPP NTN work, whereas HAPSs are considered a special case of a satellite system. Although Unmanned Aerial Vehicle (UAV) constitute a part of airborne networks, their standardization has a separate track in 3GPP. In this survey the focus is on satellites in the context of 5G and beyond (i.e., 5G+).

In Release 14, 3GPP started to consider satellite communications in a study on scenarios and requirements for next generation access technologies [3]. In subsequent releases (i.e., Releases 15, 16, and 17), 3GPP considered satellite communication networks from several aspects, such as NR, architectures, use cases, scenarios, management, and orchestration. This survey comprehensively reviews the works on the standardization of satellite communication networks with a focus on 3GPP activities.

### A. MOTIVATION AND CONTRIBUTIONS

In the literature, there are several reviews and surveys on satellite systems. Table 1 provides a comparative overview of the existing surveys that discuss standardization efforts in the area of SatNets. The most common topic among existing surveys is the different 3GPP architectures for 5G with satellite access. Nevertheless, the discussion on SatNet related 3GPP standardization therein is just touching the surface as exiting surveys objective is to give a broad view of the SatNet state-of-the-art. In contrast, this review aims to present a dedicated and comprehensive review of the 3GPP standardization work in the area of SatNets. The scope of this review spans across several areas, from services and system aspects to radio access network. Regarding the contributions, this work:

- Provides a comprehensive survey of the 3GPP standardization activities in the area of satellite networks and communication from Release 14 to Release 18.
- Highlights the 3GPP use cases for satellite access in 5G and their applications.
- Discusses the required adaptation of NR for SatNets from the 3GPP perspective.
- Summarizes the potential requirements for the management and orchestration of integrated satellite components in a 5G network.
- Presents an overview of standardization efforts from organizations other than the 3GPP.
- Discusses future directions to be taken in standardization efforts for 6G satellite communication networks.

### B. PAPER ORGANIZATION

The remainder of this paper is organized as follows. Section II gives a brief description of the satellite access network elements and highlights the characteristics of satellite networks from the perspective of 3GPP. Section III gives an overview of 3GPP standardization activities with respect to satellite networks. Section III-B describes the satellite access networks use cases in the context of 5G. The architectures of integrated satellite access networks and 5G networks are presented in Section IV. Section V discusses the adaptation of the New Radio for satellite networks. In particular, subsection V-A specifies the constraints associated with satellite networks and subsection V-B highlights the NR impacted areas and their potential solutions. Section VI sheds the light on the management and orchestration aspects of 5G networks with integrated satellite access components. The activities of the non-3GPP standardization organizations are discussed in Section VII. Section VIII highlights important standardization directions that are required for the full integration of satellite networks with 6G networks. Section IX draws the essential conclusions.

## II. SATELLITE ACCESS NETWORK ELEMENTS AND CHARACTERISTICS IN 3GPP STANDARDIZATION

Due to the wide service coverage of SatNets and their reduced vulnerability to natural disasters and physical attacks, the 3GPP sought to define the expected role of SatNets in 5G+ through the following points in TR 38.811 [10]:

- Provide 5G service in unserved areas that cannot be covered by terrestrial 5G networks (e.g., isolated and remote areas, on aircrafts and ships) and underserved areas (e.g., suburban and rural areas).
- Upgrade the performance of limited terrestrial networks in a cost-effective manner.
- Support the reliability of 5G service by providing service continuity for M2M/IoT devices or for passengers on-board moving platforms and ensuring service availability anywhere, especially for critical communications and railway, maritime, and aeronautical communications.
- Enable 5G network scalability by providing efficient multicast and broadcast resources for data delivery towards the network edges or even user terminal.

As mentioned in 3GPP TR 38.811, satellite access networks consist of the following elements [10]:

- User Equipment (UE) or a specific terminal to the satellite system in case the satellite doesn't serve UEs directly.
- A service link which is the radio link between the UE and the space platform.
- A space platform carrying a payload which may have one of these two configurations:
  - A bent-pipe payload that performs radio frequency filtering, frequency conversion, and amplification.

**TABLE 1.** Comparison of existing survey papers.

| Reference | Discussion of 3GPP activities Releases 15, 16, 17 | Discussion of 3GPP activities Release 18 | Summary of other standardization organization activities | Impacted areas of NR in integrated 5G SatNet | Management Orchestration of SatNet | 3GPP Satellite Use cases | Architectures |
|---|---|---|---|---|---|---|---|
| [4] | Focused on 15 & 16 | No | No | No | No | No | Yes |
| [5] | No | No | No | No | No | No | No |
| [6] | Yes | No | No | Focused on three areas only | No | No | Yes |
| [7] | No | No | No | Focused on two areas only | No | No | Yes |
| [8] | Yes | No | No | No | No | No | Yes |
| [9] | Very brief | No | No | No | No | Yes | Yes |
| Our work | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

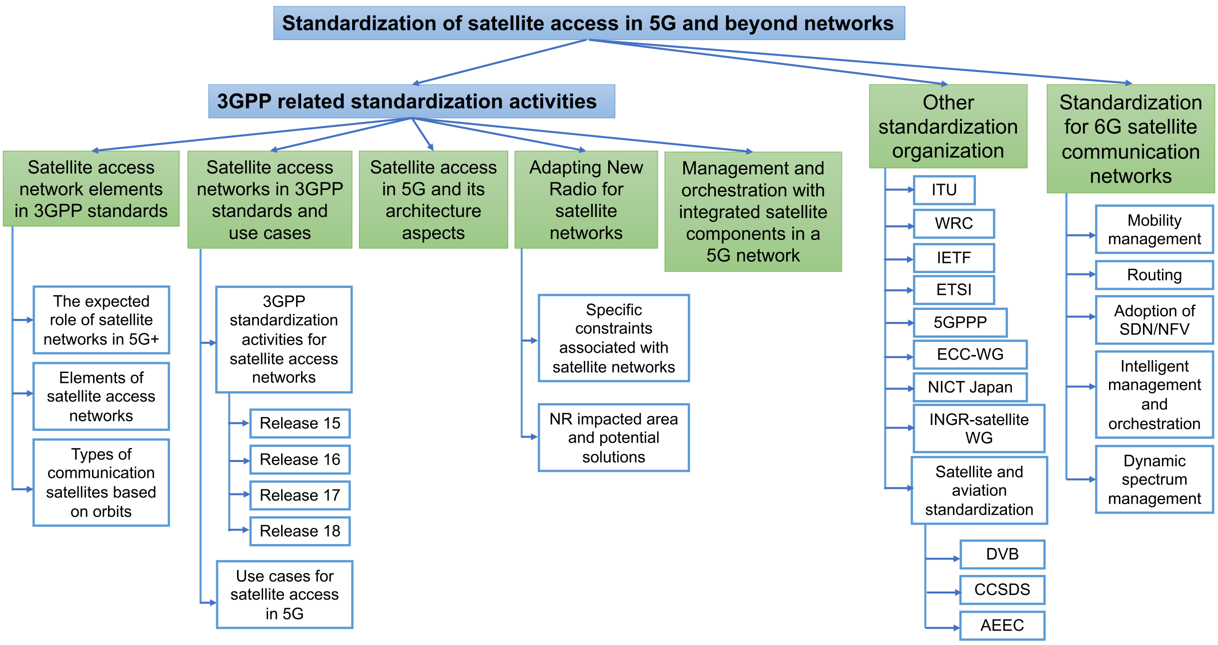



**FIGURE 1.** Paper organization (main sections appear in green boxes).

  – A regenerative payload offering radio frequency filtering, frequency conversion, and amplification as well as demodulation and decoding, switch and/or routing, coding and/or modulation. It is equivalent to how a base station functions (e.g., 3GPP 5G Next Generation Base station (gNB)) on-board a satellite.

- Inter-satellite links (ISLs) in case of a regenerative payload and a constellation of satellites. An ISL may operate in RF frequency or optical bands.
- Gateways that connect the satellite access network to the core network.
- Feeder links which refer to the radio links between the gateways and the space platform.

In 3GPP TR 22.822 [11] communication satellites are classified into the following four types based on their orbits:

- Along the Equator plane at an altitude of 35,786 km GEO satellites are located. A GEO satellite can provide continuous coverage as its orbiting speed is synchronised with the earth's rotation.
- Non-Geostationary Orbiting (NGSO) satellites which do not stand still with respect to the earth. A number of satellites (a constellation) is required to provide service continuity over time. At lower altitudes a larger number of satellites is required. The main types of NGSO satellites are the following:
  – LEO satellites, at altitudes ranging from 500 km to 2,000 km, and with orbital plane inclination angles ranging from 0 up to 180 degrees (prograde and retrograde orbits). These constellations are located below the first Van Allen belt and above the International Space Station and debris.
  – MEO satellites, at altitudes ranging from 8,000 to 20,000 km. The orbital plane inclination angles range from 0 up to 180 degrees (prograde and retrograde orbits). The MEO constellations are located above the Van Allen belts.
  – Highly Eccentric Orbiting (HEO) satellites, with operational altitudes ranging between 7,000 km and more than 45,000 km. The inclination angle is selected so as to compensate, completely or partially, for the relative motion of the earth with respect to the orbital plane, allowing the satellite to

cover successively different parts of northern land masses (e.g. Western Europe, North America, and Northern Asia).

## III. OVERVIEW OF SATELLITE ACCESS NETWORK 3GPP STANDARDIZATION AND USE CASES

From the early stage of 5G standardization activities, 3GPP considered the integration of satellite systems to be a valuable asset to complement and integrate terrestrial NR networks. Therefore, several Study Items (SIs) and Work Items (WIs) were initiated within the Technical Specification Group (TSG) of the Radio Access Network (RAN), the Service and System Aspects (SA), and the Core Network and Terminals (CT).

As an extension to terrestrial networks, satellites were first mentioned in a deployment scenario of 5G in 3GPP TR 38.913 Release 14. This was to provide 5G communication services for areas where terrestrial coverage was not available and also to support services that could be accessed more efficiently through satellite systems, such as broadcasting services and delay-tolerant services. In 3GPP TS 22.261 Release 15, "Service requirements for next generation new services and markets," the first analyses that described the significant role that satellites could play in 5G systems were provided. However, the focus of TS 22.261 was on satellites in NR for industrial and mission critical services.

The increasing interest in integrating satellites with 5G led to the definition of NTNs by 3GPP. Although NTNs include other aerial systems (e.g., HAPSs), the 3GPP community considers satellites as the main case and other aerial systems as a special case of satellites. Release 16 is frozen and Release 17 is still open with an expected deadline on December 2021. Release 17 is working on NTNs for 5G systems, which adopt satellites to support underserved areas (e.g., isolated and remote areas, onboard aircrafts and vessels). Obviously, satellite access networks are becoming an integral part of the 3GPP standardization activities of 5G and beyond networks. Following the 3GPP satellite related activities is important for industry and academia. Therefore, this section focuses on highlighting the satellite related activities in 3GPP Releases 15, 16, 17, and 18.

### A. 3GPP STANDARDIZATION ACTIVITIES FOR SATELLITE ACCESS NETWORKS

Through Releases 15, 16, 17, and 18, 3GPP launched several standardization activities to support the integration of 5G terrestrial networks and SatNets. The following points summarizes the 3GPP standardization activities related to satellites:

- Release 15: In 2017, two SIs were initiated: (1) 3GPP TR 38.811 "Study on NR to support Non-Terrestrial Networks" under the RAN TSG; and (2) 3GPP TR 22.822 "Study on using Satellite Access in 5G" under the SA TSG. The first SI aimed to define the NTN deployment scenarios and their system parameters as well as to identify the required NR adaptation to accommodate NTNs. Also preliminary solutions were introduced to address the impacted areas of NR. Although the second SI was initiated in 2017, it was moved to Release 16.
- Release 16: The SA TSG had four activities: (1) an SI on "Study on using satellite access in 5G" [11]; (2) an SI on "Study on architecture aspects for using satellite access in 5G" [12]; (3) a WI on "Integration of Satellite Access in 5G" (WI#800010-5GSAT, Release 16); and (4) an SI on "Study on management and orchestration aspects with integrated satellite components in a 5G network" [13]. The first and second SIs introduced a number of use cases on utilizing satellite-based access components for service provisioning in 5G. This led to identifying corresponding modified or new requirements related to connectivity, roaming, QoS, UE, security, and regulatory. Finally, the most critical issues (and potential solutions) related to the orchestration and management of 5G with integrated satellite components were addressed in [13]. With respect to the NR 3GPP activities the SI "Solutions for NR to support Non-Terrestrial Networks (NTN)" [14] was completed at the end of 2019. This SI completed the work that was initiated in Release 15 [10]. A set of required adaptations to enable NR technologies and operations in satellite networks were addressed, covering several issues in RAN1 (Physical layer), RAN2 (Layer 2 and 3), and RAN3 (Interfaces).
- Release 17: Work on the SI entitled "Study on architecture aspects for using satellite access in 5G" [12] continued and was last updated in March 2021. By the end of 2019, two WIs for NTNs had been initiated: (i) "Solutions for NR to support NTN" [14], under RAN activities; and (ii) "Integration of satellite components in the 5G architecture" [15], under SA. For the former, the activities are in the final stage and it was last updated on June 2021. However, the objective is the following points: (i) identification of how the physical layer is impacted and proposing potential solutions; (ii) evaluating the NR performance in certain deployment scenarios (GEO based satellite access, LEO based satellite access) through simulations of system level (cell) and link level (radio link); and (iii) Specifying the upper layers potential requirements for each of the considered architectures. The goal of the latter WI was to extend the analysis provided in [12] through the following: (i) identification of impacted areas in NR systems due to the integration of satellite components in 5G; (ii) analysis of the issues related to the interaction between the core network and the RAN; and (iii) identification of solutions for the two highlighted use cases (terrestrial and satellite network roaming and 5G fixed backhaul). Several areas were considered, such as network discovery and selection and network slicing. For Release 17, the freeze of the RAN1 physical layer specifications is scheduled to be in December 2021. This is to be followed by the Stage 3 freeze (RAN2, RAN3 and RAN4) by March 2022 and

the ASN.1 freeze and the performance specifications completion is planned for September 2022 based on the timeline agreed back in December 2019.

- Release 18: The June 28 – July 2, 2021 Workshop on Release 18, which is the start of 5G-Advanced, is to specify the topics of Release 18 with submissions divided into three areas (preliminary agenda): Enhanced Mobile Broadband (eMBB) driven work, Non-eMBB driven functionality and cross-functionality for both. This 3GPP workshop on the radio specific content of Release 18 reviewed over 500 presentations by companies and partner organizations, to identify topics for the immediate and longer-term commercial needs. The Release 18 Package Approval was decided at the December 2021 TSGs (#94-e) Plenary meeting. The time duration for the release in RAN is tentatively set at 18 months. The detailed discussions on how to consolidate topics into WIs and SIs started after the RAN#93-e meeting in September 2021. This meeting will see progress on 'high-level descriptions' of the objectives for each topic. The list of topics include the following [16]:
  - Evolution for downlink Multiple-Input Multiple-Output (MIMO)
  - Uplink enhancements
  - Mobility enhancements
  - Additional topological improvements (Integrated Access Backhaul (IAB) and smart repeaters)
  - Enhancements for Extended Reality (XR)
  - Sidelink enhancements (excluding positioning)
  - RedCap evolution (excluding positioning)
  - NTN evolution, including both NR and IoT aspects
  - Evolution for broadcast and multicast services
  - Expanded and improved positioning
  - Evolution of duplex operation
  - Artificial Intelligence (AI)/Machine Learning (ML)
  - Network energy savings
  - Additional RAN1/2/3 candidate topics:
    - Set 1: UE power savings, enhancing and extending the support beyond 52.6GHz, Carrier Aggregation (CA)/Dual-Connectivity (DC) enhancements (e.g., Multi-Radio/Multi-Connectivity (MR-MC), etc.), Flexible spectrum integration, Reconfigurable Intelligent Surfaces (RIS).
    - Set 2: UAV, Industrial Internet of Things (IIoT)/ Ultra-Reliable Low-Latency Communication (URLLC), <5MHz in dedicated spectrum, other IoT enhancements and types, HAPSs, Network coding.
    - Set 3: Inter-gNB coordination, network slicing enhancements, multiple universal subscriber identity modules), UE aggregation, security enhancements, Self-Organizing Networks (SONs)/Minimization of Drive Test (MDT).
  - Potential RAN4 enhancements.

The importance of the NTN evolution has been very visible in RAN meetings, including RAN#93-e. In addition, satellite access might be discussed under other topics, such as mobility management and evolution for broadcast and multicast services. A summary of the 3GPP satellite related standardization activities is presented in Table 2. The most important meeting of standardization organizations are summarized in Table 6.

### B. USE CASES FOR SATELLITE ACCESS IN 5G

In March 2017, as part of Release 14, the 3GPP initiated an SI to analyze the feasibility of satellite integration into 5G network (3GPP TR 22.822 [11]). The initial goal was to bring together satellite operators and other companies to create aligned contributions in the support of satellites in the 5G standardization. The two SIs 3GPP TR 38.811 and 3GPP TR 38.821 had been already completed. They studied the role of satellites in the 5G ecosystem. In addition, the challenges of a co-existing satellite-terrestrial network had been analyzed taking into account different architectural options.

On the basis of satellite networks characteristics introduced in Section II above, three main use case categories are defined, namely service continuity, service ubiquity, and service scalability, as shown in Figure 2. **Service continuity** use cases provide continuous access to services granted by the 5G system, while users move between terrestrial and satellite networks. Use cases considering fleets of such UE (whether locally grouped or dispersed) are also included in this category. **Service ubiquity** use cases serve potential users wishing to access 5G services in "unserved" or "underserved" areas by terrestrial networks, which will be possible through 5G satellite access network service. **Service scalability** use cases utilize the distinguished capability of satellites in broadcasting or multicasting a similar content over a large area, and potentially directly to UEs. likewise, a satellite network can also be utilized to off-loading terrestrial networks traffic during busy hours by broadcasting or multicasting delay-tolerant data in less busy hours. Table 3 summarizes the satellite access use cases in [10] and [11] and their applications. To realize these use cases, some requirements need to be fulfilled by 5G+ systems:

- Service continuity shall be supported between satellite-based access networks and land-based 5G access owned by a single operator or by multiple operators with guaranteed QoS while switching to or from terrestrial to satellites.
- Provide the optimum network selection.
- Support Nb-IoT and mMTC services.
- The use of satellite links shall be supported within the core network as well as between the core network and the radio access network by modifying the 3GPP system to adapt to the latencies caused by satellite backhaul.
- Reciprocal cooperation is required between mobile operators and satellite operators to ensure good service areas available for customers.

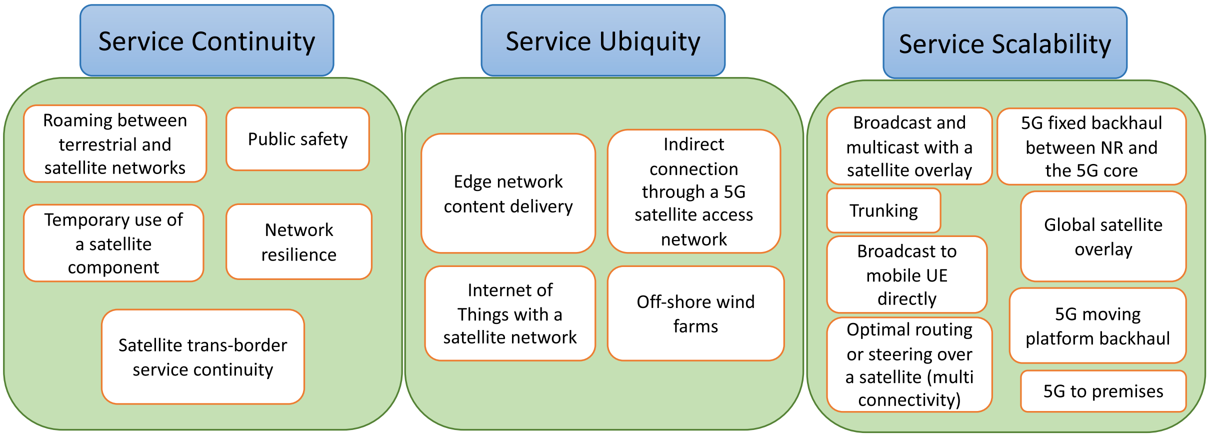



**FIGURE 2.** The three categories of satellite access use cases in 5G.

**TABLE 2.** Summary of 3GPP satellite related standardization activities.

| Release | Item code | TSG | Title | Status |
|---|---|---|---|---|
| Release 15 | TR 38.811 | RAN | Study on NR to support NTN | Completed October 2020 |
| Release 16 | TR 22.822 | SA | Study on using satellite access in 5G | Completed June 2018 |
| Release 17 | TR 23.737 First stage | SA | Study on architecture aspects for using satellite access in 5G | Started Release 16, June 2018 Last update Release 17, March 2021 |
| | TR 23.737 Second stage | SA | Integration of satellite components in the 5G architecture | Started June 2020 Last update June 2021 |
| | TR 28.808 | SA | Study on management and orchestration aspects with integrated satellite components in a 5G network | Completed March 2021 |
| | TR 38.821 | RAN | Solutions for NR to support NTN | Started Release 16, June 2018 Last update Release 17, June 2021 |
| Release 18 | 920035 (5GSATB) | SA | 5G system with satellite backhaul | Completed June 2021 |
| | 920034 (SCVS) | SA | 5G system with satellite access to support control and/or video surveillance | Started June 2021 |

- A 5G system supporting both terrestrial access and satellite access shall distribute user traffic between the tow access types optimally.
- A 5G system with satellite access shall support services with QoS indicators adapted to GEO-based satellite access with RTT of 600-800 ms, MEO-based satellite access with RTT of 125-250 ms, and LEO-based satellite access with RTT of 30-50 ms [17]. These RTT values include the delays of processing on both ground and orbit as well as the variable propagation delays. In satellite communication, propagation delay varies due to changes in satellite and user positions, which lead to different slant ranges.
- UEs with satellite access shall be able to reject or accept connections with the satellite based on the supported QoS indicators and the available accesses.
- A 5G system with multiple access shall have the capability of selecting the access technologies combination that serves UEs based on access technology availability, QoS parameters, pre-emption, and targeted priority.

## IV. SATELLITE ACCESS IN 5G AND ITS ARCHITECTURE ASPECTS

An essential requirement for the integration of satellite networks in 5G and beyond is to specify the architecture of the integrated networks. The 3GPP community discussed and presented several integration architectures that describe different integration scenarios. However, the 3GPP architectures consider a satellite network as a component in the 5G network. It is worth investigating how the integration architecture can be if a 5G network is considered as a component in a satellite network. This section describes the 3GPP architectures of integrating satellite access in 5G.

In TR 38.811 [10], the 3GPP community introduced two types of satellite access networks:

- A broadband access network serving Very Small Aperture Terminals (VSATs) mounted on a moving platform (e.g. aircraft, vessel, train, bus). In this context, broadband refers to at least 50 Mbps data rate and even up to several hundreds Mbps for downlink. The service links operate in frequency bands allocated to satellite and aerial services (fixed, mobile) above 6 GHz.
- Narrow- or wide-band access network serving terminals equipped with semi-directional antenna (e.g., handheld terminal). In this context, narrow-band refers to less than a 1 or 2 Mbps data for downlink. The service links operate typically in frequency bands allocated to mobile satellite services below 6 GHz.

In terms of architecture, Figure 3 shows a comparison between a typical satellite network physical architecture and a 3GPP NG-RAN architecture. In the context of 5G communications, the N2 interface supports control plane signalling

**TABLE 3.** Satellite access use cases in 5G.

| Use case | Description | Application |
|---|---|---|
| Roaming between terrestrial and satellite networks [11] | UE will have worldwide connectivity via terrestrial and/or satellite networks while roaming between different terrestrial and satellite operators. Optimal network selection will be possible when both terrestrial and satellite networks are available. | Tracking shipping containers worldwide. |
| Broadcast and multicast with a satellite overlay [11] | The high demand for digital content distribution services by a large number of UEs might lead to the saturation of the transmission capabilities of the mobile network operator (MNO). A satellite network operator (SNO) can boost the capacity of terrestrial MNOs and serve UEs that are located beyond terrestrial network coverage. | TV broadcasting and video streaming. |
| Edge network content delivery [10] | Offloading popular media and entertainment content from the mobile network infrastructure and delivering it at the network edge, where it may be stored in a local cache or further distributed to the UEs. | Broadcast channel to support multicast delivery to 5G network edges. |
| Broadcast to mobile UE directly [11] | Public safety authorities want to be able to instantaneously alert the public of catastrophic events and provide guidance during disaster relief. Also media and entertainment industry can provide entertainment services in vehicles (cars, buses, trucks). | Broadcast or multicast service directly to UE whether handheld or vehicle mounted. |
| Public safety [10] | To achieve continuity of services for emergency responders, such as police, fire brigade, and medical personnel, while exchanging messages and voice services in outdoor conditions anywhere and under any mobility scenarios. | Access to emergency responder equipment (handset or vehicle mounted). |
| Internet of Things with a satellite network [11] | An IoT service provider uses a constellation of LEO satellites that can provide continuous global coverage for UEs with limited RF and energy capabilities. | Reporting items or people positions on a continuous basis for security and tracking purposes. |
| Temporary use of a satellite component [11] | When a disaster occurs, elements of the 5G RATs may be partially or completely destroyed. The normal terrestrial network access may no longer be available.. However, communication services are required to provide first aid, emergency support, restore security, and organize logistics. 5G satellite RATs can be used to provide the required access to 5G networks. | Significant earthquake, flood, or war. |
| Network resilience [10] | To prevent a complete network connection outage on critical network links that require high availability. | Secondary or backup connection (although potentially limited in capability compared to the primary network connection). |
| Trunking [10] | A network operator may want to interconnect various 5G local access network islands. | Industrial sites. |
| Optimal routing or steering over a satellite (multi-connectivity) [11] | At the edge of the radio coverage of a 5G terrestrial RAT, the performance of eMBB and mMTC services might be limited at certain times. Delay-insensitive communication can be routed through satellites whereas delay-sensitive communication can be achieved through terrestrial 5G RATs. | Automated factories or industrial sites in remote areas. |
| Satellite trans-border service continuity [11] | 5G terrestrial coverage is not always available near countries borders, and UEs crossing borders need to switch from one operator to another. A 5G satellite access network covering border areas can provide continuous coverage and support a smooth transition from one operator to another. | Communication coverage for travellers and intelligent transportation systems. |
| Global satellite overlay [11] | When the distance between two sites increases, the difference in latency between air and optical fibre transmission media may become critical for some applications. A constellation of LEO satellites, where each satellite is equipped with a gNB and interconnected with other neighbouring satellites via ISLs, provides an overlay mesh network for users that have a need for long distance connectivity with improved latency performance or specific end-to-end security. | Critical application domains, such as High Frequency Trading (HFT), Banking or Corporate communications for global organizations with distributed sites around the world. |
| Indirect connection through a 5G satellite access network [11] | UEs with no direct access to the 5G network or satellite communication can access a 5G network through a relay enabled UE and a bent-pipe satellite-enabled or 5G satellite-enabled interconnection. | UEs on a commercial jet or maritime cruise vessel. |
| 5G fixed backhaul between NR and the 5G Core [11] | Satellite backhaul provides a cost efficient option for mobile operators to provide services in rural areas where terrestrial infrastructure is not available. The site of a cell tower in a rural area can be connected to the 5G core through satellite backhaul. | Remote and isolated villages with low-density populations. |
| 5G moving platform backhaul [11] | To provide a backhaul connection for 5G base stations mounted on trains or airplanes where there is no 5G terrestrial coverage. | Internet and communication services for users on-board trains or planes. |
| 5G to premises [11] | A terrestrial cellular operator works with a satellite operator to provide better services for customers in unfavourable geographical areas with old terrestrial network infrastructure, using a new home or office gateway unit to combine the available signals from satellite and terrestrial networks, and to present good WIFI coverage within the premises. Satellites are used to broadcast and multicast media. Caching can be done on the gateway. Unicast will use the cellular route, especially for delay-sensitive applications | Supports Internet and multimedia intensive applications in rural and remote areas. |
| Off-shore wind farms [11] | At an off-shore wind farm, the wind power plant communication network connects to the on-shore and inland remote service centre through a 5G satellite connection. | Connecting remote off-shore wind farms to the service centre. |

between RAN and 5G. The N3 interface performs the role of conveying user data from the RAN to the user plane function. The N6 interface provides connectivity between the user plane function and any other external (or internal) networks or service platforms, such as the Internet, the public cloud or private clouds. To integrate satellite access networks in

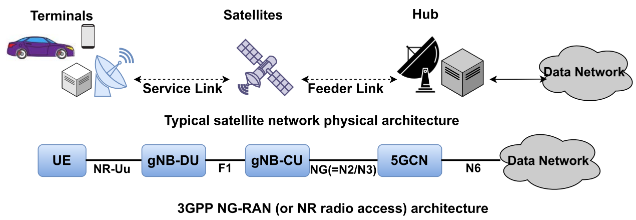



**FIGURE 3. Comparison between the NG-RAN logical architecture and the satellite network physical architecture.**

5G, 3GPP TR 38.821 introduced the following three types of satellite-based NG-RAN architectures:

- **Transparent satellite-based NG-RAN architecture:** The satellite payload implements frequency conversion and a radio frequency amplifier in both uplink and downlink directions. Several transparent satellites may be connected to the same gNB on the ground through New Radio Uplink Unicast (NR-Uu).
- **Regenerative satellite-based NG-RAN architectures:** The satellite payload implements regeneration of the signals received from earth. The satellite payload also provides ISLs between satellites. An ISL may be a radio interface or an optical interface that may be 3GPP or non-3GPP defined. The regenerative satellite-based NG-RAN architecture has two types:
  - gNB processed payload (has both gNB Centralized Unit (gNB-CU) and gNB Distributed Unit (gNB-DU))
  - gNB-DU processed payload
- **Multi-connectivity involving satellite-based NG-RAN:** This may apply to transparent satellites as well as regenerative satellites with gNB or gNB-DU function on board.

Figure 4 illustrates the aforementioned satellite access network architectures and how the satellite access components are mapped onto the 5G architecture. In the context of 3GPP standards, N1 refers to a transparent interface that transfers the UE information, related to connection, mobility, and sessions, to the 5G core access and mobility management function.

## V. ADAPTING NEW RADIO FOR SATELLITE NETWORKS

The new radio access standard is developed by 3GPP for the 5G mobile networks. Since NR was originally developed for terrestrial networks, some adaptations are required to use NR in satellite access in order to cope with the differences between terrestrial and satellite networks (e.g., high propagation delays, satellites as base stations moving in high speeds, large footprints that may have millions of users). Although 3GPP has introduced some adaptations and potential solutions to meet the requirements of integrating satellite networks in 5G, it is worth investigating the idea of introducing a newer radio access standards that is specifically designed for the future integrated 6G and beyond networks (i.e., terrestrial, aerial, and space networks). This section discusses the constraints associated with satellite networks and the NR impacted areas with some potential solutions.

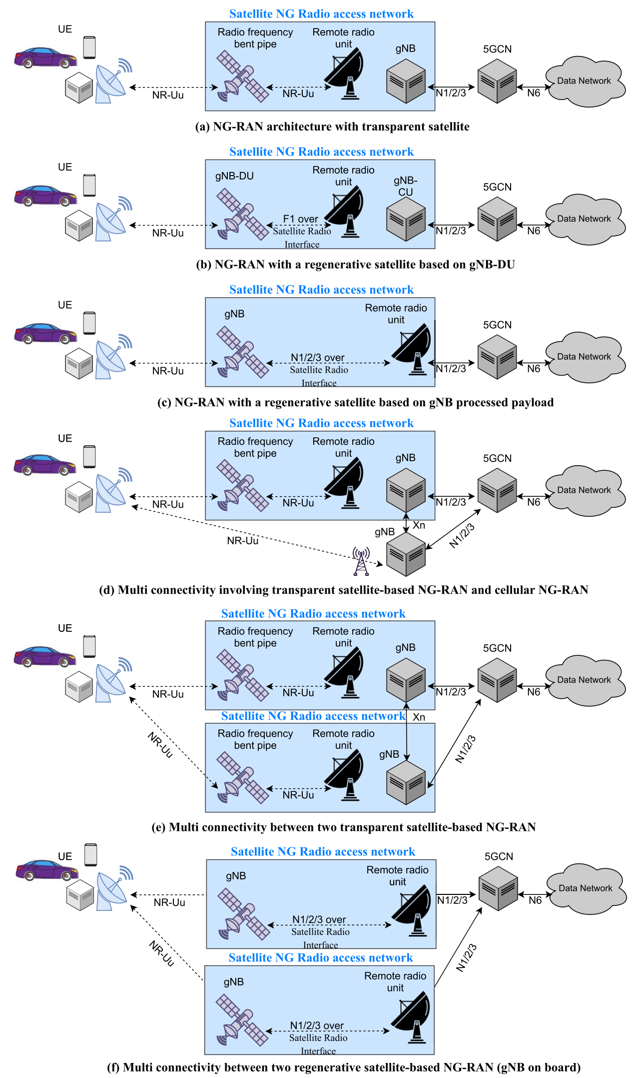



**FIGURE 4. The three types of satellite-based NG-RAN architectures described in [14].**

The technical reports 3GPP TR 38.811 [10] and 3GPP TR 38.821 [14] discussed channel modeling for satellites, where channel model parameters were provided while taking different user environments and atmospheric conditions into consideration. Some design constraints are identified and the impacted areas of NR are explained in the following two subsections.

### A. SPECIFIC CONSTRAINTS ASSOCIATED WITH SATELLITE NETWORKS

Compared to cellular systems, there are some design constraints that need to be addressed when considering satellite network deployment scenarios [10], [14]:

- **Propagation channel:** the channel has a different multi-path delay and Doppler spectrum model. However, for narrowband signals and frequency bands below 6 GHz, the time disparity may be ignored. Certain outdoor conditions and line-of-sight operations are necessary for the UE communication via satellite.

- **Frequency plan and channel bandwidth:** The allocated spectrum to a satellite system is respectively $2 \times 15$ MHz (Uplink (UL) & Downlink (DL)) at S band and about $2 \times 2.5$ GHz for UL and $2 \times 2.4$ GHz for DL at Ka band. Satellite systems at S and Ka bands use mostly circular polarizations. Therefore, with frequency re-use and efficient spectrum allocation among different cells, the maximum channel bandwidth per cell may reach $2 \times 15$ MHz (UL and DL) at S band and up to $2 \times 2.4$ GHz (UL and DL) at Ka band. However, inter cell interference should be minimized.
- **Power limited link budget:** Two main design aspects need to be considered:
  - Maximizing the throughput for a certain transmit power from the satellite on the DL and from the UE on the UL.
  - Maximizing the service availability under severe fading situations (typically between 20 and 30 dB in Ka band for 99.95% availability).
- **Cell pattern generation:** Satellites have larger cells compared to cellular networks. In particular, a LEO satellite at an altitude of 550 km under an elevation of 40° has a coverage area of 1.05 million km$^2$ with an approximate radius of 580 km. The elevation angle is the angle between the satellite and a horizontal plane as seen by a ground user or gateway. The coverage area of a single satellite is defined as a region of the Earth surface in which the satellite can be seen under an elevation angle equal or greater than the minimum elevation angle determined by the link budget requirements of the system. The largest coverage area is achieved under an elevation of 0°. However, communication under low elevation angles can be hindered by natural barriers. For efficient communication and for savings within a link budget, higher elevation angles are used. For example, OneWeb constellation applies the elevation of 55° for users' stations and Starlink, for the first shell (layer at the altitude of 550 km), applies an elevation angle of 40° for users' stations [18]. On the other hand, a 5G microcell coverage area is approximately 12.5 km$^2$. In addition, the cells are moving in case of NGSO satellite. This creates a significant difference in propagation delay between UE at the cell edge and UE at the cell centre, and the difference in propagation delay increases as the altitude of the satellite decreases. Accordingly, when the position of UE is not known by the network, contention-based channel access might be impacted.
- **Propagation delay characteristics:** Satellite systems have much greater propagation delays than terrestrial systems, which can impact all round-trip signaling times, especially at transport (data transfer) and access levels. In [19], a detailed analysis of the satellite systems propagation delays is provided.
- **Mobility of the infrastructure's transmission equipment:** For GSO satellites, the transmission equipment is considered almost static with respect to the UEs which results in small Doppler effects. For NGSO satellites, by contrast, create higher Doppler effects due to their relative movement to the earth. For example, a LEO satellite at 600 km altitude creates a Doppler shift of 400 kHz on ground-satellite downlinks with carrier frequency of 20 GHz, and 600 kHz on uplinks with carrier frequency of 30 GHz. As a reference, the system bandwidth for NB-IoT is only 180 kHz [20]. The Doppler depends on the frequency band and the relative velocity of the satellite with respect to the UE. The Doppler effect will continuously modify the carrier frequency, phase, and spacing. However, most of the Doppler shift and variation rate can be compensated by utilizing the predictable motion of satellites as well as UE location if known.
- **Service continuity between land-based 5G access and non-terrestrial-based access networks:** Different handover triggering mechanisms are required in order to give preference to cellular communication. The handover procedure should support both regenerative and bent-pipe satellites. In addition, it should handle handover preparation and failure while also supporting lossless handover. Handover can be due to intra-non-terrestrial network mobility as well as between non-terrestrial and cellular networks. For more details about service continuity the reader may refer to [21].
- **Radio resource management adapted to network topology:** Unlike cellular systems where access control is typically located close to the UE, in satellite systems access control is mostly located at the satellite base station, gateway, or hub level, which may prevent an optimal response time for access control. Hence, pre-grants, Semi-Persistent Scheduling (SPS), and/or a grant-free access scheme would be beneficial.
- **Terminal mobility:** Very high speed UE with speeds of up to 1,000 km/h need to be supported.

### B. NR IMPACTED AREAS AND POTENTIAL SOLUTIONS

The aforementioned satellite related design constraints have impacts on some features of NR as documented in 3GPP TR 38.811 [10] and 3GPP TR 38.821 [14]. The following points provide a brief description of how NR is impacted, and Table 4 summarizes the potential solutions to support NR in satellite networks.

- **Handover paging:** The fast movement of LEO satellites and their many beams mean that UEs are only kept within a beam for a few minutes. The rapid change creates problems for paging as well as for handovers for both stationary UEs and moving UEs. A handover has to be executed quickly otherwise the UE may not make use of the satellite resources efficiently and may suffer a loss of data. With fixed tracking areas on the ground, there is no one-to-one correspondence between moving beams

**TABLE 4.** Impacted NR areas and potential solutions to support satellite networks.

| Satellite network specifics | Effects | Impacted NR features | Potential adaptations | Potential areas of impact to be further studied |
|---|---|---|---|---|
| Motion of the space vehicles (especially for Non-GEO-based access network) | Moving cell pattern | Handover paging | The NR UE may need to be capable of reporting its geo-location to the satellite RAN. Using the ephemeris information of the NGEO satellites, the network can determine which satellite/beam covers that location of a UE at any given time and for which duration. | Taking advantage of the knowledge of the UE location and satellite ephemeris information to adapt the NR handover and paging protocols needs further study. If the adjacent beams of the same satellite use different frequencies or different polarization, the NR beam management procedures need to be modified. |
| | Delay variation | Tracking area (TA) adjustment | Knowing the satellite orbits and UE position, the delay variation is quite predictable. Also, the transmission timing of the UE has to be adjusted over the borders of individual TTIs. | Solutions need to be studied to ensure the alignment of uplink signals over the satellite links to overcome the predictable delay of SatNets. |
| | Doppler | Synchronization in downlink | To meet the condition of 5ppm, the satellite altitude has to be above 13,000 km. For the Doppler shift amplitude to be compensated, it has to be less than 48 kHz for S band and 480 kHz for Ka band | In case the aforementioned conditions are not met, further studies are required to accommodate the high Doppler shift during the cell synchronization procedure in SatNets. |
| Altitude | Long latency | Hybrid automatic repeat request (HARQ) | Dealing with a higher number of parallel HARQ processes and its feasibility for non-terrestrial networks have been addressed in [22] [14]. | The impact of long RTT delays on NR HARQ operations. Also the impact on UEs and serving satellite gNBs should be considered when the number of HARQ processes is either extended or limited/disabled for longer SatNet delays. |
| | | MAC/Radio Link Control (RLC) Procedures | NR UE and base stations must size their transmission buffers, the retransmission time-out mechanisms, and the number of allowed retransmissions according to the longest RTT to be anticipated. UL scheduling delay parameters are expected to be redefined to accommodate the RTT of the associated deployment scenario. | No further study required. |
| | | Physical layer Procedures (ACM, power control) | For LEO satellites, ACM may be used to adapt to the large variation of free space loss. The variation is sufficiently slow compared to the 20 ms worst case RTT. ACM can also react to shadowing fades to a large extent, but still unable to follow fast fading. | Further studies are needed to define the required margin for power and ACM control loops to cope with the long RTT. |
| Cell size | Differential delay | Time advance in random access response (RAR) message | For satellites, it is expected that a time advance mechanism will need to be modified to compensate for the propagation delay. | Further study is required as time advance should compensate for differential delay/distance. |
| | | Physical random access channel (PRACH) | The current window for the PRACH response in NR cannot cover the long RTT. Therefore, the random access response window length in NR should be revisited to accommodate the RTT of satellites. However, extending the window size in the existing procedure introduces unnecessary UE monitoring intervals. For satellites, the current NR preamble format needs to be extended considering different footprint of satellite cells. | The solution to handling long RTT with the consideration of power saving at the UE side needs to be further studied. Further studies should be done if a new random access preamble format is needed for satellites. |
| Duplex mode | Regulatory constraints | Access scheme (time division duplex (TDD)/ frequency division duplex (FDD)) | When considering satellite networks, this guard time should equal the round trip delay. Although this guard time may be acceptable in the case of LEO access system, there is a need to deal with the variable delay. | In case the regulations allow it, TDD mode can be considered for LEO-satellite-based access network with some required NR modifications. |
| Satellite Payload performance | Phase noise impairment | Phase tracking reference signal (PT-RS) | Typical phase noise masks of state-of-the-art bent pipe of satellite payloads can be efficiently compensated by the current NR design in the absence of important Doppler shifts and/or residual CFO at a carrier frequency of up to 30 GHz. To support eMBB by SatNets, the modulation order should not always be low. PTRS is needed in SatNets at high carrier frequencies, where the maximum received SNR is limited by the phase noise. | Due to the high speed of LEO satellites, a solution is needed in the case of important Doppler shifts and/or residual CFO, or in the presence of the specific phase noise masks of on-board payloads that are different from the ones considered in cellular networks, or with very large channel bandwidths. |
| | Back-off | Peak-to-average power ratio (PAPR) | The use of CP-OFDM for downlink does not restrict NR operation in SatNets, but it may affect the system performance as explained in section V.B. | PAPR reduction techniques of CP-OFDM signal for downlink would be beneficial for optimizing the capacity of non-terrestrial networks and therefore could be considered in future studies. |
| Network architecture | RAN Mapping | Protocols | In [10] three mapping options are described that prevent the need to create new interfaces or reference points, as described in Figure 4. The timers associated to the protocols transported over the feeder and service links (e.g., F1, N1, N2 and N3 reference points) may need to be extended. In the processed payload option, it is recommended that the satellite implements some kind of "intermediate" node, which could be based on the outcomes of 3GPP TR 38.874 [23], and see what areas of impact it may create. | The N1/N2/N3 and GTP-based F1 interface protocols may need to be adapted to accommodate the satellite feeder link characteristics (long delay, BER). Other impacts on NR specification may have to be considered, such as location update, paging, and handover RAN related protocols and handling of network identifies. |

and fixed tracking areas or registration areas, which is necessary for the paging process.

- **Adjustment of tracking area:** Moving satellites generate strong delay variations, and a rapid change in the propagation distance between the UE and BS via satellite. This delay largely exceeds the Transmission Time Interval (TTI) of NR, which is equal to or less than 1 ms. Hence, the Tracking Area (TA) alignment is an important feature of NR that will be impacted by the introduction of satellites in 5G to ensure the synchronization of all the uplink transmissions at the gNB reception point.
- **Synchronization in downlink:** The UE has to detect both the primary and secondary synchronization signals in order to acces a 5G network. These synchronization signals allow frequency and time corrections as well as the detection of Cell ID. In cellular networks, a UE has to get good one-shot detection probability at $-6$ dB received baseband Signal-to-Noise Ratio (SNR) condition with less than 1% false alarm rate, with robustness against initial frequency offset up to 5 ppm. It is expected that these requirements defined for terrestrial UE will be kept the same for SatNets UE. Even though the SNR level of satellite systems is typically in the range of $-3$ to

13 dB SNR, the satellite movement creates a higher Doppler shift, depending on the frequency band and the velocity of the satellite relative to the UE. However, this can be compensated for at the demodulator.

- **The process of hybrid automatic repeat request:** The Hybrid Automatic Repeat Request (HARQ) process is a time-critical mechanism. In SatNets, the Round Trip Time (RTT) normally exceeds the maximum conventional HARQ timers or the maximum possible number of parallel HARQ processes. This means that simply extending the number of HARQ processes linearly to RTT might not be feasible for some UE due to memory restrictions and the maximum possible parallel processing channels. Also, the impact of this delay has to be considered by the gNBs on the number of their active HARQ processes. Although NR has extended the number of HARQ processes in Rel. 15 to 16 processes, for SatNet NR the number of HARQ processes may need to be further extended flexibly according to the induced RTT delay.
- **MAC/Radio link control procedure:** For LEO satellite systems, the one way propagation delay changes continuously (e.g., 2-7 ms for 600 km orbit). The Automatic Repeat Request (ARQ) requires that the transmitted packets be buffered and released only after the successful receipt of an acknowledgement or until a time out. A larger transmission buffer is required due to the long RTT, which also limits the number of retransmissions allowed for each transmitted packet. The ARQ transmit buffer size and retransmission mechanism must be designed for the longest possible delay (i.e., at the lowest elevation). Scheduling mechanisms must be able to cope with the long RTT.
- **Physical layer procedure (automatic coding and modulation, power control):** The limited power available at the UE and satellites and the large free-space loss make the power margin very limited. Thus, only a limited amount of power control is available for satellite links. Due to the long delay in the loop, it is not possible that the power control tracks fast fading, but may be used to track slower power variations. The slow reaction time, due to long RTT, is expected to impact the performance of some physical layer procedures, particularly those with close control loops, such as Automatic Coding and Modulation (ACM) and power control. However, most control loops require certain implementation adjustments, but not a fundamentally different design.
- **Time advance in random access response message:** Time advance mechanisms ensure that transmissions from all UE operating in the same cell are synchronized when received by the same gNB. A time advance command is provided to the UE in a Random Access Response (RAR) message during initial access and later to adjust the uplink transmission timing. The maximum value of the time advance command constrains the maximum distance between UEs and base station, which defines the allowed cell size.
- **The physical random access channel:** It is necessary to consider the long RTT impact on Physical Random Access Channel (PRACH). For a given beam covering a cell, there is one common propagation delay for all served UE, and one relative propagation delay for each served UE. If the common propagation delay can be compensated, then the satellite PRACH signal design will depend on the relative propagation delay, which is limited to a TA range of up to 200 km in current NR specifications. However, when the TA is of thousands of kilometers a satellite PRACH signal and procedure design need to be modified.
- **Access scheme (time division duplex/frequency division duplex):** Most existing satellite systems operate in the frequency bands designated for the Frequency Division Duplex (FDD) mode with a defined transmit direction. For some frequency bands, the Time Division Duplex (TDD) mode is possible. When considering the TDD mode, a guard time is necessary to prevent the UE from simultaneously transmitting and receiving. This guard time directly depends on the propagation delay between the UE and gNB. This guard time will directly impact the useful throughput and hence the spectral efficiency.
- **Phase tracking reference signal (PT-RS):** Phase variations in time domain can be caused by different phenomena, including the presence of phase noise, frequency drifts due to Doppler shift, or due to insufficient frequency synchronization (e.g., residual CFO), etc. In NR, Phase Tracking Reference Signal (PT-RS) has been introduced to compensate for phase errors. The PT-RS configuration in NR is very flexible and allows user-specific configurations depending on scheduled MCS/bandwidth, UE RF characteristics, demodulation reference signal configuration, waveform, etc. PT-RS configuration flexibility is beneficial for SatNets.
- **Peak-to-average power ratio (PAPR):** A key component in satellite payload architecture is a power amplifier. It exhibits nonlinear behavior when operating near saturation in an effort to increase power efficiency. Nonlinear distortion causes constellation warping and clustering, thus complicating signal reception. PAPR is a measurement that determines the vulnerability of the transmitted signal to nonlinear distortion, where higher values indicate a worse impact.

  In the NR downlink, Cyclic Prefix – Orthogonal Frequency Division Multiplexing (CP-OFDM) is used resulting in higher PAPR values compared with the underlying modulation in a single carrier. When a satellite transponder is sufficiently wide and powerful to accommodate more than one FDM carrier, each of which is a different NR CP-OFDM signal, the satellite amplifier is backed off to minimize the intermodulation between these FDM carriers within the same transponder. As a result, the distortion introduced is small. For communicating with small UEs, the satellite amplifier is used to send only one NR CP-OFDM downlink. It is highly desirable to operate the amplifier with as small output power backoff (OBO) as possible. But, due to the higher PAPR of CP-OFDM signal, sufficient OBO is necessary. To close the link, it may be necessary to reduce the power of CP-OFDM carrier or to operate the CP-OFDM carrier with a lower modulation and coding mode. Either way, the forward link capacity is reduced significantly. On the uplink, DFT-spread-OFDM might be beneficial. For satellite communications, low PAPR waveforms are desired.

- **Protocols:** Mapping is needed between the NG-RAN logical architecture and the SatNet architecture (the two architectures are depicted in Fig. 3). Several mobility scenarios should be considered, specifically the mobility induced by the motion of satellites, the motion of UEs from one beam to another beam generated by the same satellite, the motion of UEs between beams generated by different satellites, and the motion of UEs between satellites and cellular access. Location updating, paging, and handover RAN related protocols need to accommodate the extended delay of intra-satellite access mobility, the differential delay when mobility is between a satellite and a cellular network, and the mobility of the cell pattern generated by NG-satellites.

## VI. MANAGEMENT AND ORCHESTRATION WITH INTEGRATED SATELLITE COMPONENTS IN A 5G NETWORK

Integrating satellite access networks into 5G networks increases network complexity. To fully utilize integrated network resources and gain the advantages of integration, efficient management and orchestration is necessary. Orchestration allows network services and resources to be managed and controlled on an integrated basis and optimized. Thus, time spent on processes is shortened by rapidly and flexibly allocating network components and resources.

In 2019, the 3GPP TSG SA initiated a study on management and orchestration aspects of a 5G network with integrated satellite components. The study aimed at studying business roles as well as service, orchestration, and network management of a 5G network integrated with satellite components. The scope of the study covered non-3GPP defined satellite access, NTN RAN-based satellite access, as well as backhaul aspects. The study outcome was presented in TR 28.808 [13] which included potential requirements and solutions to integrate satellites in 5G networks, such as network slice management and monitoring and management of gNB components.

The study presented two reference management architectures for integrated satellite components, as shown in Figure 5. The first reference architecture was for the management of a 3GPP RAN integrating a satellite NR-RAT with a terrestrial RAT. The second reference architecture was for the management of a non-3GPP satellite RAN integrated in a 5G network. The potential requirements for the management and orchestration of integrated satellite components in a 5G network are shown in Figure 6. The requirements are presented in three categories: (1) network slice management requirements; (2) management of satellite components; and (3) monitoring of satellite components.

Compared to terrestrial NR, the impact of integrating satellites mainly comes from MEO/LEO scenarios where satellites carry gNB components (e.g., gNB-DU) and move faster than the earth. More improvements are required to compensate for the long delays and RTT that affect some of the key performance indicators and monitoring functionality in 5G networks. The conclusion of the study was that the concept of Self-Organizing Networks (SONs) for 5G requires some enhancements to support the mobility of non-terrestrial gNBs. Although efficient network management is essential in future integrated networks in order to fully utilize the available network resources, the standardization work on NTN management is nevertheless quite limited within the 3GPP working groups.

## VII. OTHER STANDARDIZATION ORGANIZATIONS

There are several other standardization organizations contributing to the standardization activities towards integrating satellite and terrestrial networks. Some of these organizations are from the telecommunication sector, whereas others are from the satellite and aviation sectors. Table 5 highlights a sample of the most recent standardization document published by standardization organizations other than 3GPP. The following paragraphs shed the light on the role that such standardization organizations are playing in the process of enabling and supporting the integration of satellite and terrestrial networks.

### *a: THE INTERNATIONAL TELECOMMUNICATION UNION (ITU) STANDARDIZATION*

In ITU terminology, the 5G system is called IMT-2020. The IMT-2020 network architecture is envisioned to be access network-independent and with a core network common to Radio Access Technology (RAT) for IMT-2020, as well as existing fixed and wireless networks. The IMT-2020 core network control mechanisms will be decoupled from the access network technologies. The IMT-2020 network should support new RATs for IMT-2020, evolved IMT-advanced RATs, satellite networks, fixed broadband network access, and Wireless Local Area Network (WLAN) access networks. In July 2020, 3GPP 5G has been formally endorsed as ITU IMT-2020 5G standard. The M family of ITU-R recommendations refers to 5G systems. One of the ITU-R Study Groups 2020 is the Study Group 4 Satellite services. Systems and networks for the fixed-satellite service, mobile-satellite service, broadcasting-satellite service and radio determination-satellite service. Study Group 4 consists of three Working Parties (WPs) [24]:

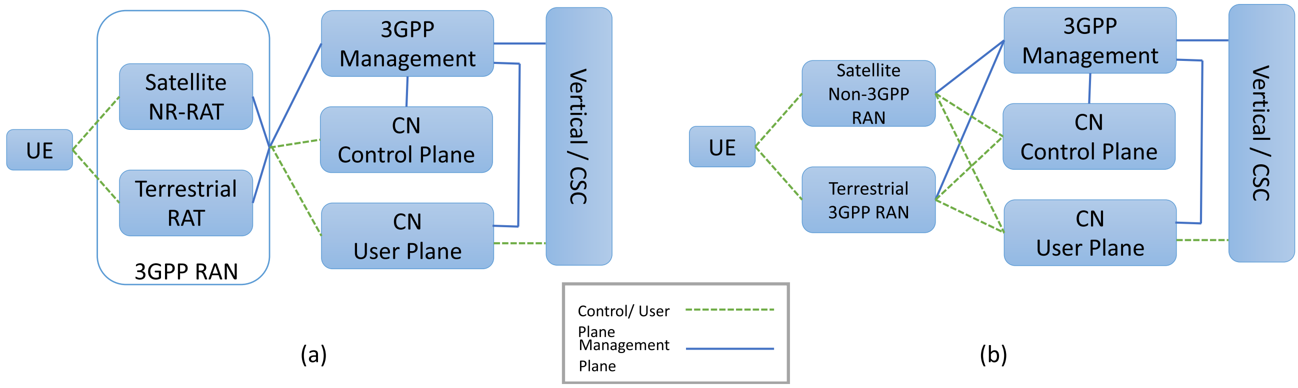



**FIGURE 5.** Reference management architectures for integrated satellite components as described in [13]. (a) Reference architecture for the management of a 3GPP RAN integrating a satellite NR-RAT with a terrestrial RAT. (b) Reference architecture for the management of a non-3GPP satellite RAN integrated in a 5G network.

- WP 4A Efficient orbit/spectrum utilization for the fixed-satellite service (FSS) and broadcasting-satellite service (BSS).
- WP 4B Systems, air interfaces, performance and availability objectives for the fixed-satellite service (FSS), broadcasting-satellite service (BSS) and mobile-satellite service (MSS), including IP-based applications and satellite news gathering (SNG).
- WP 4C Efficient orbit/spectrum utilization for the mobile-satellite service (MSS) and the radio determination-satellite service (RDSS).

ITU-R WP 4B has given special consideration to the study of Internet Protocol (IP) related system aspects and performance, and they have developed new and revised recommendations and reports on IP over satellite to meet the increasing demands of satellite links to carry IP traffic. This group cooperates closely with the ITU Telecommunication Standardization Sector.

### b: THE WORLD RADIO CONFERENCE (WRC)

World radio communication conferences are held every three to four years. WRC reviews and, if necessary, revises the Radio Regulations, the international treaty governing the use of the radio-frequency spectrum and the geostationary-satellite and non-geostationary-satellite orbits. Revisions are made on the basis of an agenda determined by the ITU Council, which takes into account recommendations made by previous world radio communication conferences. WRC-19 took place in Sharm El. Sheikh, Egypt on October 28 to November 22, 2019, and 3,540 delegates from 165 countries attended. The members took the following decisions [25]:

- Embedded SIM (ESIM) – expected to provide reliable and high bandwidth internet services to aircraft, ships, and land vehicles.
- Resolution lays out technical and regulatory conditions for three types of ESIM communicating with a GSO FSS space stations within the frequency band 17.7-19.7 GHz (space to earth) and 27.5-29.5 GHz (earth to space).
- Regulatory frameworks for sharing between GSO and non-GSO satellite systems in the 50/40 GHz range. Also sharing between GSO FSS, BSS & MSS and non-GSO FSS satellite systems.
- Deployment process should be based on milestone to avoid spectrum warehousing by large non-GSO satellite constellations.
- One of the new regulations adopted is that non-GSO systems have to deploy 10% of the constellation within two years, 50% within five years and the full deployment within seven years. As explained by the ITU, this milestone-based approach is to provide a regulatory mechanism to help ensure that the Master International Frequency Register reasonably reflects the actual deployment of such non-GSO satellite systems in specific radio-frequency bands and services [24]. In addition, this is to create a balance between the proper functioning of coordination mechanisms, the prevention of radio-frequency spectrum warehousing, and the operational requirements related to the deployment of non-GSO systems.

### c: THE INTERNET ENGINEERING TASK FORCE (IETF)

IETF is a large open international community of network designers, operators, vendors, and researchers concerned with the evolution of Internet architecture and the smooth operation of the Internet [26]. Under IETF, the Transport and Services Area covers a range of technical topics related to data transport in the Internet, such as protocol design and maintenance at Layer 4 (e.g., Transmission Control Protocol (TCP), User Datagram Protocol (UDP), and Stream Control Transmission Protocol (SCTP)), congestion control and (active) queue management, and QoS and related signaling protocols. The transport area subcommittee of the IETF are working with network operators to standardize a multipath deployment scheme that includes fixed gateways and satellites for the backhauling of the 5G network. With Multi-Path TCP (MPTCP), communication service providers can extend the coverage and the bandwidth of 5G services. This will address the issues where in some areas the fixed network

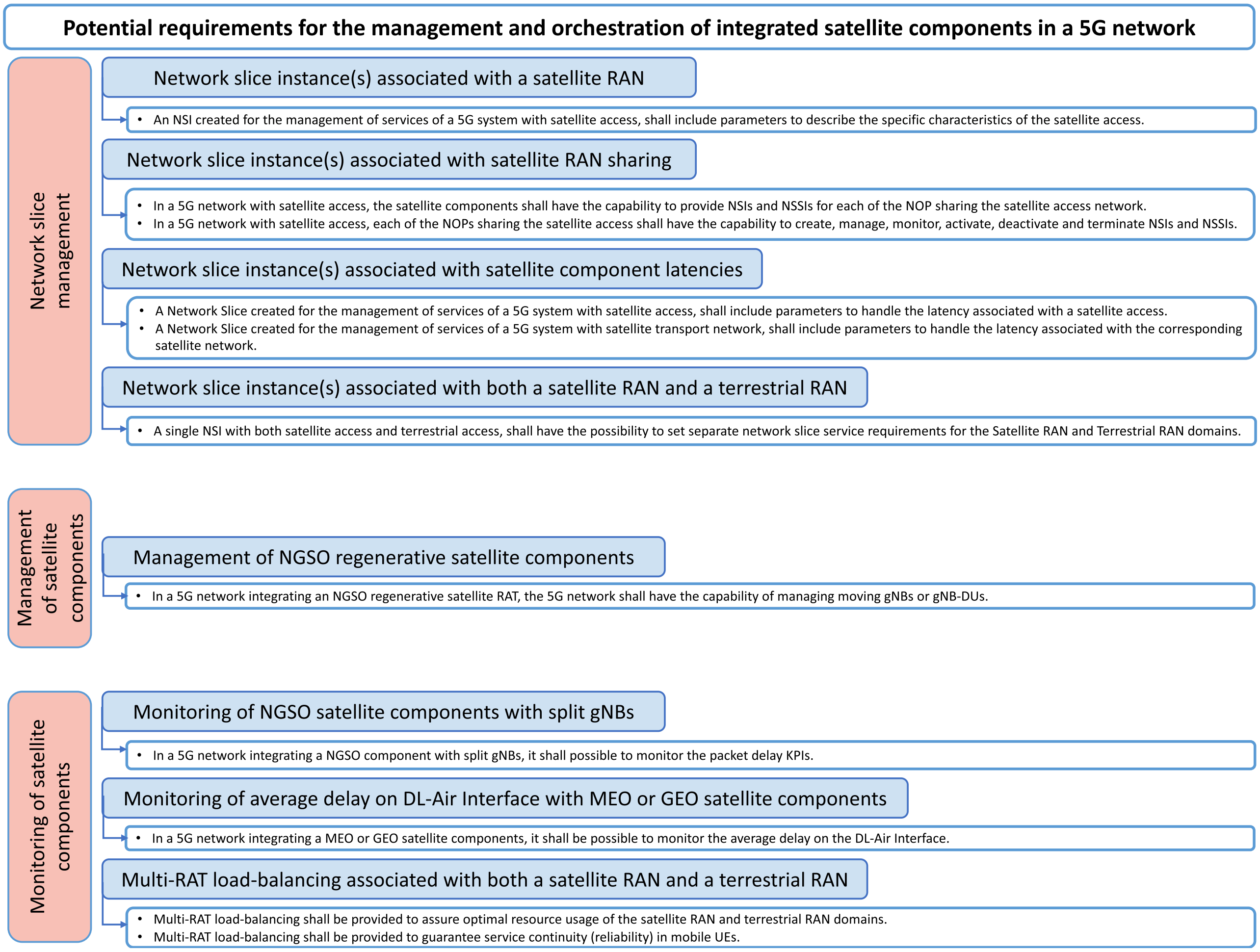



**FIGURE 6.** Potential requirements for the management and orchestration of integrated satellite components in a 5G network.

is not able to deliver enough bandwidth for the backhauling. The MPTCP working group has developed mechanisms that add the capability of simultaneously using multiple paths to a regular TCP session without making any assumption about the support of the communicating peers. In this context, satellite networks can be considered as one of the options when more than one path is used for backhauling.

### d: THE EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (ETSI)

ETSI has investigated a number of component technologies that will be integrated into future 5G systems, such as Network Function Virtualization (NFV), Mobile Edge Computing (MEC), Millimeter Wave Transmission (mWT), and Non-IP Networking (NIN) [27]. The objective of ETSI activities is to define the end-to-end SatCom system that can be fully integrated in 5G. The standardization work is undertaken by the following technical committees:

- Satellite Earth Stations and Systems (TC-SES): Defines all aspects related to satellite earth stations and systems. Within TC-SES, the SCN working group (Satellite Communication and Navigation) covers radio and transmission aspects related to fixed and mobile satellite systems operating in any bands allocated to FSS, MSS, or global navigation satellite systems operating in any bands allocated to RDSS. ETSI TC-SES has established a working relationship with 3GPP. This has allowed the development of standards for mobile satellite as well as broadband satellite multimedia systems, which are mainly based on 3GPP system architecture and radio protocols.
- Network Function Virtualization (ISG-NFV): Produces the technical specifications for the virtualization of network functions.
- Open Source MANO (OSM): Develops a software reference implementation of ETSI Management and Orchestration (MANO).
- Multi-Access Edge Computing (TC-MEC): Produces the technical specifications for realizing Multi-Access Edge Computing (MEC) in the context of content delivery (multicasting and caching).

### e: THE 5G INFRASTRUCTURE PUBLIC PRIVATE PARTNERSHIP (5G PPP)

The 5G PPP is a joint initiative between the European Commission and the European ICT industry. The 5G PPP will

**TABLE 5.** Highlights of a sample of the most recent standardization document published by standardization organizations other than 3GPP.

| Organization | Document | Contribution description | Publication year |
|---|---|---|---|
| ITU-R 2020 | Study Group 4 Satellite services WP 4A | Studies efficient orbit/spectrum utilization for the fixed-satellite service (FSS) and broadcasting-satellite service (BSS). | 2020 - ongoing |
| ITU-R 2020 | Study Group 4 Satellite services WP 4B | Studies systems, air interfaces, performance and availability objectives for the fixed-satellite service (FSS), broadcasting-satellite service (BSS) and mobile-satellite service (MSS), including IP-based applications and satellite news gathering (SNG). | 2020 - ongoing |
| ITU-R 2020 | Study Group 4 Satellite services WP 4C | Studies efficient orbit/spectrum utilization for the mobile-satellite service (MSS) and the radio determination-satellite service (RDSS). | 2020 - ongoing |
| WRC | The Radio Regulations edition of 2020 | Contained the Radio Regulations adopted by the World Radio communication Conference of 1995 (WRC-95) and reviewed by the subsequent World Radio communication Conferences including the latest conference WRC-19 (Sharm el-Sheik, 2019). WRC reviews and revises the Radio Regulations, the international treaty governing the use of the radio-frequency spectrum, and the geostationary-satellite and non-geostationary-satellite orbits. Revisions are made on the basis of an agenda determined by the ITU. | 2020 |
| IETF | Multipath TCP v1 specification in RFC 8684 | Standardized a multi-path deployment scheme that includes fixed gateways and satellites for the backhauling of the 5G network. | 2020 |
| ETSI | 5G NR requirements for support of assisted global navigation satellite system (A-GNSS) (3GPP TS 38.171 version 16.2.0 Release 16) | Established the minimum requirements for both UE based and UE assisted FDD or TDD AGNSS terminals which have NG-RAN access | 2021 |
| 5GPPP | White paper: Vision and Societal Challenges Work Group | Described the European vision for the 6G network ecosystem. it covered areas related to 6G research from a technical, societal, policy, and business perspective. The paper dedicated one section to non-terrestrial networks. | 2021 |
| ECC Working Group | WGFM#99, WGFM#98, WGFM#96, WGFM#95 | inventory of satellite monitoring capabilities, satellite downlinks in Q and V bands, M2M-IoT via satellite | 2011-ongoing |
| NICT Japan | Study Group on the Integration of Satellite Communications and 5G/Beyond 5G | The document identified the use cases that Japan would need by 2040. It highlighted some standardization requirements (e.g., standard communication protocols for every layer) that need to be considered in order to realize the identified use cases. | 2021 |
| IEEE INGR Satellite Work Group | IEEE 5G and Beyond Technology Roadmap-Satellite | The topics considered in the INGR Satellite WG 2021 edition of the roadmap are the following: applications and services, reference architectures, new MIMO-based PHY, antenna and payload, machine learning and artificial intelligence, edge computing, QoS/QoE, security, network management and standardization. | 2020- ongoing |
| CCSDS | Several documents (recommended standards, recommended practices, informational reports, experimental reports, records, historical) | Contributions in the areas of space internetworking services, mission operations and information management services, spacecraft onboard interface services, system engineering, cross support services, space link services. | 1982-ongoing |
| AEEC | ARINC Project Paper 792A | Defines a satellite communication system that supports multi-modem Ku-band and Ka-band communication with fiber optics interfaces. The specification will enable the use of electronically steerable antennae that can service one or more Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite networks. A mature draft of ARINC Project Paper 792A is expected by April 2022. | 2021- ongoing |
| AEEC | Ku/Ka Band Satellite (KSAT) Subcommittee Meeting Report | Discusses ARINC standards for broadband satellite systems and aircraft installation provisions for Ku-Band and Ka-Band satcom equipment. This equipment provides standardized network interfaces and domain separation for non-safety satcom installations. | Annual report |

deliver solutions, architectures, technologies, and standards for the ubiquitous 5G communication infrastructures. In June 2021, The 5G PPP infrastructure association published a new white paper, "Vision and Societal Challenges Work Group," which described the European vision for the 6G network ecosystem [28]. This white paper covered key areas related to 6G research from a technical, societal, policy, and business perspective, providing a vision for future mobile networks. The paper dedicated one section to non-terrestrial networks.

#### *f: THE ELECTRONIC COMMUNICATION COMMITTEE (ECC) WORKING GROUP*

ECC is an organization of the European Conference of Postal and Telecommunications Administrations. The ECC Working Group Frequency Management (WG FM) is responsible for developing strategies, plans, and implementation advice for the management of the radio spectrum. WG FM44 deals with satellite communications in particular [29].

#### *g: THE NATIONAL INSTITUTE OF INFORMATION AND COMMUNICATION TECHNOLOGY (NICT) JAPAN*

The Study Group on the Integration of Satellite Communications and 5G/Beyond 5G of the National Institute of Information and Communications Technology (NICT) Japan identified the use cases that Japan would need by 2040 [30]. The themes of these use cases were the Internet of Things, smart cities, maritime and aviation, transportation infrastructures, and responding to emergency disasters. The use cases require the integration of satellite networks and 5g+ networks. The report produced by NICT highlighted some standardization requirements (e.g., standard communication protocols for every layer) that need to be considered in order to realize the identified use cases.

#### h: IEEE INTERNATIONAL NETWORK GENERATION ROADMAP (INGR) - SATELLITE WORK GROUP

IEEE INGR-Satellite WG produced two editions of its roadmap report in 2020 and 2021 [31], [32]. The 2021 Edition of the INGR Satellite Working Group Report discussed several topics related to satellites in future networks, including applications and services, reference architectures, new MIMO-based PHY, antenna and payload, machine learning and artificial intelligence, edge computing, QoS/Quality of Experience (QoE), security, network management and standardization. Under each topic, the related challenges, enablers, and potential solutions were highlighted.

### A. SATELLITE AND AVIATION STANDARDIZATION

#### a: DIGITAL VIDEO BROADCASTING (DVB)

This is a forum created by industry to define a set of standards used for TV broadcasting via cable networks, satellite, or terrestrial. One of the widely adopted standards of DVB is the DVB-S2 broadcast channel. To support satellite based broadband telecommunication services a Return Channel (DVB-RCS/2) specifications has been introduced. TC-BROADCAST reviews the technical specifications proposed by DVB and then the specifications are published by ETSI. One of the limitations of DVB specifications is their proprietary features at the levels of radio access, protocol stack, and architecture. This has resulted in interoperability problems among satellite access networks from different solution vendors, and it has led to a fragmented SatCom market.

#### b: THE CONSULTATIVE COMMITTEE FOR SPACE DATA SYSTEMS (CCSDS)

CCSDS was formed in 1982 by the major space agencies of the world to provide a forum for discussing common problems in the development and operation of space data systems [33]. CCSDS has been actively developing standards for data-systems and information-systems to promote interoperability and cross support among cooperating space agencies, to enable multi-agency spaceflight collaboration (both planned and contingency) and new capabilities for future missions. The CCSDS standardization work reduces the cost of spaceflight missions by allowing cost sharing between agencies and cost-effective commercialization. CCSDS has six technical areas with twenty-three working groups. The working body responsible for defining communications standards is the Space Link Service, composed of six working groups. It defines two main links between earth and space probes: telemetry and telecommand. The Space Internetworking Services Area (SIS) supports the work of the CCSDS by providing services and protocols to address networked interactions of many forms: - between spacecraft and earth-based resources, - among spacecraft, - between spacecraft and landed elements, and - within heterogeneous spacecraft.

#### c: THE AIRLINES ELECTRONIC ENGINEERING COMMITTEE (AEEC)

Develops engineering standards and technical solutions for avionics, networks, and cabin systems that foster increased efficiency and reduced life cycle costs for the aviation community [34]. Their standardization work is overseen by the subcommittee Network Infrastructure and Security. This committee works on developing IP-based standards for connectivity and security suitable for aircraft and enabling fleet-wide solutions using open standards for reduced complexity, higher reliability, increased flexibility, lower development costs, longer lifespans, and easier configuration and maintenance. ARINC is AEEC Project Paper 848 - "Secure Broadband IP Air-Ground Interface (SBAGI)," which defines a secure communications interface method between aircraft system IP network and the a ground IP network hosted by the manufacturer of the aircraft original equipment, airline system or a 3rd party. This interface is standardized at the network level with consideration of the overall security context.

## VIII. STANDARDIZATION FOR 6G SATELLITE COMMUNICATIONS NETWORKS

Most of the standardization work carried out by 3GPP and other standardization organizations focuses on the physical and MAC layers. Consideration has also been given to defining satellite use cases and architectural options in the context of integrated satellite 5G networks. The following subsections highlight several issues that need to be considered in standardization work in order to achieve the complete integration of satellite and terrestrial 6G networks. Figure 7 summarizes these future standardization directions.

### A. MOBILITY MANAGEMENT

LEO satellites provide shorter propagation delays and higher data rates than GEO satellites. However, these advantages come with the price of frequent handover and topology changes, which yields a time-varying communication channel. Handovers in LEO SatNets are of three types:

- Intra-satellite handovers, which occur between satellite beams.
- Inter-satellite handovers, which occur between satellites.
- Inter-access network handovers (also known as vertical handovers), which occur either between satellites belonging to different access networks or from a SatNet to an ariel network or terrestrial network (or vice versa) in integrated terrestrial-NTN systems.

In 6G future networks, LEO SatNets will not only serve rural or remote areas but will also provide communication services and coverage in urban and highly populated areas.

**TABLE 6.** Summary of important standardization meeting mentioned in this paper.

| Organization | Event | Date | Description |
|---|---|---|---|
| 3GPP | Workshop on Release 18 | June 28 – July 2, 2021 | The start of 5G-Advanced, is to specify the topics of Release 18 |
| 3GPP | RAN#93-e meeting | September 2021 | This meeting to discuss how to consolidate topics into WIs and SIs and provide 'high-level descriptions' of the objectives for each topic |
| 3GPP | TSGs (#94-e) Plenary meeting | December 2021 | Approval of Release 18 package |
| WRC | WRC-19 (Sharm El. Sheikh) | October 28 to November 22, 2019 | WRC reviews and revises the Radio Regulations, the international treaty governing the use of the radio-frequency spectrum, and the geostationary- satellite and non-geostationary-satellite orbits. |
| AEEC | Ku/Ka Band Satellite (KSAT) Subcommittee Meeting | January 5-6, March 3, December 13-15, 2021. | Discusses ARINC standards for broadband satellite systems and aircraft installation provisions for Ku-Band and Ka-Band satcom equipment |

Such a scenario will lead to thousands of UE being connected to an LEO satellite and this large group of users will need to go through a frequent handover process at almost the same time. Managing the handover of thousands of users simultaneously or semi-simultaneously using conventional handover management schemes will create huge network loads. New handover management schemes are required to deal with this issue in 6G LEO SatNets.

For mobility management in IP-based networks, IETF introduced a number of protocols, such as Mobile Internet Protocol version 6 (MIPv6) and Proxy Mobile Internet Protocol version 6 (PMIPv6). However, such protocols were not designed to deal with the high topology change rate in SatNets, where everything is moving including the gNB (LEO satellite base station). A number of approaches have been proposed to address this problem [35]. Nevertheless, the concept of separating control plane and data plane of Software Defined Network (SDN) is a promising approach to efficiently manage SatNet topology.

The fast-moving footprint of LEO satellites affects the paging procedure, which is primarily related to the tracking area management. The tracking area is the satellite coverage area (footprint); it can be fixed or moving. Although the moving tracking area accommodates the LEO satellite moving footprint, it results in high paging loads that are difficult to manage by the network. In addition, supporting dual-connectivity and vertical handovers in future LEO SatNets requires novel mechanisms to provide seamless mobility in integrated 6G networks and to improve global network coverage and service.

### B. ROUTING

One very important characteristic of LEO mega-constellations is the ability of satellites to form networks and communicate with each other through ISLs [36]. Due to the frequent topology changes in an LEO SatNet, ISLs have a limited lifetime. In addition, some ISLs may get congested due to high traffic loads at certain partitions of the SatNet. Moreover, as LEO SatNets are expected to serve different types of applications, there are certain QoS requirements (e.g., packet delivery delay, packet delivery ratio) that need to be met for each type of applications. Therefore, successful data delivery will require robust routing schemes that can fulfil the QoS requirements of each application type and adapt to the unique characteristics of LEO SatNets. For example, delay-tolerant routing is suitable for delay-tolerant applications, while multi-path routing is required to support applications with high bandwidth requirements. Thus, it is crucial to develop standard routing protocols that adapt to the SatNet dynamic environment and satisfy the various user application requirements. Standards should support interoperability among the different satellite constellations and operators. Moreover, cross network routing (i.e., across satellite, aerial, and terrestrial networks) should be considered to achieve the full integration in 6G. To support efficient routing, topics such as resource allocation, network monitoring, and congestion control should be considered as part of the standardization work.

### C. ADOPTION OF SDN/NFV

The SDN/NFV paradigms will play a key role in future integrated networks. However, the use of SDN/NFV in an LEO SatNet has not yet been fully investigated. Several software-defined satellite network architectures have been proposed in the literature, such as centralized, distributed, and cluster-based [35]. Nevertheless, SDN-based solutions for SatNets should be considered in standardization works to provide compatibility and interoperability among the integrated network components and the different vendors and service providers. For instance, on-board SDN-compatible routers could be developed following a specific standard to operate on LEO satellites and provide a softwareized routing function that can adapt to changes in the dynamic environment of LEO SatNets.

NFV is going to be particularly necessary to hide the complications of integrated networks from the user side. NFV can be used in various applications, such as the virtualization of mobile base stations, content delivery networks, and platforms as a service. The virtualization of network functions deployed on general purpose standardized hardware is expected to reduce service and product introduction times as well as capital and operational expenditures. According to ETSI, an important part of the NFV environment control should be accomplished through automation and orchestration. ETSI created a separate stream, MANO, within NFV describing how flexibility should be controlled.

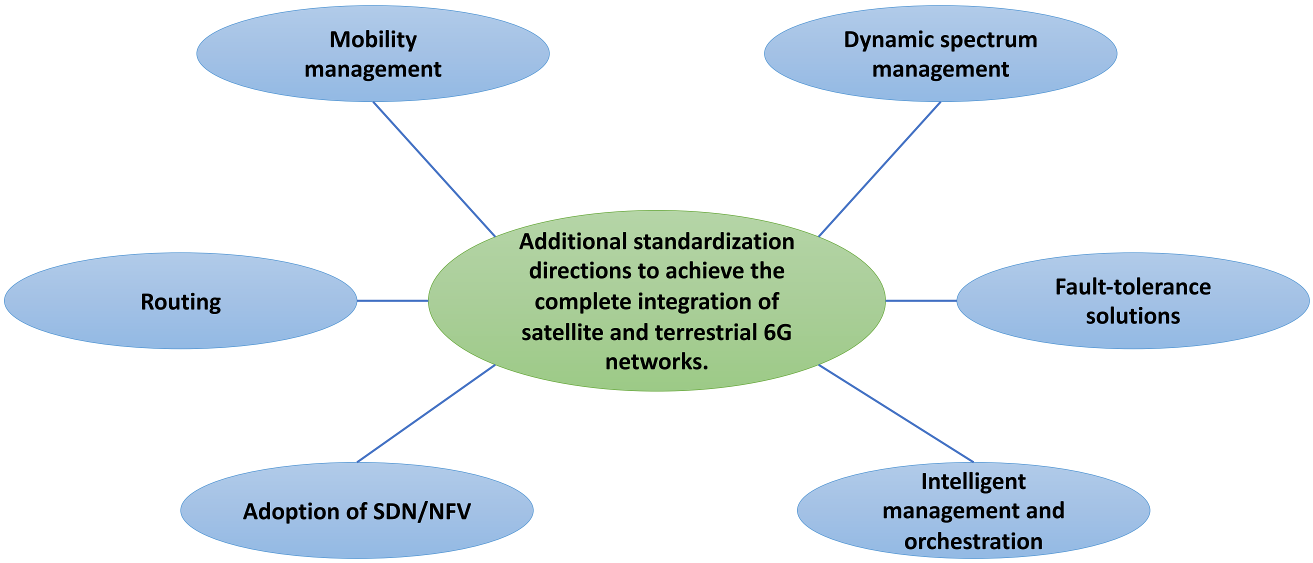



**FIGURE 7.** Additional standardization directions to achieve a full integration of SatNet and terrestrial 6G networks.

ETSI introduced a full set of standards to enable an open ecosystem where Virtualized Network Function (VNF) can be interoperable with independently developed management and orchestration systems. Many major network equipment vendors have announced support for NFV. On the other hand, major software suppliers announced that they will be providing NFV platforms to be used by equipment suppliers to build their NFV products. However, in the area of satellite networks, the adoption of these concepts and technologies is still in its infancy. Further investigations are required to identify the requirements needed to adopt NFV in SatNets. In addition, the support for NFV should be considered in the design of satellite network components.

### D. INTELLIGENT MANAGEMENT AND ORCHESTRATION

AI and ML will be an integral part of 6G networks, especially at the level of network management and orchestration. ETSI launched the Industry Specification Group (ISG) on Experiential Networked Intelligence (ENI) in February 2017 [37]. ENI is an entity that provides intelligent network operation and management recommendations and/or commands to an assisted system (i.e., an existing system leveraging the intelligent capabilities of ENI). ENI has two operation modes: Recommendation mode and Management mode. The former provides insights and advice to the operator or assisted system, whereas the latter may also provide policy commands to the assisted system [38]. In another effort to advance network automation, 3GPP introduced the concept of SON [39] where AI/ML can be applied to automate several network management functions. However, both ENI and SON concepts are still limited to the 5G context and may not be sufficiently agile in coping with the immense levels of complexity, heterogeneity, and mobility in the envisioned beyond-5G integrated networks. To support the intelligence and autonomous nature of 6G, the concept of Self-Evolving Network (SEN) was presented in [40], [41]. SEN considers the integrated architecture of 6G and beyond. SEN utilizes AI/ML to make future integrated networks fully automated, and it intelligently evolves with respect to the provision, adaptation, optimization, and management aspects of networking, communications, computation, and infrastructure nodes' mobility. SEN can be adopted to support real-time decisions, seamless control, intelligent management in SatNets to achieve high-level autonomous operations. Nevertheless, SEN is quite a recent concept and has not yet been considered by standardization organizations.

### E. FAULT-TOLERANCE SOLUTIONS

Satellite network environment is very vulnerable to faults and malfunctioning that are difficult to fix while the satellite being in space. Satellites communication functionality might get disabled which makes the satellite be as a dead node in the network. In addition, upgrading a satellite base station is not as easy as upgrading a terrestrial base station [42]. Moreover, the satellite scarce power supply my disturbs the normal telecommunication functionality. Therefore, the satellite network design should be based on the concept of fault-tolerance in order to maintain the survivability of the network. In addition, the satellite related standardization activities should support the fault-tolerance concept in future densely deployed satellite networks.

### F. DYNAMIC SPECTRUM MANAGEMENT

Dynamic and efficient spectrum management is important in SatNets due to the pervasive growth of wireless communications and the ever-increasing demands by bandwidth-hungry UE [43]. The problem of spectrum scarcity is one of the key challenges facing future SatNets as more satellites are deployed and more applications are emerging. The factors of unpredictable user mobility and satellite mobility make dynamic spectrum allocation necessary but difficult as well. Dynamic spectrum allocation needs to be considered on multiple levels to mitigate inter-cell interference in multi-beam satellite systems, inter-satellite interference, and interference between satellites and terrestrial communications when bands are shared. In addition, spectrum management must consider higher frequency bands (THz) [44] and the option of using free space optical (FSO) [45] communications as they are expected to be utilized in future SatNets. Although various kinds of static and dynamic spectrum allocation schemes have been studied by satellite researchers, this issue is not covered sufficiently in the standardization works.

## IX. CONCLUSION

To merge the ecosystems of satellite and terrestrial communications and steer the research and standardization communities from classical bent-pipe satellite systems to the mega-constellation satellite systems is not an easy task. Standardization is one of the main enablers for the integration of satellites and terrestrial networks. The 3GPP community has achieved some advancements in the NTN integration with 5G from a standardization perspective. However, more standardization efforts are needed to realize the full integration of SatNets and 5G+ on the physical layer level up to the application level.

## REFERENCES

[1] F. Jejdling, *Ericsson Mobility Report*, Nov. 2021.

[2] G. K. Kurt, M. G. Khoshkholgh, S. Alfattani, A. Ibrahim, T. S. Darwish, M. S. Alam, H. Yanikomeroglu, and A. Yongacoglu, "A vision and framework for the high altitude platform station (HAPS) networks of the future," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 729–779, 2nd Quart., 2021.

[3] *Study on Scenarios and Requirements for Next Generation Access Technologies*, 3GPP, document TR 38.913, 2017.

[4] F. Rinaldi, H.-L. Maattanen, J. Torsner, S. Pizzi, S. Andreev, A. Iera, Y. Koucheryavy, and G. Araniti, "Non-terrestrial networks in 5G & beyond: A survey," *IEEE Access*, vol. 8, pp. 165178–165200, 2020.

[5] S. C. Burleigh, T. De Cola, S. Morosi, S. Jayousi, E. Cianca, and C. Fuchs, "From connectivity to advanced internet services: A comprehensive review of small satellites communications and networks," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–18, Mar. 2019.

[6] A. Guidotti, S. Cioni, G. Colavolpe, M. Conti, T. Foggi, A. Mengali, G. Montorsi, A. Piemontese, and A. Vanelli-Coralli, "Architectures, standardisation, and procedures for 5G satellite communications: A survey," *Comput. Netw.*, vol. 183, Dec. 2020, Art. no. 107588.

[7] A. Guidotti, A. Vanelli-Coralli, M. Conti, S. Andrenacci, S. Chatzinotas, N. Maturo, B. Evans, A. Awoseyila, A. Ugolini, T. Foggi, L. Gaudio, N. Alagha, and S. Cioni, "Architectures and key technical challenges for 5G systems incorporating satellites," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2624–2639, Mar. 2019.

[8] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5G from space: An overview of 3GPP non-terrestrial networks," *IEEE Commun. Standards Mag.*, vol. 5, no. 4, pp. 147–153, Dec. 2021.

[9] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, "Satellite communications in the new space era: A survey and future challenges," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 1, pp. 70–109, 4th Quart., 2021.

[10] *Technical Specification Group Radio Access Network, Study on New Radio (NR) to Support Non-Terrestrial Networks (NTN)*, 3GPP, document TR 38.811, 2020.

[11] *Technical Specification Group Services and System Aspects, Study on Using Satellite Access in 5G, Stage 1*, 3GPP, document TR 22.822, 2018.

[12] *Technical Specification Group Services and System Aspects, Study on Architecture Aspects for Using Satellite Access in 5G*, 3GPP, document TR 23.737, 2021.

[13] *Technical Specification Group Services and System Aspects, Study on Management and Orchestration Aspects with Integrated Satellite Components in a 5G Network*, 3GPP, document TR 28.808, 2021.

[14] *Solutions for NR to Support NTN*, 3GPP, document TR 38.821, 2021.

[15] *3GPP SA WG, Update to 5GSAT: Integration of Satellite Access in 5G*, document SP-180326, 3GPP, 2020.

[16] *Advanced Plans for 5G*. Accessed: Feb. 23, 2022. [Online]. Available: https://www.3gpp.org/news-events/2210-advanced_5g

[17] Telesat. *Telesat Lightspeed*. Accessed: Feb. 23, 2022. [Online]. Available: https://www.telesat.com/

[18] S. Cakaj, "The parameters comparison of the '*Starlink*' LEO satellites constellation for different orbital shells," *Frontiers Commun. Netw.*, vol. 2, pp. 1–15, May 2021. [Online]. Available: https://www.frontiersin.org/article/10.3389/frcmn.2021.643095

[19] Y. Lee and J. P. Choi, "Performance evaluation of high-frequency mobile satellite communications," *IEEE Access*, vol. 7, pp. 49077–49087, 2019.

[20] I. Leyva-Mayorga, B. Soret, M. Röper, D. Wübben, B. Matthiesen, A. Dekorsy, and P. Popovski, "LEO small-satellite constellations for 5G and beyond-5G communications," *IEEE Access*, vol. 8, pp. 184955–184964, 2020.

[21] H. Chung, J. Kim, G. Noh, S. H. Won, T. Choi, and I. Kim, "Demonstration of service continuity based on multi-connectivity with cellular and satellite access networks," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2021, pp. 1400–1402.

[22] O. Kodheli, A. Guidotti, and A. Vanelli-Coralli, "Integration of Satellites in 5G through LEO constellations," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–6.

[23] *Technical Specification Group Radio Access Network, NR, Study on Integrated Access and Backhaul*, 3GPP, document TR 38.874, 2019.

[24] *ITU M Series*. Accessed: Feb. 23, 2022. [Online]. Available: https://www.itu.int/rec/R-REC-M/en

[25] *World Radiocommunication Conferences (WRC)*. Accessed: Feb. 23, 2022. [Online]. Available: https://www.itu.int/en/ITU-R/conferences/wrc/Pages/default.aspx

[26] A. Ford, C. Raiciu, M. J. Handley, O. Bonaventure, and C. Paasch, *TCP Extensions for Multipath Operation with Multiple Addresses*, Standard RFC 8684, Mar. 2020. [Online]. Available: https://rfc-editor.org/rfc/rfc8684.txt

[27] *European Telecommunications Standards Institute (ETSI)*. Accessed: Feb. 23, 2022. [Online]. Available: https://www.etsi.org/standards#Pre-defined%20Collections

[28] *5G Infrastructure Public Private Partnership (5G PPP)*. Accessed: Feb. 23, 2022. [Online]. Available: https://5g-ppp.eu/european-vision-for-the-6g-network-ecosystem/

[29] *Electronic Communications Committee's (ECC)*. Accessed: Feb. 23, 2022. [Online]. Available: https://cept.org/ecc/groups/ecc/wg-fm/fm-44/client/introduction/

[30] *The Integration of Satellite Communications and 5G/Beyond 5G*, Nat. Inst. Inf. Commun. Technol. (NICT), Tokyo, Japan, 2021.

[31] *An IEEE 5G and Beyond Technology Roadmap-1st Edition*, IEEE International Network Generations Roadmap—Satellites, IEEE Future Networks, 2020.

[32] *An IEEE 5G and Beyond Technology Roadmap-2nd Edition*, IEEE International Network Generations Roadmap—Satellites, IEEE Future Networks, 2021.

[33] *The Consultative Committee for Space Data Systems (CCSDS)*. Accessed: Feb. 23, 2022. [Online]. Available: https://public.ccsds.org/about/default.aspx

[34] *Airlines Electronic Engineering Committee (AEEC)*. Accessed: Feb. 23, 2022. [Online]. Available: https://www.aviation-ia.com/articles/aeec-sets-standards

[35] T. Darwish, G. Kurt, H. Yanikomeroglu, G. Lamontagne, and M. Bellemare, "Location management in IP-based future LEO satellite networks: A review," 2021, *arXiv:2101.08336*.

[36] Q. Chen, G. Giambene, L. Yang, C. Fan, and X. Chen, "Analysis of inter-satellite link paths for LEO mega-constellation networks," *IEEE Trans. Veh. Technol.*, vol. 70, no. 3, pp. 2743–2755, Mar. 2021.

[37] *ETSI Experiential Networked Intelligence Industry Specification Group (ENI ISG)*. Accessed: Feb. 23, 2022. [Online]. Available: https://www.etsi.org/technologies/experiential-networked-intelligence

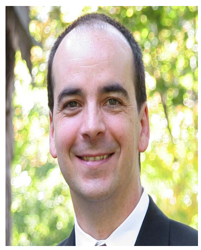
[38] Y. Wang, R. Forbes, U. Elzur, J. Strassner, A. Gamelas, H. Wang, S. Liu, L. Pesando, X. Yuan, and S. Cai, "From design to practice: ETSI ENI reference architecture and instantiation for network management and orchestration using artificial intelligence," *IEEE Communications Standards Magazine*, vol. 4, no. 3, pp. 38–45, Sep. 2020.

[39] *Technical Specification Group Services and System Aspects, Telecommunication Management, Self-Organizing Networks (SON) Concepts and requirements*, 3GPP, document TS 32.500, 2020.
[40] T. Darwish, G. K. Kurt, H. Yanikomeroglu, G. Senarath, and P. Zhu, "A vision of self-evolving network management for future intelligent vertical HetNet," *IEEE Wireless Commun.*, vol. 28, no. 4, pp. 96–105, Aug. 2021.
[41] A. Farajzadeh, M. G. Khoshkholgh, H. Yanikomeroglu, and O. Ercetin, "Self-evolving integrated vertical heterogeneous networks," 2021, *arXiv:2106.13950*.
[42] S. Wang, Y. Zhao, and H. Xie, "SN-FFC: Improving survivability of LEO satellite network with forward fault correction," in *Proc. ACM SIGCOMM Conf. Posters Demos*, 2018, pp. 90–92.
[43] Y. Liang, J. Tan, H. Jia, J. Zhang, and L. Zhao, "Realizing intelligent spectrum management for integrated satellite and terrestrial networks," *J. Commun. Inf. Netw.*, vol. 6, no. 1, pp. 32–43, 2021.
[44] K. Tekbıyık, G. K. Kurt, A. R. Ekti, A. Görçin, and H. Yanikomeroglu, "Reconfigurable intelligent surfaces empowered THz communication in LEO satellite networks," 2020, *arXiv:2007.04281*.
[45] A. U. Chaudhry and H. Yanikomeroglu, "Free space optics for next-generation satellite networks," *IEEE Consum. Electron. Mag.*, vol. 10, no. 6, pp. 21–31, Nov. 2021.

**TASNEEM DARWISH** (Senior Member, IEEE) received the M.Sc. degree (Hons.) in electronics and electrical engineering from the University of Glasgow, U.K., in 2007, and the Ph.D. degree in computer science from Universiti Teknologi Malaysia (UTM), Malaysia, in 2017. From 2017 to 2019, she was a Postdoctoral Fellow at UTM. From 2019 to 2020, she was a Research Associate at Carleton University, Canada. In 2020, she started working as a Postdoctoral Fellow at Carleton University on a collaborative project with MDA Space to investigate mobility management in future LEO satellite networks. She is currently a Postdoctoral Fellow at the Department of Systems and Computer Engineering, Carleton University. Her current research interests include mobility management in future LEO satellite networks, edge/fog computing and data offloading in HAPS, vehicular *ad-hoc* networks, and intelligent transportation systems. She was a recipient of the UTM Alumni Award for Science and Engineering, in 2017. She was awarded the Malaysia International Scholarship (MIS), from 2013 to 2016. She is an Active Reviewer for several IEEE journals, such as IEEE INTERNET OF THINGS JOURNAL, IEEE ACCESS, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS.

**GUNES KARABULUT KURT** (Senior Member, IEEE) received the B.S. degree (Hons.) in electronics and electrical engineering from Bogazici University, Istanbul, Turkey, in 2000, and the M.A.Sc. and Ph.D. degrees in electrical engineering from the University of Ottawa, ON, Canada, in 2002 and 2006, respectively. From 2000 to 2005, she was a Research Assistant with the CASP Group, University of Ottawa. Between 2005 and 2006, she was with TenXc Wireless, Canada. From 2006 to 2008, she was with Edgewater Computer Systems Inc., Canada. From 2008 to 2010, she was with Turkcell Research and Development Applied Research and Technology, Istanbul. Between 2010 and 2021, she was with Istanbul Technical University. She is currently an Associate Professor of electrical engineering at Polytechnique Montréal, Montréal, QC, Canada. In addition, she is an Adjunct Research Professor at Carleton University. Her current research interests include space information networks, satellite networking, wireless network coding, wireless security, space security, and wireless testbeds. She is a member of the IEEE WCNC Steering Board. She is a Marie Curie Fellow and has received the Turkish Academy of Sciences Outstanding Young Scientist (TÜBA-GEBIP) Award, in 2019. She is the Chair of the IEEE Special Interest Group titled "Satellite Mega-Constellations: Communications and Networking." She is serving as an Associate Technical Editor (ATE) for *IEEE Communications Magazine*.

**HALIM YANIKOMEROGLU** (Fellow, IEEE) is currently a Professor with the Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada. His primary research interest includes wireless communications and networks. His research group has made substantial contributions to 4G and 5G wireless technologies. His group's current focus is the aerial (UAV and HAPS) and satellite networks for the 6G and beyond-6G era. His extensive collaboration with industry resulted in 39 granted patents. He is a fellow of Engineering Institute of Canada (EIC) and Canadian Academy of Engineering (CAE). He has received several awards for his research, teaching, and service, including the IEEE ComSoc Fred W. Ellersick Prize, in 2021; the IEEE VTS Stuart Meyer Memorial Award, in 2020; and the IEEE ComSoc Wireless Communications Technical Committee Recognition Award, in 2018. He is serving as the Chair for the IEEE ComSoc Technical Committees Board and the Chair for the IEEE Wireless Communications and Networking Conference (WCNC) Steering Committee. He has served as the General Chair or the TP Chair for several conferences, including three WCNCs and two VTCs. He has also served as the Chair for the IEEE's Technical Committee on Personal Communications. He is a Distinguished Speaker for both IEEE Communications Society and IEEE Vehicular Technology Society.



**MICHEL BELLEMARE** received the B.Eng. degree in communications engineering from the Université de Sherbrooke, Sherbrooke, QC, Canada, in 1986. He has gained experience in terrestrial and space wireless communications in various companies, such as Nortel Networks, Ultra Electronics, and SR Telecom. He is currently a Space Systems Architect at MDA Corporation, Sainte-Anne-de-Bellevue, QC, Canada.

**GUILLAUME LAMONTAGNE** received the B.Eng. and M.Eng. degrees from the École de Technologie Supérieure (ÉTS), Montréal, QC, Canada, in 2007 and 2009, respectively. His experience in satellite communications started through internships and research activities with the Canadian Space Agency (CSA), in 2005; and the Centre national d'études spatiales (Cnes), France, in 2006 and 2008. In 2009, he joined MDA and held various communication systems engineering and management positions before being appointed as the Director of Technology, Payloads, in 2019. Through this role, he is leading MDA's research and development activities for satellite communications as well as establishing the related long term development strategy.