IEEE

# IEEE INGR

## International Network Generations Roadmap

*2023 Edition*

# Satellite

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*An IEEE Future Networks Technology Roadmap*

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# ABSTRACT

The fifth generation (5G) wireless communication systems development has brought about a paradigm shift using advanced technologies; including softwarization, virtualization, massive MIMO, and ultra-densification, in addition to introducing new frequency bands. However, as societal needs for any form of information grow, it is necessary to satisfy the UN's Sustainable Development Goals (SDGs). Migrations to 6G and beyond systems are envisioned to provide augmented capacity, so massive IoT, with better performance relying on optimization made possible by artificial intelligence, it is absolutely necessary. Non-Terrestrial Networks (NTNs), including satellite systems, High-Altitude Platforms (HAPs), and Unmanned Aerial Vehicles (UAVs), provide the best solutions to connect the unconnected, unserved, and underserved in remote and rural areas.

Over the past few decades, Geo Synchronous Orbits (GSO) satellite systems have been deployed to support broadband services, backhauling, Disaster Recovery and Continuity of Operations (DR-COOP), and emergency services. Recently, novel non-GSO satellite systems are attracting significant interest. Within the next few years, several thousands of Low Earth Orbit (LEO) satellites and mega-LEO constellations will provide global internet services, offering user throughput comparable to terrestrial mobile or fixed access networks.

This report represents the 2023 Edition of the INGR Satellite Working Group Report, following the previous three editions [1], [2], [3]. This edition of the INGR Satellite Working Group Report addresses NTN and 6G more in detail, adding further contributions on optical wireless communications, artificial intelligence techniques, seamless handover, security, and recent standardization efforts given the prospected unification of terrestrial and NTN components of 6G.

**Key words**

Satellite Communications, Satellite Networks, Waveforms, MIMO, mmWave, OFDM, QoS, QoE, Security, Network Architecture, LEO, MEO, GEO, HAP, UAV, MEC, AI/ML, IoT, Artificial Intelligence (AI), Machine Learning (ML)

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# INGR ROADMAP

## 1. INTRODUCTION

Numerous applications and vertical network integrations, including machine-to-machine communications, mobile broadband, and virtual and augmented reality demonstrated the vast potential of the fifth-generation (5G) of wireless communications and now deployment and implementations are in progress around the world. Emerging applications, such as precision agriculture, health care, and autonomous driving cars, demand that the research into 6G and beyond must provide global connectivity and satisfy the UN's Sustainable Development Goals (SDGs). ITU estimates 2.9 billion people are offline (37% of the world's population), which shows an important recent increase in connectivity caused by the COVID emergency, but that still leaves the world's poorest regions far behind. Non-Terrestrial Networks (NTN), including satellite systems, High-Altitude Platforms (HAPs), and Unmanned Aerial Vehicles (UAVs), provide the best solution to connect the unconnected, unserved, and underserved in remote areas. These systems play a significant role in 5G and 6G as complementary solutions for ubiquitous coverage, broadcast, multi-cast provision, and emergency and disaster recovery.

This is the 2023 edition of the IEEE International Network Generation Roadmap (INGR). This edition describes various needs, challenges in achieving these needs, and potential solutions toward 6G satellite systems. This satellite roadmap report does not endorse any one solution, company, or research effort.

A list of acronyms and a reference for a suitable glossary of terms are provided at the end in Section 12.

### 1.1. 2023 Edition Update

The 2023 edition of the satellite roadmap has been revised, updated, and improved in all its parts. The most significant updates are provided in Sections 0, 0, and 9. In particular, the most significant modifications are outlined below:

- Section 0 now concentrates on the reference NTN architectures and interfaces, while the application scenarios have been moved to Section 6.2.
- Section 5.4 on PHY-layer issues now includes optical wireless communications and their adoption in the NTN context, including challenges, needs, and solutions.
- Section 0 on Artificial Intelligence (AI) and Machine Learning (ML) has been improved with the survey of more techniques for both supervised and unsupervised learning.
- Section 5.7 on edge computing has been revised and updated to better cover network virtualization, computation offloading, MEC, caching, orbital computing, etc.
- Section 0 on security now includes considerations on zero-trust architectures for NTN.
- Section 5.10 on network management has been revised and some parts removed. New contributions have been added to deal with seamless handover issues and user mobility support for NTN.
- Section 6.2 deals with use cases, referring to architecture implications considering various cases with satellite backhaul, direct satellite, and IoT.

- Section 9 on conclusions, recommendations, and future work has been completely revised and updated to align with the new contents of this report.
- Finally, Appendix B has been updated with the recent progress made by 3GPP with NTN standardization (Release 17) and details on the expectations on NTN for Releases 18 and 19.

All the aspects included in this 2023 edition of the satellite report are strategic for the satellite industry.

## 2. WORKING GROUP VISON

Satellite communications and, in general, NTN have impressive momentum today. These systems encompass aerial technologies at different altitudes and with different characteristics in terms of coverage and propagation delays. In particular, we will consider solutions provided by satellites in Low-Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO). Especially, LEO systems are very popular, being deployed with constellations of thousands of satellites, or “mega-LEO” constellations. In addition to satellites, we can also consider UAVs and HAPs that can provide more focused coverage and represent a good solution for low-cost local / regional coverage. NTN systems are part of the 5G/6G standardization established by 3GPP Release 17, frozen in June 2022.

Unlike traditional network, network analysis, planning, and optimization will be updated from two dimensions to three dimensions (3D), where the heights of communications nodes are also considered.

The vision of successful technology within the next ten years with high bandwidth, low latency, and dense connectivity results in the verticals shown in Table 1.

*Table 1. Verticals and Drivers (Source: S. Kota, Keynote Talk, EAI WiSAT 2020)*

| *Verticals* | *Drivers* | *Enablers* |
|---|---|---|
| **Healthcare** | • Remote and rural diagnosis<br>• Surgery and treatment | • Video streaming<br>• VR / AR / mixed reality<br>• Advanced robotics<br>• THz band communications |
| **Autonomous Cars** | • Advanced sensors<br>• Laser scanners<br>• THz arrays for 3D images | • Terrain mapping<br>• Route optimization<br>• Safety |
| **Manufacturing** | • Intelligent industrial automation<br>• Novel sensing | • Autonomous equipment<br>• Data analytics<br>• Massive IoT |
| **Precision Agriculture** | • Non-Terrestrial Networks<br>• Ubiquitous wireless access | • Soil moisture measurements<br>• Precise monitoring of plant illness, temperature, humidity |
| **Education** | • Remote access<br>• Imaging processes | • Video streaming<br>• AR / VR / XR |
| **Smart Infrastructure** | • Intelligent communications<br>• Powerline communication | • IoT sensor networks<br>• Pervasive AI<br>• Automation |
| **Non-Terrestrial Networks** | • MEO / LEO constellation<br>• UAV, HAP<br>• Navigation systems | • Space IoT<br>• Terrestrial off loading<br>• AI/ML |
| **Smart City** | • Intelligent traffic management<br>• Traffic offloading<br>• Monitoring | • Mobile edge computing<br>• AI/ML |

| *Verticals* | *Drivers* | *Enablers* |
|---|---|---|
| **Space-Based Hosting Services** | • Ultra-low latency web services<br>• Rural access to global knowledge base | • Emergence of high bandwidth satellites<br>• Deployment of ultra-dense LEO / MEO satellite networks<br>• Enhanced computing and storage capability of various types of satellites platforms |
| **Satellite-based IoT Services** | • Low latency satellite-based IoT service provisioning<br>• Low-cost low-delay operations<br>• Rural and suburban coverage | • Agricultural sensor networks<br>• Marine sensor networks<br>• Remote monitoring |

New satellite components will be implemented to make satellite systems successful in the next ten years. Note that the evolution of satellite technology is commonly slower than terrestrial communication technologies because of the time required for building and deploying satellites. That said, the life cycle of satellite technology is longer than that of terrestrial wireless technologies.

The satellite industry must address the following issues to reach the target of 6G successfully:

- New innovation business models for effective end-to-end costs of the systems, including space, ground terminals, gateways, and user equipment
- Spectrum sharing challenges and interference mitigation technologies between existing GSO and non-GSO systems
- Adaptive coding and modulation methods for atmospheric attenuation at high-frequency bands
- Performance and cost tradeoffs for the inter-satellite links vs. number of gateways for the mega-constellations of LEO systems
- Engaging virtualization for satellite resource sharing as well as introducing federated satellite networking concepts
- How to best integrate satellite and terrestrial networks; possibly through Software Defined Networking (SDN) and Network Function Virtualization (NFV)
- Unification of the satellite (NTN) and terrestrial systems
- Integrated network architecture to meet new service needs with expected QoS / QoE requirements
- Integrating the different aerial components in the future network architectures, including non-GSO Systems, UAV, and HAPs
- Exploitation of pervasive Artificial Intelligence (AI) and Machine Learning (ML) techniques
- Address new aspects of network management (resources, routing, handover, and mobility) and mobile edge computing and their impact on system design

Civil society will benefit from satellite 5G/6G networks as these systems will complement terrestrial systems, extending the coverage of new services into unconnected areas and providing broadband services worldwide. In addition, the satellite 5G/6G will be the only option for global monitoring of remote areas via terrestrial sensors for environment conditions, global tracking, remote plant monitoring, security, and safety, to name a few. Satellite 5G/6G will make it possible to provision new services on a global scale and better Key Performance Indicators (KPI) to terrestrial 5G/6G in particularly critical scenarios (emergency, terrestrial network congestion), fulfilling the expectations of the UN's SDGs.

The application areas where current satellite communication networks play a crucial role are illustrated in Figure 1. We expect these uses to continue and be augmented in the Beyond 5G (B5G) era [4].

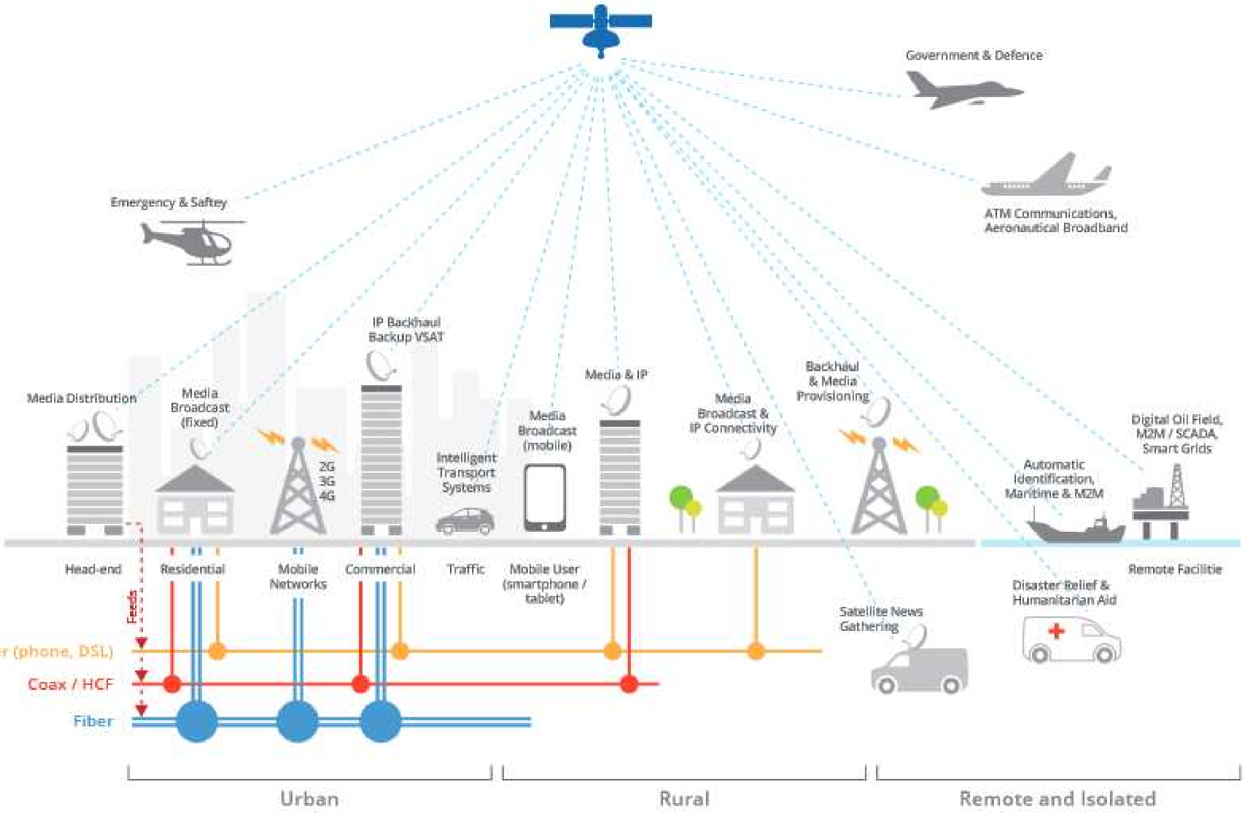


*Figure 1. Communications Application Domains Typically Addressed by Satellite Networks (Source: ESOA 5G Whitepaper) [4]*

There are three service scenarios classified in 5G/6G, which are enhanced Mobile BroadBand (eMBB), Ultra-Reliable and Low-Latency Communications (URLLC), and massive Machine-Type Communications (mMTC). The eMBB scenario is aimed mainly at further evolution of broadband services, such as high-quality video streaming and big data cloud storage. Thus, the technical focus of eMBB is improving the spectrum efficiency and data rate. The URLLC scenario is for low-latency and for reliability-critical services such as remote surgery, industry automation, driving safety, metaverse, and digital twin. As the name suggests, it focuses on guaranteeing transmission latency and reliability. The mMTC scenario is mainly for dense machine-type communications, such as body monitoring and smart city, focusing on energy efficiency and network capacity [5].

ITU (and others) have categorized wireless communication services with the use case triangle illustrated below in Figure 2 [6]. Note that a general characteristic changes along each edge of Figure 2's triangle as one approaches a vertex. Satellite communications provide a suitable solution when users are remote, moving, or have otherwise challenged terrestrial connectivity (for instance, needing simultaneous broadcast to millions).

When Figure 2 use cases are served terrestrially, the service design will generally build a system that suits the required Average Traffic Density (ATD), primarily by changing cell size, frequency allocations and using MIMO. When these use cases are served by satellite, achievable ATD is limited due to the relatively large satellite coverage. Improving these traffic density limits (for instance, via terrestrial caching and retransmission or by very dynamic satellite link coverage and capacity modification) is a key part of the required development for B5G satellite communications systems.

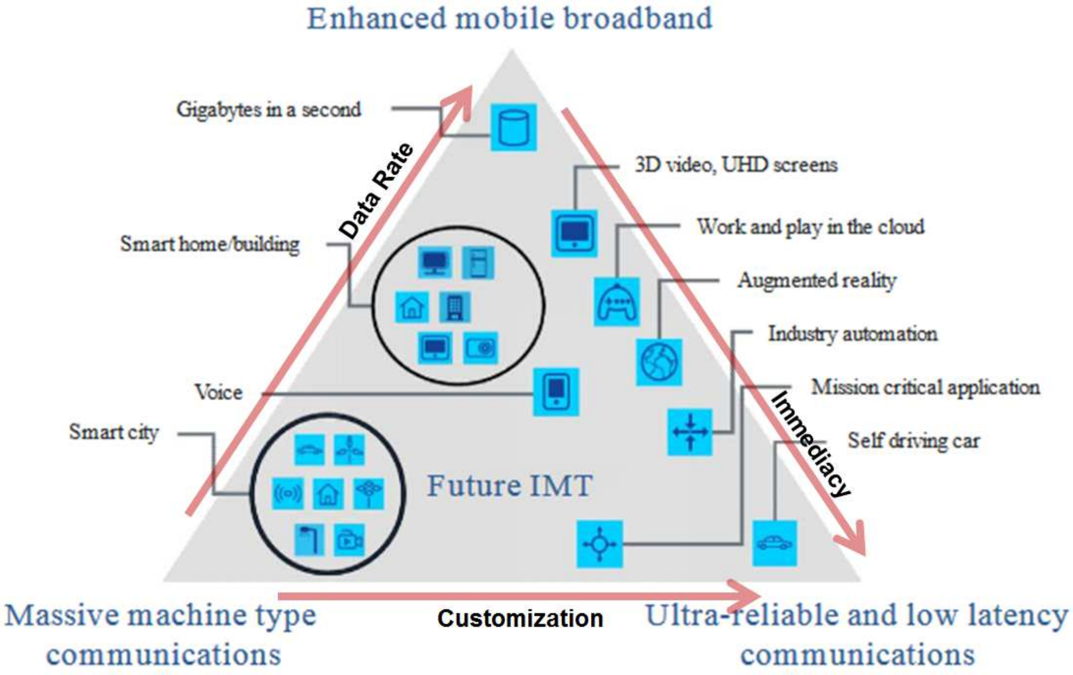


*Figure 2. Modern Wireless Use Cases (Source: IMT-2020 / 1-E, Enhanced by Present Authors)* [6]

ITU has established the Network 2030 group to develop the next-generation wireless network, basically B5G/6G systems. Their report is available in the summer of 2023.

In the emerging 6G era, network services will continue to evolve with the key features of intelligence, complexity, dynamics, and customization. 6G is envisioned as a technology convergence network of information-communication-data where big data and AI are fundamental components, i.e., native AI. A soaring number of intelligent services, such as networked robots, cognitive Internet of Things (IoT), self-driving vehicles, and digital twins, will require abundant networked AI capability.

## 2.1. Scope of Working Group Effort

Table 2 describes various topics covered in this 2023 edition.

*Table 2. Topics and Descriptions*

| *Topic* | *Scope* |
|---|---|
| **Applications and Services** | 5G/6G satellite applications for urban, rural, and remote areas. There is a need to expand from the current 5G to the future 6G applications and services. New services, such as space-based hosting services or lowering the latency of web services over Non-Terrestrial Networks (NTN) can be considered. |
| **Reference Architectures** | A total of 12 use cases are discussed, including backhaul services over LEO / MEO / GEO satellites, UAV, and HAPs. Further, 22 use cases for direct access to satellite and NTN networks are also discussed. Six physical layer scenarios for LEO-based satellite-IoT scenarios were also discussed. Three reference architectures of 5G/6G satellites, including non-virtualized for the near-term (3 years), separately virtualized for the mid-term (5 years), and integrated virtualized for the long-term (10 years) are described. |
| **mmWave Adoption in Satellite System** | The use of the mmWave band (Q/V/W) has been investigated to cope with the spectrum demand of the next generation of satellite networks. |
| **Antenna and Payload** | Various antenna systems for ground stations, satellite feeder links, user links, inter-satellite links, and end-users are briefly discussed. |
| **Machine Learning and Artificial Intelligence** | Classification of ML techniques for non-terrestrial networks is described. |
| **Edge Computing** | Computation offloading, MEC caching, deployment, and orchestration are discussed. |
| **QoS / QoE** | QoS and QoE are discussed in terms of propagation delay and architecture. |
| **Security** | Secure air interface, network architecture, trust management, end-to-end security management, etc., are addressed in this report. |
| **Network Management** | Mobility management, radio resource management, and routing are described. SDN and NVF are discussed. |
| **Standardization** | The current status of 3GPP, ITU, ETSI, and IEEE standardization activities on satellite 5G/6G, including NT, are discussed. |

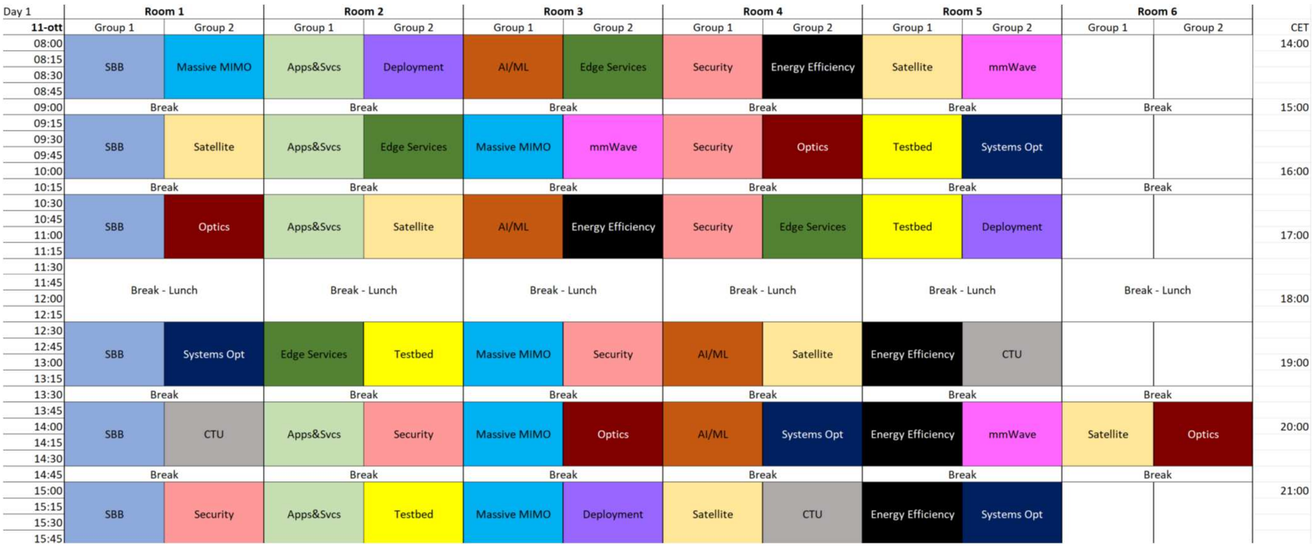
## 2.2. Linkages and Stakeholders

The various topics discussed in this roadmap, along with needs, challenges, and potential solutions, will guide the industry, government, operators, and standard organizations. Some of the stakeholders are identified below.

- Industry manufacturers and operators – e.g., Avanti, iDirect, Lockheed Martin, Loral Space, O3B, OneWeb, SES, SpaceX, TeleSat, ViaSat
- User communities
- Regulators – e.g. Federal Communications Commission (FCC)
- Space Agencies – e.g., NASA, ESA, ISRO, DLR, JAXA
- Governments – Defense Information Systems Agency (DISA)

- Standard Development Organizations (SDOs) – e.g., IEEE, Internet Engineering Task Force (IETF), International Telecommunication Union – Radio Sector (ITU-R), Telecommunication Sector (ITU-T), Third-Generation Partnership Project (3GPP), European Telecommunication Standards Institute (ETSI), 5G Public Private Partnership (5GPPP), as well as research institutions and laboratories.

The satellite working group interacts with other areas in INGR, as shown in Figure 3, which provides the details of the cross-meetings carried out by the different working groups.



| Day 1 | Room 1 | | Room 2 | | Room 3 | | Room 4 | | Room 5 | | Room 6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11-ott | Group 1 | Group 2 | Group 1 | Group 2 | Group 1 | Group 2 | Group 1 | Group 2 | Group 1 | Group 2 | Group 1 | Group 2 | CET |
| 08:00 | SBB | Massive MIMO | Apps&Svcs | Deployment | AI/ML | Edge Services | Security | Energy Efficiency | Satellite | mmWave | | | 14:00 |
| 08:15 | | | | | | | | | | | | | |
| 08:30 | | | | | | | | | | | | | |
| 08:45 | | | | | | | | | | | | | |
| 09:00 | Break | | Break | | Break | | Break | | Break | | Break | | 15:00 |
| 09:15 | SBB | Satellite | Apps&Svcs | Edge Services | Massive MIMO | mmWave | Security | Optics | Testbed | Systems Opt | | | |
| 09:30 | | | | | | | | | | | | | |
| 09:45 | | | | | | | | | | | | | |
| 10:00 | | | | | | | | | | | | | 16:00 |
| 10:15 | Break | | Break | | Break | | Break | | Break | | Break | | |
| 10:30 | SBB | Optics | Apps&Svcs | Satellite | AI/ML | Energy Efficiency | Security | Edge Services | Testbed | Deployment | | | |
| 10:45 | | | | | | | | | | | | | |
| 11:00 | | | | | | | | | | | | | 17:00 |
| 11:15 | | | | | | | | | | | | | |
| 11:30 | Break - Lunch | | Break - Lunch | | Break - Lunch | | Break - Lunch | | Break - Lunch | | Break - Lunch | | |
| 11:45 | | | | | | | | | | | | | |
| 12:00 | | | | | | | | | | | | | 18:00 |
| 12:15 | | | | | | | | | | | | | |
| 12:30 | SBB | Systems Opt | Edge Services | Testbed | Massive MIMO | Security | AI/ML | Satellite | Energy Efficiency | CTU | | | |
| 12:45 | | | | | | | | | | | | | |
| 13:00 | | | | | | | | | | | | | 19:00 |
| 13:15 | | | | | | | | | | | | | |
| 13:30 | Break | | Break | | Break | | Break | | Break | | Break | | |
| 13:45 | SBB | CTU | Apps&Svcs | Security | Massive MIMO | Optics | AI/ML | Systems Opt | Energy Efficiency | mmWave | Satellite | Optics | |
| 14:00 | | | | | | | | | | | | | 20:00 |
| 14:15 | | | | | | | | | | | | | |
| 14:30 | | | | | | | | | | | | | |
| 14:45 | Break | | Break | | Break | | Break | | Break | | Break | | |
| 15:00 | SBB | Security | Apps&Svcs | Testbed | Massive MIMO | Deployment | Satellite | CTU | Energy Efficiency | Systems Opt | | | 21:00 |
| 15:15 | | | | | | | | | | | | | |
| 15:30 | | | | | | | | | | | | | |
| 15:45 | | | | | | | | | | | | | |

*Figure 3. Map of Cross-Team Meetings Showing Working Group Interactions*

# 3. TODAY'S LANDSCAPE

## 3.1. Current State of Technology and Research

Geostationary satellites at 36,000 km above the earth are currently used as High Throughput Satellite (HTS) systems. An HTS provides a capacity (throughput) many times that of a traditional satellite system (HTS delivering up to 200 Gbps). HTS can provide more than 50 Mbps capacity to individual customers. Today's novel satellite systems are planned under the name of Very High Throughput Satellite (VHTS) systems with 500 Gbps of capacity and Ultra-High Throughput Satellite (UHTS), achieving capacities larger than 1 Tbps. Some VHTS systems are:

- ViaSat-2 satellite (launched in 2017): Ka band GEO satellite, 40 gateways (GWs), 300 Gbps total network capacity.
- Viasat-3 (launched in 2023): Three Ka band GEO satellites, over 100 GWs, more than 100 Mbps residential internet service, enabling 4K ultra-high-definition video streaming, up to 1 Gbps for maritime use.
- Inmarsat's Global Xpress (GX) network: Ka band satellite system made of Inmarsat-5 GEO GX satellites; GX5 satellite (2019) meets the growing demand across Europe and the Middle East for aviation and commercial maritime; GX5 satellite uses 6 GWs, has 89 small Ka band beams, six fully steerable beams to point at traffic hotspots. GX5 will allow download speeds of more than 60 Mbps with a latency of around 600 ms.
- Eutelsat Konnect is a very-high-throughput satellite (VHTS) communication satellite. It was successfully launched by an Ariane 5 rocket from the Guiana Space Center. Eutelsat Konnect satellite will deliver high-speed broadband and mobile connectivity across Europe, North Africa, and the Middle East. It has a capacity of 500 Gbps in the Ka band.

However, non-GSO such as Medium Earth Orbits (MEO) and LEO systems have recently brought further innovation into satellite systems since they substantially reduce the delay time at which information is provided as compared to what is possible with GSO satellites. This promising breakthrough of connecting the unconnected and Earth Stations in Motion (ESIM) providing high bandwidth internet services to aircraft, ships, and land vehicles form the landscape to reap the benefits of the digital economy is in high demand. Currently operating and future planned non-GSO systems are shown in Table 3.

*Table 3. Current and Planned Non-GSO Systems [7] with Updates by Authors*

| ***Characteristics*** | ***Other 3 Billion O3b (SES)*** | ***Starlink (SpaceX)*** | ***Lightspeed (Telesat)*** | ***Amazon (Kuiper)*** | ***OneWeb (to be Merged with Eutelsat)*** |
|---|---|---|---|---|---|
| Data Rate | 1 Gbps | Download 100 Mbps (median, tests Q4 2022)<br>Upload 16 Mbps (median, tests Q4 2022) | Download (min, req.): 50 Mbps<br>Upload (min, req.): 10 Mbps | Download: 400 Mbps (Prototype 2021) | Download up to 150 Mbps (tests 2023)<br>Upload of 30-70 Mbps (tests 2023) |

| ***Characteristics*** | ***Other 3 Billion O3b (SES)*** | ***Starlink (SpaceX)*** | ***Lightspeed (Telesat)*** | ***Amazon (Kuiper)*** | ***OneWeb (to be Merged with Eutelsat)*** |
|---|---|---|---|---|---|
| No. of Satellites | 20 MEO satellites (second generation, called mPOWER system, has started its deployment with planned up to 24 MEO) | 3912 as of April 2023 with first- and second-generation satellites (FCC application up to 42000 satellites) | 2 launched (198 planned) | Planned to 3236 (FCC application up to 7774) | 583 as of March 2023, Planned 648 |
| Latency | 150 ms | Tests Q4 2022: 40-60 ms | Expected 30-50 ms | Low latency | Below 100 ms |
| Orbit/Altitude | MEO equatorial ring / 8063 km / no ISLs | LEO circular orbits with five shells at 540-570 km + 340 km | LEO / 78 polar orbit satellites (1015 km) and 1100 inclined orbit satellites (1325 km) | LEO / 590-630 km (3 shells) | LEO near-polar circular orbits / 1200 km / no ISLs in the first generation |
| Frequency Band | Ka | Ku, Ka, and E for next-generation | C, Ka, Ku | Ka | Ka, Ku |
| Scheduled Status | 2013-2019 (2022-mPOWER) | 2020 | Deploying satellites in 2025 | 2026-2029 | End of 2022 |

The current landscape is not only inclusive of non-GSO systems, but also constituted by Non-Terrestrial Networks (NTNs) that are composed of UAVs and HAPs. There are currently several case studies of non-terrestrial connectivity deployments in different countries. Recently, HAPs technology is acquiring an important role in 5G/6G satellite integration.

The term HAPS refers to a communication platform in the stratosphere (e.g., 18-24 km above the ground) that can utilize solar power to operate for several months without disturbances and provide connectivity for a large area with a diameter of up to 200 km. There are three classes of HAPS: (1) Balloons (e.g., Alphabet's Loon [8]) have limitations on the payload weight and available power and have the problem of having no means to control their position over a specific area. (2) Fixed-wing platforms (e.g., Stratospheric Platforms, Airbus Zephyr, and Thales Stratobus) [9] have larger weight, power, and flight time capabilities than balloons. (3) Airships (e.g., Sceye) are the widest platforms, exceeding 100 m in length and 30 m in height, with a payload weight of several hundred kg, powered above 10 kW, and autonomy for up to one year.

The HAPs can be solar or hydrogen-powered [10] and can fly in an energy-efficient fashion to lift the heaviest possible payload, including cameras, radar, and gNodeBs for many applications.

## 3.2. Drivers and Technology Targets

MEO satellites flying at an altitude between 8,000-20,000 km and LEO satellites flying at an altitude between 400-2,000 km provide latencies of 5-50 ms for LEO and 100-150 ms for MEO, respectively. In summary, advances in satellite design, manufacturing, and launch (reusable) service capabilities have enabled the design and future deployment of non-GSO Fixed Satellite Service (FSS) constellations. New generations of GEO satellites are taking advantage of these developments, allowing launch of low-cost, lightweight, and highly-flexible spacecraft. Furthermore, significant steps have been made to offer commercial mission-extension services to all satellites, especially those in GEO orbits.

Additionally, advances in antenna and ground terminal technology have enabled the usage of 50/40 GHz frequency bands for both GSO FSS networks and non-GSO FSS networks.

HAPs can be used to provide fixed broadband connectivity and mobile user connectivity for backhauling traffic. HAPs typically fly at 20-50 km altitude and provide broadband connectivity and telecommunication services to particularly underserved and rural communities, especially those in remote areas. This use of HAPs has become more viable due to technological evolution, such as advances in solar panel efficiency, battery energy density, lightweight composite materials, and antennas. The other frequency-sharing challenges of the non-terrestrial networks are discussed in Section 0 of the report.

## 3.3. Satellite 5G Deployment Challenges from the Market Standpoint

Post-pandemic, the resurgence in focus on satellite connectivity was incredible in 2022 with an optimistic outlook. Investment in NTN technology increased considerably. This was particularly evident at 2023's Consumer Electronics Show (CES) event in Las Vegas and the Mobile World Congress (MWC) event in Barcelona, with several new product announcements for satellite connectivity in 5G and a wide variety of connectivity to ground-based services directly to mobile handsets, satellite antennae, and backhaul solutions at a reduced cost.

### 3.3.0. LEO Expansion

The expansion of LEO constellations has continued unabated for the past few years. SpaceX continues to launch LEO satellites with the Falcon reusable rockets, launching over 50 CubeSats for Starlink and other suppliers. CubeSats are built to standard dimensions (Units or U) of 10 cm x 10 cm x 10 cm. They can be 1U, 2U, 3U, or 6U in size and typically weigh less than 1.33 kg (3 lbs) per U. NASA's CubeSats are deployed from a Poly-Picosatellite Orbital Deployer (P-POD). Starlink is aimed at creating a high-speed, low-latency broadband internet network accessible in remote and rural locations across the globe. Starlink is the global market leader in the LEO networks, with over 3,000 satellites in operation. Their residential broadband service is available globally, with new countries signing up monthly. Starlink now claims more than 400,000 customers worldwide.

UK's OneWeb has launched over 500 satellites, nearing its expected goal. Lync and AST SpaceMobile have similarly expressed satisfaction with the progress. In the US, FCC granted permission for Kuiper (Amazon) to enter the market for satellite services.

The ongoing war in Ukraine drove a need for satellite coverage to help Ukraine keep connectivity intact despite its infrastructure coming under constant attack. Satellite providers (including Starlink) stepped in to enable emergency broadband communications.

### 3.3.1. Connectivity Technical Innovation

There is an increase in the commercial adoption of hybrid satellite-terrestrial connectivity. In 2022, 3GPP Release Version 17 was published. New chipsets supporting 3GPP Release 17 for mobile handsets and devices are coming from leaders such as Qualcomm (Snapdragon Satellite), Samsung, and Mediatek. Qualcomm launched an Iridium-supported satellite chipset that enabling support for lower-power, low-latency connections.

For LPWAN, new technologies that provide terrestrial and satellite connectivity through a single communication RF chipset are emerging. For example, the LoRa Edge LR1120 chipset supports sub-GHz LoRa, SATCOM S band, and 2.4 GHz LoRa. Incumbent satellite operators such as Inmarsat, Iridium, ORBCOMM, and Globalstar contribute more than 80% of global satellite IoT connectivity revenues. However, emerging start-ups offering low-power and low-cost IoT connectivity through LEOs, based on small satellite constellations, are expected to gain ground and may account for approximately 20% of the global market by 2026.

### 3.3.2. Direct Services to the User Device

New niche players such as Skylo (partnered with Globalstar) and Bullit (UK phone vendor for rugged outdoor use, sold under the brands of Caterpillar and Motorola) are providing direct voice and messaging capabilities from handsets directly via satellite over LEO and GEO. Apple launched limited emergency calling and texting with the iPhone 14 in mid-2022 in partnership with Globalstar.

Single-communication RF chipset supporting terrestrial and satellite connectivity can also be implemented on existing IoT devices through a firmware upgrade with no or minimal hardware changes, allowing vendors to leverage existing certifications, devices, and ecosystems. For example, Sateliot and OQ have developed similar solutions that enable existing NB-IoT devices to communicate via satellite, requiring only a firmware update to the devices without any changes to the hardware or antenna.

Significant investments are also ongoing in the MEO and GEO segments. In partnership with Boeing Commercial Satellite Systems, SES O3B is targeting the MEO segment for lower latency services.

The industry awaits the emergence of Amazon Kuiper, expecting a major constellation launch of over 3,000 satellites over the next few years.

### 3.3.3. HAPS

High-altitude platforms (HAPS) significantly extend coverage in many parts of the world where circumstances and regulations allow. Remote connectivity is still an issue in the UK, with large parts of the rural countryside having poor coverage. British Telecom (BT) has partnered with Stratospheric Platforms Ltd (SPL) to perform trials of HAPS-based technology to boost rural mobile coverage.

BT is looking ahead to using hydrogen-powered aircraft to deliver mobile signals to difficult-to-reach consumer and business customers. In this initial stage, it is testing the technology using a tall building, carrying out trials at its R&D facility in Adastral Park alongside SPL, using the latter's HAPS kit, specifically antenna technology designed to be mounted on a HAPS vehicle. HAPS vehicles sit in the stratosphere, above the flight paths of aircraft, but some way below LEO satellites.

In Japan, Softbank has launched a HAPSMobile network provided in the sky, which makes it possible to build a broad service area of 200 km in diameter and provide network connectivity services in the sky.

### 3.3.4. Concerns — Space Congestion

The congested LEO segment in low earth space is a commonly voiced concern. There is yet, other than ITU, little regulation of LEO orbits. As more players enter the market, there is a concern that collisions may occur if preventative actions are not reinforced. For now, it seems there is enough space for all.

Space pollution is also an ongoing concern. The astronomy community's voice is being largely ignored. Ground-based space telescopes' field of vision is being negatively affected as each space train of LEO satellites gets launched. One task made more hazardous by the deployment of such a large of LEO satellites is the identification of potential earth-bound meteorites or asteroids.

### 3.3.5. Satellite Industry Consolidation

As in any other successful field, the balance between higher efficiency obtained through consolidation and market monopoly is beginning to come under attention in the fast-growing LEO-supported networks. One major potential acquisition is that of Inmarsat by Viasat. The European Commission has opened an in-depth investigation into Viasat’s proposed acquisition of Inmarsat, fearing it might harm competition in the in-flight connectivity market. In February 2023, The UK’s Competition and Markets Authority gave provisional approval for the deal. INTELSAT and SES are also in discussions about a possible merger.

Since 2017, the cost charge per Mbit/sec over satellite has been reduced by 40% or more, depending on the service type. Satellite interconnectivity is disrupting the more traditional communication market. The old perception of a satellite being “niche” and expensive is being challenged. Satellite networks are now perceived as a real affordable alternative for global communications, particularly in regions where connectivity is challenging or non-existent. As a result, the global market opportunity has attracted new partnerships between Tier-1 Telecom players (Vodafone, Verizon, AT&T, T-Mobile, Apple, Microsoft) and satellite players (AST SpaceMobile, Amazon Project Kuiper, OneWeb, SpaceX, Globalstar, SES).

### 3.3.6. The Unconnected

In November 2021, the International Telecommunications Union (ITU) released a report estimating 37% of the world’s population has never used the internet. Throughout 2022, the possibilities for connectivity of populations and enterprises in remote areas continued to improve with increasing capacity coming online using a growing number of constellations, increasing number of service providers, reduced costs, and technical innovation further enhanced by the partnership between satellite providers, Tier-1 telecom providers, and cloud hyper-scalars.

### 3.3.7. Chinese Satellite Market

With the continuous progress of key technologies in China’s satellite industry, the market size has been driving continuous growth in recent years. The size of China’s satellite application market in 2021 was 435.4 billion yuan (about 61 billion US$), an increase of 8.9% year-on-year. The scale of China’s satellite application industry is expected to increase to 552.58 billion yuan in 2023. The satellite communication market will grow to 78.37 billion yuan in 2022. Regarding the segmented application market of communication satellites, the market size of mass consumer communication services is 63.45 billion yuan, accounting for 81% of the overall market. The market size of satellite fixed communication services is 11.65 billion yuan, accounting for 15% of the overall market. The mobile communication market has a scale of 3.28 billion yuan, accounting for 4% of the overall market. In addition, according to the constellation spectrum application submitted by China Satellite Network to ITU, China Satellite Network plans to build a huge constellation system (sometimes referred to as the “Guowang” or national network) consisting of 12,992 LEO satellites.

### 3.3.8. Various Headlines of March 2023

At the beginning of March 2023, the EU defined a €6 billion LEO project called IRIS, essentially designed to reduce the continent’s reliance on Starlink et al. EU seeks new solutions to address the growing need for governmental services that ensure resilient connectivity to support their security operations, connect critical infrastructures beyond EU borders (e.g., Arctic region or Africa), manage crises, and support border and maritime surveillance.

OneWeb has been launching satellites at an impressive rate. The 17th lunch of 40 satellites on March 9, 2023, brings the total OneWeb constellation to 582 satellites. The third launch with SpaceX represents the penultimate mission for achieving global coverage.

Efforts to incorporate 3GPP's NTN standard into upcoming smartphones is ramping up, enabling direct satellite-to-phone communications. In late February 2023, rugged phone brands Cat and Qualcomm announced satellite-capable devices. Viasat partnered with Ligado to offer Direct-to-Device (D2D) services via the latter's SkyTerra satellite network.

German operator Deutsche Telekom plans to start using satellite to ensure full global coverage for its IoT offering. The company is working with Intelsat and Skylo to add satellite to its existing terrestrial IoT networks – including NB-IoT, LTE-M, 4G, and 5G – to create what it calls a "global network of networks". It has successfully tested several use cases and plans to launch a commercial offer in the second quarter of 2023. Expected applications include networking wind turbines in remote regions, recording water levels and weather data, and providing broadband connections at sea.

Samsung announced that it will build phone components that connect directly to satellites. Samsung also said its Exynos-based satellite services will support two-way text messaging and high-definition image and video sharing. That would be an important development considering today's phone-to-satellite services generally support only slow-speed emergency messaging.

LEO firm Sateliot has teamed up with Gospace Labs to connect the latter's IoT solution to monitor the water quality with a testing kit via 5G satellite networks that would act as an early warning system. Gospace water management IoT solution monitors contaminants in water by measuring pH acidity levels, temperature, water flow, and water level when deployed in specific areas, such as bridges. Hooking it up to Sateliot's 5G satellite constellation will allow the system to ping a notification alert when "unusual situations occur" such as floods or unsafe drinking water.

Elon Musk's satellite telecoms operation Starlink has reportedly sent out emails to start a global roaming service, allowing a Starlink user to connect from almost anywhere on land in the world.

Switzerland's Salt has struck a deal with SpaceX, Elon Musk's satellite broadband company, to offer its customers mobile usage beyond the reach of traditional cellular networks, backup coverage, and direct connections when roaming abroad via the networks of participating carriers. Rural areas, such as the Great Aletsch Glacier area in Valais and the Canton of the Grisons, look set to benefit from the deal. Customers, says Salt, can use the service on their handset without extra equipment or changes.

China is testing terahertz space communication technologies and 6G communications with experimental satellites. China recently announced it had started working on 6G using IoT as one of its main drivers.

# 4. FUTURE STATE (2033)

## 4.1. Vision of Future Technology

The novel 6G systems will support new societal needs as per the UN's SDGs, which cannot be fully satisfied by the 5G systems. The 6G network is envisioned to be pervasively intelligent, reliable, and scalable, providing global broadband connectivity integrating terrestrial networks, NGSO, UAVs, and HAPs. According to one source [11], possible 6G high-level use cases are:

- Holographic-Type Communication (HTC)
- Extended Reality (ER)
- Tactile Internet
- Digital Twin
- Pervasive Intelligence
- Intelligent Transport and Logistics
- Enhanced Onboard Communications
- Satellite for IoT and Earth observation
- Global Ubiquitous Connectability.

Future 6G systems will adopt new technologies, such as:

- Mega constellations and mixed orbit constellations, providing 3D networks
- Use of mmWave frequency bands and optical links
- Space communications and IoT
- Pervasive use of Machine Learning / Artificial Intelligence (ML/AI) paradigms
- Tactile Internet
- Advanced security schemes based on quantum satellites.

The development targets of the 6G network are shown in Figure 4. The peak data rate is expected to reach from 100 Gb/s to 1 Tbps, 10 to 100 times larger than the present 5G network. The latency is expected to decrease to 0.1 ms, only a tenth of that of 5G networks. Other targets include higher positioning accuracy, higher energy efficiency, extreme ultra-reliability, larger connectivity density, and longer battery lifetime. Beyond the three main scenarios of eMBB, URLLC, and mMTC in the 5G network, new application scenarios are proposed for the 6G network.

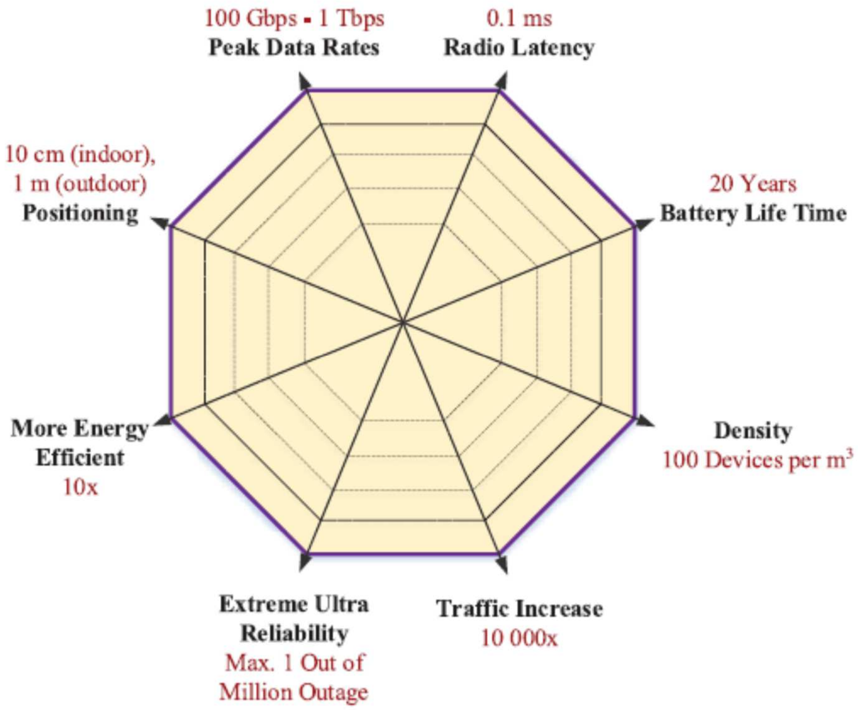


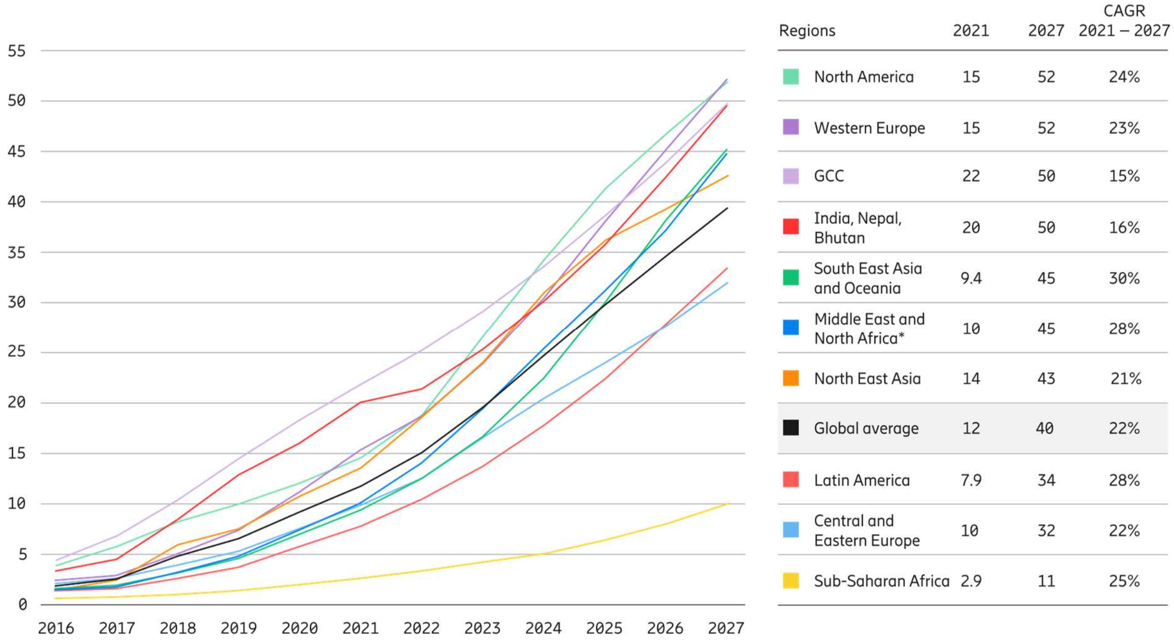
*Figure 4. 6G Key Performance Indicators (KPIs)* [12]

Table 4 provides KPIs, comparing 5G and 6G (referring to terrestrial systems).

*Table 4. KPIs (Source: N. Rajatheva et al., White Paper on Broadband Connectivity in 6G)*

| ***KPI*** | ***5G*** | ***6G*** |
|---|---|---|
| **Peak data rate** | 20 Gbps | 1 Tbps |
| **Experienced data rate** | 0.1 Gbps | 1 Gbps |
| **Peak spectral efficiency** | 30 bps/Hz | 60 bps/Hz |
| **Experienced spectral efficiency** | 0.3 bps/Hz | 3 bps/Hz |
| **Maximum bandwidth** | 1 GHz | 100 GHz |
| **Area traffic capacity** | 10 Mbps/m$^2$ | 1 Gbps/m$^2$ |
| **Connection density** | $10^6$ devices/km$^2$ | $10^7$ devices/km$^2$ |
| **Energy efficiency** | Not specified | 1 Tb/J |
| **Latency** | 1 ms | 100 µs |
| **Reliability (PER)** | $10^{-5}$ | $10^{-9}$ |
| **Jitter** | Not specified | 1 µs |
| **Mobility** | 500 km/h | 1000 km/h |

Due to the proliferation of rich-video applications, enhanced screen resolution, Machine-to-Machine (M2M) communications, mobile cloud services, etc., the global mobile traffic will continuous to increase in an explosive manner, up to 5016 EB (Exa = $10^{18}$) per month in the year 2030 compared with 62 EB per month in 2020 [13]. The terrestrial user trend, estimated by Ericsson for future years *(see Figure 5)*, shows an exponential increase in all the regions. This motivates multiple parties' interest in the 6G satellite systems because they're complementary with terrestrial networks and the opportunity of assuring service continuity in those areas that terrestrial systems cannot cover easily or at all. It will likely be difficult for terrestrial 5G/6G systems to accommodate the tremendous volume of mobile traffic in 2030 and beyond.



| Regions | 2021 | 2027 | CAGR 2021 – 2027 |
|---|---|---|---|
| ■ North America | 15 | 52 | 24% |
| ■ Western Europe | 15 | 52 | 23% |
| ■ GCC | 22 | 50 | 15% |
| ■ India, Nepal, Bhutan | 20 | 50 | 16% |
| ■ South East Asia and Oceania | 9.4 | 45 | 30% |
| ■ Middle East and North Africa* | 10 | 45 | 28% |
| ■ North East Asia | 14 | 43 | 21% |
| ■ Global average | 12 | 40 | 22% |
| ■ Latin America | 7.9 | 34 | 28% |
| ■ Central and Eastern Europe | 10 | 32 | 22% |
| ■ Sub-Saharan Africa | 2.9 | 11 | 25% |

* All Middle East and North Africa figures include GCC countries.

*Figure 5. Ericsson Mobility Report: Mobile Data Traffic Outlook* [13]

## 4.2. Architectural Framework and Reference Architecture

Table 5 provides a reference architectural framework for near-term (three years), mid-term (five years), and long-term (ten years). These architectures are detailed in Section 4.2.2.

*Table 5. Challenges Architectural Framework*

| | ***Near-term (3 years)*** | ***Mid-term (5 years)*** | ***Long-term (10 years)*** |
|---|---|---|---|
| Reference architectural description | RA-1: Non-virtualized 5G satellite networks | RA-2: Separate virtualized 5G satellite networks | RA-3: Integrated virtualized 5G satellite networks |
| Key feature of the reference architecture | Satellite segment as a traffic carrier or tunnel for the UE / SBS traffic to the rest of the 5G infrastructure | Satellite networks and 5G terrestrial networks virtualized separately | Satellite networks and 5G terrestrial networks virtualized and integrated |

### 4.2.1. Non-Terrestrial Elements Considered

We focus on the following NTN elements: Low Altitude Platforms (LAPs), High Altitude Platforms (HAPs), Low Earth Orbit (LEO) satellites, Medium Earth Orbit (MEO) satellites, Geostationary Orbit Satellites (GEO), and Highly Elliptical Orbit (HEO) satellites. Figure 6 illustrates the NTN elements. Table 6 represents the approximate orbital altitude.

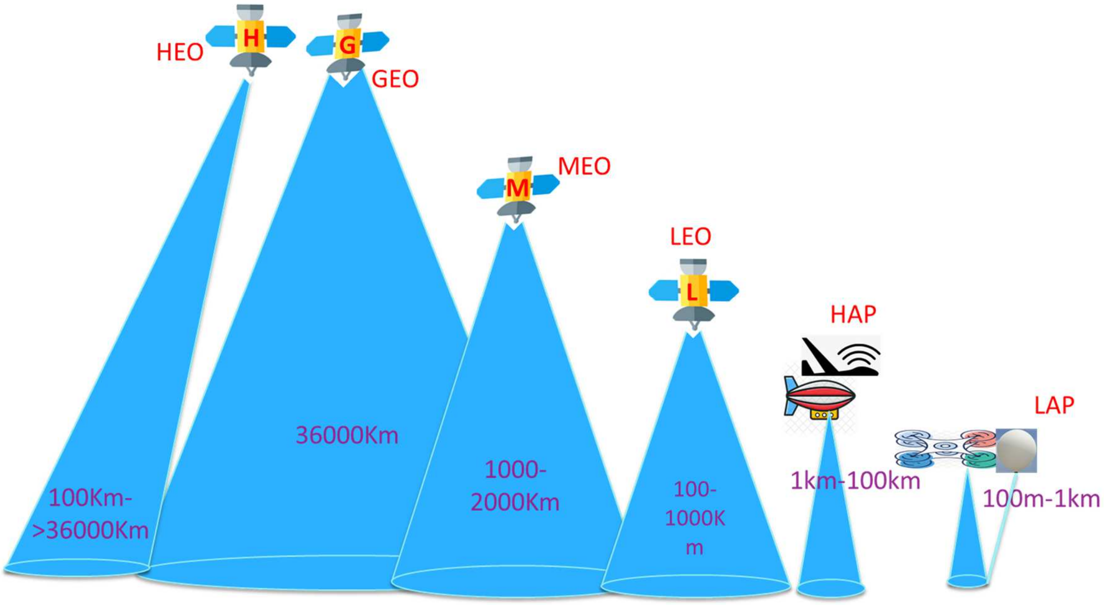


*Figure 6. Non-Terrestrial Network Elements Considered in this Report*

*Table 6. NTN Elements and Altitude Range*

| ***Type of NTN*** | ***Name*** | ***Approximate orbital altitude*** |
|---|---|---|
| LAP | Low Altitude Platforms (UAVs belong to this category) | 100 m – 1 km |
| HAP | High Altitude Platforms | 1 km – 100 km |
| LEO | Low Earth Orbit satellites | 100 km – 1000 km |
| MEO | Medium Earth Orbit satellites | 1000 km – 2000 km |
| GEO | Geostationary Orbit Satellites | 36000 km |
| HEO | Highly Elliptical Orbit satellites | 100 km to > 36000 km |

Figure 7 illustrates cases studies that include Low Altitude Platforms (LAPs), High Altitude Platforms (HAPs), Low Earth Orbit (LEO) satellites, Medium Earth Orbit (MEO) satellites, Geostationary Orbit Satellites (GEO), and Highly Elliptical Orbit (HEO) satellites. This figure also illustrates interface codes that will be further expanded in Sections 4.2.2 and 0.

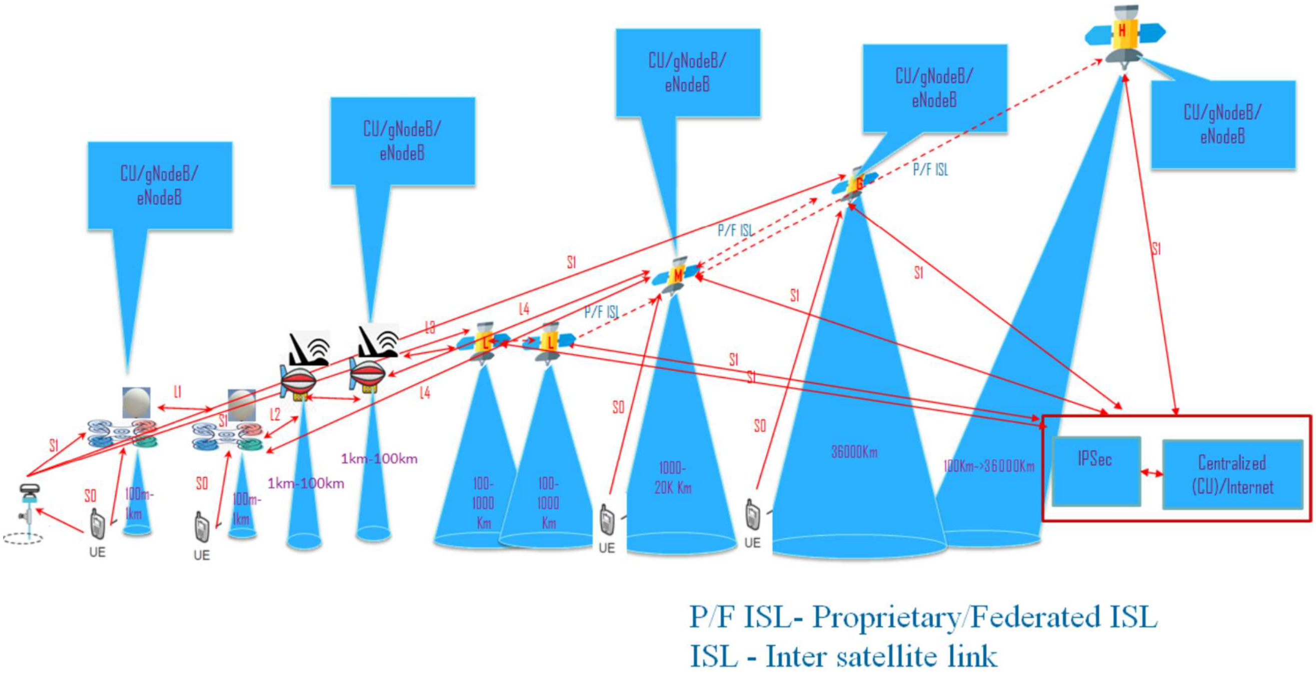


*Figure 7. Representation of Use Cases Addressed in the Following Subsections*

### 4.2.2. Reference Architectures

One of the most important aspects of 5G satellite integration is the Reference Architecture (RA). This report considers three RAs *(see Table 5)* with non-virtualized satellite network (Reference Architecture-1, RA-1), separate virtualized satellite network (RA-2), and integrated virtualized 5G satellite networks (RA-3). RA-1, RA-2, and RA-3 correspond to the near-term, mid-term, and long-term architectural requirements. In RA-2 and RA-3, several use cases can be considered as per the implementation of the Management and Network Orchestration (MANO) modules.

Table 7 shows the relationship between the satellite 5G interfaces defined in TR 38.821 Rel. 16 and those considered in this document. Section 0 presents alternative scenarios and use cases where these interfaces are presented and used.

*Table 7. Interface Equivalence: this Satellite Roadmap vs. 3GPP 38.821 Rel. 16 for 5G Satellite Integration*

| ***No.*** | ***Interface defined in this INGR Satellite Edition 2 (Sx: S stands for interfaces relevant to the satellite segment)*** | ***Connectivity (bi-directional)*** | ***Equivalent links or traffic for these links in 5G terrestrial networks should be carried*** | ***Closely related link specified in 3GPP TR 38.821 Rel. 16 (2019-12)*** | ***Remarks*** |
|---|---|---|---|---|---|
| 1 | S1 | DU-LEO, STBS-LEO, LEO-CU, and LEO-Ground station. | F1, N1, N2, and N3 | The closest interfaces are NR-Uu, $N_G$, NGU, and F1 over SRI, which runs over the S1 interface of this document transparently. Satellite Radio Interface (SRI) is used in 3GPP TR 38.821 Rel 16 instead of S1. | Equivalent standards from other organizations, such as ITU, may be considered for this specification. However, IEEE Standardization is also a possibility. MIMO capability can also be considered. |
| 2 | S2 | Inter-satellite link for enabling Federation between satellite network operators | Not applicable | None. Only the general name Inter satellite link (ISL) is used. Xn interface, in Rel.16 document, is defined over ISL in a non-federated single service provider's satellite network. On the other hand, S2 in this document is defined across different service providers. | Standardization can be considered by IEEE to enable federation, sharing of network resources, bandwidth utilization, and lowering the cost of operation. MIMO capability can also be considered. |
| 3 | S3 | DU-HAP | Not applicable | None | Standardization can be considered by IEEE to support the use of DU to HAP link, enabling industry and lowering the cost of operation. MIMO capability can also be considered. |
| 4 | S4 | HAP-LEO | Not applicable | None | Standardization can be considered by IEEE to enable standardization of DU to HAP link, enabling industry and lowering the cost of operation.<br>MIMO capability can also be considered. |
| 5 | M1 | Terrestrial 5G MANO to Satellite MANO | Not applicable | None | IEEE INGR SDN group can work with the 5G satellite working group to define these interface specs. |

#### 4.2.2.1. Reference Architecture-1: Non-Virtualized 5G-Satellite Networks

Figure 8 and Figure 9 depict RA-1, where the 5G terrestrial networks use the existing satellite networks as a traffic tunnel or bent-pipe scheme for carrying traffic. As shown in the figure, the control and the data traffic over the interfaces N1, N2, and N3, as defined in 3GPP TS 23.501, are tunneled to the 5G control and data planes, respectively. RA-1 essentially utilizes the non-3GPP communication for the 5G user traffic.

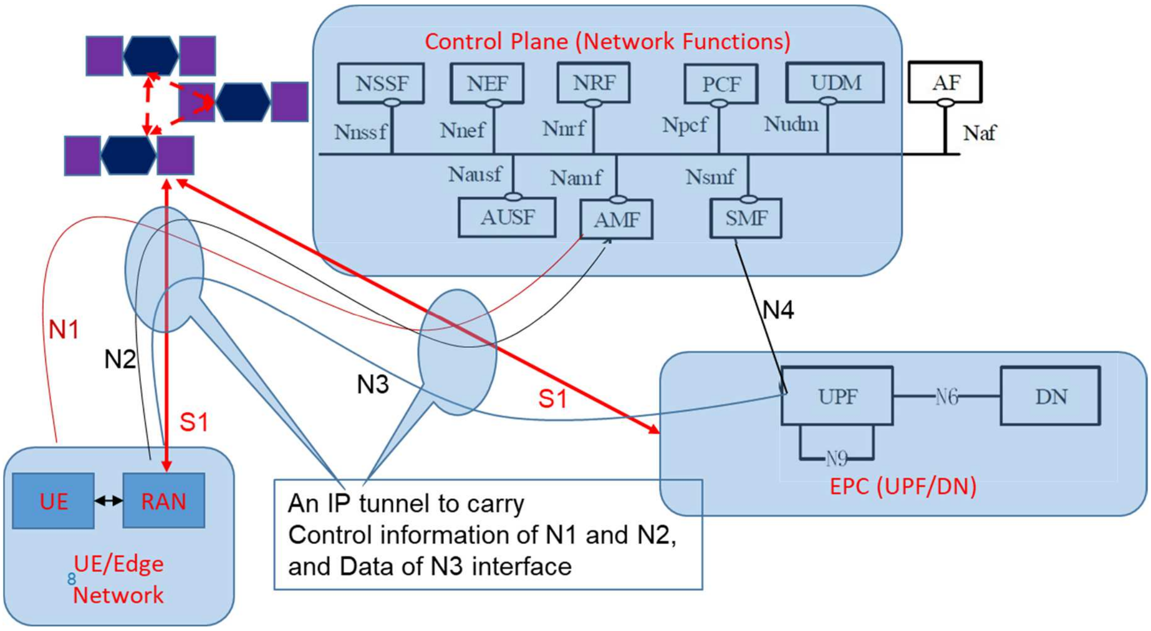


Figure 8. Reference Architecture-1: Non-Virtualized 5G Satellite Networks

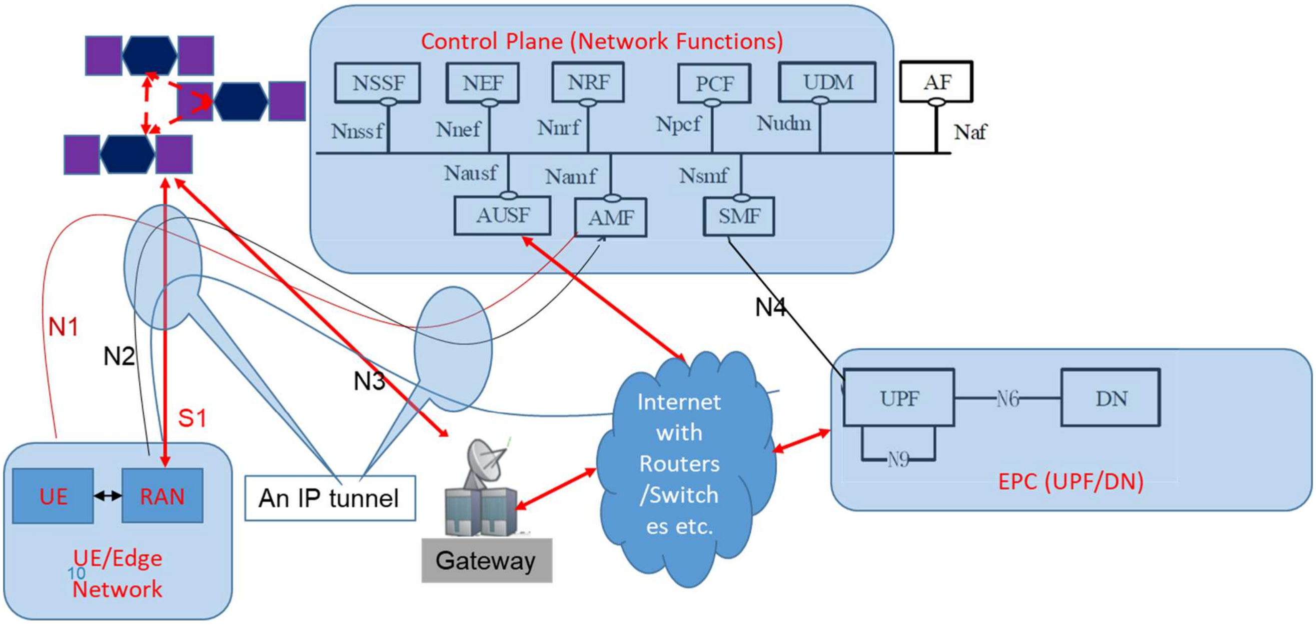


Figure 9. Different Depiction of Reference Architecture-1

#### 4.2.2.2. Reference Architecture-2: Separately Virtualized 5G-Satellite Networks

In Figure 10, the RA-2 depicts how the satellite network is a virtualized network infrastructure similar yet separated from the terrestrial 5G virtualized network. The satellite network virtualization characteristics can face different networking challenges, network function requirements, and implementation scenarios. The evolution of non-virtualized non-federated satellite networks can lead to a virtualized satellite network with federation capability beyond the existing terrestrial 5G networks in the next three to five years. The control plane design, control operations, network slicing, network functions, network interfaces, network orchestration approaches, and all such network functional aspects do not necessarily match the virtualized satellite and virtualized terrestrial 5G networks. In such a medium-term development of satellite networks, RA-2 is best suited for 5G-satellite integration.

We define two additional network functions: Satellite Edge-computing Function (SEF) and Satellite Network Federation Function (SNF) in addition to those defined as 3GPP network functions. A part of SEF is considered where the Satellite Edge Computing (SEC) framework for 5G satellite integration enables multi-layer caching and inter-satellite cache exchange [14]. Each separately virtualized network (i.e., satellite and terrestrial 5G) maintains separate MANO modules for their management activities. The interface between the satellite MANO and terrestrial 5G MANO is M1, which ensures standardized interaction between the two MANOs. The traffic from UE / edge segment comprising the data and control information carried over the interfaces N1, N2, and N3, as per the definition of 3GPP standard TS 23.501, is carried over the satellite network to the virtualized terrestrial 5G networks. An example of the SDN controller in satellite networks is described in the paper [15].

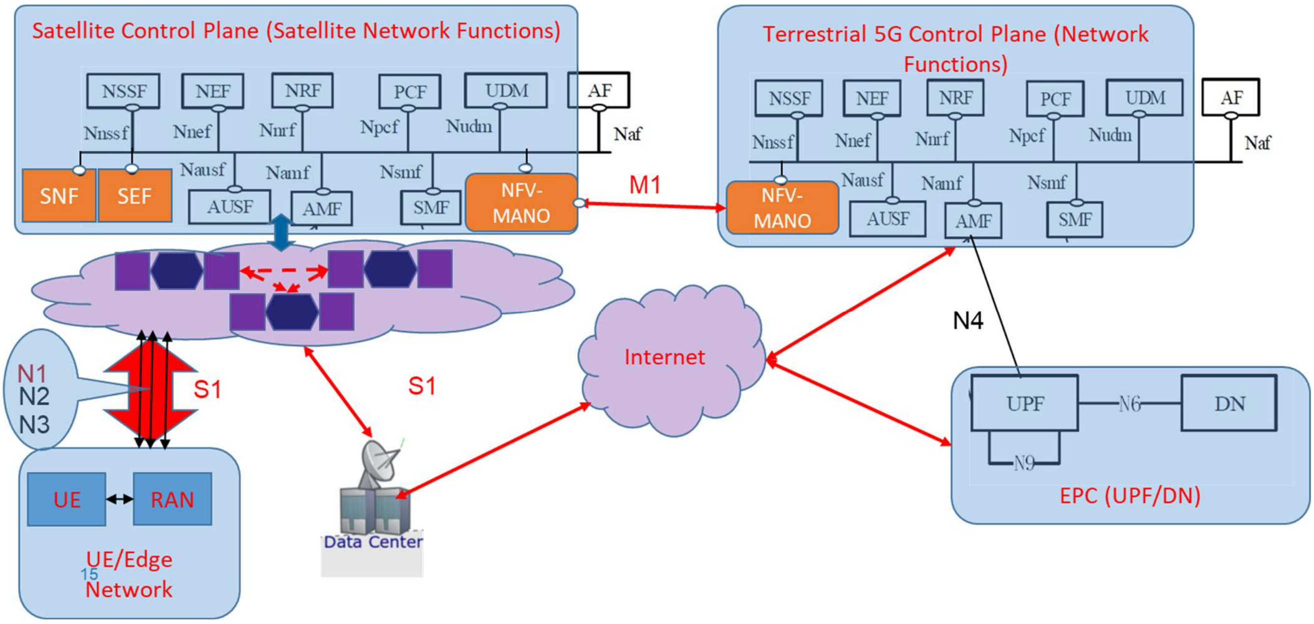


*Figure 10. Reference Architecture-2*

### 4.2.2.3. Reference Architecture-3: Integrated Virtualized 5G-Satellite Networks

In the long-term vision of the future of satellite and 5G evolution, it is expected that the two will evolve into an integrated virtualized 5G-satellite network system, as it is shown in the RA-3 in Figure 11. The integrated virtualized network infrastructure is expected to have only one MANO for the satellite and terrestrial segments. The satellite segment consists of LEO, MEO, and GEO satellites as well as UAVs and HAPs. The integrated MANO module of the network is responsible for carrying out resource management, routing packets, channel management, slice management, edge computing decisions, and federation functions.

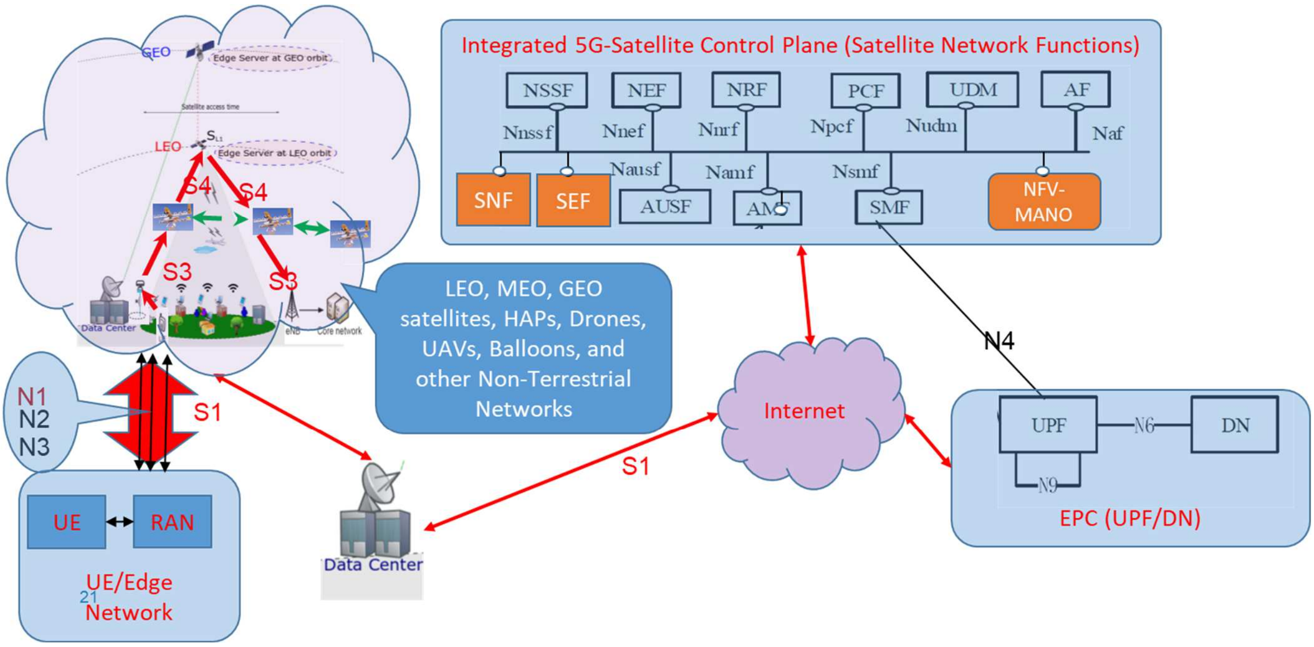


Figure 11. Reference Architecture-3

# 5. NEEDS, CHALLENGES, ENABLERS, AND POTENTIAL SOLUTIONS

## 5.1. Summary

The needs outlined for the different topics of our activity are addressed in detail in this section. This section describes challenges and solutions for the different needs identified, referring to the topics outlined in Table 2.

## 5.2. Applications and Scenarios

### 5.2.1. Challenges

The undeniable advances of fiber and terrestrial mobile networks are impacting linear video broadcast, which has been the strongest satellite communication market, displacing it with individually delivered content steered by return link analytics. The analytics are effective and help adapt the content to the users in a quasi-addictive manner that straight linear media cannot match. Particularly, younger users (for instance, “Millennials”) watch much less traditional TV (and rarely have fixed phone lines).

From these premises, one can envisage a wide range of scenarios for what will happen next. While it is impossible to elaborate on all of them here, one may elucidate several likely outcomes.

(1) The first bounding outcome is that growth in data demand (mainly driven by video customized to individual users, steered by analytics) will become so extreme (current growth rates exceeding 30% per year) as to render it unacceptable not to be connected, even when in remote locations or moving. We may call this the “broadband” scenario; the “High Throughput Satellites” and upcoming large (> hundreds of satellites) constellations address this scenario. Most of the use cases defined by ITU belong to the enhanced Mobile Broadband (eMBB) scenario.

(2) A second bounding outcome is the mMTC (massive Machine-Type Communications) IoT, where ultimately nearly everything is periodically sending data (i.e., status or readings), resulting in such large volumes across large areas that satellites must augment terrestrial wireless connections. The satellite solutions required for this are not very different from those of the broadband scenario above, although for the most affordable “Things,” one would want to use the lower frequency satellite bands, such as C band and below. One key aspect of this scenario is its diverse nature regarding types of devices, data, and location. For instance, one might want to connect all wild and domestic animals over 50 kg in mass, all public and private vehicles, all major civil installations, all homes, and possibly all people. The development and growth of this scenario is a significant evolution since the first edition of this report. It is increasingly clear that satellite communications are critical as the number of desired truly remote connections grows.

All people with smartphones are already connected and use GPS and other Global Navigation Satellite Systems (GNSS). GNSS systems are already the time reference for the world and are increasingly taken for granted in any mobile device. GNSS systems will continue to be improved. In the future, one will not get lost unless by intention.

(3) A final bounding outcome, not necessarily exclusive from those above, is a “broadcast resurgence” scenario. The broadcast resurgence can augment eMBB content choices, but is fundamentally a different mode of delivery, providing different user experiences. For broadcast resurgence, the linear media content providers take advantage of caching at the user equipment, bigger screens, immersive media (perhaps in 3D), and some standardized user equipment

analytics to deliver compelling, high-quality program content to mass markets broadly segmented by language and geography. Broadcast resurgence could be partly motivated by user privacy concerns and governmental or commercial motivations to enhance social coherence with similar content for everybody. Broadcast resurgence is perfectly viable once entire countries are connected via optical fibers but will still be an essential and quite likely scenario in lesser-developed regions where fiber to the home may still be decades away.

Latency is often considered a significant drawback for satellite links. This is certainly true for links of broadband geostationary satellites (their round trip propagation delay being about 0.5 s), but it is much reduced for the mega-constellations being launched, which can offer below 10 ms single hops. Furthermore, since the speed of light in a fiber is about 2/3 that of in free space and the lower orbit mega-constellation links may sometimes beat long-distance fiber for transoceanic links between securities trading centers.

Satellites can help 5G networks achieve sub-1 ms latency by multi-casting content to caches located at individual cells. This is one of the satellites "sweet spots" in the 5G ecosystem. Mobile Edge Computing (MEC) at these cache sites is a natural adjunct.

A possible 5G application is provided in Appendix A, with a discussion of challenges and solutions.

*Table 8. Challenges Associated with Applications and Scenarios*

| ***Near-term Challenges: 2020-2023*** | ***Description*** |
|---|---|
| Satellite for eMBB | Although the satellite is a primary broadcast medium, there are only testbeds for its contribution to eMBB |
| ***Mid-term Challenges: 2024-2025*** | ***Description*** |
| Satellite for mMTC | Costs of device deployments and system operation, battery life |
| ***Long-term Challenges: 2026-2030*** | ***Description*** |
| Satellite for URLLC | Delay issue |

### 5.2.2. Potential Solutions

*Table 9. Solutions Associated with Applications and Scenarios*

| ***Near-term Challenges: 2020-2023*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Satellite for eMBB | Linear video often also licenses content for eMB |
| ***Mid-term Challenges: 2024-2025*** | ***Potential Solutions to Mid-term Challenges*** |
| Satellite for mMTC | Standardization and initial focus on streamlined device functionalities to help economies of scale and subsequent cost reductions |
| ***Long-term Challenges: 2026-2030*** | ***Potential Solutions to Long-term Challenges*** |
| Satellite for URLLC | Caching to have data already in place, integrated MEC |

## 5.3. Architecture

### 5.3.1. Architecture for 6G-Satellite Integration

*Table 10. Overall Needs*

| ***Needs*** | ***Description*** |
|---|---|
| Need 1: Architecture for 5G-satellite integration | 5G-satellite integration requires new integration architectures to meet the traffic performance requirements and the objectives of an integrated network. |
| Need 2: To achieve federated satellite networks | Federated networking among multiple satellite network service providers can help lower costs and improve the coverage footprint. |
| Need 3: 5G-MANO to satellite-MANO interface | In the mid-term architecture, the 5G terrestrial and satellite networks interwork through the respective MANO interfaces, thereby needing a 5G-MANO to satellite-MANO interface, M1. |
| Need 4: 5G-Satellite integration interfaces | New satellite networking interface definitions are needed for 5G-satellite integration. The S1 interface defined for UE and LEO satellites is required to be developed. The interface between satellites of multiple service providers, S2, is also to be developed. |
| Need 5: Integrated 6G-satellite MANO | In the long-term architecture, the 6G terrestrial and satellite networks interwork through an integrated MANO that uses drones, HAPs, UAVs, LEO, MEO, and GEO satellite clusters in an integrated fashion. The S3 interface required for SBSs to HAPS / drones / UAVs is essential. Further, the interface between HAP / drones / UAVs and LEO satellite, S4, must be developed. |

#### ~~5.3.1.1.~~5.3.1.0. Challenges

*Table 11. Challenges Associated with Architecture for 5G-Satellite Integration*

| ***Near-term Challenges: 2020-2023*** | ***Description*** |
|---|---|
| Challenge 1: Network architecture for non-virtualized satellite-5G integration | To develop a network architecture for integrating terrestrial 5G networks with non-virtualized satellite networks |
| Challenge 2: 5G performance assurance in non-virtualized satellite networks | To ensure latency and other performance metrics expected out of 5G network services over a non-virtualized satellite network |
| Challenge 3: Satellite-5G integration interfaces | To develop S1 and S2 interface definitions / standards |
| ***Mid-term Challenges: 2024-2025*** | ***Description*** |
| Challenge 4: Satellite-5G MANO integration interfaces | To develop M1 interface between satellite MANO and terrestrial 5G MANO |
| Challenge 5: Network architecture for separately virtualized satellite-5G integration | To develop a network architecture for integrating terrestrial 5G networks with virtualized satellite networks |
| ***Long-term Challenges: 2026-2030*** | ***Description*** |
| Challenge 6: Network architecture for integrated-virtualized satellite-5G integration | To develop a network architecture for integrating terrestrial 5G networks with virtualized satellite networks |
| Challenge 7: Interfaces for SBS to HAP / UAV / drone and HAP / UAV / drone to LEO satellite | To develop S3 interface for communication between SBSs and HAP / drones / UAVs and S4 interface between HAP / UAV / drones to LEO satellites |

#### ~~5.3.1.2.~~5.3.1.1. Potential Solutions

*Table 12. Potential Solutions to Address Architecture for 5G Satellite Integration*

| ***Near-term Challenges: 2020-2023*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Network architecture for non-virtualized satellite 5G integration | The network RA-1, described in this document, is one possible solution. |
| Challenge 2: 5G Performance assurance in non-virtualized satellite networks | Ensure continuous connectivity for 5G traffic. Identify the 5G traffic flows and provide necessary resources such as bandwidth and latency-minimized path selection, thereby ensuring quality of service. |
| Challenge 3: Satellite 5G integration interfaces | Solutions can be developed by IEEE Standards Board / Committee / WG. |
| ***Mid-term Challenges: 2024-2025*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 4: Satellite-5G MANO integration interfaces | Solutions can be developed by IEEE Standards Board / Committee / WG. |
| Challenge 5: Network architecture for separately virtualized satellite-5G integration | The network RA-2, described in this document, is one possible solution. |
| ***Long-term Challenges: 2026-2030*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 6: Network architecture for integrated-virtualized satellite 5G integration | The network RA-3, described in this document, is one possible solution. |
| Challenge 7: Interfaces for SBS to HAP / UAV / drone and HAP / UAV / drone to LEO satellite | Solutions can be developed by IEEE Standards Board / Committee / WG. |

The solutions associated with each challenge are further detailed below.

- Solution to challenge 1: See the description of Reference Architecture-1 in Section 4.2.2.1.
- Solution to challenge 2: Ensuring the 5G latency and other performance requirements is very important for the integrated 5G non-virtualized satellite networks. The 5G traffic flow carried over the satellite network shall be provisioned with enough bandwidth, latency-minimized path selection, and other mechanisms for ensuring 5G QoS parameters. Using the LEO network in conjunction with UAVs, HAPs, and drones can also ensure the latency is within acceptable limits. GEO and MEO satellite network segments can be considered only if they can ensure the delay requirements. Call admission control process can be utilized to determine if the 5G requirements can be met.
- Solution to challenge 3: A solution can be developed by IEEE Standards Board / Committee / WG.
- Solution to challenge 4: A solution can be developed by IEEE Standards Board / Committee / WG.
- Solution to challenge 5: See the description of Reference Architecture-2 in Section 4.2.2.2.
- Solution to challenge 6: See the description of Reference Architecture-3 in Section 4.2.2.3.
- Solution to challenge 7: A solution can be developed by IEEE Standards Board / Committee / WG.

## 5.3.2. Architecture for LEO Satellite-based Internet of Things

### 5.3.2.1. Challenges

Table 13 provides the challenges associated with satellite IoT architecture and scenarios.

*Table 13. Challenges Associated with Satellite IoT*

| ***Near-term Challenges: 2020-2023*** | ***Description*** |
|---|---|
| Challenge 1 | Low processing capability at the edge |
| Challenge 2 | High interference |
| Challenge 3 | Low uplink SNR |
| ***Mid-term Challenges: 2024-2025*** | ***Description*** |
| Challenge 4 | Initial synchronization and large RTT |
| Challenge 5 | Frequent data generation in IoT or fast small payload transmission |
| ***Long-term Challenges: 2026-2030*** | ***Description*** |
| Challenge 6 | High Doppler shift due to low earth orbits |
| Challenge 7 | Massive random access for large IoT deployments |

### 5.3.2.2. Potential Solutions

Table 14 provides potential solutions for the challenges described in Table 13.

*Table 14. Potential Solutions to Address Satellite IoT*

| ***Near-term Challenges: 2020-2023*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Solution-1: Broadcast information signal to all the visible satellites | Broadcast information signal to all the visible satellites (motivation from LoRa architecture) [16] |
| Solution-2: Interference mitigation | Interference mitigation by successive interference cancellation along with combining schemes |
| Solution-3: Collection of data from multiple satellites | Combining information received from multiple satellites of the constellation using narrow bandwidth for IoT |
| ***Mid-term Challenges: 2024-2025*** | ***Potential Solutions to Mid-term Challenges*** |
| Solution-4: Using GNSS data for pre-compensation | Using GNSS data for pre-compensation before random access |
| Solution-5: Using transmission reduction schemes | Using transmission reduction schemes to transmit intermittently, coding schemes for small packets |
| ***Long-term Challenges: 2026-2030*** | ***Potential Solutions to Long-term Challenges*** |
| Solution-6: Autonomous TA and frequency adjustments | Autonomous TA and frequency adjustments, use GNSS data for pre-compensation, use of single carrier waveforms, extending usages of mm-wave / THz waveform designs |
| Solution-7: Use non-orthogonal or rate-splitting multiple access schemes | Use non-orthogonal or rate-splitting multiple access schemes |

## 5.4. Novel PHY Layer Options for Satellite Networks

### 5.4.1. Introduction

The subject of physical layer issues was devoted to MIMO and RF-optical systems in the second edition of the Satellite Roadmap of the IEEE International Network Generations Roadmap (INGR). The third issue was dedicated to mmWave. In the current fourth edition, we provide the latest advances in optical communications and quantum communications. Quantum computers have been able to break some of the most prominent cryptographic schemes without the aid of any artificial intelligence. So, the capacity to break cryptographic codes using quantum computers is expected to increase in the coming years. Paradoxically, one of the possible solutions to protect communications is resorting to quantum techniques. Therefore, this new roadmap version has provided an initial state of the art, challenges, needs, and solutions for quantum communications.

It should be, however, pointed out that quantum communications are based on optical communications. At least the key exchange is conducted in the optical domain. To address communications in view of this issue, we have also updated the wireless optical part provided in the second roadmap report.

The mmWave and optical-based communication strategies were proposed to complement and support the following satellite needs: capacity, robustness, and security from the physical layer point of view. However, the new generation of satellite networks will also be equipped with inter-satellite, satellite-UAV links, and satellite-to-airplane to deploy the future 3D satellite networks to provide global coverage with the lowest possible latency integrated with terrestrial networks. Moreover, it is expected that new applications, such as those based on augmented reality and/or those related to climate change monitoring, will play a key role in 6G systems. In this latter case, hybrid constellations that permit combining earth observation and communications may likely emerge. In practical terms, it will be required to use other bands to support these new services since the current C, Ka, Ku ones are quite crowded. For that reason, this edition of the IEEE INGR Satellite Report has explored the use of optical bands, while the 2022 INGR considered mmWave radio communications only as possible solutions to cope with the spectrum demand of the next generation of satellite networks.

### 5.4.2. mmWave PHY

This section is divided as follows: First, the frequency range that encompasses the mmWave band, the sub-bands it contains, its channel characteristics, and its current commercial interest are defined. Next, a review of the state-of-the-art on its theoretical background, measurement campaigns, and hardware development is provided. Finally, the challenges and the potential solutions to the main issues of the mmWave band in satellite networks are reported.

#### 5.4.2.1. Definition of the mmWave Band

By definition, the mmWave band groups all frequencies whose wavelengths falls in the range of 1-10 mm. According to ITU nomenclature, it corresponds to the Extreme High Frequency (EHF) band and encompasses the set of frequencies ranging from 30 GHz to 300 GHz. This EHF band can be subdivided into the following sub-bands: Q (33-50 GHz), V (50-75 GHz), W (75-110 GHz), D (110-170 GHz), and G (170-300 GHz). Note that the Ka band goes from 26.5 to 40 GHz. Part of the Q band is included in the Ka band since neither ITU-R nor IEEE officially recognize the Q band, but ISO does. If the ISO notation is used, then the definition of the mmWave bands is aligned with the set of frequencies that have a wavelength of millimeters. Consequently, it means that part of Ka band, i.e., 26.5-30 GHz, is outside of the mmWave region. That is why there is an “overlapping” with Ka band. Furthermore, IEEE defines the V band in the 40-75 GHz range, whereas ISO considers the range of the V band between 50 and 75 GHz. However, not all the spectrum of these bands is dedicated to satellite communications. Specifically, Table 15 shows the allocated frequencies for the uplink and downlink satellite transmissions and their available spectrum. Note that from the initial 270 GHz spectrum of the mmWave band, only 10 GHz are available for satellite communications. Nevertheless, no spectrum is yet assigned for satellite communications in the D and G bands. Finally, after showing the definition of the mmWave band, the following section details its channel characteristics.

*Table 15. Uplink, Downlink, and Available Spectrum for the mmWave through Satellite (per ITU-R Regulations)*

| ***Frequency Band*** | ***Uplink*** | ***Downlink*** | ***Available Uplink Spectrum*** | ***Available Downlink Spectrum*** |
|---|---|---|---|---|
| Q | 42.5-43.5 GHz<br>47.2-50.2 GHz | 37.5-42.5 GHz<br>47.5-47.9 GHz<br>48.2-48.54 GHz<br>49.44-50.2 GHz | 4 GHz | 6.32 GHz |
| V | 50.4-51.4 GHz | 71-75 GHz | 1 GHz | 4 GHz |
| W | 81-86 GHz | 75-76 GHz | 5 GHz | 1 GHz |

### 5.4.2.2. Channel Characteristics at the mmWave Bands

As we know, the higher the frequency, the larger the path losses. Nonetheless, it is also important to consider the atmospheric effects since the wavelength of these bands is very small. In this regard, Figure 12 shows the attenuation in dB/km of the atmospheric gases, i.e. oxygen, water vapor, and its aggregated attenuation. Results are obtained from ITU-R.676 [17]. Similarly, Figure 13 shows the rain attenuation in dB/km in terms of the frequency for different rainfall rates. These attenuations are extracted from ITU-R [18]. From Figure 12, it is possible to observe that, in the Q band for frequencies ranging between 33-47 GHz, the primary gas attenuation is due to water vapor, whereas the remainder of its frequencies, 47-50 GHz, is dominated by the attenuation of oxygen. The attenuation of the gas in this band increases with the frequency.

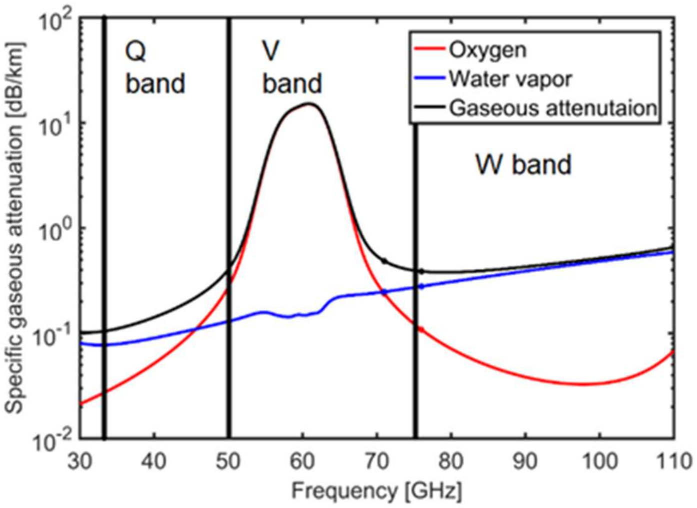


*Figure 12. Attenuation in dB/km of the Atmospheric Gasses: Oxygen, Water Vapor, and Total Pressure = 1 013.25 hPa; Temperature = 15°C; Water Vapor Density = 7.5 g/m$^3$*

The attenuation of the oxygen practically dominates the V band. The water vapor attenuation dominates only for frequencies from 71-76 GHz. In this band, the attenuation that introduces the oxygen has a different behavior with the frequency increase. From 50-61 GHz, the attenuation of the oxygen increases with the frequency, but from 61-75 GHz reduces its attenuation with the augmentation of the frequency (*see Figure 12*). The range from 53-67 GHz has attenuation larger than 10 dB/km, which is quite high for being used in satellite communications. So, it means that in this band, it is better to use its lower and upper frequencies instead of its middle region. For that reason, the frequencies for the uplink are placed at the band of 50.4-51.4 GHz and the downlink ones are allocated at 71-75 GHz. The frequencies in the range from 51.4-71 GHz are not used due to the large attenuation by oxygen. In the W band, the water vapor attenuation increases with frequency.

On the contrary, the oxygen attenuation decays until 94 GHz and from that to 110 GHz rises with frequency. For that reason, the band of 94 GHz is considered an atmospheric transparent window that attracts applications for mmWave radar, astronomy, and defense. The band from 77-81 GHz is used by automotive radar.

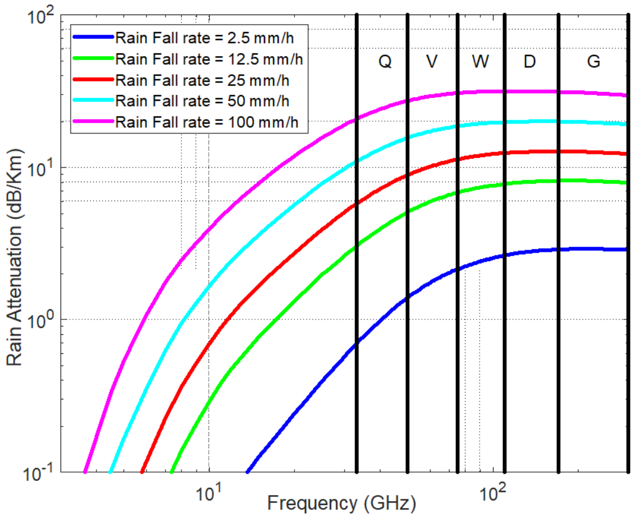


*Figure 13. Rain Attenuation in dB/km Across Frequency for the Rainfall Rates of 2.5 mm/h*

**Legend**: (light rain in blue), 12.5 mm/h (medium rain in green), 25 mm/h (heavy rain in red), 50 mm/h (downpour in cyan), and 100 mm/h (tropical in magenta) (Source: Horizontal Polarization Antenna [18])

From Figure 13, it is possible to observe that the higher the frequency, the higher the attenuation in dB/km that introduces the rain. Note that mmWave bands are quite sensitive to the attenuation that introduces the rain. The attenuation for all rainfall rates has a similar pattern to the frequency. Initially, the attenuation increases notably with frequency, but from a certain value of frequency, it turns a flat shape, independent of the rainfall rate. From this figure, is possible to conclude that: i) mmWave bands should have diversity on ground stations to augment the probability of not having clouds nor rainfall that fade the downlink from / uplink to the satellite, ii) large power amplifiers need to have a large margin to close the link budgets in case of rain, iii) robust adaptive channel coding schemes can be used to overcome atmospheric effects as much as possible, and iv) dynamic link layer adaptation depends on meteorological information. On the other side, these bands are quite interesting for being used as inter-satellite, moon-to-satellite, or inter-planetary communications due to their large available bandwidth and the absence of rainfall effects and clouds.

### 5.4.2.3. Commercial Interest in mmWave

Although mmWave bands have larger propagation losses, these bands are less used and so the larger will be the available spectrum for satellite communications. This means that, by resorting to these bands, the number of gateways will be lower, so the ground segment cost will be reduced. As these frequency bands are new for mmWave communications through satellites, they open new business opportunities to satellite operators [19]. In November 2021, the FCC approved the broadband satellite constellation of Boeing in the following bands: 37.5-40 GHz, 40-42 GHz, 47.2-50.2 GHz, 50.4-51 GHz, and 5-71 GHz for Inter-Satellite Links (ISL) [20]. Communications from the ground station to the satellite will be mainly in the Q band (37.5-40 GHz, 40-42 GHz, 47.2-50.2 GHz) and part of the V band (50.4-51 GHz), whereas in the ISL are committed fully in the V band. The case of Boeing, which received FCC approval in August 2020 for a 2000 non-geostationary-satellite orbit (NGSO) broadband satellite constellation; 720 satellites of the Ku / Ka band constellation previously approved and 1280 additional V band satellites operating at the bands 37.5-42 GHz (space-to-earth), 47.2-50.2 GHz (earth-to-space), and 50.4-51.4 GHz (earth-to-space) at a nominal altitude of 8500 km [21]. FCC has also approved SpaceX for using V band [22]. In this case, it plans to launch 7518 very-low-earth orbit (VLEO) NGSO satellites operating at altitudes from 335 km to 346 km in the framework of its Gen2 system [23]. The bands they will operate are: 37.5-42 GHz (space-to-earth), 47.2-50.2 GHz, and 50.4-51.4 GHz (earth-to-space). This complements its existing 4425 NGSO satellites that use both Ku and V spectrum for user links and Ka and V bands for gateway links and telemetry. Recently, Astra has also filed to the FCC to use a constellation of 13620 LEO satellites at an altitude of 700 km in V band [24]. Similarly, other satellite companies; such as Amazon, Inmarsat, Intelsat, Hughes, and Telesat; have asked FCC to use V band. On the GEO side, EUTELSAT launched its Konnect VHTS satellite using Q/V band feeder links to provide fixed broadband and mobile connectivity across Europe in September 2022 [25]. This band and mmWave have attracted the commercial interest of satellite companies to deploy new satellites or expand their current constellations. At this point, it is necessary to point out that previous frequency margins for the V band follow the FCC criteria (40-75 GHz).

### 5.4.2.4. State-of-the-Art on mmWave Band through Satellite

#### Theoretical Studies

The interest in using mmWave bands to maximize the data rates in very / ultra-high throughput systems has been investigated theoretically. In particular, the impact of receive power limitations on the achievable system performance has been analyzed. The studies [26], [27] have clearly emphasized that the main bottlenecks for the use of mmWave bands are the high atmospheric losses and the smaller output power delivered by the RF hardware compared to more mature technologies in lower bands (e.g., Ka band). Preliminary models (ITU-R recommendations) for the characterization of atmospheric attenuation in mmWave bands have been used in these works to run numerical simulations. Results [28] illustrate the poor performance of a W band gateway to GEO satellite link (feeder link) if no site diversity is used to compensate for rain and cloud attenuation. Where a state-of-art feeder link in the Ka band could support 18.1 Gbps for 99.9% of the time, a W band link would be limited to 2.8 Gbps. However, site diversity is an efficient (but expensive) countermeasure to overcome this constraint, as confirmed by other results [29]. This supports the interest in using the Q/V/W bands for feeder links in GEO systems. Thanks to the larger bandwidth in the Q/V/W bands, the number of ground stations needed to support a target sum data rate can be significantly reduced compared to a similar GEO system with only Ka band feeder links. For example, a system with an aggregated bandwidth of 350 GHz would necessitate 70 Ka band feeder links (2.5 GHz of uplink bandwidth / two polarizations per link / full frequency reuse) instead of 35 W band links. Even though a few more redundant gateways are necessary to guarantee the desired system availability in the Q/V/W bands, this countermeasure has a minor impact on the total number of links. As discussed in the research [30], these conclusions cannot be generalized to feeder links for LEO mega-constellations. The results [30] show that a typical mega-constellation with satellites connecting with two gateway stations simultaneously can support higher data rates with links in the W or the Q/V band than in the Ka band. However, sufficient availability of the system can only be guaranteed with a larger number of ground stations deployed worldwide. Whereas 30 Ka band ground stations would suffice in the scenario [30] to reliably deliver data in 85% of the worldwide area targeted for service, 40 ground stations in the W band would be required to achieve the same performance.

Regarding performance evaluation, the authors in “Nanosatellite-5G Integration in the Millimeter Wave Domain: A Full Top-Down Approach” [31] presented a novel network architecture for an integrated nanosatellite 5G system operating in the mmWave domain. Similarly, the authors validated the feasibility of establishing mmWave connections to access terrestrial nodes using non-terrestrial stations and shed light on the research challenges associated with non-terrestrial networks [32]. The same conclusions were obtained in which a terrestrial terminal was deployed to communicate with a satellite placed at different altitudes, elevation angles, and propagation scenarios [33]. The authors observed that satellite operations in the bandwidth-constrained below-6 GHz spectrum offer limited channel capacity, which might be insufficient to satisfy the most demanding beyond-5G use cases. The performance can be improved by considering mmWave transmissions, despite the very long transmission distances and the severe attenuation experienced at those frequencies. Notably, the reduced probability of path blockage in the rural scenario may improve the achievable capacity by more than 100% at high elevations compared to an urban scenario.

While the adoption of the mmWave spectrum for non-terrestrial networks seems promising, solutions are being proposed for the development of new waveforms and modulation schemes, e.g., impulse-based Ultra-WideBand (UWB) modulation. In UWB information is encoded depending on the characteristics of the transmitted pulse, as a viable approach to reduce the non-linear signal distortion typically experienced at high frequencies [34]. Moreover, cognitive spectrum techniques may enable dynamic spectrum utilization in different bands while minimizing interference.

Other studies indicated that the availability of multi-layered hierarchical networks, i.e., the orchestration among different aerial / space platforms, can provide better coverage, resilience, and flexibility compared to standalone deployments, which makes them suitable for several fields in future networks, including control and emergency communication in rural areas [33]. Software-defined networks may also offer a programmable, scalable, and customizable framework to integrate space, air, and ground components for matching traffic demands with the available network capacity [35]. In “Space-Air-Ground Integrated Network: A Survey” [36] software-defined space-air-ground integrated networks are proposed to cooperate with vehicular networks to support diverse, seamless, efficient, and cost-effective vehicular services. Similar results were described in other reports [37]. The potential of multi-layered non-terrestrial network integration is exposed [38]. In recent years, private organizations have also funded projects to provide broadband internet to the world by combining the persistence of satellites and HAPs with the flexibility of UAVs, such as Airbus Zephyr’s initiative [39]. As a case study [33], the authors demonstrated via simulations that better wireless coverage can be provided when a standalone space layer is assisted by HAPs operating in the stratosphere. The intermediate HAP can amplify the signal from the upstream satellite before forwarding it to the ground while ensuring a quicker deployment and lower costs compared to space-borne stations.

### Measurements Campaigns

Regarding the missions on the mmWave bands, i.e., Q, V, and W; all were dedicated to studying these bands' propagation conditions. At this moment, there is no commercial service working on these bands. They are addressed to measure the channel characteristics of these bands. So, the transmissions are based on beacons. One of the first missions on the mmWave band was by ITALSAT devoted to characterizing the attenuation that introduces the atmospheric elements in the bands of Ku (18.7 GHz) and Q (39.6 GHz, 49.5 GHz). The frequency of 18.7 GHz was vertically polarized and the 39.6 GHz was circularly polarized, whereas the 49.5 GHz switched its polarization between vertical and horizontal. Three radio links were conducted, uplink in 18.7 GHz and downlinks in 39.6 GHz and 49.5 GHz, and uplink in 39.6 GHz and downlink in 49.5 GHz [27]. After that, the propagation experiments in the Q/V bands were conducted using the Aldo Paraboni payload included in the Alphasat GEO satellite from Inmarsat. It includes two experiments: i) a communication payload in the V band at frequencies 47.9 and 48.1 GHz for the earth-to-space links and a payload in the Q band at frequencies 37.9 and 38.1 GHz for space-to-earth communications and two beacons operating at the Q and Ka bands at 39.402 GHz and 19.701 GHz, respectively. The communication experiment sends DVB-S2 waveform [40]. Similarly, Eutelsat launched an experimental Q/V band payload on Eutelsat 65° West GEO satellite to evaluate the channel characteristics of these bands [41]. For the channel characterization in the W band, the first satellite transmission was conducted by the W-Cube mission from ESA [29], which simultaneously transmits from a LEO satellite at an altitude of 530 km a beacon at 75 GHz (W band) and another one at 37.5 GHz (Q band). Its results will be used to compare the obtained channel models with the pre-existing ones in both bands and generate new ones. Another mission is the EIVE ARTES project from ESA [42], which tests data downloading from a LEO satellite at an altitude of 500 km using the E/W bands. The signal bandwidth is 5 GHz and the experiment will validate the use of these bands for future 5G, 5G+, and 6G communications through satellite. The frequencies to test are 71-76 GHz. Note that the E band, according to WRC'12, encompasses frequencies 60-90 GHz.

**Hardware Development**

Regarding the commercial solutions on the mmWave band, it is currently only possible to obtain limited COTS for the Q band and specific purpose subsystems in the Q and V bands for scientific missions [43], [44], [45]. On the contrary, for the W band, it is impossible to obtain any commercial product in the satellite field. Note that the first satellite transmission on this band was conducted on September 2022 in the W-Cube mission. This is not the case for terrestrial communications, since the band 77-81 GHz is used for automotive radar in Advanced Driver Assistance Systems (ADAS). It is expected that there will be, in a short time, commercial hardware in this band. This band requires developing high-power amplifiers for the transmitter at the W band with high DC-RF efficiency and low noise amplifiers for compensating the large propagation loss at the W band [46].

#### 5.4.2.5. Challenges

The mmWave band for satellites faces several challenges. We have distributed them in three parts: (1) near-term, (2) mid-term, and (3) long-term. The near-term changes are the ones that can be adopted in the framework 2020-2023. The mid-term ones will be adopted in 2024-2025. Finally, the long-term ones will be introduced in the 2026-2030 period.

(1) In the near-term, the challenges that mmWave through satellite will face are the following. First, harmonization of the frequency range and terminology of the mmWave bands. Thus, it will be possible to speed up the standardization of new components, obtain affordable equipment (really needed), and increase its adoption by the satellite industry. Secondly, it will be possible to introduce the results of the satellite missions at the W band into the current models for predicting

channel losses. The third stage improves the efficiency of the power amplifiers and obtains mmWave equipment at an affordable cost. This is valid for all bands of interest. This would permit extending the coverage of mmWave signals to larger distances and increase its adoption.

(2) In the mid-term, there are challenges that mmWave should consider facing. In the first approach, fade mitigation techniques should be developed and implemented. The higher the frequency band used, the larger the attenuation from path, rain, and clouds. In the long term, using satellites at multiple orbits may increase the mutual interference if they use frequency reuse schemes to increase the capacity. This issue is critical when the transmitted signals have a large bandwidth. Consequently, it is key that interference mitigation techniques be implemented in the next generation of mega-satellite constellations. As a third challenge, new antenna solutions that increase the multiplexing gain of mmWave systems are of interest. It will be possible to extend the use of another band of mmWave for satellites (e.g., D, G) and relax the requirement of power amplifiers with a high efficiency and/or increase the number of power amplifiers. These latter issues are critical in small satellites, such as the nanosat ones, since the power they can transmit and the physical area in which the antennas can be placed are quite reduced.

(3) Finally, it is assumed that mega-satellite constellations will be operating in the long term. Consequently, it is expected that the resulting satellite networks will support 6G requirements. In particular, the capacity and latency constraints. In this regard, the challenge will be supporting multi-beam satellite architectures with fast handovers.

*Table 16. Challenges Associated with Capacity*

| ***Near-term Challenges: 2020-2023*** | ***Description*** |
|---|---|
| Harmonization of its frequency bands | It would be necessary to harmonize the terminology and range of the mmWave bands to speed up the standardization of its commercial products and reduce its costs, which will help drive affordable equipment and facilitate its adoption. |
| Updating channel models | Current channel attenuation models for mmWave are based on estimations. After the channel testing missions in the mmWave band, it would be necessary to update -if necessary- the initial estimations of the channel losses provided by the models with the ones obtained from the beaconing missions (e.g., EIVE, W-Cube). |
| Efficiency of the power amplifiers | The use of mmWave increases by the factor channel propagation losses. Consequently, large arrays and high-power amplifiers must be used to transmit the data. However, the transmitted power is limited by the efficiency of the amplifiers. It will be necessary to increase their efficiency to improve beamforming techniques' performance. Solutions to obtain affordable equipment costs would help spread the adoption of the mmWave band. |
| ***Mid-term Challenges: 2024-2025*** | ***Description*** |
| Fade mitigation techniques | At this stage, fade mitigation techniques must be devised and implemented to cope with the mmWave channel impairments. Note that the higher the frequency band, the larger the attenuation from the path and atmospheric losses (e.g., rain, clouds, etc.). In addition, measures against channel blockage have to be introduced. |
| Interference mitigation techniques | The next generation of mega-satellite constellations will combine multi-orbit satellites, HAPs, and terrestrial infrastructure in a transparent way. To increase the capacity, frequency reuse schemes will be used. It is key that signals from satellites at different orbits be received correctly although they use the same resources simultaneously. |

| | |
|---|---|
| Antenna solutions that reduce the channel propagation losses | As it is well known, the higher the frequency, the larger the propagation loss. In this case, new antenna solutions that reduce this effect would permit the relaxation of the requirement of power amplifiers with a very large efficiency and/or the use of many antennas. This is critical in small satellites, such as the nanosats, since the power and space of the antennas are limited. |
| ***Long-term Challenges: 2026-2030*** | ***Description*** |
| Fast satellite architectures of high capacity | In this scenario, a mega-constellation of satellites will be operating. To increase their capacity, multi-beam architectures will be supported. However, if 6G requirements are to be fulfilled, it is required that fast beam management techniques be implemented. |

#### 5.4.2.6. Potential Solutions

As in the previous section, the potential solutions to the challenges for the use of mmWave via satellite are also classified into the following categories: short-term (2020-2023), medium-term (2024-2025), and long-term (2026-2030).

*Table 17. Potential Solutions to Address Capacity*

| ***Near-term Challenges: 2020-2023*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Harmonization of its frequency bands | If all key actors in a technology’s standardization, adoption, and implementation are aligned, its adoption will speed up. This should be the case for the mmWave band since multiple definitions exist for the same band and different classifications of the mmWave bands exist. So, cross-cooperation to have a uniform definition of the mmWave band is desirable in the next years. |
| Updating channel models | The current channel losses at high frequency from ITU-R result from theoretical models. It would be interesting to see results come from real satellite transmissions in mmWave, such as Alphasat, W-Cube, and EIVE, and be integrated into the subsequent of ITU-R channel models. |
| Efficiency of the power amplifiers | To increase the efficiency of the power amplifiers and electronic hardware when they work at very large frequencies, it is recommended to use Gallium Nitride (GaN) since it supports smaller form factors and larger efficient components compared to silicon-base. |
| ***Mid-term Challenges: 2024-2025*** | ***Potential Solutions to Mid-term Challenges*** |
| Fade mitigation techniques | The larger the frequency, the higher the channel losses due to propagation and atmospheric effects. To cope with these issues, the following strategies can be used: i) site diversity, ii) new modulation and coding schemes robust to channel impairments, iii) introduce meteorological information to link layer schemes to compensate the atmospheric impairments, iv) increase the power margin in the link budget to protect the transmission, and recently v) use reconfigurable intelligent surfaces (RIS). |
| Interference mitigation techniques | The next generation of satellite networks will combine multi-orbit satellites, HAPs, and terrestrial components in an integrated way. Moreover, it will use frequency reuse schemes to increase the capacity. It will require the use of interference cancellation techniques to remove the interference from different satellites. In this regard, artificial intelligence will be vital in recognizing and removing interference. Finally, new waveforms, such as the OTFS, could be of interest to combine communication and earth observation networks. Thus, the same satellite network will be used for different applications. |
| Antenna solutions that reduce the channel propagation losses | In mmWave, an array of beamformed antennas is used to obtain a multiplexing gain to cope with the channel losses. In this situation, increasing the effective area of the antennas by incorporating new materials with appropriate conductivities and dielectric constants may also increase their gain. |

| *Long-term Challenges: 2026-2030* | *Potential Solutions to Long-term Challenges* |
|---|---|
| Fast satellite architectures of high capacity | Mega-satellite constellations will be equipped with multiple transmission bands (mmWave, TeraHert, K, and optical bands) to increase their capacity and augment their robustness to the channel impairments. Then, a potential solution to support multiple transmission bands is using automatic beam-switching strategies guided by artificial intelligence. |

### Solution to Harmonization of the mmWave Frequency Bands

The adoption of mmWave technology by the industry is crucial to its success. If the definition of the bands in mmWave were homogenous for all key actors, it would speed up its global adoption. In this case, cross-communication among institutions will be essential in the coming years.

### Solution to Updating mmWave Channel Models

The mmWave band spans from 30 to 300 GHz frequency range, but commercial solutions only exist for the Q band (33-50 GHz) and the V band (50-75 GHz). The results from the current missions in the W band (i.e., W-Cube, EIVE) will be available soon. Although ITU-R provides results for the channel losses for frequencies up to 1000 GHz, they are only estimations. The results from the mmWave channel measures of these missions should be compared with the theoretical ones provided by ITU-R models[17],[18] and introduced in the following versions of such documents.

### Solution to Efficiency of the Power Amplifiers

At high frequencies, the mmWave hardware is typically associated with severe power limitations for electronic components like DACs, phase shifters and combiners, and power amplifiers, which are required to process many antenna outputs and very wide bandwidths. In this context, the adoption of the Gallium Nitride (GaN) technologies on satellites [47] allows the use of smaller form factors and more efficient components compared to their silicon counterparts, thereby saving fuel and area on the payload and improving operational efficiency [48], [49].

### Solution to Fade Mitigation Techniques

The mmWave signals can suffer from a large attenuation based on the propagation path and atmospheric channels. In this case, fade mitigation techniques must be adopted. From the physical layer point of view, the following solutions can be introduced: i) site diversity, ii) new modulation and coding schemes robust to channel impairments, iii) meteorological information in link layer schemes to compensate for the atmospheric impairments, iv) increased power margin in the link budget to protect the transmission, and recently v) use of Reconfigurable Intelligent Surfaces (RIS). In this last case, the RIS bypasses blockage by generating multiple Line-of-Sight (LoS) links.

### Solution to Interference Mitigation Techniques

Future satellite networks will combine multi-orbit satellites and be integrated with the terrestrial networks seamlessly and transparently. Frequency reuse schemes will be used to increase the capacity of the satellite networks. However, this means that interferences among satellites may exist. Especially between LEO-GEO and LEO-LEO constellations at different orbits as well as LEO / GEO with HAPs. This is critical when the transmitted signals have a large bandwidth, as in the case of mmWave where interference mitigation techniques may help. For instance, artificial intelligence strategies could detect narrow-band interference. Note that apart from removing the interference, it is of utmost interest to recognize the existence of interference, determine its typology, and adapt the canceller methods by appropriate learning strategies. Furthermore, the next generations of satellite networks will combine both communication and earth observation systems. In this regard, the use of new waveforms that permit combining both worlds, such as the OTFS waveforms, may help to reduce interferences between different types of satellite networks.

**Solution to Antenna Solutions that Reduce Channel Losses**

Spacecraft system manufacturers are also developing future satellite stations using new reconfigurable phased antennas, offering electronic beam-steering with lower energy consumption than mechanical products. These also offer reduced size, weight, and power improvements compared to existing antenna technologies. Such advanced antenna solutions make it possible to implement multibeam architectures, typically operating in the mmWave bands, so that information is simultaneously sent to different spot beams on the ground, thereby maximizing spectrum efficiency [49], [50]. Furthermore, new achievements in the satellite industry simplify the deployment of flexible payloads, allowing services to autonomously adapt to evolving requirements even after launch and throughout the satellite lifetime, supporting cross-band inter-beam configurations.

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

Furthermore, the use of antennas with a reduced beam size and large effective area will allow additional gains. All of these elements will increase the transmitted EIRP and received power. In this case, new materials with appropriate dielectric constants may help to increase the resulting effective area [50].

**Solution to Fast Satellite Architectures of High Capacity**

The mega-satellite constellations will be equipped with Inter-Satellite Links (ISL) and multi-beam antennas to increase connectivity and reduce latency. If one link from one technology does not work, another one will be used or, in the case of high-capacity demand, several technologies will be used simultaneously. In this situation, it is proposed as a potential solution to use automatic switching strategies based on artificial intelligence. In addition, analog beamforming may help increase its response when the signal bandwidth is large. However, when analog beamforming is used, it will be necessary to consider techniques to compensate for the deviation of the components with time.

### 5.4.3. Optical Wireless Communications over Non-Terrestrial Networks

Current 5G communications already support optical connections for inter-satellite links. However, in 6G, new use cases will be introduced, such as optical communications both in the feeder and in access links. Moreover, 6G will provide service using multiple transmission media: land, aerial, and space. The optical links are expected to support the capacity needs of the new services offered by 6G and provide higher resilience and security to communications. Optical Wireless Communications (OWC) systems will be combined with radio bands, such as terahertz and mmWave, to offer hybrid systems that provide a higher capacity, resilience, and security. Note that optical bands have a very large bandwidth and are license free. Operators will exploit this advantage to reduce costs and guarantee the satellite infrastructure sustainability. However, there are risks because the optical and radio links in the feeder and access channels can be faded by atmospheric impairments.

Regarding inter-satellite links, fast-tracking and acquisition systems are a must. In this regard, using hybrid systems that combine the properties of the radio and optical worlds will allow resilient communication systems of high capacity with fast tracking and acquisition. As for security issues, it is necessary to comment that quantum-based security schemes are expected to emerge as potential ways to provide almost perfect security. Today, quantum computers can break current cryptographic schemes without the help of artificial intelligence, so alternative security schemes are needed. Quantum-based schemes may be the possible solution to achieve perfect security for quantum computers. Note that the key exchange is transmitted via optical links in quantum communications, while the data channel may be either optical or radio. As a result, quantum communications may be considered a particular type of hybrid optical-radio communication scheme. So overall, OWC will be vital to address capacity, resilience, and security issues for 6G communication systems.

This section is divided into optical wireless communication systems and quantum-based communication systems. There will be an update on the state-of-the-art / missions and the current challenges, needs, and potential solutions for future optical satellite system capacity, resilience, and security.

#### 5.4.3.1. Optical Wireless Communications for Capacity and Resilience

Currently, satellite optical communications are divided into links between satellites and links between the satellite and earth stations, airplanes, or drones (considering a 3D NTN network). In the first case, the challenge lies in acquiring the optical beam of two moving objects at high speed and perhaps in different directions. In the second case, the challenge lies in compensating for the atmospheric propagation effects that are introduced into the optical beam. Such effects involve clouds, rain, and turbulence of the optical channel. This section is composed of two parts: The first summarizes the current state of the art on the missions of OWC over non-terrestrial networks. The second outlines the challenges and needs for OWC to provide higher capacity and resilience for the short- term, mid- term, and long-term.

#### 5.4.3.2. Missions on Optical Wireless Communications

Internationally, the leading institutions in satellite optical communications are NASA, MIT, JAXA, NICT, ESA, and DLR. NASA, MIT, and the University of Florida have developed the TBIRD mission, which aims to demonstrate the feasibility of links from a small satellite to ground with transmission speeds up to 200 Gbps (non-continuous transmissions) [51]. In 2022, the Click A mission was placed into orbit and the Click B/C is planned to be launched in late 2023 [52]. For its part, NICT has developed optical equipment for both the space segment and terrain in NGEO and GEO satellites. It also has satellites to perform optical communications experiments (e.g., ETS-VI). Examples of NICT missions are SOCRATES (LEO-ground links at 10 Mbps IM/DD detectors wavelengths of 1500 nm and apertures of 0.98 m) or HICALI (GEO-ground links at 10-40 Gbps with wavelengths of 1500 nm) [53]. ESA started its satellite optical communications through the SiLEX mission to put into orbit the first European optical payload (LEO satellites) [54]. On geostationary satellites, ESA developed the optical experiment installed on Inmarsat's Alphasat satellite [55]. For its part, DLR has developed the OSIRISv program, which is the source of its missions OSIRISv1 (2017 optical LEO-ground links up to 200 Mbps), OSIRISv2 (optical LEO-ground links up to 1 Gbps embarked between the payload of the BYROS satellite), OSIRISv3 (optical links from the International Space Station -ISS- to the ground at 10 Gbps embarked on the Airbus Bartolomeo platform on the ISS), and OSIRIS4CubeSAT (design of a compact optical payload for a CubeSat embarked on the PIXL-1 mission) [56].

6G communications systems present scenarios where it is necessary to service applications that require bandwidth and feeder links with greater capacities to support the increase in coverage (e.g., direct satellite connection). Likewise, the emergence of quantum communications has increased the interest in having terrestrial optical stations. ESA also has the Skylight initiative to support satellite optical communications research, development, and evolution to facilitate in-orbit testing [57]. Part of this is called Hydron and consists of developing a broadband communications network in space called "Fiber in the Sky" [58]. Finally, ESA has the Ops-Sat space lab program, which aims at in-orbit validation. This edition is oriented to optical communications from CubeSats and optical links between satellites [59].

#### 5.4.3.3. Challenges

The challenges of OWC are the losses of communications due to the bursty nature of the optical channel with the atmospheric impairments (ground-satellite links), the high cost of the equipment, and the tracking of the optical links. However, these issues are expected to be less relevant in the next few years since the need for broadband communication systems is quite important. The next generation of satellites will include optical elements in their hardware to cope with the high data rates demanded, especially in NGSO mega-satellite constellations where handover between the links (inter-satellite, ground station to satellite, airplane-satellite) will be necessary.

#### 5.4.3.4. Needs

Currently, satellite tests validate transmission from a single satellite to the ground station, drone / UAV, airplane, vehicle, or ship. However, it will be necessary to validate the equipment for communicating at very large bandwidths in the mid-term, combining radio and optical bands simultaneously. In the long term, there will be a need to implement multiple optical inter-satellite links based on MIMO techniques applied to optical signaling. Furthermore, resilient connectivity and high capacity will be necessary from ground to satellite. Thus, satellite networks oriented to data center applications would permit sustainable computing infrastructures.

#### 5.4.3.5. Solutions

Current equipment for non-terrestrial OWC results from modifying / reusing the equipment adopted for astronomical to conduct LEO/GEO optical tests. However, significant advances are required to achieve compact optical ground stations. In this regard, portable types of equipment for terrestrial-satellite optical measurements have emerged with tracking capabilities for NGSO / airplane / HAPS transmissions to and from ground stations. By doing so, lower costs may be possible and extend the use and capabilities of optical ground stations. Regarding the capacity and resilience of optical communications, the solution will come by integrating optical and radio schemes. In this type of solution, switching between the radio and optical systems is critical. The use of artificial intelligence systems that permit modeling the channel characteristics of the optical and radio links is one of the potential solutions for increasing the capacity and resilience of optical communications. Especially in 5G solutions, the need for broadband communications makes it difficult to allocate these new broadband services in the classical Ka and Ku bands. Radio bands from mmWave and Terahertz may be necessary. However, using large bands may suffer more atmospheric impairments and combining both bands may help. Resorting to MIMO techniques in the RF band, using multiple apertures in the optical bands, combined with advanced signal processing at the transmitter and receiver, may also help to reduce the effect of optical and radio impairments. The distribution of the MIMO and optical apertures may help reduce the presence of fading in communications (e.g., optical-radio beamforming, antenna aperture selection, etc.). Here, it is necessary to comment that optical beams with larger beam sizes may be required to provide a large coverage time and upload / download high traffic that MEC services under satellite are under consideration.

#### 5.4.3.6. Quantum Communications

Quantum communications have emerged as a hot topic in optical wireless communications because they provide security against quantum computers. Quantum schemes base their security on the inviolability of quantum physics; specifically, the Heisenberg Uncertainty Principle and the principle of photon polarization. The former states that measuring any system's quantum states without altering them is impossible. The latter states that a non-legitimate receiver cannot copy the qubits of a legitimate user due to the no-cloning theorem. In quantum communications, the key exchange is transmitted via optical links where the data channel may be optical or radio. In this regard, several satellite missions have been launched / will be launched to test the validity of quantum-based schemes. This section is divided into two subsections. The first one reviews the current state of the art on the existing missions on quantum communications. The second one shows the challenges and needs of quantum communications over satellite networks in short-term, mid-term, and long-term.

#### 5.4.3.7. Missions on Quantum Communications

Globally, four missions have already tested quantum optical communications. On GEO satellites: i) the LCT flying quantum payload developed by DLR on board the Alphasat I-XL satellite [60], ii) the Japanese Socrates mission, which carries a quantum communications payload in a cube located in LEO orbits [61], iii) the Chinese Micius satellite in 2017, which consisted of a LEO link at 1200 km through the DV-QKD decoy state system [62], and iv) the Singaporean SpooQy-1 mission, of the Spectral Space and the Center for Quantum Technologies (CQT) of the University of Singapore has managed to send quantum signals in a 3U CubeSat using the technique of entangled photons [63]. Techniques like that are used in optical fiber communications. The first two missions measured quantum states on GEO and LEO satellites, respectively. In the last two, the key exchange has already been introduced. In the case of the Micius mission, it has been reported that its key generation rate was only 0.12 bits/s. That is why other strategies, such as CV-QKD, seem more interested in obtaining a higher key generation rate.

#### 5.4.3.8. Challenges

Quantum communications can be used to provide security using optical networks, but several challenges occur when optical wireless networks are used. First, optical beams size can allow an eavesdropper to collect desired information. Second, the key exchange rate is low. So, there is a need to develop techniques for detecting when the signal is affected by fading because of atmospheric impairments or eavesdroppers. Hence, techniques like signal processing, modification of the constellation design, alternative QKD systems, and holistic approaches to security may be necessary to provide security schemes for high-speed 6G networks.

#### 5.4.3.9. Needs

Current quantum experiments test downlink communications with a single satellite. However, the idea of quantum communications is to increase security at the constellation level. So the development of quantum communication networks will be a real need. In mid-term development, quantum repeaters will be needed. Next, key exchange systems working at a high data rate will be required at a large scale. Another need is the adequacy of equipment for optical transmissions to support quantum communications' specific needs, although both traditional and quantum are based on optical links (part of the key exchange).

#### 5.4.3.10. Solutions

Quantum-based solutions like QKD have been exported from optical fibers to non-terrestrial communications. However, this translation may be inaccurate since the optical fiber channel is wired, whereas the non-terrestrial one is inherently wireless. Therefore, the detection of eavesdroppers could be different. In this regard, holistic solutions based on the physical layer in combination with radio technologies and alternative security schemes, such as blockchain, will be required to detect the presence of eavesdroppers in federated systems. The use of artificial intelligence for key management and detection of eavesdroppers needs to be investigated for the next generation of quantum-based schemes. Integration of optical fiber and optical wireless with typical waveforms may be used. Optical fiber is a dispersive channel and optical wireless may suffer the effect of turbulence. Hence, the use of multicarrier-optical systems may help to combat these impairments.

*Table 18. Challenges Associated with Optical Wireless Communications for Capacity, Resilience, and Security*

| ***Near-term Challenges: 2020-2023*** | ***Description*** |
|---|---|
| Optical MIMO waveforms compatible with 5G requirements | NR systems use CP-OFDM waveforms. However, it requires complex data and Intensity Modulation (IM) / Direct Detection (DD). In this case, it is necessary to introduce Hermitian transformations, which halve the capacity of the optical systems. So, low-cost heterodyne systems or efficient IM / DD ones that can work with complex data must be investigated. |
| Develop FSO / RF schemes | Theoretical development of FSO / RF schemes that permit the achievement of higher capacities, resilience, and security managed by an AI system. Quantum communications are considered a use case of hybrid optical-radio communications from the physical layer point of view. |
| Security schemes based on MIMO physical layer security into account | Currently, security in communications is introduced at the network layer using encryption, integrity, and authentication algorithms. At the physical layer, the main concern is the spectral efficiency and robustness to channel impairments. A joint design of the two layers would be needed in the future. Otherwise, a large part of the MIMO gain is absorbed by the redundant bits to provide security. Thus, 3GPP systems will follow the principle of secure by design. Alternative solutions to DV and CV-QKD systems should be investigated. |
| ***Mid-term Challenges: 2024-2025*** | ***Description*** |
| Integration of the optical MIMO in the satellite's payload. Feeder / inter-satellite links hardware considerations | LEO / GEO and LEO-LEO will use inter-satellite links to provide coverage extension. However, it increases the complexity of the onboard processing. In this regard, onboard processing complexity may be reduced if optical links are also considered in the feeder links. Thus, part of the traffic would be destined for the current GEO / LEO satellite beam without modulating from electrical to optical format. Doppler effects should be compensated in inter-satellite links, mainly in inter-orbit satellite links (e.g., LEO-GEO). |
| Upper layer developed | Integration of the protocols of optical / radio schemes for reducing the switching in the satellites and reducing the switching between the radio and optical parts. |
| Fading / eavesdropping in quantum-based schemes | Strategies for overcoming the fading in quantum-based schemes and detecting that communication is being eavesdropped in a satellite channel are very important. Robust waveforms alternative to DV and CV must be implemented efficiently to avoid attacks from a quantum computer. The fast generation rate of quantum keys in satellite communications is a current open challenge. |
| ***Long-term Challenges: 2026-2030*** | ***Description*** |
| 6G requirements into the MIMO satellite payload | To transmit 6G communications using optical bands, the hardware parts for optical and radio waveforms must be integrated. Minimum implementation costs of MIMO and multiple aperture-based solutions have to be achieved, |

| | |
|---|---|
| Mega-constellations supporting MIMO | Switching between the optical and radio components of the satellite, terrestrial, and non-terrestrial, have to be studied. Reduction in switching, low energy consumption, and large service continuity are key for supporting the service requirements of 6G. |
| Integration of quantum equipment for FSO links | Adapt the quantum equipment, initially devised for optical fiber networks to non-terrestrial ones. Larger key generation rates, robustness to EDF amplifiers, and reduced sizes will be a real challenge. |

*Table 19. Potential Solutions to Address Optical Wireless Links for Capacity, Resilience, and Security*

| ***Near-term Challenges: 2020-2023*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Optical MIMO waveforms compatible with 6G requirements | A potential solution would be to use optical modulations instead of adapting non-optical ones to the optical format to satisfy 6G requirements. In this regard, coherent optical modulations, such as CO-OFDM, could be a way to implement optical feeder links according to 6G and beyond requirements. Another parameter to use is the wavelength. In this scenario, it is recommended to resort to 1550 nm ones since its window has lower channel impairments, which permits the implementation of optical MIMO waveforms in an efficient way. Thus, Erbium Doped lasers would be used. |
| Pointing errors | Robustness of the optical systems to pointing errors. In this regard, using MIMO systems in the optical and radio domains may help, especially in NGSO communications. Using advanced tracking algorithms to fuse optical and radio localization techniques may be interesting. In the case of hybrid optical / radio links, the fusion of radio and celestial image-based synchronization would help improve the satellites' pointing, acquisition, and tracking. |
| Security schemes based on MIMO physical layer security into account | The use of holistic solutions that consider diversity in the band and quantum-based ones may be the research line to follow. The coding schemes may be based on post-quantum solutions instead of the classical cryptographic ones such as RSA and AES. Also, advanced signal processing that hides the information may be useful. |
| ***Mid-term Challenges: 2024-2025*** | ***Potential Solutions to Mid-term Challenges*** |
| Implementations of optical MIMO channel tracking | Efficient implementations of the signal processing algorithms for optical tracking should be conducted. |
| Robustness to turbulences | The use of adaptive optics, hybrid RF / FSO schemes, and coding schemes may help to reduce the residual error of the turbulence of the optical channel. Minimum switching between the optical and radio schemes should be developed using AI techniques. |
| Design of MIMO-ready on-board processors | Develop regenerative satellite payloads to support optical and radio communications with minimum switching. Regenerations for the optical inter-satellite, feeder, and access links. |
| ***Long-term Challenges: 2026-2030*** | ***Potential Solutions to Long-term Challenges*** |
| Mega-constellations supporting MIMO | The next generation of non-terrestrial networks will be formed by mega-constellations of satellites capable of communicating with HAPS / drones / airplanes / ground stations in the feeder, access, and inter-satellite links. Doppler and synchronization issues have to be overcome. Optical and radio-based synchronization schemes will be fused to increase the convergence rate of the synchronization algorithms. |
| Optical fiber-optical wireless non-terrestrial systems | The optical fiber and optical non-terrestrial wireless systems should be integrated using a single waveform and a unique quantum-based security scheme as much as possible. Cooperation with radio and classical systems for providing capacity and resilience (e.g., beamforming) must be tested. |

| | |
|---|---|
| Integration of optical wireless and quantum equipment | Portable equipment and lightweight optical ground stations instead of current astronomical ground stations may be the solution for practical optical measurements with single waveforms, such as multicarrier, to overcome the impairments of the optical fiber and FSO channel, especially if the targets are in motion. |

## 5.5. Antennas & Payload

Satellites are an integral part of today's communications network, first in providing timing via GNSS signals, next in broadcast, then in mobile, and lastly for augmenting terrestrial capacity, especially in unserved or underserved regions. As the number of satellites continues to grow, sophisticated antenna and payload systems will support reliable and robust communications.

Table 20 shows the three main technical needs of the satellite industry today that have implications for antenna and payload technologies.

*Table 20. Overall Needs*

| ***Needs*** | ***Description*** |
|---|---|
| Capacity | Higher communications capacities are required, both per user and on aggregate. |
| Robustness | Under all conditions, the antenna system must be reliable and interoperable with other satellite provider assets. |
| Security | System elements must not impair communications security. |

Before addressing the overall needs for future communications networks, an overview of current antenna technology for both ground and space segments will be provided. Ground antennas for satellite links are typically large reflector antennas due to the need to capture signals traveling from a far distance between the ground and the satellite and these antennas are typically mechanically steered via gimbals. The ground antennas can be used judiciously in array configuration to support higher data rate links [64].

Antennas used on satellites are typically high gain, either reflector antennas, fixed arrays, or simple phased arrays.

For the space-to-earth links, future antennas may migrate from a single reflector-type with a high gain antenna operating over a narrow frequency band to an antenna system with intelligence and the ability to reconfigure its parameters to optimize link performance. This will be a primary requirement for successfully operating mega-constellations in LEO orbit. Satellites in GEO orbit will also benefit from this flexibilization to quickly adapt to the evolution of the market during their 15-year lifetime. Parameters such as frequency bands, polarization, beam and null-steering, and adjusting the number of spot beams may be part of the reconfiguration of the antenna system. Achieving this performance within reasonable size, weight, power, and cost constraints will be challenging.

Finally, using optical links to support a very high data rate and secure transmissions will become part of satellite payloads, supporting both space-to-space and space-to-ground links.

For an overview, the different antenna technologies considered in the different links of a satellite system are summarized in the following table. Current and future technologies are listed in the table below.

*Table 21. Current and Future Antenna Technologies*

| | ***Today*** | ***Future*** |
|---|---|---|

| | | |
|---|---|---|
| Ground stations (gateways) | Large C / X / Ku / Ka band reflector antennas | Large Q/V/W reflector antennas<br>Telescope (optical links) |
| Satellite – feeder links | Multi-beam reflector antennas with a single feed per beam architecture | Q/V/W band reflector antenna with a single feed per beam architecture<br>Telescope (optical links) |
| Satellite – user links | Multi-beam reflector antennas with multiple feeds per beam architecture | Multi-band active antennas supporting flexible beamforming (phased arrays with hybrid architectures, metasurfaces, etc.)<br>Large-scale arrays using satellite swarms |
| Satellite – inter-satellite links | Medium-gain antennas, such as S band patch antennas | Small reflector antennas<br>Telescope (optical links) |
| End users | Reflector antennas | Multi-band active antennas (phased arrays, metasurfaces, etc.) with limited complexity and a low-power consumption |

### 5.5.1. Challenges

#### Capacity Needs

System capacity can only be raised by using higher capacity links (typically needing more bandwidth as there are practical power limits) and by having more available network paths, as would be possible if there was interoperability. Interoperability between satellites and ground stations needs to be addressed early on to avoid the mistakes of early terrestrial generation cellular services. Satellite communications should be able to use competing ground stations or space assets, like terrestrial cellular service providers sharing ground infrastructure.

In the near term, a high-capacity system will primarily rely on deploying active antennas to support large bandwidths of potentially several GHz. For antennas deployed on the user side, the major challenge will be reducing the costs to reach a large consumer base. This will be of paramount importance for the success of LEO mega-constellations for the delivery of broadband internet services. In the satellite payloads, the main efforts will focus on finding the best trade-off between the antennas' flexibility and power consumption. In this context, hybrid (analog / digital) solutions will be considered. To this end, advanced digital processors in the satellite payloads will have to be interfaced to the RF front ends through several phase-synchronized ports.

In the mid and long terms, these antennas will be enhanced with multi-axis scanning capabilities and advanced handover mechanisms. This will further flex the exploitation of the network resources and enable, for example, real-time seamless access to different provider networks in different orbits.

The challenges associated with the capacity needs are summarized in Table 22.

*Table 22. Challenges Associated with Capacity Needs*

| ***Near-term Challenges: 2020-2023*** | ***Description*** |
|---|---|
| Frequency bandwidth | Operation over a wide frequency bandwidth is needed to maximize capacity and interoperability. |
| Processor constraints | Digital processors are required for flexibility, but they constrain payload designs due to their input-output interfaces, the merging of too much in one place at the processor, and a need for universal synchronization at all ports that may need to be combined. |
| Low size, weight, power, and cost | Implementation cost and SWaP can limit the deployment of technologies needed to advance satellite communications. |

| ***Mid-term Challenges: 2024-2025*** | ***Description*** |
|---|---|
| Tracking and frequency bandwidth | Tracking satellites in the same orbit or different orbits will require multi-axis scanning capability over a wide frequency bandwidth. This applies to both space and ground segments. |
| ***Long-term Challenges: 2026-2030*** | ***Description*** |
| Tracking, frequency bandwidth, and handover | The ability to track and perform a seamless handover (make-before-break) to another satellite outside of the provider network over a wide frequency bandwidth. This applies to both space and ground segments. |

### Robustness

A reconfigurable payload can address many challenges encountered by a communications satellite. For example, configuring the payload to operate over multiple frequency bands can be used to mitigate weather events using a lower frequency band.

(1) First, the ability to change its beam shape to optimize coverage based on capacity or emergency and during spacecraft maneuvers is key.

(2) Second, with the increase in satellites, the likelihood of unwanted interference can be mitigated by beamforming.

(3) Finally, it can be advantageous to change the frequency of operation downwards to avoid deleterious atmospheric effects on signal propagation due to atmospheric effects, such as heavy rain, etc. *(see Figure 13)*. The agility of the system to cope with a highly crowded spectrum environment can be facilitated by introducing advanced spectrum-sharing solutions (e.g., based on machine-learning approaches). However, this innovative approach can only be efficiently included in future satellite networks if the antenna and payload subsystems can cooperate and exchange information with other entities (e.g., interferers in terrestrial networks).

*Table 23. Challenges Associated with Robustness*

| ***Challenge*** | ***Description*** |
|---|---|
| Weather | Weather causes attenuation, refraction and scattering, impairing signal quality and availability. |
| Reconfigurability | The antenna system needs to be able to reconfigure its beam pattern to optimize service, detect / mitigate interference, and change frequency to avoid atmospheric propagation effects. |
| Interoperability | The antenna system needs to be interoperable with other satellite provider assets to enable a network-centric architecture. |
| Detection and mitigation of interference | As the number of satellites continues to grow, preventing and mitigating unwanted interference will require the antenna system to detect where the interference is coming from and reconfigure the beam pattern to null the interference while maintaining communications within the main beam. Similarly, to comply with regulatory standards, beam shaping may be needed to not interfere with other satellites. |

### Security

The tightness of antenna beams and avoidance of unneeded coverages improves physical security by reducing opportunities for eavesdropping on the downlink and interference on the uplink. Similarly, payload repeater electronics mitigate interference via filtering and level control functionality. Unless the repeater demodulates and decodes, it can only enhance physical security. However, the main challenges are not from eavesdropping, which any proper satellite link design has already obviated by proper data encryption and authentication, but from availability degradation by interference. Table 24 below addresses this.

*Table 24. Challenges Associated with Security*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Interference | Co-frequency signals overlap, intentional or not |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| More interference | Even more co-frequency signals overlap, intentional or not |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Pervasive interference | No more links limited by thermal noise |

### 5.5.2. Potential Solutions

Table 25 through Table 27 below address potential solutions for the challenges associated with capacity, robustness, and security.

*Table 25. Potential Solutions for Capacity Needs*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Frequency bandwidth | Better devices; architectures with arrays of time- and phase-synchronized antennas to support MIMO-based solutions; standardization would be a way to achieve this. |
| Processor constraints | Improved processors enabled by adopting denser semiconductor logic (but still rad-hardened). |
| Low size, weight, power, and cost | For the satellite payloads, use active antennas with a hybrid beamforming design to find a trade-off between the high flexibility of digital beamforming and the low power consumption of analog beamforming. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Tracking and frequency bandwidth | Active phased arrays with digital phase shifters integrated with onboard processing to allow flexible and robust implementation of multiple channels, beams, and beam shaping in general. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Tracking, frequency bandwidth, and handover | Metamaterial antennas, high-power MEMs, ground terminals with active phased arrays with element digital phase shifters, and signal processing hardware / algorithms. |

*Table 26. Potential Solutions Associated with Robustness*

| ***Near-term Solutions: 2022-2025*** | ***Description*** |
|---|---|
| High-performing solid-state devices, with improvement in performance at RF and in a space environment | Active phased arrays require solid-state devices to implement the receivers and exciters behind each element. These solid-state devices need to operate efficiently at both higher power and frequency and survive the environments encountered in space.<br>Using GaN devices allows for implementing solid state power amplifiers in conjunction with digital predistortion and efficiency enhancement techniques to optimize performance. These techniques may approximate the efficiency of a TWTA with reduced size and mass. |
| Detection and mitigation of interference | Signal processing combined with active phased arrays with digital phase shifters will allow for a flexible and robust implementation of multiple beams and beamforming in general. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Increase reliability | Increasingly modular payload units and antenna designs can efficiently allocate onboard resources.<br>The same applies to gateway electronics. |
| Attenuation due to rain in higher frequency bands (e.g., Q/V band) | Using larger Q/V band antenna reflectors for the feeder links will increase the link margins, then the robustness against rain fades. Antennas with a diameter of up to 10 m at the gateway side and 2.4 m at the satellite side can be envisioned. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Cognitive capability | Self-configuring, self-repairing antenna and payload subsystems. |

*Table 27. Potential Solutions to Address Security*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Interference | Careful system design based on presumed interference. Countermeasures are static. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| More interference | Systems must recognize interferences and jamming in real-time and take active countermeasures. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Pervasive interference | Cognitive radio |

## 5.6. Machine Learning and Artificial Intelligence

The applications of ML and AI have been widely explored for mobile and wireless networking. It is now being considered a key 6G enabler, as described in the recent whitepaper on ML in 6G wireless communication networks by S. Ali *et al.* [65]. In recent years, there has been a lot of interest in ML applications for non-terrestrial networks as well, including networking with satellites, UAVs, and HAPs [66], [67], [68]. Instead of using traditional fixed rules based on heuristics, non-terrestrial networks must adopt ML methods to achieve higher data rates, global coverage, reliability, and security. AI encapsulates ML, i.e., how a computer can learn to perform a task by combining data with algorithms.

ML is broadly classified into three categories: (i) supervised learning, (ii) unsupervised learning, and (iii) reinforcement learning. The three categories are explained in brief below.

- In supervised learning, inputs and outputs are available with enough labeled data to explore. Key concepts include classification and regression techniques, understanding training and generalization errors, underfitting and overfitting models, and dataset shifts. Some learning models include linear regression, statistical logistic regression, supervised classifiers, Support Vector Machines (SVMs), Artificial Neural Networks (ANNs), and Deep Neural Networks (DNNs). Related work on applying supervised learning for non-terrestrial networks is being researched [69], [70].
- In unsupervised learning, data is available for training, but the output is not labeled. Hence, subgroups with similar characteristics among the variables are discovered without guidance. Some learning models include Gaussian Mixture Model (GMM), Expectation-Maximization (EM), hierarchical clustering, K-means clustering, and unsupervised soft-clustering. A recent family of approaches is based on the generative models, such as Auto Encoders (AE) [71], in each of its flavors-Adversarial AE (AAE) [72], Variational AE (VAE) [73], and Generative Adversarial Network (GAN).
- Reinforcement Learning (RL) is different from supervised and unsupervised. In RL, an agent learns from interactions with an environment to achieve long-term goals. The goal is usually to maximize the reward. The agent should be able to partially or fully sense the environmental state and take actions to influence the state. RL is very useful in unknown environments, especially for non-terrestrial networks[73],[74], where network conditions are often unknown.

These three categories and their learning models are used in several ML applications for non-terrestrial networks. Specifically, the ML application can be classified into five different needs shown in Figure 14 and listed below.

- **Need #1:** AI-driven network planning for optimized routing and handover, in terms of efficiency and energy costs considering multiple access and positioning of the mobile users.
- **Need #2**: ML for applications including image / video delivery, situational awareness, traffic prediction, etc.
- **Need #3**: AI-driven enhanced security, including applications in public safety networks.
- **Need #4:** ML for resource management, including energy power management and data caching.
- **Need #5:** AI-driven physical layer communications, including channel modeling, spectrum allocation, adaptive configurations of coding schemes, etc.

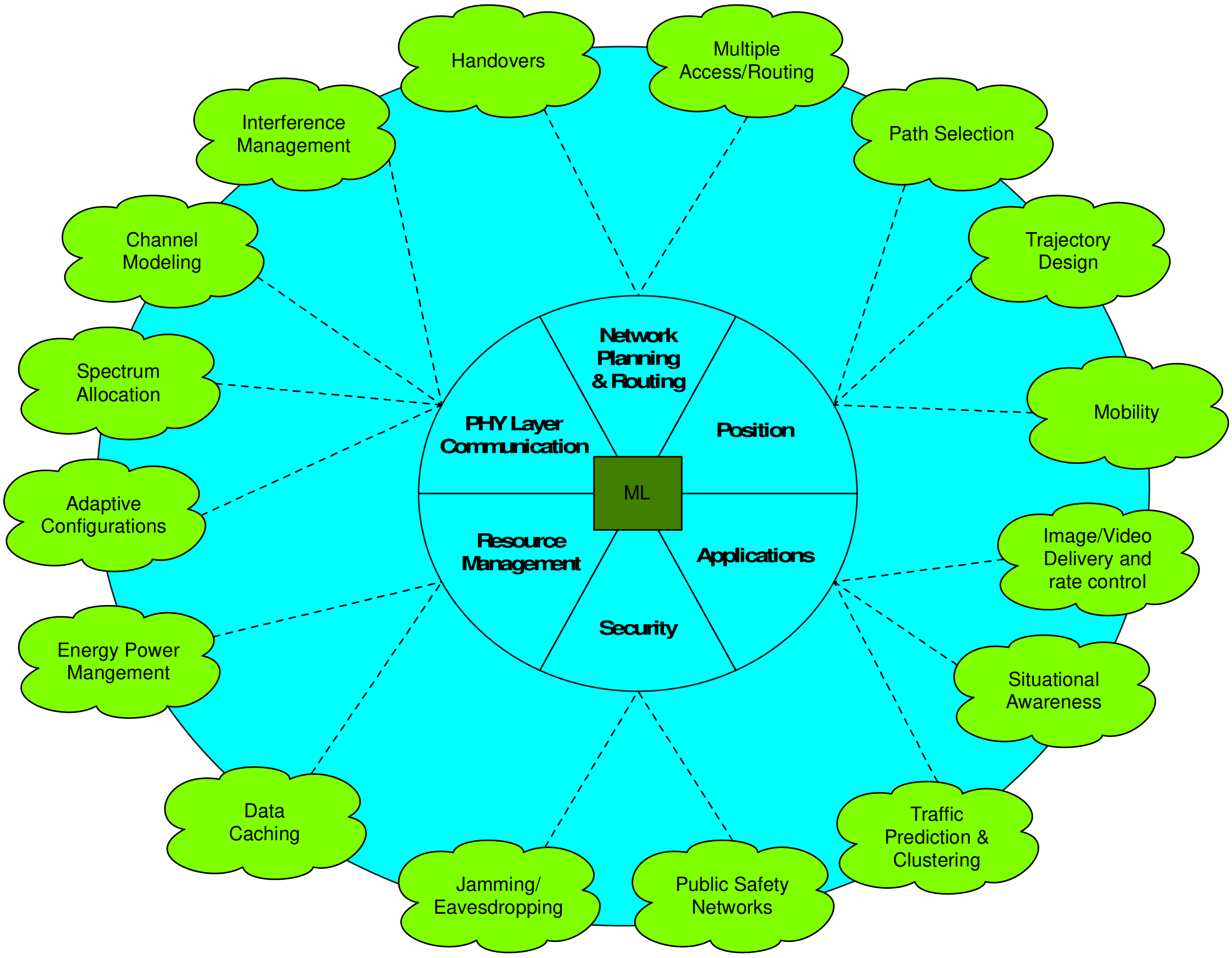


*Figure 14. Classification of ML Applications for Non-Terrestrial Networks*

### 5.6.1. Challenges

In the previous section, we have identified five needs for this topic. The challenges are almost common to all these needs. These challenges are described in the table below based on near-term, mid-term, and long-term challenges.

*Table 28. Challenges Associated with All Needs*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge #1: Efficient dataset generation | Several ML applications for non-terrestrial networks are in unknown territories where a dataset may not be available. For such scenarios, the challenge is to generate and provide an efficient dataset. Other challenges to be addressed include training data, splitting data, training intervals, the accuracy of predictions, etc. |
| Challenge #2: Learning efficiency | The three major ML techniques are supervised, unsupervised, and RL. However, several algorithms exist within these broad categories. In the near-term, it is required to identify which categories / algorithms are required and provide advantages related to different use cases considered for ML applications. |
| Challenge #3: Centralized vs. distributed ML techniques | Central and distributed networked systems have pros and cons. Concerning ML techniques, there has been a lot of focus on federated and distributed learning. On the other hand, with respect to technologies, MEC, content delivery networks, D2D, and blockchain are being considered for the future. The applications and tradeoffs between centralized and decentralized ML approaches for non-terrestrial networks should be measured and compared. In addition to allowing the generation of a global model without violating data privacy, federation techniques can be employed on a MEC-based infrastructure to make the model training phase of participating nodes more efficient. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge #4: Deployment overhead | ML is computationally expensive both for training and running ML models. The general hardware requirements should be gathered and widely deployed to enable in-time updates. Second, the storage capacity should also be revised and updated. |
| Challenge #5: Cross-layer cooperation | In general, cross-layer cooperation and optimization are essential for the performance of wireless networks. Similarly, cross-layer cooperation is also required for machine learning algorithms utilized at different layers. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge #6: Standardization of ML techniques | The current research in ML applications for non-terrestrial networks is still disordered. Standardizing AI/ML applications and methods to measure performance and create benchmarks for these strategies is critically important. This is a long-term challenge, and other near-term challenges must be addressed to complete the scandalization. |
| Challenge #7: Network-centric AI to user-centric AI; 5G to 6G | To boost the integration of NTN with the 5G/6G technology, we need a change in the AI paradigm. From Network-centric AI, we need to move toward user-centric AI. The former analyzes information from network entities to make more informed decisions on optimizing network resources; the second is focused on understanding individual user needs and preferences to provide personalized recommendations and experiences. The first approach is suitable for the communication infrastructure based on the 5G slicing; the second can make the slicing dynamic according to the users' needs. |
| Challenge #8: AI as a service (like an API) | AI as a service (AIaaS) can automate various processes in developing NTN infrastructure based on 5G/6G technology. This automation process can lead to increased efficiency and reduced development time. This increment in efficiency can lead to cost savings and improvement of scalability. Indeed, by leveraging AIaaS, 6G technology companies can save on infrastructure, hardware, and software development costs. Instead of building everything from scratch, companies can use pre-built AI solutions and frameworks. Further, AIaaS enables scalability of AI solutions as the demands of 6G technology increase. Companies can scale up or down without worrying about infrastructure and resource limitations. |

### 5.6.2. Potential Solutions

In previous sections, we have identified needs and challenges for ML and AI application with non-terrestrial networks. This section presents tables that describe the solutions corresponding to each need.

*Table 29. Potential Solutions to Address Need #1: AI-driven network planning for optimized routing and handover, in terms of efficiency and energy costs considering multiple access and positioning of the mobile users*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge #1: Efficient dataset generation | Data generation and collection by considering unified hierarchical and hybrid architecture consisting of UAVs, LEO, MEO, and GEO satellites. Analysis of periodic burst traffic and selection of shortest route for traffic dissemination. Efficient data generation by considering the proper horizontal and/or vertical placements for HAPs and UAVs, the trajectory of UAVs and satellites, UE's position, detection of UAV flying path and status, positioning of next-hop satellites, etc. |
| Challenge #2: Learning efficiency | Learning efficiency and accuracy of deep learning (DL) techniques to distribute traffic with reduced computational cost using distributed training. The learning efficiency of commonly used ML algorithms for detection and localization should be compared. These algorithms include Bayesian, SVM and MLP solutions, use of ANNs, KNN, DA, SVM and NN-based classification, Kernel density estimation, and the use of DL. |
| Challenge #3: Centralized vs. distributed ML techniques | Analysis and comparison of distributed and centralized routing techniques, especially in the case of hierarchical architecture with UAVs, LEO, MEO, GEO satellites, and HAPs. Performance analysis of centralized and distributed ML techniques for proper detection, localization, and optimal trajectory design. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge #4: deployment overhead | Identification of training and testing locations and efficient distribution of algorithms weights using Federated Learning (FL). Identification of deployment locations, including the integration of ML at edge / cloud / source and evaluation of deployment overhead. |
| Challenge #5: Cross-layer cooperation | The challenge is mostly specific to the network layer, but the ML algorithms used at the physical layer for better transmission should be taken into account. Both physical and network ML integration should be taken into consideration for designing proper positioning strategies. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge #6: Standardization of ML techniques | Standardization of ML techniques and identification of efficient algorithms for finding optimal routing paths. Proper standardization process to be followed addressing challenges for efficient data generation and learning efficiency. |

*Table 30. Potential Solutions to Address Need #2: ML for applications including image / video delivery*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge #1: Efficient dataset generation | Both real experiments and simulations can be targeted for efficient dataset generation. Specific video factors, including frame rate, resolution, and bit rates, should be taken into consideration. |
| Challenge #2: Learning efficiency | The learning efficiency of RL algorithms, which are typically useful in unknown territories, should be compared, especially the use of Q-learning and Actor-Critic (A3C) methods. |
| Challenge #3: Centralized vs. distributed ML techniques | Investigation of integrating ML techniques with Content Delivery Networks (CDNs) and edge delivery services for video delivery. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge #4: Deployment overhead | Identification of deployment locations and exploring ML implementations at both server and clients. |
| Challenge #5: Cross-layer cooperation | This need is specific to the application layer, but network feedback, including packet losses, congestion, etc., should be taken into consideration when using ML for efficient video delivery. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge #6: Standardization of ML techniques | Revisiting Quality of Experience (QoE) metrics and integration of ML factors that can influence video QoE. |

*Table 31. Potential Solutions to Address Need #3: AI-driven enhanced security*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge #1: Efficient dataset generation | Selection of security targets for dataset generation, including eavesdropping mitigation, interference, and jamming mitigation, spoofing protection, interception of malicious nodes, pilot identification for UAVs, etc. |
| Challenge #2: Learning efficiency | Analysis of learning efficiency for ML techniques used for enhanced security, including Q-learning, CNN-based detection, and classification based on LD, QD, SVM, KNN, RandF, etc. |
| Challenge #3: Centralized vs distributed ML techniques | Performance analysis of centralized and distributed ML techniques for guaranteeing privacy, integrity, and confidentiality. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge #4: Deployment overhead | Flexible deployment of non-terrestrial networks, including UAV networks where several public safety applications rely on flying nodes to create secure infrastructure for communication after a disaster, during critical rallies, etc. |
| Challenge #5: Cross-layer cooperation | Analysis of ML applications for security at different layers and exploiting cross-layer cooperation. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge #6: Standardization of ML techniques | Extending the current wireless security standards, such as Wired Equivalent Privacy (WEP) and WiFi Protected Access (WPA) to the non-terrestrial application integrated with ML algorithms. |

*Table 32. Potential Solutions to Address Need #4: ML for resource management*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge #1: Efficient dataset generation | Selection of efficient dataset generation for resource management targets, such as spectrum allocation and caching, network coordination, multi-modal multi-task offloading, and deployment of base stations. |
| Challenge #2: Learning efficiency | Analysis of learning efficiency for ML techniques usually used for resource management, including LR, SVMs, K-means, distributed RL, ESN, and LSM-based techniques. |
| Challenge #3: Centralized vs. distributed ML techniques | Performance analysis of centralized and distributed ML strategies for resource management, better network planning, and improved energy efficiency and power control. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge #4: Deployment overhead | Deployment of NTN systems, including UAV, optimizing energy efficiency and recharging IoT ground nodes under the wireless-powered communication paradigm. |
| Challenge #5: Cross-layer cooperation | Gathering requirements at different layers and improving cross-layer cooperation for better resource management. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge #6: Standardization of ML techniques | Standardization of ML techniques for resource management with better learning efficiency. |

*Table 33. Potential Solutions to Address Need #5: AI-driven physical layer communications*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge #1: Efficient dataset generation | Selection of appropriate channel models for performance evaluation and dataset generation. Use of ANNs and ensemble methods for predicting Received Signal Strength (RSS). |
| Challenge #2: Learning efficiency | Comparison of estimated RSS errors from the actual RSS measurements. |
| Challenge #3: Centralized vs. distributed ML techniques | Performance analysis of centralized and distributed ML techniques for predicting RSS, interference management, and configuration of transmission parameters. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge #4: Deployment overhead | Identification of deployment locations with UAVs and satellite systems. |
| Challenge #5: Cross-layer cooperation | Improving performance by considering ML's application at the higher network and link layers. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge #6: Standardization of ML techniques | Comparison with existing standards, including DVB-S2X for satellite communications for adaptive coding and modulation. |

## 5.7. Edge Computing

### 5.7.1. Challenges

Multi-access Edge Computing (MEC) is a concept consolidated for use in terrestrial infrastructures, whose deployment has already started years ago under the definition of Mobile Edge Computing (MEC). The MEC market has been growing dramatically in the last few years because of the increasing deployment of service-based architectures and the need to offer services to users as close to their location as possible. This trend is expected to grow in the coming years, whereby all available communication infrastructures can be considered a possible means for enabling a more widespread implementation of MEC functionalities. In this respect, the application of these concepts in satellite-based systems (integrated with terrestrial counterpart) is considered an enabler for different services, possibly opening new market opportunities towards the definition of the so-called Satellite-as-a-Service paradigm, through which the satellite (or NTNs in a broader sense) will provide specific services, such as in-orbit data processing, analytics, etc.

However, the peculiarities of the satellite environment coupled with the MEC service requirements introduce important challenges and threats. Notably, MEC services may require significant computation and power resources, which current satellite systems cannot offer because their system design was usually conceived for other tasks. As such, allocating MEC functionalities in space has important implications ranging from onboard spacecraft design to MEC service optimization.

On the other hand, it is of paramount importance to stress the value brought by MEC-enabled satellite systems in terms of KPI to the B5G ecosystem. Such a concept can help distribute the necessary resources to perform computing in the network, reducing overall energy consumption. Moreover, using a satellite inherently has a large coverage capability, which will simplify the access to computing and caching facilities from many users, independent of their specific position (i.e., in rural and unconnected areas). Finally, the combination of AI concepts and (v)LEO satellite systems may further reduce the latency to achieve an almost zero perceived latency, which the B5G ecosystem alone (i.e., without support from NTN segments) can hardly achieve (i.e., multi-connected or unconnected scenarios).

The main identified opportunities for the satellite industry relate to NFV, computation offload, satellite MEC caching, service discovery, and MEC orbital systems, which are shortly surveyed in the following.

**NFV Support**

A network function can be placed at the edge node or the central location. To make the appropriate split, a proper system design must be carried out to make the overall communication chain effective. The main reason to place functions at the edge is to reduce the communication needs to the central location via satellite hop. Edge placement will imply the deployment of more network functions – when the function is placed at the edge, this function must be managed to ensure that the same service quality is offered to the subscribers. On the other hand, placement at the edge will require trust in the edge node for the specific functionality – a remote node is very easy to tamper with, including man-in-the-middle attacks. Sensitive information for the system’s functioning, such as user profiles or credentials, should not be placed at the edge.

Placement at the edge requires available computation and storage resources – a function will consume a set of resources when placed at the edge, especially important in the case of mobile-edge nodes that cannot connect to a fixed power supply. Placement at the edge will require backhaul resource consumption –a function placed at the edge node must communicate with the central location.

**Computation Offloading**

Computation offloading techniques have been introduced to allow the offload of processing-intensive tasks from reduced capabilities devices to powerful devices. In a satellite scenario, multiple offloading approaches can be considered from ground to space and the reverse. An integrated terrestrial satellite environment is considered in [74], where various challenges are illustrated. Among others, computation offloading is considered for reducing latency concerning legacy data center-based solutions. The authors consider an integrated satellite and terrestrial network for IoT applications [75], where an incentive mechanism is proposed for optimally selecting the destination of the task offloading. A game-theoretic approach is considered [76] for enabling an edge computing-based offloading mechanism in an IoT application scenario.

An integrated satellite-terrestrial approach for computation offloading brings several challenges but also opens several possibilities. Since the main application scenario would be the Internet of Things with all the possible differences, an integrated-terrestrial-satellite approach would first focus on the data source. In some applications, the data to be processed could be on the ground, while in others, the source could be on the satellite (e.g., surface analysis). This opens several challenges for deciding the node bringing the computation. To this aim, several intermediate layers could be considered (e.g., HAPs, UAVs, vLEO), giving the possibility to bring their computational capabilities to the system. Another interesting area could be exploring a distributed computation approach where multiple devices collaborate. To this aim, the distributed approach could become very challenging when considering satellites as devices.

### Satellite MEC Caching

In integrated satellite-terrestrial networks, MEC caching services can be deployed in satellite orbital constellations or a single satellite to store useful data to improve security or reduce the delay by minimizing the transmission between the satellite and ground. The authors introduce a three-layer architecture (Customer-Gateway-Satellite) for the space-based cloud [77]. The LEO satellites are treated as cloud data storage centers instead of relay nodes, in which data servers are deployed on the satellites. A two-layer caching model is also introduced to support the content delivery service, reducing downlink and uplink bandwidth consumption. The satellite and ground station layers perform joint caching [78]. Within a similar architecture, the work [79] considers the tradeoff between the caching hit rate and the required offline file placement time, in which the authors intend to reduce the file placement time by preserving a certain level of cache hit rate. The social relationships among the users are applied to assist the satellite cloud in determining the content of video files to cache to achieve better QoE[80]. In addition, the work in [81] proposes an on-path caching-enabled fetching strategy to improve the file distribution performance by considering the satellite's and ground station's spatial-temporal changes.

Caching in satellites is needed to store the data, which can be used repeatedly, but the satellite has limited storage space. Determining the caching data by utilizing the limited storage size and analyzing the data is very challenging. On the other hand, the availability of onboard caching coupled with AI mechanisms can be leveraged to predict data requests and hence possibly meet the stringent requirements of URLLC services. There are, however, still several challenges to realizing satellite MEC caching. We will only list the main ones. First, the satellite's mobility should be considered a challenge since the topology of the satellite network is dynamically changing. Second, for the reference scenario, the power supply is very limited to support the data transmission and data processing over satellites. Third, due to the limited processing power of the satellites, it is hard to process the cached content (e.g., search a segment of cached video) over the satellites. Fourth, the hit rate is difficult to guarantee when the potential data amount and types can be extremely massive in the reference scenario. As such, the popularity of the cached content must be taken into account in the dynamic storage of content, possibly resulting in pre-emptive approaches for freeing the available capacity in favor of contents that are newer or, in any case showing a larger interest from users in the sense of their demands.

### Orbital Systems

When employing satellites, MEC services should consider the satellite orbital constellations due to their impact on service continuity and delay on the ground. The authors[81] consider the scenario that MEC platforms with computation and storage resources are deployed on LEO satellites, called "LEO-MEC". The authors[82] propose the Orbital Edge Computing (OEC) system to include CubeSat as part of the edge computing facility in a space-based architecture.

In this context, integrating a dense vLEO and LEO orbital system with a distributed approach will be of paramount importance, especially by exploiting inter-satellite links. It will also be important to consider the specific applications that such a system would be able to support, with particular attention to IoT and related applications.

More importantly, it is worth considering the different configurations that could be adopted for exploiting MEC concepts in space, i.e., the satellite infrastructure (GEO and/or LEO constellations). In this respect, both direct access and backhaul options could be considered, i.e., with gNodeB being positioned as access to the satellite (backhaul), onboard the satellite, and at the other side of the satellite network. These configurations introduce some important implications at the computation resource level, especially in terms of power and computation budget as well as in terms of cache, so the possible tradeoff with the corresponding implementation on the ground should be considered too.

Finally, the design of such integrated MEC-NTN systems has to consider that computation resources available on satellites are usually unloaded (or with little load) when specific satellites cover areas with a very sparse user density (i.e., over deserts, rural areas, or oceans). It would be convenient to allocate computing tasks to those satellites, although forwarding the requests may require an additional delay, possibly not fitting the specific service requirement.

### Service Discovery

Edge computing facilities allow for the implementation of several services by exploiting virtualization. In such a scenario, it will become of paramount importance to discover the available services and where they are located. The authors[83] present a decentralized and revised Content-Centric Networking (CCN)-based MEC service deployment / discovery protocol and platform. The authors mainly focus on an IoT terrestrial scenario by demonstrating the effectiveness of the proposed approach. The authors[84] propose a protocol for supporting the distributed k-nearest service discovery, demonstrating that it allows scalable, locality-aware, name-based service discovery. It also allows routing for the target nodes avoiding redundant lookup message exchanges across the edge networks. Moreover, the new frontier of edge computing is that of allowing for more distributed system design, possibly resulting in the edge-to-edge and edge-to-cloud instances, which have their immediate application in multi-tier multi-orbit satellite networks, where each node implements either edge or cloud server instances.

From the literature, it is clear that service discovery is an important challenge in edge computing. At this moment, only a few works consider their impact on satellite networks, highlighting the importance of their adoption in space communications. The challenges to be considered in this area are mainly related to the satellite environment due to its specific characteristics that impose strict constraints on service discovery. Moreover, edge computing has usually been approached for deployment in terrestrial networks as a fixed infrastructure. In contrast, mobility can introduce further challenges to be properly understood and a more effective design must be carried out.

### Deployment and Orchestration

When facing a distributed scenario, it becomes of paramount importance to deploy and orchestrate the different resources and services efficiently. While deployment entails efficiently deploying the different applications, orchestration involves their joint management with the available physical resources. The authors[83] jointly consider the service discovery with their optimal placement in a terrestrial network. The authors[85] focus on an orchestration layer for integrated terrestrial and satellite networks. Even if not directly considering edge computing, the orchestration problem is highlighted. A similar approach is considered[86], where the TALENT platform is presented. The work[87] surveys the most important challenges for MEC orchestration and deployment strategies by considering 5G architectures as a reference use case.

From the industry development point of view, the problem of application placement and orchestration is of paramount importance. Their impact is very big, considering a service can be effectively used if placed in the correct position. This is even more important in the case of a satellite system that considers different constellations impacting service availability. Still, from the same point of view, it could be very important to understand how satellite components can be integrated into the related standard effort. For example, ETSI MANO is proposed for managing and orchestrating different functions. Its extension to edge computing and satellite could indeed be of interest.

Based on the peculiarities identified for each of the scenarios above and use cases, it is possible to identify some key challenges, especially concerning 1) satellite MEC caching, 2) computation offloading, 3) service discovery, and 4) orchestration / deployment, which are shortly summarized in the following table according to their urgency in time.

*Table 34. Challenges Associated with MEC*

| ***Near-term Challenges: 2023-2025*** | ***Description*** |
|---|---|
| Computation offloading | To identify which computation tasks could be offloaded to the satellite segment and in which part of it, i.e., ground infrastructure or space segment. In the latter case, attention has to be dedicated to the specific platform that should be better used in terms of HAPs, LEO, GEO, etc. |
| Satellite MEC caching | To define the content or information that could be cached onboard satellite and to investigate which platforms should be better used for this aim. An additional challenge is represented by the typical limited onboard storage available in space platforms. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Service discovery | To discover the specific availability of a service in the network, which is quite unexplored in the case of satellite systems. |
| ***Long-term Challenges: 2027-2032*** | ***Description*** |
| Orchestration and deployment | To perform orchestration between the available resources requested by different services in a distributed manner, which can be particularly cumbersome when terrestrial and satellite facilities must be jointly coordinated. |

### 5.7.2. Potential Solutions

*Table 35. Potential Solutions to Address MEC*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Computation offloading | It depends on the specific data source, i.e., terrestrial or satellite specific. In the former case, computation offloading could happen onboard the satellite with particular reference to IoT data, given the limited computation availability onboard satellites. In the latter case, instead, the availability of ISLs can be exploited to distribute computation offloading across multiple satellites. |
| Satellite MEC caching | To take advantage of space / time correlation between satellites and use of artificial intelligence schemes to predict content requests better and accordingly place contents by also exploiting power-efficient caching schemes. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Service discovery | According to the current 3GPP specification (i.e., TS 23.748), the discovery could be performed either centrally or in a distributed manner, the latter benefiting from the availability of ISLs. |
| ***Long-term Challenges: 2027-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Orchestration and deployment | Orchestration is typically performed in a centralized manner, whereby a ground station is the network node better entitled to carry out such functionality. A more dynamic approach must be taken in a multi-asset (e.g., multi-band, multi-orbit, multi-platform) satellite system. |

#### 5.7.2.1. Solution: Computation Offloading

When considering computation offloading with satellite networks, the first distinction should be put on the source of the task to be offloaded. Indeed, when considering a satellite network, data can be generated on the terrestrial side or onboard the satellite. When considering terrestrial data sources, the possible solutions could consider the role of the satellite as a remote processing node or as a relay toward a ground station. While the first solution reduces the offloading delay, the second one involves a higher delay. However, onboard processing is usually very limited, making this solution feasible in only a few use cases (e.g., IoT). Still considering terrestrial generated data, energy consumption is a figure of merit, where the satellite orbital system could impact the selection of the remote processing node. When considering satellite-generated data, two main solutions could be considered. The first would be where to place the role of inter-satellite links for deploying tasks to be processed. The second would involve ground stations acting as data sink for processing satellite-generated data.

#### 5.7.2.2. Solution: Orchestration and Deployment

In contrast to service discovery, deployment and orchestration aim to proactively deploy and then orchestrate the MEC services in each scenario. While deployment can leverage NFV principles by flexibly managing the different functions in a satellite environment, the orchestration seems better suited to a centralized approach where a ground station could be used as an orchestrator. It is worth noting that the presence of multiple orbital systems and different demands for ground users could impact dynamic service deployment policies. On the other hand, new advances in network orchestration lead to hierarchical or distributed solutions, which would scale better regarding resource usage over multi-tier satellite networks, though at the cost of increased update or synchronization signaling between the involved entities.

#### 5.7.2.3. Solution: Service Discovery

When facing MEC service discovery, the main issue is identifying which services are involved and where they are deployed in a given satellite network. We can define two main solutions by resorting to 3GPP TR 23.748, which aims to define the Edge Application Service Discovery procedure. One considers a centralized anchor point, and another considers a local anchor point. While the centralized anchor point, placed on a ground station, could be used for discovery, the services installed in each satellite in a distributed anchor point could be based on a local registry. To this aim, the presence of inter-satellite links could help in the discovery of installed services by sharing each service.

#### 5.7.2.4. Solution: Satellite MEC Caching

In general, to overcome the problem of limited data storage, caching hit rate can be improved by considering the spatial-temporal nature of the satellites. Thus, the demand for storage space will be constrained to a minimum level. The following aspects must be taken into account to realize the MEC caching in satellites. First, the mobility of the satellites is predictable as they all move in designated paths. Even though some might change the orbits, machine learning or a hidden Markov model can be used to predict the trajectory. Second, caching schemes with low computational complexity should be proposed. It is worth noting that deep learning is not quite feasible in this case. Third, for the referenced scenario, when processing the cached content, it is expected to transmit the data and offload the computational duty to the ground stations if the processing duty is not that urgent. Fourth, it is evident that not all types of data should be cached in the satellites. With the limited space, deep learning or reinforcement learning should be employed to analyze the file types to be cached in the satellites. Consequently, the hit rate will be improved under limited caching space conditions on satellites.

## 5.8. Quality of Service / Quality of Experience (QoS / QoE)

### 5.8.1. Challenges

QoS is extensively used today in broadband networks, wireless networks, multimedia services, and even the internet. Today it is one of the primary considerations in 5G and 6G networks. Networks and systems have been designed considering the end-to-end performance required by user applications and services. Most traditional internet applications, such as Email and File Transfer Protocol (FTP), are sensitive to packet loss but can tolerate delays. This is generally the opposite for interactive multimedia applications (voice, video, remote control, and interactive gaming). They can tolerate some packet loss but are sensitive to delay and variation of the delay (also called jitter). Therefore, networks should have mechanisms for allocating bandwidth resources to guarantee a specific QoS for real-time applications. Thus, QoS can be described as a set of parameters that describe the quality of a particular stream of data provided to the users. In addition, Quality of Experience (QoE) becomes important when selling satellite services to users, as they can always compare with the services provided by the terrestrial networks. QoE is often assessed by customer surveys. Users may have different experiences if the same information is presented to the users in various ways, although the QoS parameters are the same.

We can consider that QoS is related to technical performance (i.e., it is mainly technology-centered and more relevant to network operators and equipment manufacturers). There are four viewpoints of QoS defined by the ITU-T G.1000 recommendation, corresponding with different perspectives as shown in Figure 15, that is (i) customer QoS requirements, (ii) service provider offerings of QoS (or planned / targeted QoS), (iii) QoS achieved or delivered, (iv) customer survey ratings of QoS.

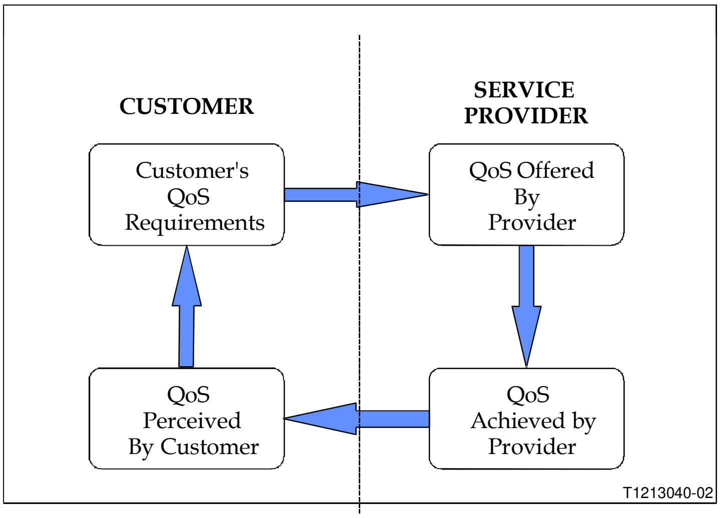


*Figure 15. The Four View Points of QoS (ITU-T G.1000)*

QoE is user-centric, based on end-user behavior. QoE is based on application, experience, and expectations for all the services received. Expectations will change with time and with the evolution of applications over time. The main QoE drivers are accessibility, sustainability, and interactivity. More details on QoE requirements for specific 5G applications can be found in the 3GPP reports in [88] [89] [90].

**QoS / QoE as much as possible close to terrestrial 5G-6G systems (time horizon of 2030)**
The aerial component of 5G-and-beyond systems will include satellites at different altitudes, HAPs, LAPs, and UAVs. This system will allow multiple layers of connectivity (called 3D space networks). These different layers have a distinct impact on the system latency (*refer to Section 0 on Reference Architectures for more details)*. The QoS-KPI levels the system can achieve heavily depend on the aerial component characteristics. Therefore, the end-to-end QoS-KPI can be measured in each subnet separately, as illustrated in Figure 16, and the end-to-end measurements can be carried out for the terrestrial and satellite network separately.

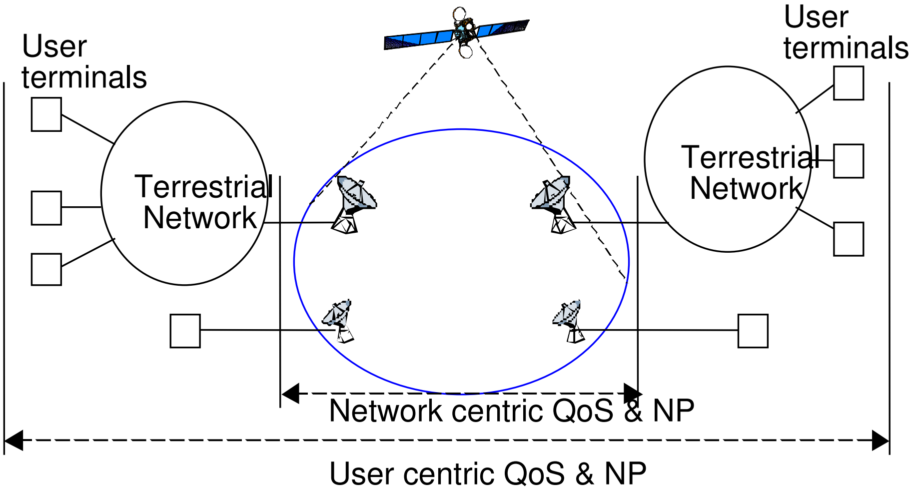


*Figure 16. User- and Network-Centric Views of QoS and Network Provision (NP) Concepts*

On the other hand, 5G – B5G – 6G are expected to support new and extremely challenging services from the latency standpoint, such as Augmented Reality (AR) / Virtual Reality (VR), gaming, streaming, and other intensive traffic classes. Interesting examples involving use cases and QoS / QoE for the aerial component with HAPs, UAVs, and LEO satellites are provided [91]. The one-way propagation delay between a UE and a satellite may range between 1 ms and 140 ms depending on the satellite's altitude and the relative position of the UE. For instance, Starlink has reported a delay of 20 ms in their recent tests. Instead, the propagation delays can be much lower, around 1 to 2 ms using HAPs and UAVs. Furthermore, in a constellation of non-geostationary satellites with Inter-Satellite Links (ISLs), the delay between a generic UE and the core network depends on the location of the communication endpoints [92].

A 5G network with satellite access will be capable of establishing (independently, even simultaneously) uplink and downlink connectivity through the 5G satellite and 5G terrestrial access networks [93]. This multipath peculiarity will have an impact on QoS requirements.

The full QoS model of 5G is detailed in 3GPP TS 23.501 [94] [95]. This specification applies to terrestrial 5G connections and satellite connections compliant with the 5G standard (i.e., direct connectivity). However, 3GPP TS 23.501 does not mention the satellite case explicitly: all the 5G QoS Identifiers (5QI) specified in 23.501 are general. In 3GPP, QoS is at the flow level concerning the treatment of traffic flows between the UE and the User Plane Function (UPF) re: the following characteristics:

1. Resource Type: Guaranteed Bit Rate (GBR), delay critical GBR, and non-GBR
2. Priority level
3. Packet Delay Budget (PDB), including core network PDB
4. Packet error rate
5. Averaging window (for GBR and delay critical GBR)
6. Maximum Data Burst Volume (for delay critical GBR).

3GPP specification TS 22.261 addresses service requirements for different 5G aspects, like network slicing, mobility needs, multiple access, and resource efficiency, including the case of satellite access [96]. TS 22.261 provides Table 36 on the propagation delay; note that network latency is well above since it includes processing and queuing effects for processing all over the system. These propagation delays impose key constraints for services and protocols, as discussed below.

*Table 36. UE to Satellite Propagation Delay (Source: TS 22.261 [96])*

| | ***UE to satellite propagation delay [ms]*** | | ***Two-way max propagation delay [ms]*** |
|---|---|---|---|
| | Minimum | Maximum | |
| LEO | 1 | 15 | 30 |
| MEO | 27 | 43 | 90 |
| GEO | 120 | 140 | 280 |

Also, the 3GPP specification TS 22.261 provides the following QoS Table 37 for satellite access.

*Table 37. QoS Requirements for Satellite Access (Source: TS 22.261[96])*

| ***Scenario*** | ***Experienced data rate (DL)*** | ***Experienced data rate (UL)*** | ***Area traffic capacity (DL)*** | ***Area traffic capacity (UL)*** | ***Overall user density*** | ***UE speed*** | ***UE type*** |
|---|---|---|---|---|---|---|---|
| Pedestrian | 1 Mbps | 100 kbit/s | 1.5 Mbps/km$^2$ | 150 kbps/km$^2$ | 100/km$^2$ | Pedestrian | Handheld |
| Public safety | [3, 5] Mbps | [3, 5] Mbps | TBD | TBD | TBD | 100 km/h | Handheld |
| Vehicular connectivity | 50 Mbps | 25 Mbps | TBD | TBD | TBD | Up to 250 km/h | Vehicle-mounted |
| Airplane connectivity | 360 Mbps / plane | 180 Mbps / plane | TBD | TBD | TBD | Up to 1000 km/h | Airplane-mounted |
| Stationary | 50 Mbps | 25 Mbps | TBD | TBD | TBD | Stationary | Building-mounted |
| Video surveillance | [0, 5] Mbps | 3 Mbps | TBD | TBD | TBD | Up to 120 km/h or stationary | Vehicle-mounted or fixed installation |
| Narrowband IoT connectivity | 2 kbit/s | 10 kbps | 8 kbps/km$^2$ | 40 kbps/km$^2$ | 400/km$^2$ | Up to 100 km/h | IoT |

The evolution of the 5G ecosystem towards 6G is expected to enable new services with unprecedented levels of QoS / QoE demands, especially in terms of delay and bit rate requirements. As such, the macro-classes defined in the context of IMT-2020, such as eMBB, URLLC, and mMTC will be extended to include new services with more stringent QoS requirements, which can be summarized in a graphical format, as shown in Figure 17 below.

The 5G system shall support QoS negotiation when using the aerial segment, considering the latency penalty to optimize the QoE experienced by UEs. A 5G service via satellite shall be able to tolerate the satellite access delay. GEO / MEO / LEO cases could have the following propagation delay values 285 ms / 95 ms / 35 ms, respectively. The 5G system with satellite access shall guarantee service availability at least 99.99% of the time.

The satellite connectivity may be unable to provide appropriate QoS levels to all 5G flows[91]. For instance, URLLC may require a PDB of 5 ms or even 1 ms to align with terrestrial systems, but this low latency value is incompatible with the use of GEO satellites but can be provided in the case of UAVs, HAPs, and some LEOs.

New use cases and existing ones already envisioned for 5G start to be considered from the 6G perspective. However, more extreme QoS requirements are foreseen owing to the technology advances promised already by the B5G expectations. The evolution of eMBB, mMTC, and URLLC is especially relevant for what concerns the supported bit rates and delays, which are expected to be in the order of

Gbps and sub-ms, respectively, hence making the design of the overall network and, more importantly, of the RAN part the keys to attaining such levels of QoS. In this respect, it is then worth noting that very low delays (i.e., < 1 ms) correspond to data exchanged between nodes at “close distance,” i.e., less than 300 km, whereby global connectivity concepts cannot just rely on standard end-to-end data distribution (i.e., producer to consumer or client to server) but rather MEC and AI/ML concepts should be envisioned. Likewise, significant user data rates are not always achievable, depending on the specific propagation characteristics and the overall considered environment.

In this regard, it is worth mentioning the new class of extreme-URLLC (eURLLC) that improves latency and reliability requirements of URLLC of at least one order of magnitude and next-generation URLLC (xURLLC) that further pushes these requirements to meet the stringent needs of new 6G applications (VR/AR, metaverse, tactile internet, car-to-car systems). Of course, such low latency requirements are only compatible with the lowest altitude platforms of NTN, such as the UAV layer, and the use of local edge processing (MEC) if some data elaboration is needed.

Finally, pervasive connectivity is expected to address a very large density of devices per square kilometer (km$^2$), raising challenges from spectrum access and interference management standpoints. Finally, it is worth pointing out that these new extreme requirements must be considered specific to different use cases and, therefore, not applicable to the overall 6G framework since different technological solutions should be worked out for various services and scenarios. From this point of view, satellite technology can meet some of the above-summarized use cases with the recent plan of LEO constellations and, in general, Very High Throughput Satellites (VHTs). However, the mentioned technical challenges must be adequately addressed in the system design.

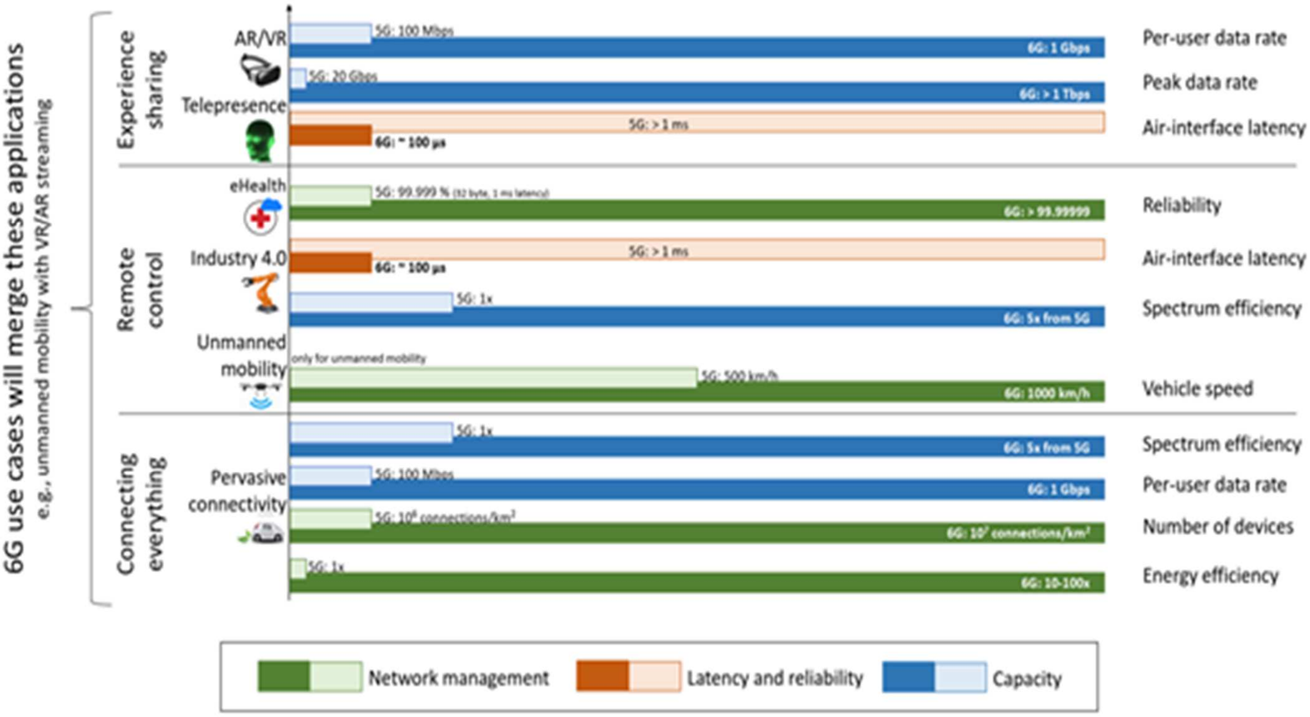


*Figure 17. 5G QoS Requirements* [97]

### QoS architecture and function virtualization for a single-layer network (mid-term view)

This mid-term challenge deals with the support of single-layer (typically LEO) satellite systems.

In the past, the main role of satellite networks has generally been perceived to provide backhauling solutions in remote or hard-to-reach locations. This assumption was based on the technical complexities of integrating satellite and terrestrial networks due to the lack of prevalent standards and the proliferation of vendor-specific solutions. 5G networks face unprecedented challenges like the diffusion of the IoT and the transformation towards an all-IP environment network. The function of networks is no longer to transmit information. Newly emerging applications require network operators to redefine the functions of communication systems to include caching, computing, and retrieving resources with intelligence regarding the context around users.

With the advent of software-defined networks and network function virtualization (SDN / NFV) paradigms, the role of satellite networks can change thanks to the ease with which they can be integrated with existing terrestrial network infrastructures[98]. Such integration will create significant new opportunities for terrestrial and satellite networks, thanks to greater flexibility in the operation and evolution of end-to-end network services. While the SDN approach is well consolidated on wired (terrestrial) networks, thanks to the match / action abstraction characterizing the operation of heterogeneous network nodes, there is no clear programming model in the satellite domain. The integrated satellite-terrestrial ecosystem will be based on the current 5G design architecture, massively building on SDN / NFV, network slicing, MEC, and Service Function Chaining (SFC) concepts. The proper configuration and placement of such functions will be important in meeting the verticals' QoS requirements concerning bandwidth and computation demand and delay constraints, to cite a few.

### QoS architecture and function virtualization for a multiple-layer network (longer-term view)

This challenge entails a long-term vision and deals with aerial components with multiple layers, thus allowing multiple connectivity alternatives. A full mesh network in space (use of S1 interface in case of the use of the satellite or use of the S3 interface in case of the use of UAV / HAP; use of S2 or a proprietary interface for the communication between satellites via ISLs) will introduce important challenges in the design of a suitable end-to-end network orchestrator able to configure network slices effectively. Further, coordination between scheduling and resource allocation policies will be needed across multiple layers. In this respect, the main challenge will be providing a suitable and flexible design concept that can scale correctly in multi-tenant networks. To this end, proper instantiation of network slices and the related dimensioning will be pivotal to meeting specific QoS / QoE requirements claimed by corresponding verticals. The overall QoS / QoE management requires a two-dimensional approach, i.e., vertically from the verticals down to the radio-resource management schemes and horizontally across all network segments.

*Table 38. Challenges Associated with QoS / QoE*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: QoS levels as much as possible close to terrestrial 5G-6G systems | To design highly efficient satellite systems (and NTN in a broader sense) able to adapt to the various flavors of traffic services and complement the terrestrial network by achieving the same QoS targets. |

| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
|---|---|
| Challenge 2: QoS architecture and functions for single-layer network | Evolution of the current 5G ecosystem to incorporate LEO constellations provided with the networking capabilities (routing, SDN, MEC, etc.) needed to meet diverse QoS requirements. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 3: QoS architecture and functions for multiple-layer network | Revolution of the space environment to allow interconnection of multiple space assets orbiting at different altitudes and using different frequency bands to enable effective data communications. In this context, a 3D satellite network is expected to appear as a mesh system extending the terrestrial infrastructure implementing beyond 5G (B5G) and 6G technologies. |

### 5.8.2. Potential Solutions

*Table 39. Potential Solutions to Address QoS / QoE*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: QoS levels as much as possible close to terrestrial 5G-6G systems | Consolidation and implementation of the 3GPP-NTN-related standards, especially concerning the use of 5G NR and the overall end-to-end orchestration models. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 2: QoS architecture and function virtualization for single-layer network | The advanced design of satellite payload allows for onboard processing and advanced networking capabilities in LEO satellite networks. Moreover, optical communication for ISL can help transfer a large amount of data and meet low delay requirements. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 3: QoS architecture and function virtualization for multiple-layer network | Consolidation of SDN concepts onboard satellite by also taking advantage of SDR implementation. Enabling networking functionalities such as automatized routing and adaptive orchestration functionalities will allow for unprecedented QoS targets. |

#### 5.8.2.0. Potential Solutions to Challenge #1 (QoS Levels as Much as Possible Close to Terrestrial 5G-6G Systems)

MEC can be employed to address some of the 5G 3GPP challenges to support the defined classes of services (i.e., eMBB, URLLC, and mMTC) in the context of 4K / 8K media, cloud gaming, virtual reality, autonomous driving, telesurgery, and IoT.

In the case of satellite systems, MEC is intended to push the computing power as closest as possible to the data producer. This also means that raw data must be kept close to the data source as well. To this aim, data caching / storage has to be implemented on the edge of the access network. Analogously, computing power must be co-located with storage or deployed in proximity to address low latency targets and reliability. However, for constrained IoT devices with satellite direct access capabilities, the satellite itself is the closest hardware that could embed computing power.

Satellite constellations still rely on a communication model based on a “bent-pipe” satellite system. In this sense, momentum towards large constellations of satellites requires reimagining the space system as an edge-computing distributed one. This concept is introduced as Orbital Edge Computing (OEC), which co-locates computing hardware with high data rates in small, low-cost satellites[99].

#### 5.8.2.1. Potential Solutions to Challenge #2 (QoS Architecture and Function Virtualization for Single-Layer Network)

Although terrestrial and aerial base stations have different peculiarities, available transmission power, link configuration capabilities, multi-user management, and so on, we can easily recognize some common sub-systems:

- An outdoor unit, including the antenna and the remote radio head, is responsible for acquiring signal samples.
- A baseband unit is responsible for mapping bits into symbols and samples and vice versa.
- One or more forwarding units, responsible for opportunistically accessing wireless resources and managing traffic queues with multiple priorities.
- One switching unit is responsible for steering traffic flows between the core network and the wireless access network or from one wireless forwarding unit to another (as in the case of relay nodes).

Each sub-system will expose a parametric configuration interface (as in the case of the remote radio heads), an application programming interface for defining specific behaviors (for example, for configuring the switching rules following OpenFlow, which is a communication protocol enabling SDN operations), and the possibility of executing Software-Defined Network (SDN) functions, including baseband, framing, and scheduling functions. A set of additional network functions can be defined at higher levels in the access network, including proxy functions and content caching.

Given the heterogeneity of the networks involved, network slicing is a key networking paradigm to ensure different grades of QoS based on the users’ and verticals’ requirements.

Taking advantage of LEO constellations would introduce further benefits in guaranteeing broad coverage and low delays using ISLs. However, this will introduce additional complexity in the definition of multi-link routing solutions to select the best path based on link characteristics and services’ peculiarities. From this standpoint, the availability of onboard processing capabilities to process packets (i.e., supporting networking functions) would greatly make the overall network operations more flexible. However, this might come with the penalty of additional processing delay.

#### 5.8.2.2. Potential Solutions to Challenge #3 (QoS architecture and function virtualization for multiple-layer network)

The 5G system should be able to combine multiple links (e.g., satellite and terrestrial) to optimize the traffic flow (routing) according to, e.g., the requested QoS levels [100].

The User Plane Function (UPF) is a fundamental component of 3GPP 5G core infrastructure system architecture (see Figure 18). According to 3GPP TS 23.501 [94], UPF tasks include packet routing and forwarding, application detection using Service Data Flow (SDF), and per-flow QoS handling. UPF is aware of QoS limitations of user plane connections (e.g., latency) attached to their endpoints [91]. Data between the end-user access and UPF is via the N3 interface (TS 23.501). Moreover, UPF communicates with the core via the N4 interface. Additional signaling between the access part and the control plane is via N1 and N2 interface. Please refer to our reference architecture in Section 4.2.2 *(see also Figure 18 below)*.

Then, UPF can facilitate using different aerial networks for those traffic classes and conditions that comply with the QoS needs. When multiple paths are available to reach the same user, the UPF can decide when to use the terrestrial or aerial ones. This function could also decide whether two paths (terrestrial / aerial) could be jointly used to improve the QoS / QoE.

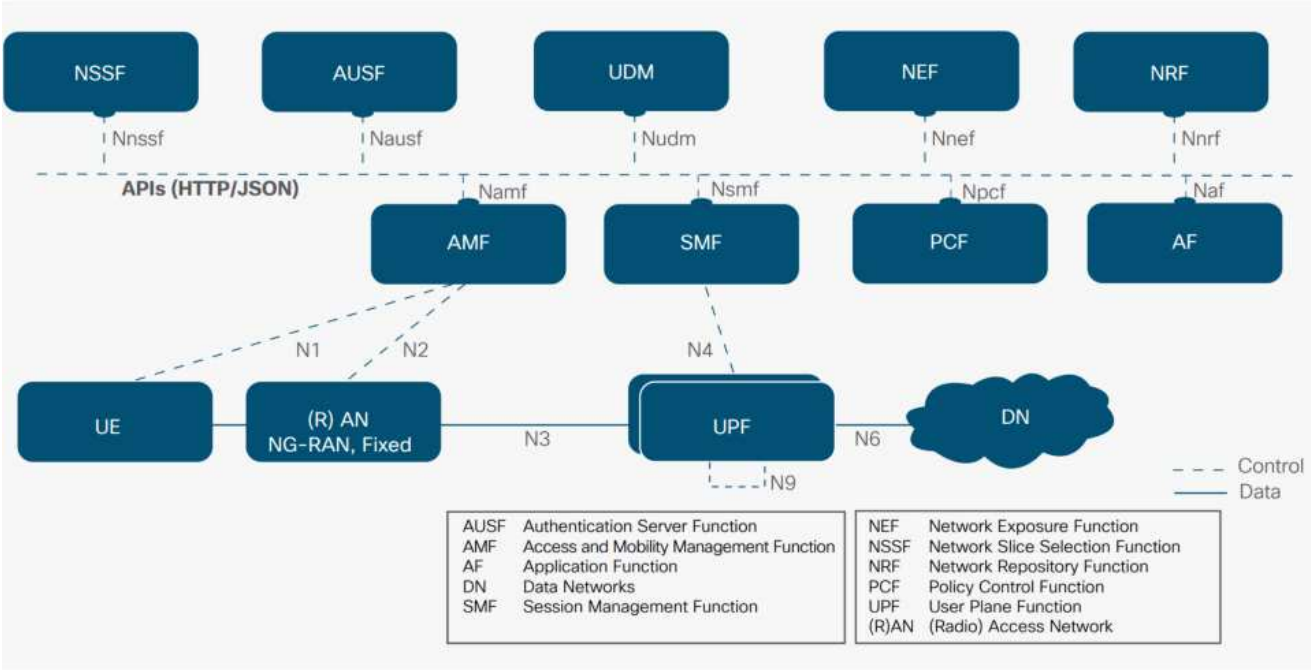


*Figure 18. 5G Network Functions Architecture, Including User Data Management (UDM) in the Core*

An optimized management plane also building on data analytics and AI-based engines would be of absolute value for handling diverse QoS / QoE requirements, instantiation, and dimensioning of network slices with respect to verticals' demands [101].

## 5.9. Security

Integrating non-terrestrial networks with terrestrial 5G and future networks will play a key role in critical infrastructure control and future large-scale industrial automation and control. An attack on these will not only have large economic impacts but will also have large-scale societal impacts as well. Moreover, with the development of a new generation of LEO and MEO satellites, there are new security concerns, for example, the malicious code injection at terminals to cause service interruption while influencing the direction of antennas.

5G satellite networks will be required for large-scale networks (e.g., an electricity provider connected to a power grid across a country, offshore wind farms, or a future city with autonomous cars). In recent years we have also seen a growth in cyber-attack motivations with an increase in the scale and sophistication of attacks and a rise in cybercrime and cyber-terrorism. While a few years back, an attack on a satellite link may have been considered an impossible task, with the advancement of technology and abundance of resources available to some of the hackers / cybercriminals, it is only a matter of time when this will become an easy target. With several business verticals adopting 5G for future growth, the value hosted and generated by 5G makes its related assets a very attractive target for attacks. Hence, we see an evolved threat landscape and securing the communication payload and the underlying networks will be of paramount importance. Cyber resilience and security assurance need to be part of 5G and future network generations [102], [103].

Security has always been considered an afterthought for most technological developments and hence always tends to be breached, as the underlying technology was never designed to be secure. Hence security-by-design concepts must be adopted for 5G development such that greater levels of security and protection can be achieved [104], [105].

Satellites have traditionally always been used as bent pipes for backhaul purposes for mobile communications. However, it is envisaged that within 5G, next-generation HTS, LEO constellations, etc., will be further integrated as compared to before. However, this provides several challenges concerning security, and the following sub-section provides details on the most relevant features that should be accounted for in the security design to help realize a seamless 5G satellite communication system [106], [107].

### 5.9.1. Challenges

#### 5.9.1.1. Secure Satellite Command and Control

Future 5G networks, leveraging software-defined networks, will drive the non-terrestrial solution to be a seamlessly integrated heterogeneous network between the terrestrial and non-terrestrial networks and within the non-terrestrial network across the orbital applications.

This Beyond 5G integrated network will usher in satellite architectures that are no longer orbital application-specific but integrated networks across all orbital applications (GEO, HEO, MEO, LEO, HAPS), as shown in Figure 19, and frame the 5G satellite architecture roadmap timeline. Due to the ubiquitous coverage and adaptable beam capacity, there will be no more stranded / fringe users [1].

The emerging LEO satellite mega-constellations have a high potential to address global connectivity problems in rural areas and densely populated metropolitan centers [108]. The designs of these networks will be challenging as they introduce new constraints in terms of their integration into existing terrestrial networks and the high dynamics of satellites, with traveling speeds of around 27,000 km/h. In addition to the reliable design of these communication networks towards 6G, the cyber-security of inter-satellite links of these mega-constellations will be another issue that needs to be addressed comprehensively.

Security concerns in satellite communication systems gain attention day by day, and emerging research studies offer new solutions and analyses for different scenarios. The problem is far beyond cyber-security challenges solely related to the communication environment. The cyber-physical security perspective should be considered holistically [109]. For example, maintaining the correct orbit and altitude is one of the critical aspects of reliable communications. The satellites in LEO are exposed to a more substantial gravity impact by the Earth than high-altitude satellites. Therefore, they require an Altitude and Orbit Control (AOC) system to provide stabilization. The AOC system acquires the location data from the GPS receiver and sensors and can command maneuver. Maneuver decisions are mainly given by the ground station's Telemetry, Tracking, Command, and Monitoring system (TTC&M). TTC&M systems sustain the operational management of satellites by conveying telemetry and command signals. An attack on telemetry or command signals can lead to interruptions in the communication services of LEO satellites or even collisions of satellites. Hence, the security aspects of these emerging networks are of paramount importance.

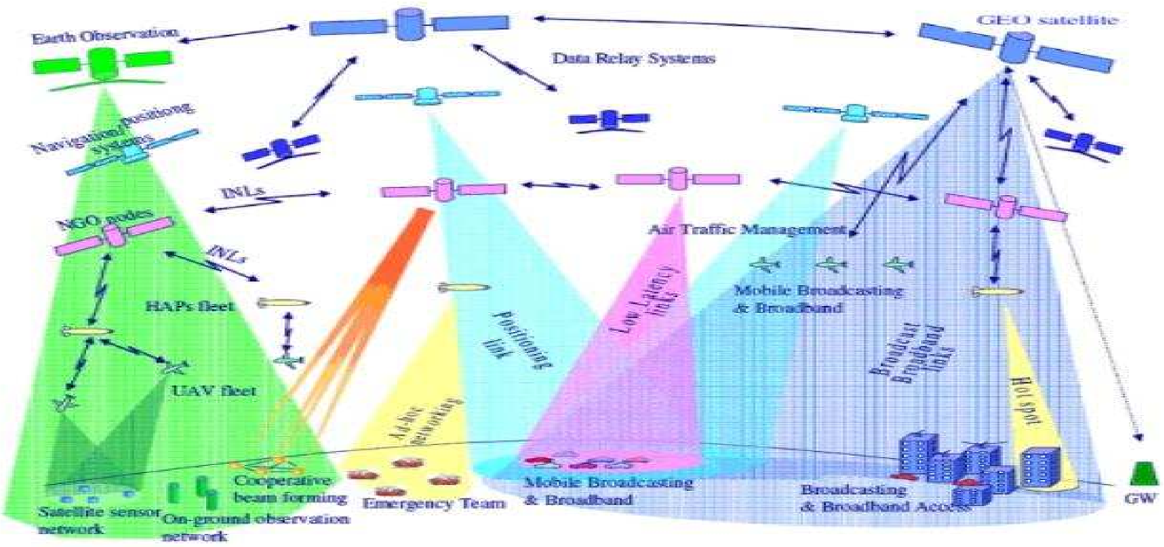


*Figure 19. GEO (Geosynchronous Orbit), HEO (Highly Elliptical Orbit), MEO (Medium Earth Orbit), LEO (Low Earth Orbit), and HAP (High Altitude Platforms)* [1]

#### 5.9.1.2. Security in Air Interface Design

The air interface in a 5G-satellite network is one of the most vulnerable links in the communication chain due to its inherent wireless nature. All communication over the air interfaces must be adequately secured. The air interface is susceptible to various attacks like Man-in-the-Middle (MitM) attacks, distributed Denial of Service (DoS) attacks, and jamming attacks. Signals received from the GEO satellite are usually very weak and could be overridden with another signal stream, and are vulnerable to illegal interception. Data confidentiality (encryption) and data integrity are important features required along with data origin authentication. There are various types of security vulnerabilities over the air that can be categorized as loss of availability, loss of confidentiality, loss of integrity, loss of control, and malicious insider attacks[110]. Typically, satellites can typically serve as 5G core or 5G user endpoints (UE). When satellites are used as 5G UEs these can be potential sources of attack due to botnets or infected malware. These can then contribute to the flooding of interfaces or the crashing of various network functions in the core network. Eavesdropping and data leakage could lead to loss of confidentiality that is caused by a man-in-the-middle attack or attack on UE via false gNodeB. Traffic modification and data modification could lead to loss of integrity. Malicious attacks on gNodeB via protocol implementation flaws or via management interface could lead to loss of control in the network. Hence, it is important to implement various prevention and mitigation techniques by way of integrity keys and encryption keys that will help secure user traffic and control traffic. At the same time, it is important to implement secure monitoring tools to detect attacks in the data and control planes and then apply further mitigation techniques. Some mitigation techniques could include beamforming, access class barring, encryption of data at rest and data in transit, and multi-factor access control, among others.

#### 5.9.1.3. Security in Network Infrastructure

5G brings about a paradigm shift in the network architecture and adopts various new technological concepts like MEC (Mobile Edge Computing), SDN (Software Defined Networking), NFV (Network Function Virtualization), network slicing, etc., to provide a fully flexible and programmable network that can be configured on-the-fly for any vertical application taking into consideration various QoS / QoE requirements and network conditions. However, many of these technologies are not mature, especially when considering their security implications. Each of these 5G enablers has unique security opportunities and associated challenges. Also, combining these in the same network creates new threats that make the 5G network even more vulnerable to attacks. Bringing these together under a satellite communication network is still in its infancy, and it is key that while these are being considered for the satellite networks, the security requirements are considered at the design phase. Hence, it is important to design a threat taxonomy to study the threats associated with each enabler and devise mitigation techniques for each threat.

When considering NFV, securing the orchestration-related APIs layer becomes very important in the 5G satellite evolving architectures as these networks would primarily tend to be software-based. Enhanced security requirements like secure segmentation, user access control, secure configuration, and secure architecture for orchestration to prevent a single point of failure need to be considered.

Different network slices handling different types of vertical sector applications are one of the key enablers for 5G that facilitates flexible resource sharing, orchestration, and scheduling. There are various security opportunities and challenges associated with security slicing. These include one slice causing a denial of service to other slices, slide channel attacks across slices, sealing between slices when UE is connected to multiple slices, and impersonation attacks against a network slice during the orchestration of slices, among others. However, there is a strict requirement to isolate the slices from each other to prevent misuse of their resources, making them susceptible to side-channel attacks. Monitoring and managing security protocols across all the security domains implies substantial additional complexity in the interfaces between the various slices. Some of the potential mitigation techniques related to slicing include the capping of resources of individual slices, authentication of individual slices, and ring-fencing of individual slices.

MEC concepts would likely be adopted in a 5G satellite architecture to move functionality to the network's edge to avoid delays to the signaling and data over the satellite. MEC deployment can help to support ultra-low latency applications. However, in addition to traditional attacks against servers and caches (e.g., via HTTP response splitting), new attacks like DoS attacks based on cache overflows with unpopular content are possible. Also, suppose sensitive security assets are compromised at virtualized functions at the edge. In that case, an attacker could maliciously reuse them to gain connectivity or carry out a spoofing, eavesdropping, or data manipulation attack. If the satellite link is used to connect the edge to the 5G core network, then these links are prone to compromise and control signaling transmitted by a MEC orchestrator in the core to the mobile edge could be spoofed or modified. Mitigation techniques could include access control, authentication, proper encryption mechanism for the security context at the edge, and intrusion detection / prevention systems for proper security monitoring.

There are also security implications due to virtualization regarding both opportunities and challenges. Some security challenges due to virtualization may include attacks on the hypervisor, compromise of VNF catalogs, wrong placement of VNF, lack of visibility of network traffic, and compromised communication among the orchestrator, virtualized infrastructure manager, and VNF catalog.

#### 5.9.1.4. Trust Management

Designing a trustworthy network and making informed trust decisions are both challenging in a 5G satellite environment. Current trust management protocols do not account for the diversity found in the 5G infrastructure with new devices, new actors and roles, new types of operators and users. Trust management protocol must consider the vertical application domain and then simultaneously slicing between the domains and layers. Using satellites within this complicated 5G arena further brings new dimensions to the equation. The trust model will evolve from a completely trusted model (in older mobile communication generations) to a completely untrusted model (in 5G). While new static trust models will need to be developed to be used as starting points, it is envisaged that to realize the true potential of 5G, dynamic trust models will be required that will be able to monitor the trustworthiness of assets in real-time and both upgrade (following a period of trust-building) or downgrade (in case of a security attack or malicious behavior) the trust levels. This dynamic trust model will consider various contexts in the network, including the type of network function that needs to be protected, type of data (e.g., control plane, user plane), types of attacks, and risk factors associated with various types of threats. Developing a Zero Trust model to take care of zero-day attacks and assume no trust in the network is also important.

#### 5.9.1.5. Delay and Energy-Aware Algorithms

5G presents stringent latency requirements as a key priority. Security always increases delays; hence, it is important to find the right balance. With the evolution of user terminals, the cost of security algorithms (in terms of delay) is no longer an issue. However, there may still be an issue when using a satellite link for transmission, especially when they inherently have large propagation delays. However, for the most constrained, battery-dependent devices with a long target lifetime, there may be a need to consider even more lightweight solutions. Also, if a 5G-satellite network is used for URLLC or mMTC applications, the impact of security delays increases many folds. Hence there is a need for ultra-reliable and low-latency security mechanisms considering battery efficiency and energy-saving aspects.

It is expected that low-cost IoT devices will be used for various use cases, such as Machine-to-Machine (M2M) and industry automation within a 5G environment. These low-capability devices do not have processing, memory, and communication capability to include several security features making them prone to MitM attacks, firmware and OS hacks, snooping and sniffing attacks, Botnet type attacks where the IoT devices start signaling overloads with the mobile network components of the operator.

The same set of algorithms for User / Device authentication and authorization cannot be used across the diverse range of 5G assets. Hence, it is important to consider new identity-based cryptography mechanisms that provide adequate security and are not energy-hungry and slow.

Quantum resistance cryptographic algorithms must be developed, as the current standard algorithms may not remain secure when quantum computers come into production. It is also important to ensure security is not compromised at the expense of supporting ultra-low latency applications. In most cases, the security context is stored at the edge cloud to support ultra-low latency applications, giving rise to additional vulnerability. Thus, care must be taken to ensure a proper security mechanism while supporting the low-latency applications at the edge cloud.

#### 5.9.1.6. Flexible and Scalable End-To-End Security Architecture

Satellite networks need to integrate seamlessly into the 5G network to provide efficient services. Traditionally, satellite networks were only used as transparent bent pipes. The use of third-party satellite networks to backhaul traffic causes the Gi / SGi (unclear) interface to be integrated with these satellite networks, which could be compromised, leaving the 5G mobile network vulnerable to attacks.

Traditionally, the satellite network provided its security services (more at layer 2) to protect the data it carried across its networks that the satellite operator locally managed. Mobile networks whose data was carried over the satellite backhauls did not have a view of this security and would provide their security. This leads to redundancy of security services (if data gets encrypted twice) or hop-by-hop security (if data is decrypted / encrypted at the edge of the satellite network). Both these mechanisms have several drawbacks. New End-to-End (E2E) security architecture is required for 5G satellite networks.

With various vertical applications supported by network slicing, it is also important to note that these will also require different security requirements. Hence, E2E security design not only needs to cater to different vertical industries, but the E2E security capabilities also need to align with business changes and security events rapidly. Hence it is important to have a flexible and reconfigurable security architecture that supports fast and efficient E2E security adaptation and deployment.

While an E2E security architecture has several benefits, as described above, it makes the network operator’s ability to find malicious traffic much more difficult. Threat actors have leveraged the benefits of E2E encryption to evade detection and secure their malicious activities. It is envisaged that threat actors will use some encryption to conceal malware delivery, command and control activity, or data exfiltration within a future 5G environment.

It is important to ensure proper encryption and integrity keys are derived from EAP-AKA or 5G-AKA mechanism during the authentication process to maintain confidentiality and integrity of the data traffic and control traffic at the RAN, edge and core. End-to-end security may need to take into account security requirements in multiple roaming domains. Each operator domain may have different security mechanisms. Hence, care needs to be considered to avoid threats from roaming partners. In such cases, it is important to take advantage of Security Edge Protection Proxy (SEPP) to stop the attacks from the roaming provider. Priority services need marking packets in the data plane and user plane to ensure proper service quality is maintained. Ensuring these markings are properly maintained across service provider domains is important.

#### 5.9.1.7. Security Management Automation and Orchestration

While it is very important to have security-by-design concepts in developing 5G and to build all preventive solutions to combat malicious attacks, one can never build a fully secure system. Hence it is equally important that security management systems are developed to monitor the security events and breaches across the network and take necessary corrective action. The diverse nature and large scale of assets in a 5G-satellite network make this a challenging task. It is key that first an integrated threat modeling and identification scheme is developed, followed by new security assurance and multi-layer security solutions. New solutions are required to share threat intelligence across the different network actors to ensure that the breaches are detected quickly and do not result in cascaded attacks. It is also envisaged that the prediction of vulnerability identification, threat surface projection, and attack detection will be based on AI and machine learning in the future.

Management and Orchestration are core components of modern Cloud Computing systems. Because these systems are complex and require fast scalability, advanced technologies have been developed to support these objectives. For example, SDN allows networks to be dynamically reconfigured without human intervention to optimize capacity, provide sufficient QoS, etc. Cloud providers such as Google, Microsoft and Amazon have developed propriety software to implement this functionality. In addition, open-source orchestration tools such as OpenStack can be used for network automation. With this perspective, tools and techniques for managing and orchestrating the security architecture are also needed to secure satellite networks. Whereas a cloud computing system tends to be homogeneous, satellite networks can be much more complex and involve not only a single satellite. Still, they may contain multiple satellites communicating over a very large distance. When one considers the B5G architecture with satellite components, as in Figure 19, it is apparent that an advanced architecture comprising multiple systems and vendors is needed to secure the entire network. Cooperation is critical to overall network security. Due to the distributed nature of the satellite architecture, it may be necessary to implement multiple SDN controllers to support programmability and scalability in the end-to-end network. Hence, the communication protocols among multiple SDN controllers need to be secured. The North Bound API and South Bound APIs for the SDN controllers also need to be secured. Orchestrators use APIs to instantiate the VNFs to support scale-out or scale-in functionality. It is important to authenticate the APIs and encrypt the communication to avoid the compromise of these APIs.

In “A Learning-Based Zero-Trust Architecture for 6G and Future Networks”[111], a layered security architecture was presented that describes how security information can be distributed across the network in a hierarchical manner. A block diagram of this approach is shown in Figure 20. Here, the Management Layer implements the security policy and allocates such, via the Distribution Layer, to the Compute Layer that contains the compute nodes. Data is collected from the compute nodes, sent back to the Management Layer, and the security policy is derived. The main idea behind this distribution is that distinct components collect security information, process it, and communicate the necessary to the upper layer for policy dissemination. This allows threats and attacks in one component of the network to be detected and disseminated to other network regions. In a typical 5G network, security monitoring tools can be embedded in the compute layer across control plane or data plane elements, namely, AMF (Access and Mobility Management Function) or UPF (User Plane Function), respectively. Data Analytics engine can pass on the metadata or alerts to the Policy Control Function (PCF) that could be part of the distribution layer or management layer. PCF, in turn, can communicate with Policy Control Enforcement Function to mitigate the attacks. Policy Control Functions can be distributed across the network in a distributed satellite architecture. Also, the enforcement points could be at the routers or switches that the respective SDN controllers can control. These enforcement points can also be distributed and will be controlled by respective SDN controllers. Hence, the communication among the Data Analytics Engine, Policy Control Functions, and Policy Control Enforcement points needs to be secured. The placement of control loops is also important. Based on the network context, traffic condition, or attack vectors, the policy controller can decide where to put the control loop and automation in the network, such as RAN, Edge, or Core of the network. The research reported in this paper was targeted toward secure federated machine learning, which can be used for terrestrial or space networks. However, the core aspect of deriving security policy at the top layer for all components within the network applies whether terrestrial, space-based with a single satellite with multiple compute nodes, which could be akin to a space-based cloud computing network, or a single vendor, multi-satellite network with many compute nodes. Taking this even further, one can envision a hybrid network with satellites from multiple vendors participating in this type of architecture. Of course, specific details about control and interfaces will need to be worked out by the network operators, but one could see a future where cyber security information is shared across networks to ensure security, which in fact, is in everyone's best interest.

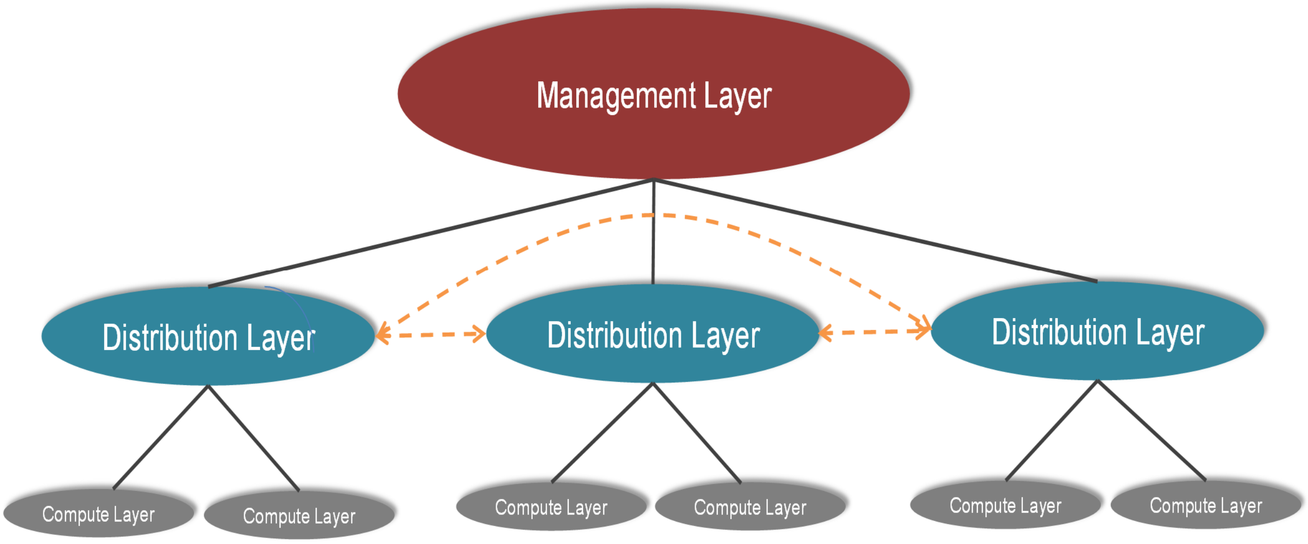


*Figure 20. Hierarchical Layered Security Architecture*

### 5.9.1.8. Real-Time Security Monitoring

Real-time security monitoring is needed to understand the security state of the network. In Figure 20, compute elements provide information to aid the Management Layer in defining the network security policy. These elements can be viewed as sensors that are used to monitor security. Identification of attacks such as DDoS, phishing, ransomware, etc., should occur across the compute elements, regardless of whether they are on one or more satellites. While computing system attacks may have commonality with traditional terrestrial network attacks, satellites have many unique subsystems. For example, command and control, telemetry, power, and communication systems must be protected and monitored in a manner that is different than computer networks.

Today, digital forensics is common practice in law enforcement investigations. Some of the tools used, including file and memory analysis, may determine whether an attack is underway or imminent. Unlike forensics, these functions must be performed in real-time to provide an adequate security view of the network. Real-time monitoring of computing processes, memory pages, and file access attempts can be used to implement a real-time malware detection system is needed to ensure a robust Beyond 5G security architecture.

### 5.9.1.9. Zero Trust Architecture for Non-Terrestrial Networks

The traditional approach to network security has been to secure the network perimeter, as illustrated with the red outline shown in Figure 21. With this approach, firewalls and other techniques are used to secure the perimeter leaving the network interior vulnerable. For example, once a device, such as a computer or even a printer, has been comprised inside of the network, it is easy with this architecture for the adversary to move freely within the network and attack other network elements.

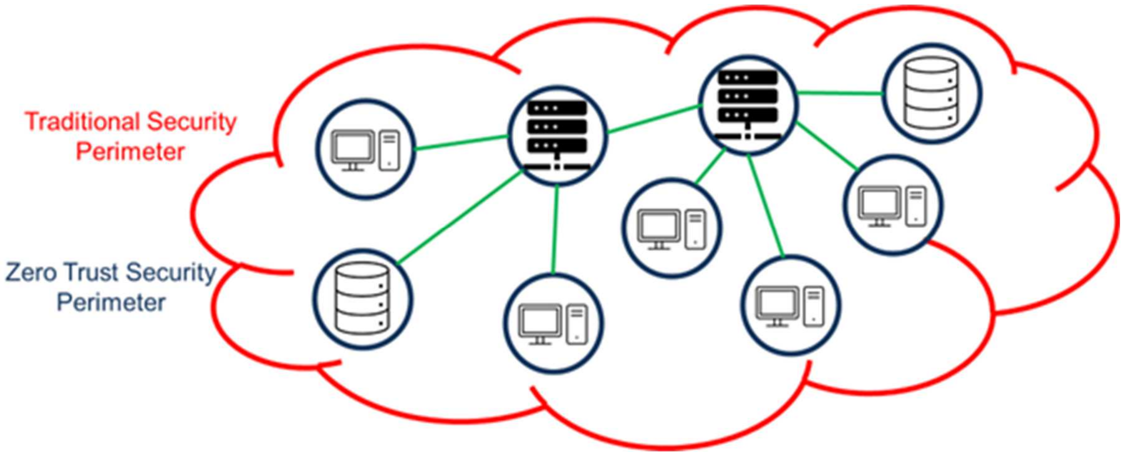


*Figure 21. Network Security Perimeters*

Given the depth and sophistication of recent cyberattacks, a need for a more modern approach to cyber security has arisen. Traditional "commercial" network security approaches have not been able to address these challenges. However, techniques have been employed for decades by the United States Department of Defense that can be used to mitigate such attacks. One example is Software-Defined Perimeter (SDP), which uses control and data planes to control access to network resources. This type of architecture with control and data planes is similar to that used in SDN but applied to network security.

A more comprehensive approach to modern cyber security must move beyond network security to device, application, data security, and more. One can think of this as a high-resolution view of network security. It is not simply about securing the perimeter but treating each element of the network architecture as its own perimeter. This can be thought of as system security and is illustrated by the blue elements of the figure and called the Zero Trust Security Perimeter. It encompasses the trust regions described in the Trust Management section of this document.

In 2019, NIST published Special Publication 800-2017 [112] that described these principles in what is called a Zero Trust Architecture (ZTA). There are seven tenets to a ZTA. The abbreviated tenets are listed below:

- T1: All data sources and computing services are considered resources.
- T2: All communication is secured regardless of network location.
- T3: Access to individual enterprise resources is granted on a per-session basis.
- T4: Access to resources is determined by dynamic policy — including the observable state of client identity, application / service, and the requesting asset — and may include other behavioral and environmental attributes.

- T5: The enterprise monitors and measures the integrity and security posture of all owned and associated assets.
- T6: All resource authentication and authorization are dynamic and strictly enforced before access is allowed.
- T7: The enterprise collects as much information as possible about the current state of assets, network infrastructure, and communications and uses it to improve its security posture.

These tenets comprise a framework, not a design document. Some may seem rather obvious and have been discussed for many years in one form or another. However, the value of the NIST document is that it has aggregated into a single document. Different organizations in the United States, including CISA [113] and the Department of Defense [114], have been attempting to define what ZT means in terms of their organizations. This is needed because ZT is a set of architectural principles that must be defined to develop and deploy effective security techniques.

One of the earliest implementations of a ZTA is Google's BeyondCorp [115]. BeyondCorp is a sophisticated approach that encompasses many different design decisions. For example, devices that connect to the network must be improved and monitored to ensure they are safe to access. The point here is that ZTA requires significant "tweaking" to customize it for a particular implementation, even to address only some of the abovementioned tenets. The complexity scales with the size of the network. It may be possible with a corporate network where the company can dictate how users and devices must operate, but that is very different from non-homogeneous, non-terrestrial networks like the one illustrated in Figure 21.

Developing a ZTA for non-homogenous, non-terrestrial networks requires addressing many issues, and much of what has been presented in this Security section can aid in doing so. For example, Trust Management, Security Orchestration, etc., can all be implemented to address a subset of needs. However, much work still needs to be done. Security situational awareness and open interfaces are essential elements that must be addressed in non-terrestrial 6G networks and beyond.

### 5.9.2. Potential Solutions

Based on the above description, we have identified the following high-level objectives:

- **Need #1:** Secure Network Infrastructure for New Generation of LEO / MEO Satellites
- **Need #2:** Trust Management and Security Algorithms
- **Need #3:** Automated Security Management, Orchestration, and Data Collection.

In the previous section, we have identified the challenges that should be addressed to support a secure satellite network architecture. These challenges and potential solutions are described in Table 40 based on near-term, mid-term, and long-term challenges.

*Table 40. Challenges and Solutions to Address the Needs Related to Security*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to near-term challenges*** |
|---|---|

| | |
|---|---|
| Challenge #1: Securing satellite communication and subsystems | Secure communication is needed across all modes of satellite communication, whether user-driven, telemetry, satellite-to-satellite, etc. Similarly, all subsystems must have built-in security mechanisms and reporting capabilities, e.g., spacecraft power, bus, etc. It is important to design satellite subsystems with cyber security as a core component. |
| Challenge #2: Open system for zero trust architecture | Since non-terrestrial networks may be non-homogenous, i.e., multi-vendor, methods to implement ZT across network boundaries should be investigated. This includes techniques, open security architectures, and interfaces that will be integrated into a ZT environment. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to mid-term challenges*** |
| Challenge #3: Fast trust management | Methods to implement Zero Trust into single and multiple satellite systems are needed to provide the best level of security. This must occur promptly to ensure that significant delays are not introduced into the security system. |
| Challenge #4: Development of autonomous security management and orchestration | Future satellite systems must have mechanisms to manage security quickly to deal with attacks before they can cause damage. If the systems can detect threats promptly and rapidly instantiate defense mechanisms, damage can be reduced. The network architecture must have components that detect attacks and management components that can quickly reconfigure the network and disseminate the defense mechanisms. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to long-term challenges*** |
| Challenge #5: Multi-vendor security interfaces | Similar to the internet, systems from different vendors will communicate to provide the best service to the customer. To ensure a secure B5G network, information sharing between vendors regarding their security state, e.g., is the system under attack, information about attacks, etc., would be beneficial. Interfaces to share such information are needed. |

## 5.10. Satellite Network Management

This section discusses the needs, challenges, enablers and potential solutions related to future satellite network management. The discussion focuses on three main aspects of network management: mobility management, radio resource management, routing, intelligent and softwarization management, network function virtualization, network slicing, and software-defined satellite networks.

### 5.10.1. Mobility Management in Satellite Networks

LEO satellites move at high speeds on low-Earth orbits, making their movement asynchronized with Earth. Therefore, efficient mobility management is essential in future satellite networks. Mobility management consists of two main components: location management and handover management. IP-based mobility management protocols introduced by IETF are designed to work on fixed infrastructure networks where the terminals are mobile. However, in satellite networks, not only terminals (users) are moving but also the LEO satellite Base Station (BS). The satellites' locations need to be handled with low signaling costs and high accuracy. The fast handover of the satellite from one gateway to another should be addressed to guarantee a soft and seamless handover. In addition, when a user is forced to switch to another satellite due to satellite movement, this handover process should be considered. As a LEO satellite has a large footprint (coverage area) and due to the fast satellite movement, a large group of users might trigger handovers simultaneously or within a short period. This event might congest the communication links with handover signaling and location updates. A new method is required to handle group handover at a low cost and efficiently.

## 5.10.2. Mobility Management in Satellite Networks — Need #1

### 5.10.2.1. Support Satellite Location Management — Challenges

LEO satellites move at high-speed resulting in frequent switching from one gateway to another. Their location and addresses must be managed while they move from one network or domain to another to keep communication with satellites. A LEO satellite can act as a mobile router or as a terminal. Both cases should be considered. In IP-based networks, location management is handled by the mobility management protocols such as MIPv6 or PMIPv6. Whenever a terminal changes its access point, it has to update its address and inform its home network. Location management for IP-based LEO satellites (both as a terminal and mobile BS) is very important to support the S1 interface of the use cases mentioned in the next Section 6 (note that these interfaces are also introduced in relation to Figure 7). However, there are several challenges to overcome. The following table summarizes the challenges related to the need for Support Satellite Location Management.

*Table 41. Challenges Associated with Support Satellite Location Management*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: Frequent IP address change due to fast LEO satellite movement (satellite as a terminal) | Frequently changing the IP address of a satellite will result in high signaling costs through the resource-scarce communication links between satellites and gateways. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge 2: Frequent IP address change due to fast LEO satellite movement (satellite as a BS) | When a LEO satellite is playing the role of a mobile BS, any changes in its address should not affect the user devices that are still connected to that satellite. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 3: Distributed location management for LEO satellite networks | Centralized location management might create bottlenecks when the locations of many LEO satellites need to be updated frequently. Distributed location management can avoid the bottleneck and single point of failure issues. However, the two main challenging issues in distributed location management are how to distribute the work of location management server and databases, and where to place the location management entities (on the ground or in space). |

### 5.10.2.2. Support Satellite Location Management — Potential Solutions

This section describes several potential solutions which address the challenges in Table 41 to support satellite location management. First, to handle the frequent IP address change, the earth's surface can be divided into clusters, and each cluster covers the area of multiple satellite footprints. A satellite moving in the same cluster does not have to change its IP address. This solution helps to reduce the frequency of IP address change of a satellite. Second, to eliminate the effect of the frequent IP address change of LEO satellite BS, a local address (to communicate with users) and a public address to connect to other networks (terrestrial or satellite) can be used. In this case, only the public address must change without affecting the local address. Third, SDN-based distributed mobility management[116] can be exploited with some modifications in satellite networks to overcome the drawbacks of centralized location management. However, one critical issue that needs to be considered is the distribution and placement of the controllers (e.g., on earth or in space).

Table 42 summarizes the potential solutions to the challenges of the first need for satellite mobility management, Support Satellite Location Management.

*Table 42. Potential Solutions to Address Support Satellite Location Management*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Frequent IP address change due to fast LEO satellite movement (satellite as a terminal) | The earth's surface can be divided into clusters that cover the area of multiple satellite footprints. When a satellite moves from one cluster to another, then the IP address needs to be changed. A satellite moving in the same cluster does not have to change its IP address. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 2: Frequent IP address change due to fast LEO satellite movement (satellite as a BS) | Changes in the address of a LEO satellite-mounted BS should be transparent to the user devices that are connected to that satellite. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 3: Distributed location management for LEO satellite networks | The concept of SDN-based distributed mobility management can be exploited with some modifications in satellite networks. |

### 5.10.3. Mobility Management in Satellite Networks — Need #2

#### 5.10.3.1. Support for Seamless Handovers — Challenges

Seamless handovers are a crucial aspect of NTNs and play a vital role in ensuring seamless communication in LEO satellite networks. Interrupted handovers can result in communication disruptions and negatively impact the user experience. It is essential to understand the technical challenges involved to ensure seamless handovers. These challenges include handover latency, interruption, load balancing, resource management, integration with existing infrastructure, and energy / cost efficiency. These challenges have been summarized in a table for easy reference. The solutions for these challenges are still being researched and developed, but it is clear that addressing these challenges is a critical step toward realizing seamless handovers in NTNs. The following table summarizes the challenges related to the need for supporting seamless handovers.

*Table 43. Challenges Associated with Support for Seamless Handovers*

| ***Near-term Challenges: 2023-2025*** | ***Description*** |
|---|---|
| Challenge 1: Handover latency and interruption | The main challenge is ensuring a seamless, smooth handover without latency or interruptions. Current handover mechanisms require L3 measurements that lead to delays that can cause interruption, particularly in the case of LEO satellites. |

| *Mid-term Challenges: 2026-2027* | *Description* |
|---|---|
| Challenge 2: Load balancing and resource management | The main challenge is allocating resources efficiently and ensuring equal load distribution among satellites. This involves complex network management algorithms, which need to be updated in real-time to ensure optimal network performance. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 3: Integration with existing infrastructure in an efficient manner | The major problem is the integration of NTNs with existing terrestrial networks, which requires compatibility and interoperability between different technologies and systems. Furthermore, considering the sustainability goals, this needs to be achieved in a cost and energy-efficient manner. |

#### 5.10.3.2. Support for Seamless Handovers — Potential Solutions

This section describes several potential solutions (summarized in Table 44) that may be utilized to address the general challenges of seamless handovers given in Table 43. First, devising faster and more scalable handover strategies to handle latency and interruption is crucial. One direction regarding this could be triggering inter-cell mobility using L1 / L2 signaling to reduce the latency. Once the handover triggering mechanisms are well established, it is important to incorporate issues such as load balancing into the user-satellite association mechanism. Ways to indicate the satellite load and available resources amongst themselves and users must be made more scalable. Eventually, seamless connectivity requires the users to connect to the terrestrial networks, which in turn requires standardization to support terrestrial and non-terrestrial networks coexisting and cooperating to improve the user experience.

*Table 44. Potential Solutions to Address Support for Seamless Handover*

| *Near-term Challenges: 2023-2025* | *Potential Solutions to Near-Term Challenges* |
|---|---|
| Challenge 1: Handover latency and interruption | Alternative handover triggers and L1 / L2 measurements need to be supported to enable faster and more reliable handovers. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 2: Load balancing and resource management | This necessitates the efficient allocation of resources, ensuring equal distribution of load among satellites. This, in turn, requires real-time network monitoring and management, virtualization and slicing to allow flexible changes and AI to make real-time decisions. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 3: Integration with existing Infrastructure in an efficient manner | This relies heavily on the development of standardization to support the interworking of satellites with terrestrial networks. |

### 5.10.4. Mobility Management in Satellite Networks — Need #3

#### 5.10.4.1. Support for Alternative Handover Triggers — Challenges

Conventional handover mechanisms rely on received power measurements to trigger the handovers. However, in NTNs, the received power variation in cells is much lower than in terrestrial cells. Combined with the possible errors in power measurement by the user devices, power-based triggers might not be plausible for satellites. Therefore, the immediate challenge is identifying the alternative measurements that can be used and their performance considering some assumptions about their availability. In the medium term, the goal would be to evaluate the practicality of acquiring the said alternative measurements regarding accuracy, resolution, and availability. In the long term, it would be imperative to determine the efficacy of the various measurements in different deployment scenarios (satellite altitude, environment, frequency, etc.) and ensure that the standardization supports acquiring these measurements so that the solutions are scalable and practical. These challenges are summarized below in the following Table 45.

*Table 45. Challenges Associated with Support for Alternative Handover Triggers*

| ***Near-term Challenges: 2023-2025*** | ***Description*** |
|---|---|
| Challenge 1: Alternative handover trigger(s) identification | Power-based handover triggers are impractical in NTNs due to the reduced variation in signal strength and the possibility of measurement errors from the user terminal. As such, it is important to look at other measurements. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge 2: Feasibility of acquiring other measurements | Received power-based mechanisms are well-established, and the acquisition of the relevant measurements is well-known. However, the feasibility of acquiring any additional measurements remains to be studied. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 3: Mapping the handover triggers to the application and deployment scenario | The users belonging to different applications have different capabilities. Similarly, equipment capabilities in terms of sensitivity, etc., as well as the propagation characteristics, vary greatly between S band and Ka band. This situation indicates the possibility (or even necessity) of using different triggers depending on the specific scenario. |

#### 5.10.4.2. Support for Alternative Handover Triggers — Potential Solutions

This section describes several potential solutions to address the general challenges of seamless handovers given in Table 45. Firstly, alternative handover triggering methods, depending on measurements such as elevation angle, distance, location, timer, etc., must be evaluated. This evaluation should consider both the user's performance and the overhead caused to the network in terms of additional signaling and measurements. Once the preliminary performance is evaluated, the feasibility of the necessary measurements can be carried out considering the standardized capabilities of the communicating nodes. For instance, in this stage, we can explore the possibility of localizing a user from the network's nodes instead of relying on GNSS measurements. In the last stage, the goal is to incorporate the alternative mechanisms into the standard and devise a method to identify the most appropriate trigger for the various deployment scenarios and applications. These potential solutions (or guidelines thereof) are summarized in Table 46.

*Table 46. Potential Solutions to Address Support for Alternative Handover Triggers*

| ***Near-term Challenges: 2023-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Alternative handover trigger(s) identification | We can start with the assumption about the knowledge of the user's location; this can be used to acquire the relative distance and/or elevation angle between the user and the satellite. Then the performance can be evaluated in terms of user experience (radio link failure and SINR) and overhead (number of handovers or ping-pongs). |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 2: Feasibility of acquiring other measurements | The network can leverage its resources to provide alternative measurements used for handover triggering. For instance, instead of the user using GNSS signals, the network can localize the user using multiple satellites (or ground stations) in its own network. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 3: Mapping the handover triggers to the application and deployment scenario | Given that both the short- and mid-term challenges are solved, the issue remains of deciding on the most appropriate handover trigger mechanisms depending on the application and deployment. For instance, in low-latency cases, the focus can be on L1 / L2 signaling, while GNSS-related parameters can be used for users that have the necessary capabilities. Moreover, it is possible to consider multiple triggers simultaneously, as in the case of conditional handovers. |

### 5.10.5. Mobility Management in Satellite Networks — Need #4

#### 5.10.5.1. Support for Terminal Handover — Challenges

LEO satellite footprints (coverage areas) might overlap. When terminals (users) are moving near the edges of satellite footprints, they might receive two fluctuating signals from both satellites. This creates the ping-pong handover effect, where a user keeps switching its connection between the two satellites. This process is resource-consuming and results in unstable communication. In terrestrial networks, terminal (user) handover is supported through the mobility management protocols introduced by IETF, such as Mobile IPv6 (MIPv6) and Proxy MIPv6 (PMIPv6). However, such protocols are designed to support terminal handovers when the terminal is moving and not the BS. With many satellites available in the sky, selecting the best satellite as the handover target might not be easy, especially considering certain QoS levels and the competition among many users. Table 47 summarizes the challenges related to the fourth need, Support for Terminal Handover.

*Table 47. Challenges Associated with Support for Terminal Handover*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: Predicting terminal handover | The movement of the LEO satellite BS forces the terminal to handover to another satellite. Although LEO satellite movement is predictable, other factors need to be considered in the handover prediction, such as channel conditions, traffic loads, and terminal mobility. |

| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
|---|---|
| Challenge 2: Avoid the ping-pong effect when terminals (users) are moving near satellite footprint edges | When terminals (users) are moving near the edges of satellite footprints, they will receive two fluctuating signals from more than one satellite. This might create the ping-pong handover effect, where a user keeps switching its connection between the two satellites. This process is resource-consuming and results in unstable communication. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 3: Selecting the handover target when multiple satellites are available | In the future, there will be many satellites available in the sky. Selecting the best satellite as the handover target might not be easy, considering certain QoS and the competition among many users. |

#### 5.10.5.2. Support for Terminal Handover — Potential Solutions

Several challenges need to be addressed to support terminal handover in satellite networks. This section provides potential solutions for the three challenges mentioned in Table 47. First, predicting terminal handover using multiple parameters can be assisted by machine learning algorithms such as reinforcement learning or deep learning. Machine learning will provide more accurate handover predictions that can adapt to changes in the communication environment. Second, to avoid the Ping-pong handover effect when a user is moving in the overlapping area of more than one LEO satellite coverage, the received signal strength from satellites should not be the only handover triggering parameter. Instead, multiple parameters should be considered to trigger a handover, such as users' mobility, satellite movement, and the required QoS. Third, in future satellite networks with mega-constellations, intelligent decision-making algorithms are necessary to evaluate the available satellite options and select the best satellite that satisfies the user QoS requirements. Supporting terminal handovers is necessary to realize use cases 8 and 9 mentioned in Section 6.1. Table 48 summarizes the potential solutions to the challenges of the third fourth of satellite mobility management, Support for Terminal Handover.

*Table 48. Potential Solutions to Address Support for Terminal Handover*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Predicting terminal handover | Implementing machine learning-assisted handover prediction based on user mobility and communication environment parameters might give more accurate results. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 2: Avoid the ping-pong effect when terminals (users) are moving near satellite footprint edges | The received signal strength from satellites should not be the only handover triggering parameter. Multiple parameters should be considered to trigger a handover, such as users' mobility, satellite movement, and the required QoS. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 3: Selecting the handover target when multiple satellites are available | Intelligent decision-making algorithms can be useful for evaluating the available satellite options and selecting the best satellite that satisfies the user QoS requirements. |

## 5.10.6. Mobility Management in Satellite Networks — Need #5

### 5.10.6.1. Support Group of Terminals Handover — Challenges

The challenges related to the fifth need, Support Group of Terminals Handover, are summarized in Table 49. When many users in a satellite footprint have to go through connection handover within a short time due to satellite movement, this may create a storm of location updates and handover signaling when the large group of users is triggering handover almost simultaneously. Besides, it requires the creation of many tunnels between the home satellite and the new satellite to forward the packets to the users, which will contest the ISLs. IETF introduced Fast Mobile IPv6 (FMIPv6) as a fast handover protocol to reduce handover delays. As the FMIPv6 protocol was not designed for group handovers, implementing such a protocol for group handover scenarios requires some enhancements. Several satellites will be available options for handover targets in future satellite networks with mega-constellations. One satellite might not be able to serve all users and satisfy all their QoS requirements.

*Table 49. Challenges Associated with Support Group of Terminals Handover*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: Handling the location update and handover signaling of a large number of users triggering handover at almost the same time | Many users in a satellite footprint have to go through connection handover within a short time period due to satellite movement. This will create a storm of binding update messages. In addition, it requires a large number of tunnels between the home satellite and the new satellite to forward the packets to the users, which will congest their ISLs. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge 2: Implementing FMIPv6 for a group of user handover | FMIPv6 can make the handover process faster. However, this protocol was not designed for group handovers. Implementing such a protocol for group handover scenarios requires some enhancements. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 3: Clustering users to groups to be handed over to different satellites based on users' QoS requirements | When a number of satellites are available as options for handover targets, choosing the right satellite for a certain group of users is a complicated problem. One satellite might not be able to serve all users and satisfy all their QoS requirements. Users must be grouped into clusters where each cluster can be served with a specific satellite. |

### 5.10.6.2. Support Group of Terminals Handover — Potential Solutions

Table 50 summarizes the potential solutions to the challenges of the fifth need for satellite mobility management, Support Group of Terminals Handover. First, terminal prioritization can be a potential solution to handle the location update and handover signaling when many users simultaneously trigger handover. Second, a representative user should be elected to implement FMIPv6 for a group of users' handovers. The elected representative can obtain a network address prefix from the next satellite and distribute the address prefix among the group of users [117]. Third, when the group of users has different QoS requirements and needs to be handed over to a group of satellites because they cannot be served by one satellite, this can be managed similarly to the multiple producers – multiple consumers problems.

*Table 50. Potential Solutions to Address Support Group of Terminals Handover*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Handling the location update and handover signaling of a large number of users triggering handover at almost the same time | Users should be prioritized based on their position, movement pattern, and required QoS level to handle many users without degrading their QoS. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 2: Implementing FMIPv6 for a group of users' handovers | The group of users should elect a representative user that can get a network address prefix from the next satellite. The obtained network address prefix can be distributed among the group of users. This will reduce the amount of signaling and delay in comparison to individually handling each user handover. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 3: Clustering users to groups to be handed over to different satellites based on users' QoS requirements | Distributing a group of users with different QoS needs to multiple satellites that can provide different QoS levels. This can be managed similarly to the multiple producers' multiple consumers' problem. |

### 5.10.7. Radio Resource Management in Satellite Networks

Radio Resource Management (RRM) is at the heart of satellite network management functionalities. RRM is crucial to optimize the communication links in S1, S3, and S4 interfaces of the use cases discussed in Section 6.1 (see also Figure 7 for a quick survey of these interfaces). There are numerous needs for efficient radio resource management in future satellite networks. First, the resource allocation process should be optimized to maximize the network utility while ensuring the end-to-end QoS of the users. This plays a significant role in efficiently using radio resources. Second, satellite networks are envisioned to play a significant role in serving IoT applications ubiquitously. Therefore, RRM should target the efficient support of mMTC. In addition, high interference is inevitable due to the deployment of many satellite systems, e.g., dense LEO constellations and the massive number of connected users / devices. Therefore, interference coordination and mitigation in satellite networks are crucial to utilize the limited frequency and power resources efficiently.

### 5.10.8. Radio Resource Management in Satellite Networks — Need #1

#### 5.10.8.1. Optimized Resource Management — Challenges

Several challenges need to be addressed to optimize the resource allocation process in future satellite networks. First, the long propagation delay associated with satellite communications directly impacts the users' QoS, making it difficult to fulfill the end-to-end QoS requirements of some users. Second, the high mobility of NGSO satellites in the MEO / LEO orbits results in frequent handovers that lead to throughput losses and further delay and signaling overhead to process and implement those handovers. Furthermore, many systems, e.g., tens of thousands of LEO satellites, MEOs, GEOs, and HAPs / UAVs, will coexist with the terrestrial networks. Consequently, the resource allocation schemes should consider the high interference between these systems to minimize the impact on the users' QoS and network performance. In addition, due to the increasing number of satellite users, resource allocation techniques' scalability should be considered.

Table 51 summarizes the challenges to optimize resource allocation in future satellite networks.

*Table 51. Challenges Associated with Optimized Resource Allocation*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: High propagation delay | It cannot support the low-latency requirements of the users. |
| Challenge 2: High mobility of NGSO satellites | Throughput losses due to frequent handovers. Delay and signaling overhead due to handover processing. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge 3: Large number of users | Scalability of resource allocation techniques. QoS guarantees. |
| Challenge 4: High interference | Interference due to a large number of different systems (GEOs, MEOs, LEOs, HAPs / UAVs, terrestrial). |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 5: Massive number of users | Scalability of resource allocation techniques. QoS guarantees. |
| Challenge 6: Much higher interference | Higher interference is caused by the coexistence of many different systems, e.g., tens of thousands of LEO satellites. |

#### 5.10.8.2. Optimized Resource Management — Potential Solutions

Numerous potential solutions can be employed to address the challenges associated with resource allocation. For example, to cope with the long propagation delay issue, access diversity can be used such that different satellite systems are accessed based on the required QoS level, e.g., low-latency applications can be assigned to HAPs, moderate-latency applications can be served by LEO / MEO satellites, and latency-tolerant services are allocated to GEO satellites. Besides, efficient handover mechanisms that utilize flexible topologies, e.g., based on SDN / NFV concepts, can be employed to overcome the high mobility issues. For scalability issues, AI/ML techniques can play an essential role in tackling these problems. This is in addition to optimizing the admission control process such that the fulfillment of the QoS requirements of the admitted users is ensured. Finally, the spatial dimensions should be exploited to mitigate the high interference in satellite networks utilizing the phased array antenna technology.

Table 52 summarizes the potential solutions for every discussed challenge.

*Table 52. Potential Solutions to Address Optimized Resource Allocation*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: High propagation latency | Access diversity using different platforms for different applications, e.g., HAPs for low-latency, MEOs / LEOs for moderate-latency, and GEOs for delay-tolerant applications. |
| Challenge 2: High mobility of NGSOs | Adopting efficient handover mechanisms utilizing SDN / NFV techniques. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 3: Large number of users | Utilizing AI/ML techniques for scalability issues of resource allocation schemes.<br>Optimizing admission control procedures to guarantee QoS satisfaction of admitted users. |
| Challenge 4: High interference | Exploiting the spatial dimensions utilizing phased array antenna technologies.<br>Coordination between different systems and centralized management approaches. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 5: Massive number of users | Utilizing more advanced AI/ML techniques for scalability issues of resource allocation schemes.<br>Optimizing admission control procedures to guarantee QoS satisfaction of admitted users. |
| Challenge 6: Much higher interference | The exploitation of spatial dimensions utilizing more advanced phased array antenna technologies.<br>More coordination and interoperability between different systems and centralized management approaches. |

### 5.10.9. Radio Resource Management in Satellite Networks — Need #2

#### 5.10.9.1. Efficient Support of IoT Applications — Challenges

Several challenges need to be addressed to support IoT scenarios in satellite networks efficiently. From a radio resource management perspective, handling two kinds of traffic, i.e., eMBB services and massive MTC, is challenging due to the different and diverse characteristics and QoS requirements of the two types of communications. For instance, eMBB applications are generally data-hungry, and their QoS is improved by increasing their data rates. However, massive MTC is characterized by its low data rate transmissions and delay-tolerance. Besides, IoT devices are generally low-cost, low-power devices. Therefore, they require energy-efficient services. This aspect is more challenging in satellite networks that are characterized by high propagation losses due to the high altitude of the access points. Moreover, the massive number of connected IoT devices poses many challenges to radio resource management in terms of scalability, availability, congestion control, and fulfillment of QoS requirements. Table 53 summarizes these challenges from the near-term, mid-term, and long-term points of view.

*Table 53. Challenges Associated with Efficient Support of IoT Applications*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: Different traffic characteristics and QoS requirements | Different traffic characteristics compared to eMBB, e.g., low data rate and latency tolerance, and different QoS requirements, e.g., energy efficiency. |
| Challenge 2: Link budget and low-power operation | Require energy-efficient service. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge 3: Large number of connected IoT devices | Scalability of network management schemes. Various QoS requirements. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 4: Massive number of connected IoT devices | Scalability of network management schemes. More various QoS requirements. |

#### 5.10.9.2. Efficient Support of IoT Applications — Potential Solutions

Several RRM techniques can be used to optimize future satellite networks to support different types of traffic, including IoT applications, efficiently. In this regard, cross-layer design can be utilized to consider the buffer dynamics in addition to the physical layer parameters of the devices. Besides, AI/ML can be employed for clustering purposes and to address scalability issues. Moreover, energy efficiency can be prioritized by RRM procedures for IoT traffic. This is in addition to possibly considering energy-harvesting solutions for low-power devices. Furthermore, network slicing and network softwarization to flexibly adapt and re-define the network slices can be an efficient solution to deal with the massive number of IoT devices connected to the satellite network. This can be achieved by utilizing the virtualized reference architectures RA-2 and RA-3, as discussed in Section 4.2.2. These potential solutions are summarized in Table 54.

*Table 54. Potential Solutions to Address Efficient Support of IoT Applications*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Different traffic characteristics and QoS demands | Cross-layer design to consider different requirements and characteristics. Utilizing AI/ML techniques. |
| Challenge 2: Link budget and low-power operation | Prioritizing energy efficiency for these applications. Considering energy harvesting solutions. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 3: Large number of connected IoT devices | Utilizing network slicing techniques and network softwarization to adapt and redefine network slices flexibly. Utilizing AI/ML techniques for scalability issues. |

| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
|---|---|
| Challenge 4: Massive number of connected IoT devices | Utilizing more advanced network slicing techniques and network softwarization to adapt and re-define the network slices flexibly. Using more advanced AI/ML techniques for scalability issues. |

### 5.10.10. Radio Resource Management in Satellite Networks — Need #3

#### 5.10.10.1. Efficient Interference Management and Spectrum Utilization — Challenges

Interference management in satellite networks is very complicated. First, the available spectrum resources are limited. However, future satellite networks are envisioned to offer many more services to many users, which can lead to a spectrum shortage. In addition, due to the coexistence of various dense systems, e.g., GEOs, MEOs, LEOs mega-constellations, HAPs / UAVs, and terrestrial networks, high interference between these systems is inevitable. Therefore, efficient interference coordination and mitigation are of utmost importance to satellite networks. The challenges of efficient interference management and spectrum utilization are summarized in Table 55.

*Table 55. Challenges Associated with Efficient Interference Management and Spectrum Utilization*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: Spectrum scarcity | Limited frequency resources. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge 2: High demand | Massive number of connected users / devices. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 3: Large number of different systems | Tens of thousands of non-GEO satellites coexist with GEOs, HAPs / UAVs, and terrestrial systems. |

#### 5.10.10.2. Efficient Interference Management and Spectrum Utilization — Solutions

Dynamic spectrum access utilizing cognitive radio technology can be employed to overcome the challenge of limited spectrum resources. The LEO / MEO satellites can be considered secondary users to GEOs and terrestrial networks. Besides, considering allocating more spectrum resources for satellite networks is important. Moreover, to manage the high interference introduced by the dense deployment of satellite systems, coordination between the different systems, e.g., utilizing the integrated architecture RA-3 (discussed in Section 4.2.2), can play a vital role in interference mitigation and avoidance. Table 56 summarizes the potential solutions for every discussed challenge.

*Table 56. Potential Solutions to Address Efficient Interference Management and Spectrum Utilization*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Spectrum scarcity | Allocating more spectrum. Utilizing dynamic spectrum access techniques. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 2: High demand | Greater frequency reuse, exploiting the spatial degrees of freedom. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 3: Large number of different systems | Coordination between different systems and centralized management approaches to mitigate system interference. |

### 5.10.11. Routing in Satellite Networks

As the race to large / mega LEO constellations is intensifying by the day, discussing routing is bound to become of utmost importance. And this is true whether it is for a standalone satellite network or an integrated satellite-terrestrial network. By standalone networks, we are essentially referring to futuristic projects such as Starlink from SpaceX that aim to provide global, broadband, and low-latency internet using large constellations of LEO satellites. Integrated satellite-terrestrial networks refer to B5G networks that will link together highly capable cellular / terrestrial networks, such as 5G ones with satellites, including the large-constellation satellite networks, to provide cutting-edge performance and absolute global coverage. Satellites have been around for a long time. What is new today is the context of large constellations of LEO satellites that are aimed to cooperate. Routing will ensure that multiple satellites autonomously relay ground-originated data packets on their way to their destination (back to the ground). We identify key needs (requirements), challenges, and potential solutions to ensure such routing becomes a reality in satellite networks.

### 5.10.12. Routing in Satellite Networks — Need #1

#### 5.10.12.1. On-Board Processing — Challenges

Without onboard processing, routing cannot take place. On-board processing will ensure that each satellite fully recovers the received packet and reads its header information to determine where to send it next (next hop). Table 57 summarizes these challenges.

*Table 57. Challenges Associated with On-Board Processing*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Expensive | The processing of packets on board the satellites can prove to be expensive (in terms of the steps involved), as each packet needs to be accurately regenerated so that routing-related information it carries can be read and acted on. |

| *Mid-term Challenges: 2026-2027* | *Description* |
|---|---|
| Limited computation power | As more and more novel routing techniques, including those that rely on AI/ML, are proposed by researchers, it is possible that the current satellite computing hardware will not be enough. Moreover, base station capabilities could be added to satellites. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Obsolescence | Satellites are expected to stay in orbit for 5+ years. During this time, new processing (demodulation, decoding) and regeneration techniques might have come about. The satellite hardware that is already in orbit will not be able to use them. |

#### 5.10.12.2. On-Board Processing — Potential Solutions

At this juncture, onboard processing is already available in the form of digital transparent processing (no demodulation and no decoding) or in the form of full regenerative processing (demodulation and decoding included) [117]. It is not yet used / tested for LEO-LEO routing decision making. One solution would be to use partial regenerative processing to reduce the cost of fully regenerative processing, where only the header packet is regenerated, which would be enough for routing. Reprogrammable / reconfigurable (from afar) hardware on the satellite would be a solution to their potential obsolescence. Table 58 summarizes the possible solutions to the onboard processing challenges.

*Table 58. Potential Solutions to Address On-Board Processing Challenges*

| *Near-term Challenges: 2022-2025* | *Potential Solutions to Near-Term Challenges* |
|---|---|
| Expensive | Partial processing where only the packet header is fully regenerated. This should reduce the processing cost. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Limited computation power | Start building embedded computer systems that are geared for AI/ML. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Obsolescence | Reprogrammable / reconfigurable payloads for flexibility. |

### 5.10.13. Routing in Satellite Networks — Need #2

#### 5.10.13.1. Routing Protocols — Challenges

Once we have inter-satellite links, onboard processing, and dual RF / FSO functionality available for operation in the context of mega-constellations, we will be able to devise efficient routing protocols for the satellite networks properly. These routing protocols are going to facilitate the multi-hop use cases described in Section 6.1. Designing routing protocols will come with certain challenges as well. Such challenges include the highly dynamic topology of the network. If an SDN strategy is employed, there will be a need to determine the best location of the controller(s). Also, with mega-constellations and global coverage of the Earth comes huge amounts of users and traffic; hence a pressing need for the routing protocols to be highly scalable. Table 59 summarizes some of the expected challenges.

*Table 59. Challenges Associated with Routing Protocols*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Changing topology | With the extremely high mobility of the satellites, including high relative velocity between satellites, the topology is constantly changing. |
| SDN | If SDN is used for routing, a central preoccupation is the location of the controller and the number of controllers. |
| Addressing | Addresses are necessary for routing purposes. IP addressing was not designed with the kind of high mobility of the satellites in mind. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| IoT Scenarios | The latency can be very critical for IoT use cases. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Global usage | A satellite-supported global internet coverage comes with huge traffic, hence the potential for congestion. |
| Extremely large network | In the long run, mega-constellations (Starlink, Kuiper, etc.) are expected to have tens of thousands of satellites. Any routing protocol should be able to easily re-adapt with the addition of new batches of satellites. |

#### 5.10.13.2. Routing Protocols — Potential Solutions

There are some possible solutions to the above-listed challenges. To accommodate IoT scenarios, for instance, the proposed routing protocols should make it a point to be latency-reduction oriented. Moreover, aside from IoT scenarios, latency, in the end, will be the main attraction and advantage of satellite networks over terrestrial networks. Table 60 summarizes the potential solutions.

*Table 60. Potential Solutions to Address Routing Protocols Challenges*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Changing topology | Novel routing protocols should be designed for this type of highly dynamic network. The predictability of the satellites' movement could be exploited. Software-defined networking (SDN) is also a good avenue. |
| SDN | Given the predictability of the satellites' movement, optimization studies could be made to find the number and location of the controllers. AI/ML could also help. |
| Addressing | Adopt a location-centric approach. Use the periodicity and predictability of satellites' locations. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| IoT scenarios | Design latency-oriented routing protocols. |

| *Long-term Challenges: 2028-2032* | *Potential Solutions to Long-term Challenges* |
|---|---|
| Global usage | Routing protocols that readily detect / avoid congestion with easy re-routing. |
| Extremely large network | Make it a point to design very scalable routing protocols. |

### 5.10.14. Intelligent and Softwarized Satellite Network Management

Future satellite networks will consist of a massive number of satellites deployed in mega-constellations. Classical network management solutions may not adapt to the rapid changes in network topology and user demands. Virtualization and softwarization are two main enablers that support agility, flexibility, and adaptability in network management. More interestingly, using artificial intelligence to support intelligent decision-making in softwarized network management enables automated network management. In 5G and beyond, network virtualization focuses on a software-based representation of the software and hardware resources in both data and/or control-plane functions. It is the main foundation of network softwarization and network slicing. Network softwarization is designing, architecting, and managing a network using software programmability properties. It supports flexibility, adaptability, and even total reconfiguration of a network on the fly.

On the other hand, Network Slicing (NS) aims to ensure service customization, isolation, and multi-tenancy support on a common physical network infrastructure by enabling logical and physical separation of network resources [118]. This can be visualized in the architectures described in Section 5.2. As satellite networks are expected to become an integral part of upcoming 5G and beyond networks, adopting SDN / NFV and NS is necessary for the evolution of satellite-terrestrial networks. This approach enables more flexible, agile, and cost-effective management and greatly supports the seamless integration of satellite and terrestrial networks. Future networks are going to be zero-touch networks that can self-evolve (i.e., with minimum human intervention in network design, deployment, management, operation, and maintenance) [119]. Therefore, the self-evolving concept should be gradually introduced in satellite networks by utilizing artificial intelligence to automate network management.

### 5.10.15. Network Function Virtualization in Satellite Networks — Need #1

#### 5.10.15.1. Network Function Virtualization — Challenges

Table 61 summarizes the satellite network function virtualization challenges.

*Table 61. Challenges Associated with Network Function Virtualization*

| *Near-term Challenges: 2022-2025* | *Description* |
|---|---|
| Providing virtualized functions using dynamic resources | In the environment of satellite networks, it is very challenging to use very dynamic resources (satellites) to fulfill the variable demands of users. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Virtualization across operators | Since multiple operators will operate satellite networks, efficient virtualization requires coordination and collaboration among operators. |

| *Long-term Challenges: 2028-2032* | *Description* |
|---|---|
| Automation of virtualization | To respond to the variable user demands and adapt to the dynamic nature of satellite networks, NFV must be able to create / remove network functions in an automated way. |

#### 5.10.15.2. Network Function Virtualization — Potential Solutions

There are some possible solutions to the above-listed challenges, which are summarized in Table 62.

*Table 62. Potential Solutions to Address Network Function Virtualization*

| *Near-term Challenges: 2022-2025* | *Potential Solutions to Near-Term Challenges* |
|---|---|
| Providing virtualized functions using dynamic resources | An efficient and intelligent resource management layer is necessary to support NFV in satellite networks. |
| *Mid-term Challenges: 2026-2027* | *Potential Solutions to Mid-term Challenges* |
| Virtualization across operators | New schemes for resource management across multiple operators are required. |
| *Long-term Challenges: 2028-2032* | *Potential Solutions to Long-term Challenges* |
| Automation of virtualization | NFV creation / management based on intelligent decisions can be utilized. |

### 5.10.16. Network Slicing in Satellite Networks — Need #2

#### 5.10.16.1. Network Slicing — Challenges

Table 63 summarizes some important challenges related to network slicing in satellite networks.

*Table 63. Challenges Associated with Network Slicing*

| *Near-term Challenges: 2022-2025* | *Description* |
|---|---|
| NS using moving resources | Unlike terrestrial networks, satellite BS is a moving network resource. |
| *Mid-term Challenges: 2026-2027* | *Description* |
| Scalable NS | NS might involve multiple operators and resources from different satellite networks. Also, integrating terrestrial and aerial networks may necessitate creating network slices across different ecosystems. |
| *Long-term Challenges: 2028-2032* | *Description* |
| Automated NS | It is challenging to automate network slicing in the dynamic environment of satellites. Automating the creation and management of network slices across different integrated networks (i.e., satellite, aerial, terrestrial) is more challenging. |

#### 5.10.16.2. Network Slicing — Potential Solutions

Some possible solutions to the above-listed challenges are summarized in Table 64.

*Table 64. Potential Solutions to Address Network Slicing*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| NS using moving resources | Satellites predicted motion can be used to reduce uncertainty. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Scalable NS | A new NS model that introduces policies on dealing with resources across different operators and networks. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Automated NS | Machine learning and prediction algorithms can be used to automate NS. |

### 5.10.17. Software-Defined Satellite Networks — Need #3

#### 5.10.17.1. Software-Defined Satellite Networks — Challenges

Table 65 summarizes some important challenges related to network slicing in satellite networks.

*Table 65. Challenges Associated with Software-Defined Satellite Networks*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Flow table management | Due to satellite motion flow tables might expire soon, and the construction of new tables consumes resources. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Distributed SDN control | The centralized nature of SDN does not suit distributed and large-scale satellite networks. |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Dynamic controller placement | Controller placement affects the performance of SDN. The placement should adapt to changes in the network. |

#### 5.10.17.2. Software-Defined Satellite Networks — Potential Solutions

Some possible solutions to the above-listed challenges are summarized in

Table 66.

*Table 66. Potential Solutions to Address Software-Defined Satellite Networks*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Flow table management | Relaying flow tables between satellites might reduce the overhead of creating new tables.<br>Intelligent predictions may play a significant role in reducing the overhead of updating flow tables. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Distributed SDN control across integrated networks | The IETF distributed mobility management architecture can be merged with SDN.<br>The hierarchical structure of controllers, which can be across integrated networks, should be adopted to reduce controllers' load and response time. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Intelligent and dynamic controller placement | Artificial intelligence and machine learning can be used to place controllers based on changes in network status dynamically. |

## 5.11. Standardization

Several challenges must be addressed for the planned and future mega-constellations of NGSO satellites, UAVs, and HAPs systems to serve the unserved and underserved remote and rural areas. Standardization activities for 5G and beyond 5G for NTN are in progress in different organizations like 3GPP, IEEE, ITU, ETSI, and others. Standardization work is needed to identify the role of the different layers in a multi-layer NTN, considering routing, distributed intelligence, joint resource management (including traffic offloading), and network management.

3GPP has recently frozen Release 17 of the specification that contains NTN systems. More details on the recent standardization work on 5G and beyond are provided in Appendix B.

The challenges for the near-term (2020-2023), mid-term (2024-2025), and long-term (2026-2030) and possible solutions are discussed below. Appendix B describes the current standardization state by 3GPP, IEEE, ITU-World Radio Conference (WRC), ETSI, and 5GPPP.

### 5.11.1. Needs

The needs for 5G and beyond 5G satellite standardizations are given in Table 67.

*Table 67. Needs for Standardization*

| | |
|---|---|
| ***Need 1*** | Reference Architecture<br>5G Satellite network architecture requires integrated architectures to meet the traffic performance requirements. |
| ***Need 2*** | Spectrum Sharing<br>Strategies for spectrum sharing for GSO and non-GSO satellite networks. Establish Effective Power Flux Density (EPFD) limits and Interference Mitigation Techniques. |

| | |
|---|---|
| ***Need 3*** | Network Management<br>New resource allocation, routing protocols, mobility management, and handover algorithms for 5G LEO satellite networks. |
| ***Need 4*** | Multilayer Network Protocols<br>New protocols for multi-layer networks to support 5G and B5G services and applications. |
| ***Need 5*** | QoS / QoE<br>New QoS framework supporting performance requirements, e.g., high bandwidth, and low latency for different applications. |
| ***Need 6*** | Edge Intelligence<br>There is a need to identify the distribution of edge intelligent tasks within the NTN architecture with changes to current MEC specifications. |

### 5.11.2. Challenges

Table 68 provides the challenges for achieving near-term, mid-term, and long-term needs.

*Table 68. Challenges Associated with Standardization Needs*

| ***Near-term Challenges: 2022-2025*** | ***Description*** |
|---|---|
| Challenge 1: Reference architecture for non-virtualized satellite 5G networks | Develop architecture for Non-Virtualized Satellite Networks. |
| Challenge 2: Spectrum sharing | Develop interference and coordination methods between GSO and non-GSO systems in terms of EPFD limits. |
| ***Mid-term Challenges: 2026-2027*** | ***Description*** |
| Challenge 3: Network management | New routing, resource management, and handovers protocols for mega-constellations |
| Challenge 4: Multi-layer network protocol | New integrated network protocol for GSO and non-GSO systems, including ISLs |
| ***Long-term Challenges: 2028-2032*** | ***Description*** |
| Challenge 5: QoS / QoE | Develop a new QoS framework for non-GSO networks supporting 5G and beyond. |
| Challenge 6: Network management | New mobility management protocols for 5G & B5G satellite networks supporting applications requirements. |
| Challenge 7: Edge Intelligence | Adapt current MEC specifications to consider the novel NTN architecture |

### 5.11.3. Potential Solutions

Table 69 provides potential solutions for the challenges described in Table 68.

*Table 69. Potential Solutions to Address Standardization Needs*

| ***Near-term Challenges: 2022-2025*** | ***Potential Solutions to Near-Term Challenges*** |
|---|---|
| Challenge 1: Reference architecture | Develop reference architecture for virtualized satellite networks. |
| Challenge 2: Spectrum sharing | Interference mitigation techniques for GSO to non-GSO systems. |
| ***Mid-term Challenges: 2026-2027*** | ***Potential Solutions to Mid-term Challenges*** |
| Challenge 3: Network management | Develop new resource management and routing protocols for 5G and B5G LEO satellite networks. Machine Learning algorithms have to be developed. |
| Challenge 4:Multi-layer network protocol | Develop new integrated network protocols for GSO and non-GSO satellite systems. |
| ***Long-term Challenges: 2028-2032*** | ***Potential Solutions to Long-term Challenges*** |
| Challenge 5: QoS / QoE | New QoS requirement and architecture for non-GSO and NTN networks supporting 5G & B5G services |
| Challenge 6: Network management | New resource management and handover algorithms using Machine Learning approaches. |
| Challenge 7: Edge intelligence | Exploit the distribution of the intelligence at different layers of the NTN system, including UAVs, HAPs, and LEOs. |

# 6. USE CASES

This section discusses four major categories of use cases, which includes satellite as backhaul service to the terrestrial network, satellite as direct access to UE, satellite-IoT, and other use cases, based on the reference architectures. Use cases discussed are (i) satellite networks as backhaul for 6G terrestrial networks, (ii) direct access satellite networks, (iii) satellite-based IoT, and (iv) other use cases.

## 6.1. Use Cases for Satellite Networks as Back-Haul for 6G Terrestrial Networks

The 2021 Edition (Edition 2) of the satellite chapter focuses on using satellite network infrastructure as back-haul infrastructure for 5G terrestrial networks. The third edition of this report has enhanced this part further to suit the 6G requirements.

The following use cases are identified for satellite networks as back-haul:

**Use Case-1:** DU to CU Bent Pipe / 1-hop relay over a LEO satellite

**Use Case-2:** DU to CU over Multi-hop LEO non-federated Network

**Use Case-3:** DU to CU over Multi-hop Federated Network

**Use Case-4:** bent pipe / 1-hop relay to DU to Gateway

**Use Case-5:** DU to Gateway back-haul over multi-hop LEO non-federated network

**Use Case-6:** DU to Gateway back-haul over multi-hop federated LEO network

**Use Case-7:** Terrestrial SBS to LEO bent-pipe / 1-hop relay to eNodeB / gNodeB

**Use Case-8:** Terrestrial SBS to eNodeB / gNodeB over LEO multi-hop non-federated network

**Use Case-9:** Terrestrial SBS to eNodeB / gNodeB over LEO multi-hop federated LEO

**Use Case-10:** UAVs as bent pipe / single-hop relay

**Use Case-11:** UAV multi-hop back-haul

**Use Case-12a-b:** UAV-LEO Integrated multi-hop back-haul.

Each one of these use cases is discussed briefly in the following sections.

### 6.1.1. Use Case-1: DU to CU Bent Pipe / 1-Hop Relay over LEO Satellites

In Use Case-1, the communication between the Distributed Unit (DU) and Centralized Unit (CU) will be carried out through a single LEO satellite that operates in a bent-pipe mode or 1-hop relay with regeneration capability. The interface used for DU-Satellite and Satellite-CU communication is defined as S1. Figure 22 illustrates Use Case-1.

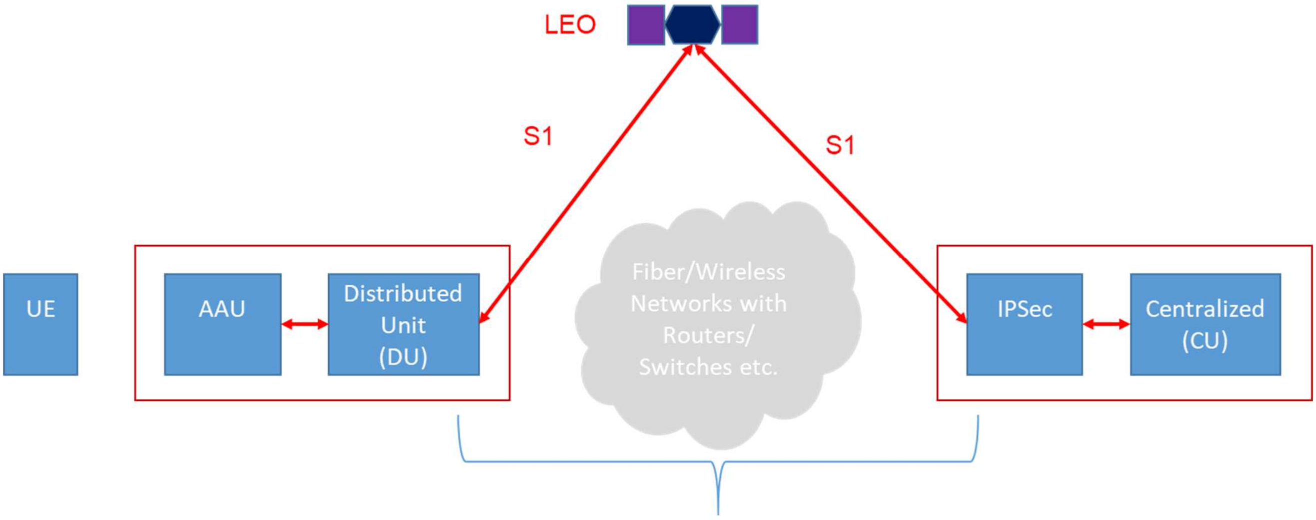


*Figure 22. Use Case-1*

### 6.1.2. Use Case-2: DU to CU over Multi-Hop LEO Non-Federated Networks

Use Case-2 considers the communication between DU and CU through a multi-hop LEO satellite network with proprietary inter-satellite links. Therefore, the satellite segment is considered a non-federated satellite network. Figure 23 illustrates Use Case-2. The interface required for DU-Satellite and Satellite-CU communication is S1.

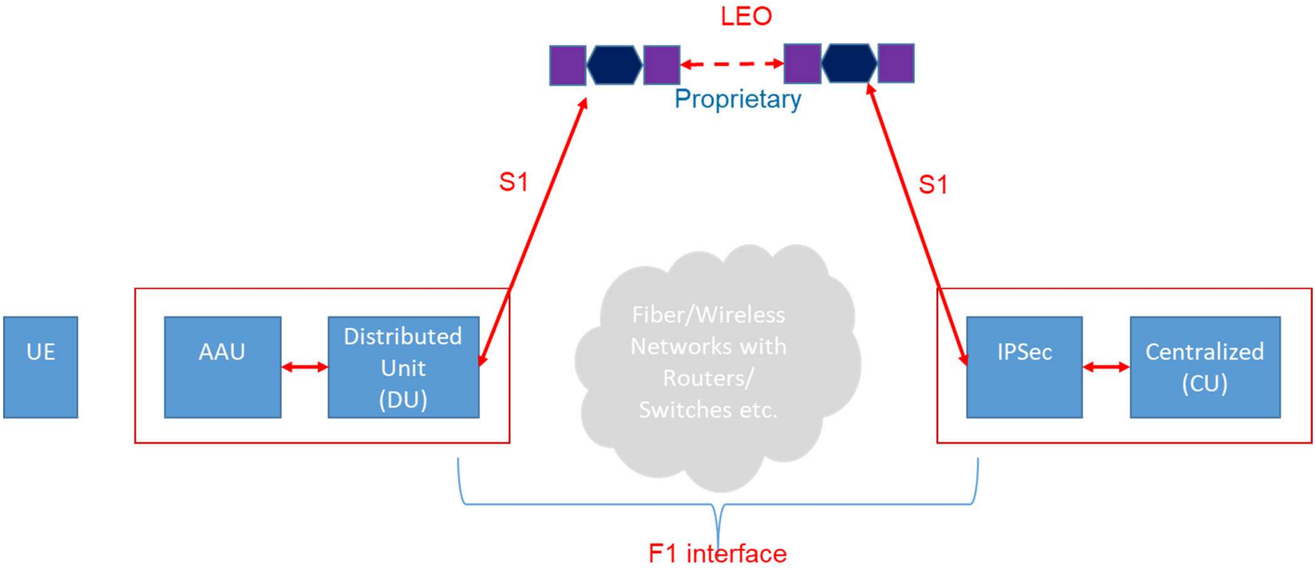


*Figure 23. Use Case-2*

### 6.1.3. Use Case-3: DU to CU over Multi-Hop Federated Networks

Use Case-3 considers the case of a DU to CU communication through a federated LEO satellite network. Here the federation permits the satellite networks belonging to multiple service providers to interwork, thereby achieving better coverage, lower cost of operation, better traffic load balancing, and above all, improved capacity utilization. Interface S2 shall be defined as a standard interface to ensure communication between satellite networks owned and operated by multiple service providers. Figure 24 illustrates Use Case-3.

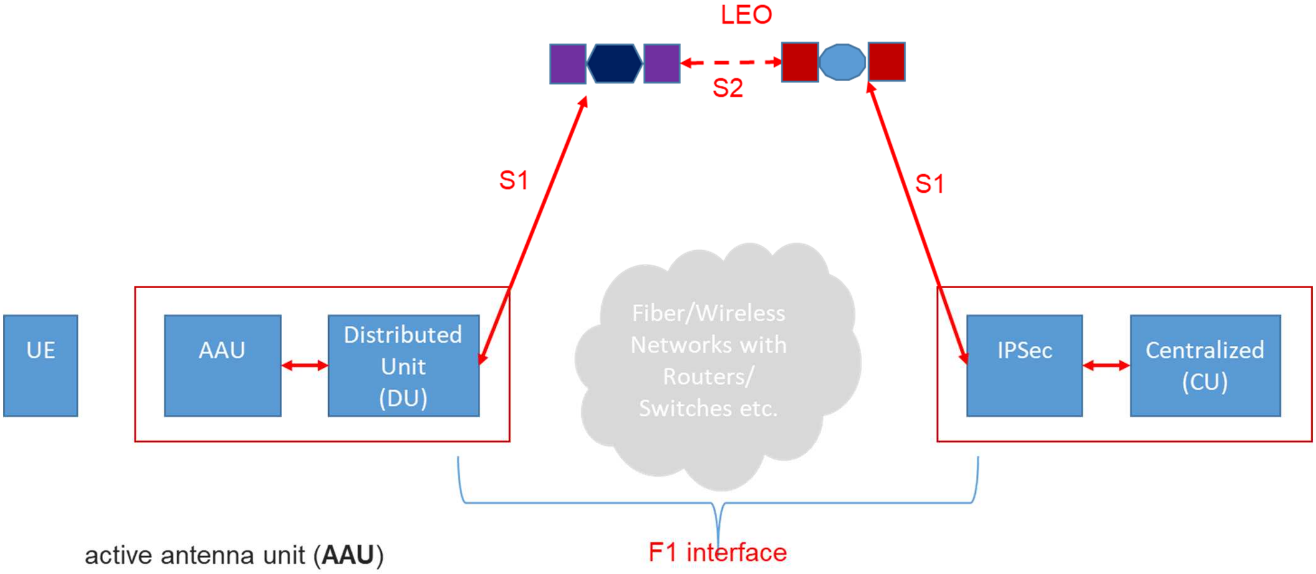


*Figure 24. Use Case-3*

### 6.1.4. Use Case-4: Bent Pipe / 1-Hop Relay to DU to Gateway

Use Case-4 considers the bent pipe / 1-hop communication between DU and CU through the Satellite Network Service (SNS) provider's gateway infrastructure and the wired network. Figure 25 illustrates Use Case-4. Here the bandwidth requirements of the communication session between the DU and CU will be considered to transfer the data between the gateway and the CU effectively.

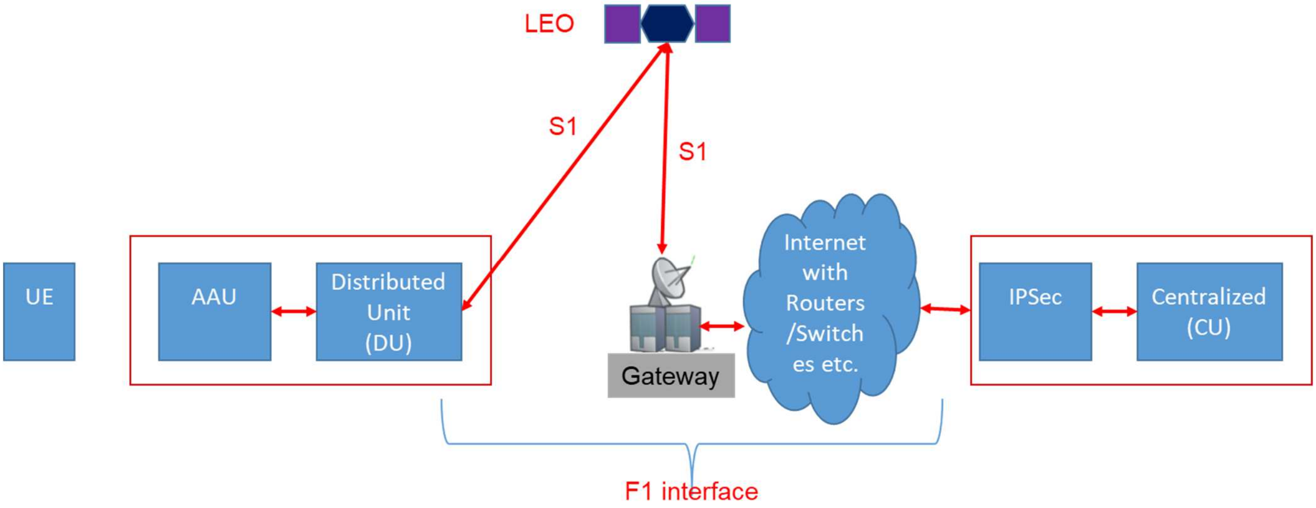


*Figure 25. Use Case-4*

### 6.1.5. Use Case-5: DU to Gateway Back-Haul over Multi-Hop LEO Non-Federated Networks

Use Case-5 consists of a multi-hop communication over the non-federated satellite network between the DU and CU through the satellite communication gateway. The inter-satellite links may be created as proprietary links as per the service provider's design requirements. Further, the bandwidth reservation between the gateway and the CU will be sufficiently provided to ensure necessary performance. Figure 26 illustrates Use Case-5.

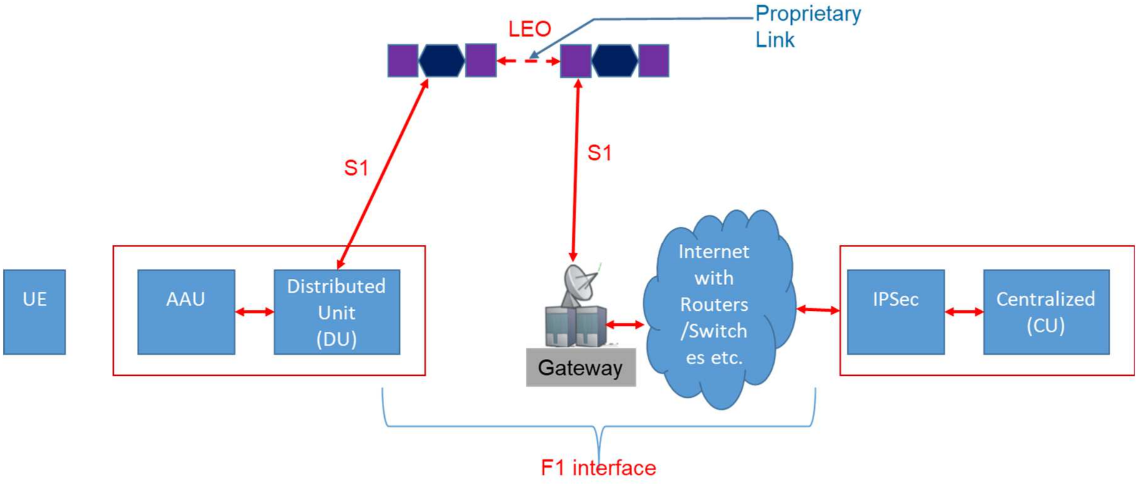


*Figure 26. Use Case-5*

### 6.1.6. Use Case-6: DU to Gateway Back-Haul over Multi-Hop Federated LEO Networks

Use Case-6 refers to the multi-hop communication between the DU and CU through the federated LEO satellite networks and the ground station gateway of the satellite networks. The DU-satellite links and Satellite-Gateway links shall be standardized S1 links. The inter-satellite links shall be S2 to achieve federated communication between the satellite networks belonging to multiple satellite service providers. Figure 27 illustrates Use Case-6.

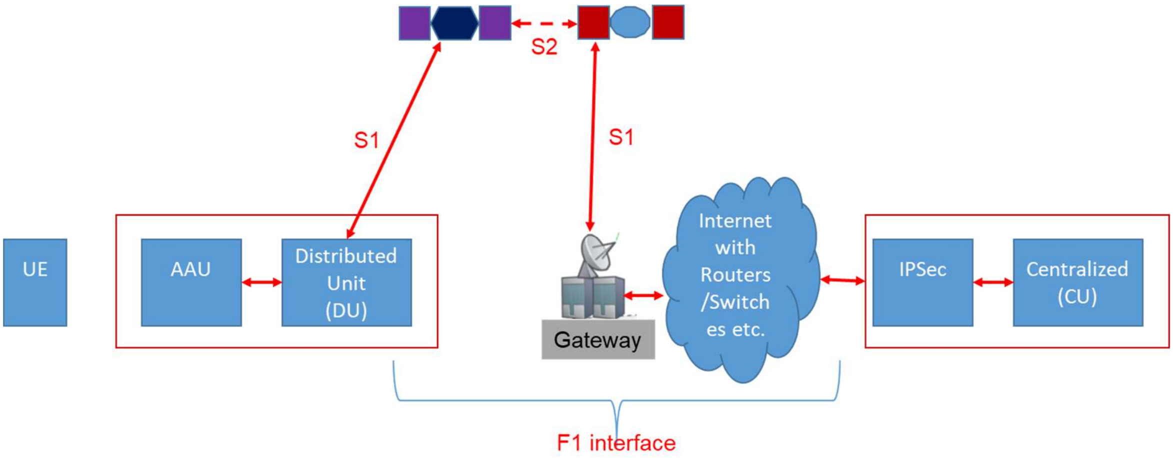


*Figure 27. Use Case-6*

### 6.1.7. Use Case-7: Terrestrial SBS to LEO Bent-Pipe / 1-Hop Relay To eNodeB / gNodeB

Use Case-7 involves communications between the Terrestrial Small Base Station (TSBS) and eNodeB / gNodeB over a single satellite operating in bent-pipe or 1-hop relay mode. The TSBS and the eNodeB / gNodeB shall use the S1 interface for communication. Figure 28 illustrates Use Case-7.

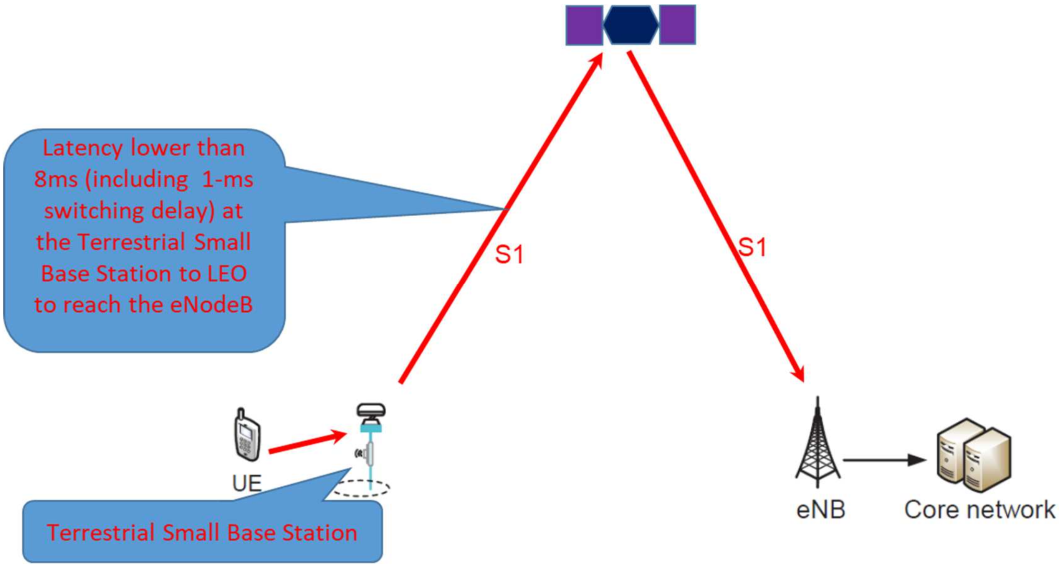


*Figure 28. Use Case-7*

### 6.1.8. Use Case-8: Terrestrial SBS to eNodeB / gNodeB over LEO Multi-Hop Non-Federated Networks

Use Case-8 considers the multi-hop communication between the TSBS and eNodeB / gNodeB over a non-federated LEO satellite network. Figure 29 illustrates Use Case-8.

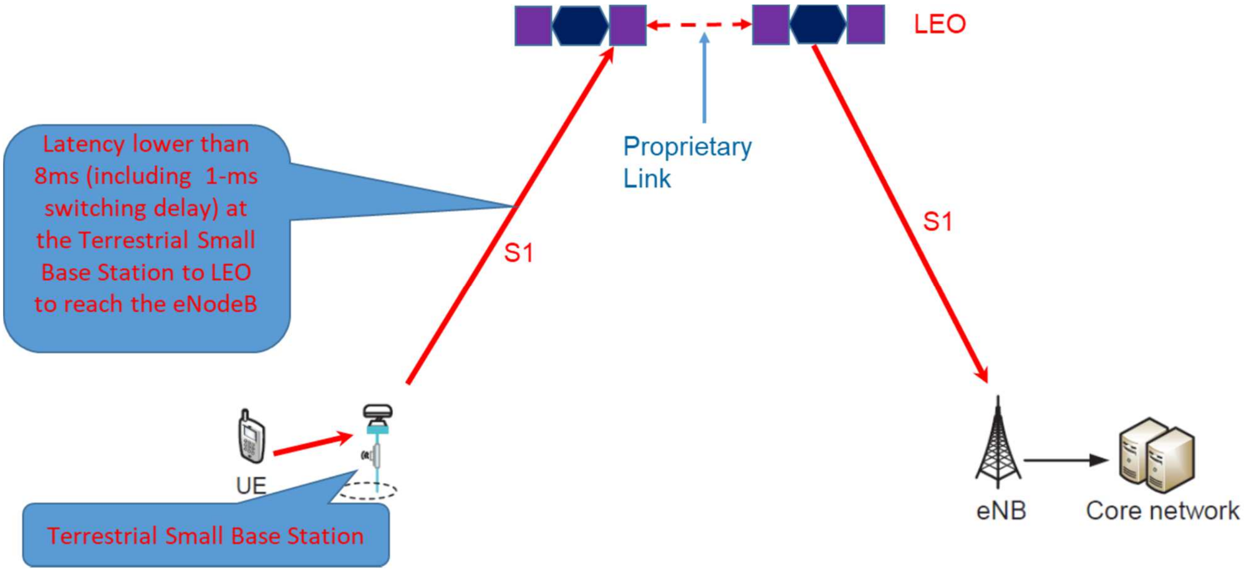


*Figure 29. Use Case-8*

### 6.1.9. Use Case-9: Terrestrial SBS to eNodeB / gNodeB over LEO Multi-Hop Federated LEO Systems

Use Case-9 considers the multi-hop communication between the TSBS and eNodeB / gNodeB over a federated LEO satellite network involving multiple satellite network service providers. Figure 30 illustrates Use Case-9.

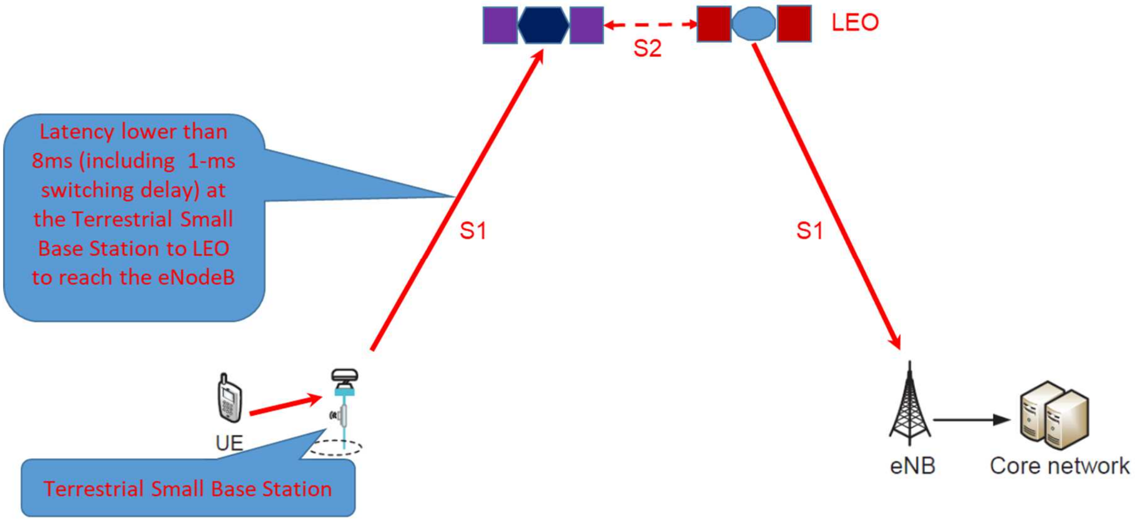


*Figure 30. Use Case-9*

### 6.1.10. Use Case-10: UAVs as Bent Pipe / Single-Hop Relay

Use Case-10 considers UAVs and HAPs to provide a 1-hop relay / bent pipe communication between the TSBS and eNodeB / gNodeB. The HAPs can be used as flying airborne base stations to connect the unconnected or the under-connected [120]. The HAPs can be integrated into the backbone network. The HAPs are considered up to 30 km [121] altitude and can provide round-trip latency of less than 1.2 ms. The interface to be defined for the communication between TSBS and the UAV / HAP platform is S3. In the case of a one-hop relay, a single HAPs functions as a “tower-in-the-air” relaying data between the TSBS and eNodeB / gNodeB where either mobile UEs or access points are located in underserved regions [122]. Figure 31 illustrates Use Case-10.

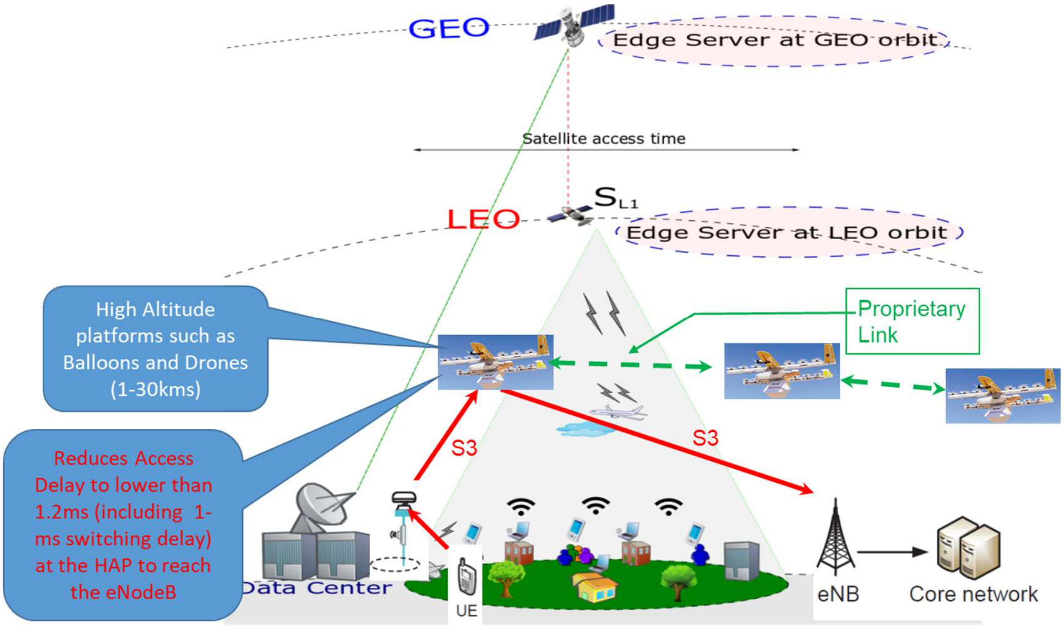


*Figure 31. Use Case-10*

### 6.1.11. Use Case-11: UAV Multi-Hop Back-Haul

Use Case-11 considers the use of UAVs / HAPs along with the LEO-MEO-GEO satellite networks to allow 5G communications where multi-hop communication is utilized at the UAV / HAP segment for enabling the TSBS-eNodeB / gNodeB communication. Figure 32 illustrates Use Case-11. Inter-UAV links can be proprietary. In this configuration, a swarm / cascade of HAPs forms a stratospheric integrated access back-haul network for the underneath local users in large, underserved regions [122].

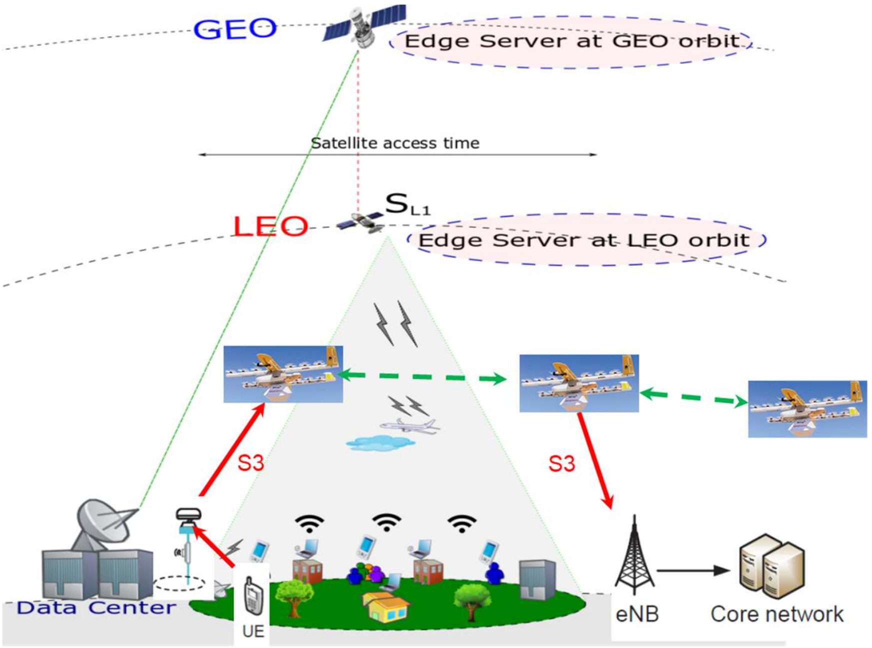


*Figure 32. Use Case-11*

### 6.1.12. Use Case-12a-b: UAV-LEO Integrated Multi-Hop Back-Haul

Use Case-12a deals with the UAV / HAP-LEO-MEO-GEO integration where the TSBS communicates with the UAV / HAP over S3 interface. Figure 33 illustrates Use Case-12a. The UAV / HAP relays the communication over S4 interface to the LEO satellites. That is, the uplink communication between the TSBS and to satellite involves UAV / HAP in a hierarchical manner. On the downlink communication between the LEO / MEO / GEO satellite to eNodeB / gNodeB, the satellite communicates directly with the eNodeB / gNodeB through S1 interface.

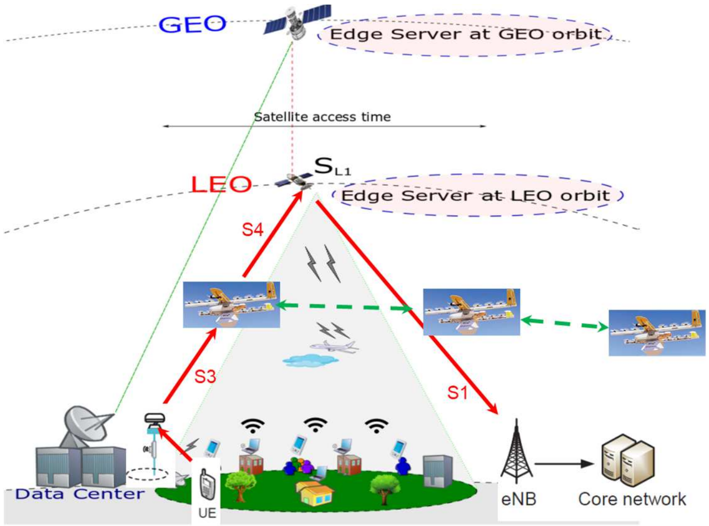


*Figure 33. Use Case-12a*

Use Case-12b deals with the hierarchical communication on uplink and downlink. That is, uplink communication in Use Case-12b is like Use Case-12a. On the other hand, downlink transmission from the satellite network involves a UAV / HAP relay through the combination of S4 and S3 interfaces. Figure 34 illustrates Use Case-12b.

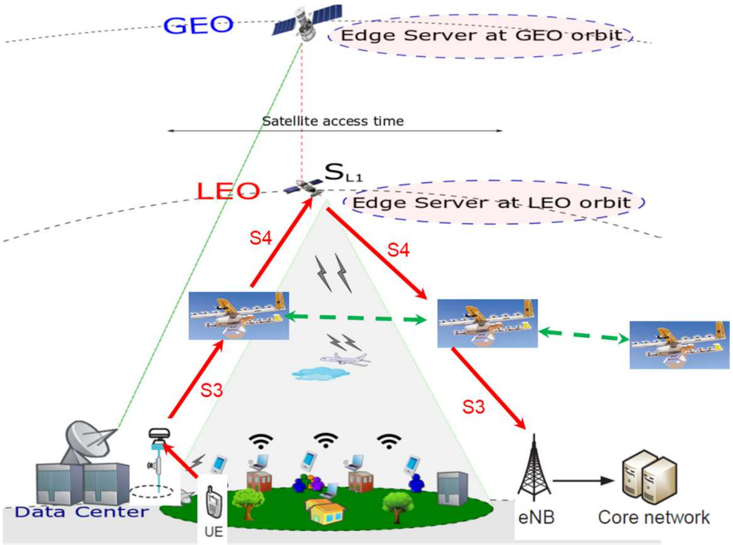


*Figure 34. Use Case-12b*

## 6.2. Use Cases with Direct Access Satellite Networks

Together with the NTN back-haul services scenarios described in the previous sections, the 2022 and the 2023 Editions of the satellite report also consider using the satellite network infrastructure as direct access. These new use cases for direct access to satellite networks focus on the entire spectrum of NTNs, which include HAPs, UAVs, and satellites. Two major directions are considered where an eNodeB / gNodeB is (i) on-NTN or (ii) on-ground. Three direct access modes for NTN nodes are considered:

1. gNodeB / eNodeB onboard the NTN node (satellite / HAPs)
2. Relay access (back-haul traffic is forwarded to another higher-level node) by the NTN node
3. Bent pipe by NTN node (satellite / HAPs).

All of the core functions of eNodeB / gNodeB are present in our assumption of eNodeB / gNodeB irrespective of its location in NTN. The use cases are divided according to use cases involving: (i) LAPs, (ii) HAPs, and (iii) satellites.

In what follows, the symbol → represents the bi-directional link between two networking elements. Further, the symbol → also indicates one segment of the end-to-end session or call where a UE originates a call that goes through the hierarchy of NTN devices before the call or session terminates at the destination located on the internet.

1) LAP NTN Nodes
   a) UE to LAP → gNodeB
   b) UE to LAP → LAP → gNodeB
   c) UE to LAP → HAP → gNodeB (non-federated and federated cases)
   d) UE to LAP → LEO → gNodeB
   e) UE to LAP → MEO → gNodeB
   f) UE to LAP → LEO → MEO → gNodeB (non-federate and federated cases)
   g) UE to LAP → LEO → MEO → GEO → gNodeB (non-federated and federated cases)
   h) UE to LAP → LEO → MEO → HEO → gNodeB (non-federated and federated cases)
2) HAP NTN Nodes
   a) UE to HAP → gNodeB
   b) UE to HAP → HAP → gNodeB
   c) UE to HAP → LEO → gNodeB
   d) UE to HAP → LEO → MEO → gNodeB (non-federated and federated cases)
   e) UE to HAP → MEO → gNodeB
   f) UE to HAP → LEO → MEO → gNodeB (non-federated and federated cases)
   g) UE to HAP → LEO → MEO → GEO → gNodeB (non-federated and federated cases)
   h) UE to HAP → LEO → MEO → HEO → gNodeB (non-federated and federated cases)

3) Satellite NTN Nodes
   a) UE to LEO → gNodeB
   b) UE to LEO → LEO → gNodeB (non-federated and federated cases)
   c) UE to MEO → gNodeB
   d) UE to LEO → MEO → gNodeB (non-federated and federated cases)
   e) UE to MEO → MEO → gNodeB (non-federated and federated cases)
   f) UE to GEO → gNodeB
   g) UE to LEO → MEO → GEO → gNodeB (non-federated and federated cases).

Each one of these use cases is discussed briefly in the following sections.

### 6.2.1. Direct Access Use Case-1.a: UE to LAP → gNodeB

In direct access Use Case-1.a, the communication between UE and CU will be carried out through a single LAP that operates in a bent-pipe mode or 1-hop relay with regeneration capability. Further, we assume that LAP has all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communication is denoted as S0. Interface S1 defines the communication between LAP and CU. Figure 35 illustrates Direct Access Use Case-1.a.

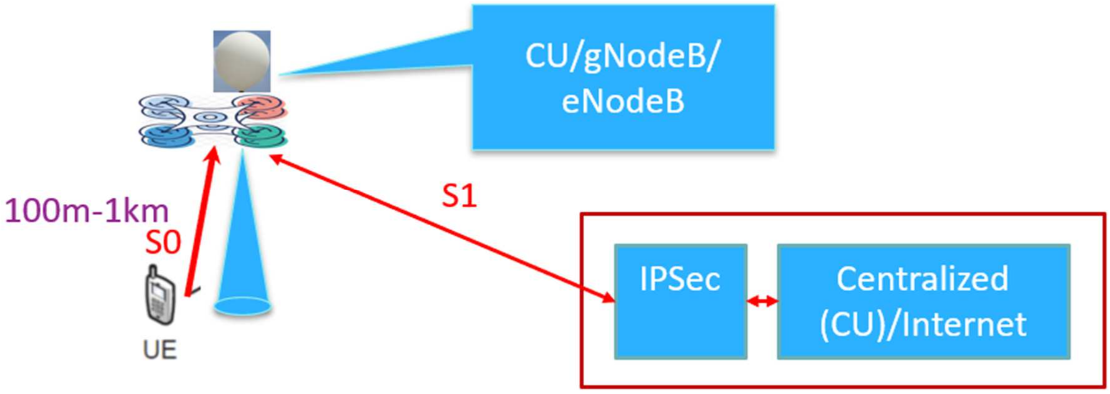


*Figure 35. Direct Access Use Case-1.a*

### 6.2.2. Direct Access Use Case-1.b: UE to LAP → LAP → gNodeB

In the Direct Access Use Case-1.b, the communication between UE and CU will be carried out through multiple LAPs that operate in a bent-pipe mode or with regeneration capability. The UE communicates with the CU through multiple LAP nodes. Further, we assume that LAP has all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communications is defined as S0. Interface S1 defines the communication between LAP and CU. The interface used for communication between two LAP nodes is denoted as L1. Figure 36 illustrates Direct Access Use Case-1.b.

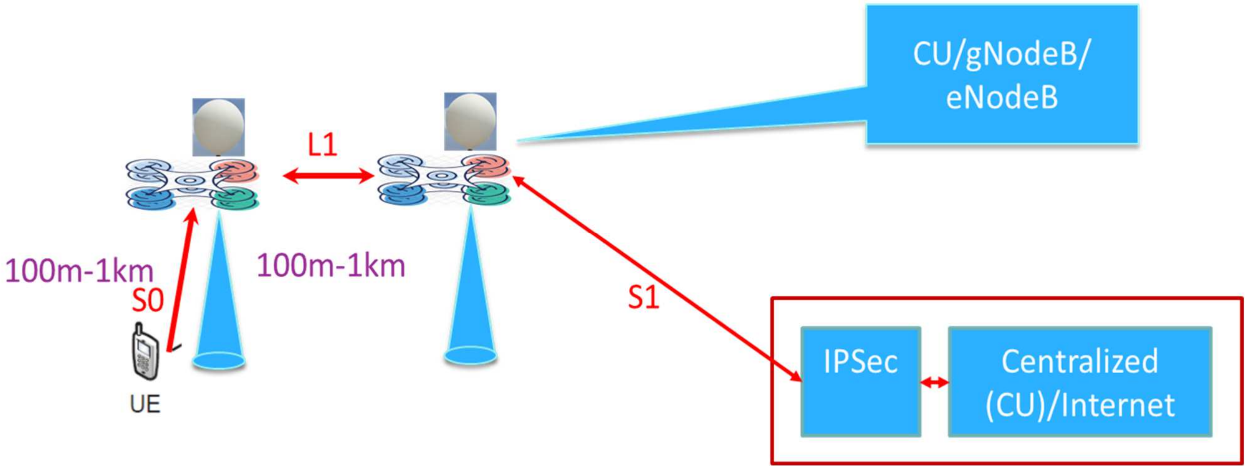


*Figure 36. Direct Access Use Case-1.b*

### 6.2.3. Direct Access Use Case-1.c: UE to LAP → HAP → gNodeB (Non-Federated and Federated Cases)

In the Direct Access Use Case-1.c, the communication between UE and CU will be carried out through LAP and HAP nodes that operate in a bent-pipe mode or with regeneration capability. The LAP and HAP nodes can belong to the same service provider (non-federated) or a different service provider (federated case). The L2 interface is used to communicate between LAP and HAP. Further, the LAP and HAP nodes have all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communications is denoted as S0. Interface S1 defines the communication between HAP and CU. Figure 37 illustrates Direct Access Use Case-1.c.

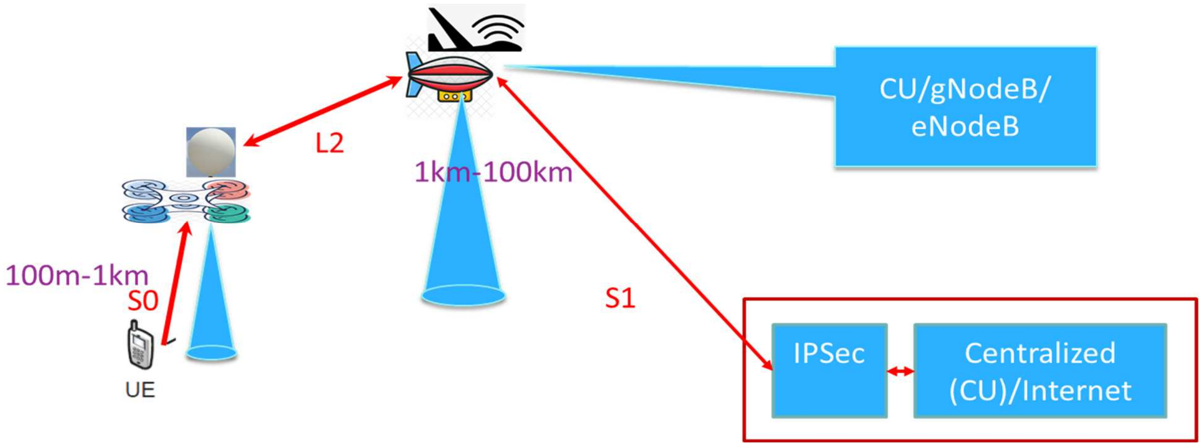


*Figure 37. Direct Access Use Case-1.c*

### 6.2.4. Direct Access Use Case-1.d: UE to LAP → LEO → gNodeB

In the Direct access Use Case-1.d, the communication between UE and CU will be carried out through LAP and LEO that operate in a bent-pipe mode or with regeneration capability. The LAP and LEO nodes can belong to the same service provider (non-federated) or different service providers (federated case). The L3 interface is used to communicate between LAP and LEO. Further, the LAP and LEO nodes have all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communication is denoted as S0. Interface S1 defines the communication between LEO and CU. Figure 38 illustrates Direct Access Use Case-1.d.

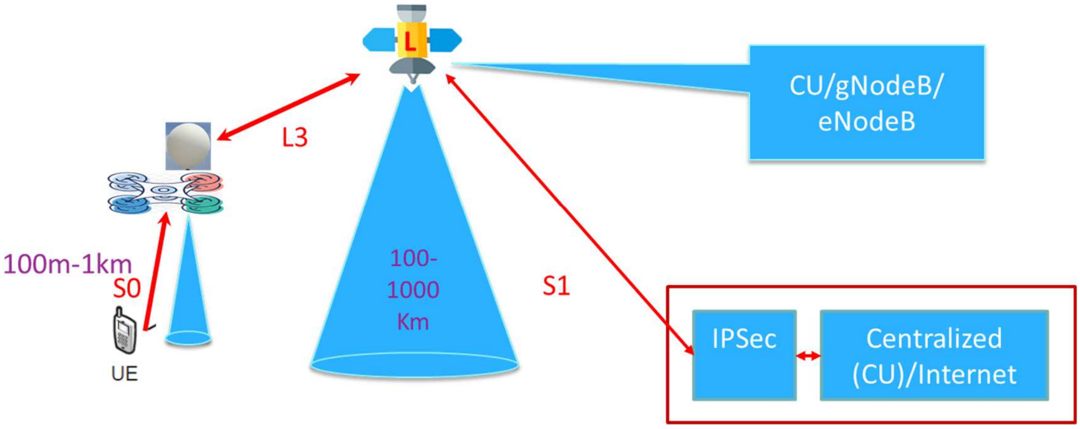


*Figure 38. Direct Access Use Case-1.d*

### 6.2.5. Direct Access Use Case-1.e: UE to LAP → MEO → gNodeB

In the Direct Access Use Case-1.e, the communication between UE and CU will be carried out through LAP and MEO nodes that operate in a bent-pipe mode or with regeneration capability. The LAP and MEO nodes can belong to the same service provider (non-federated) or different service providers (federated case). The L4 interface is used to communicate between LAP and MEO. Further, we assume that LAP and MEO nodes have all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communication is defined as S0. Interface S1 defines the communication between MEO and CU. Figure 39 illustrates Direct Access Use Case-1.e.

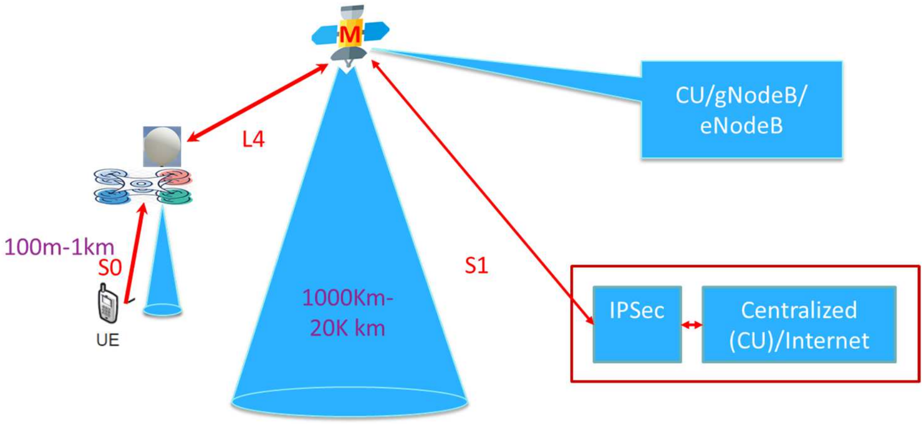


*Figure 39. Direct Access Use Case-1.e*

### 6.2.6. Direct Access Use Case-1.f: UE to LAP → LEO → MEO → gNodeB (Non-Federated and Federated Cases)

In the Direct Access Use Case-1.f, the communication between UE and CU will be carried out through LAP, LEO, and MEO, respectively. All the nodes operate in a bent-pipe mode or with regeneration capability. The LEO and MEO can belong to the same service provider (non-federated case) or different service providers (federated case). In the case of non-federated systems, proprietary ISL is used to communicate where, as in the case of federated, S2 (federated ISL) interface is used to communicate between LEO and MEO. Further, we assume that LAP, LEO, and MEO nodes have all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communication is denoted as S0. Interface S1 defines the communication between MEO and CU. Figure 40 illustrates Direct Access Use Case-1.f.

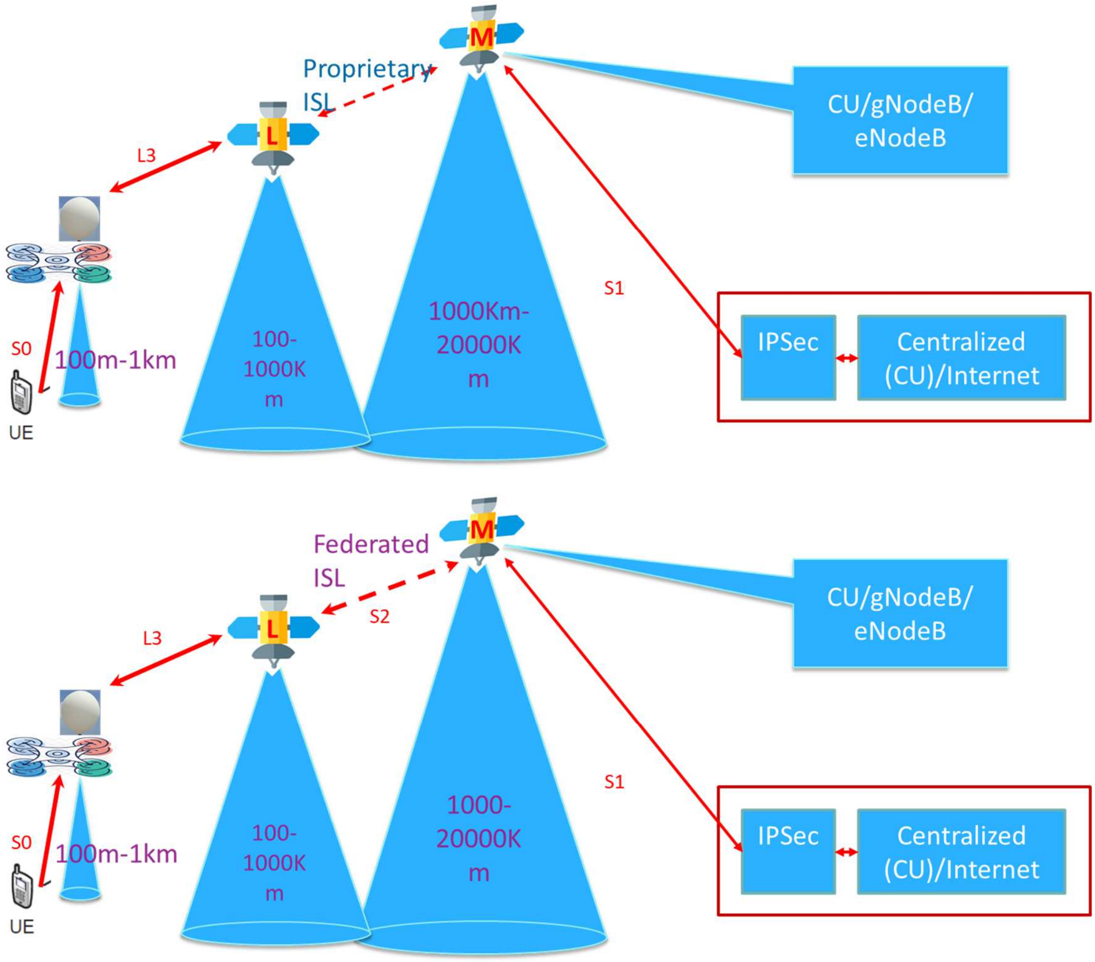


*Figure 40. Direct Access Use Case-1.f (Top: Non-Federated Case, Bottom: Federated Case)*

### 6.2.7. Direct Access Use Case-1.g: UE to LAP → LEO → MEO → GEO → gNodeB (Non-Federated and Federated Cases)

In the Direct Access Use Case-1.g, the communication between the UE and CU will be carried out through LAP, LEO, MEO, and GEO, respectively. All the nodes operate in a bent-pipe mode or with regeneration capability. The LEO, MEO, and GEO can belong to the same service provider (non-federated) or different service providers (federated case). In the case of non-federated systems, proprietary ISL is used to communicate between LEO, MEO, and GEO, whereas in the case of federated, S2 (federated ISL) interface is used to communicate between LEO, MEO, and GEO. Further, we assume that LAP, LEO, MEO, and GEO nodes have all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communication is denoted as S0. Interface S1 defines the communication between GEO and CU. Figure 41 and Figure 42 illustrate Direct Access Use Case-1.g for non-federated and federated cases, respectively.

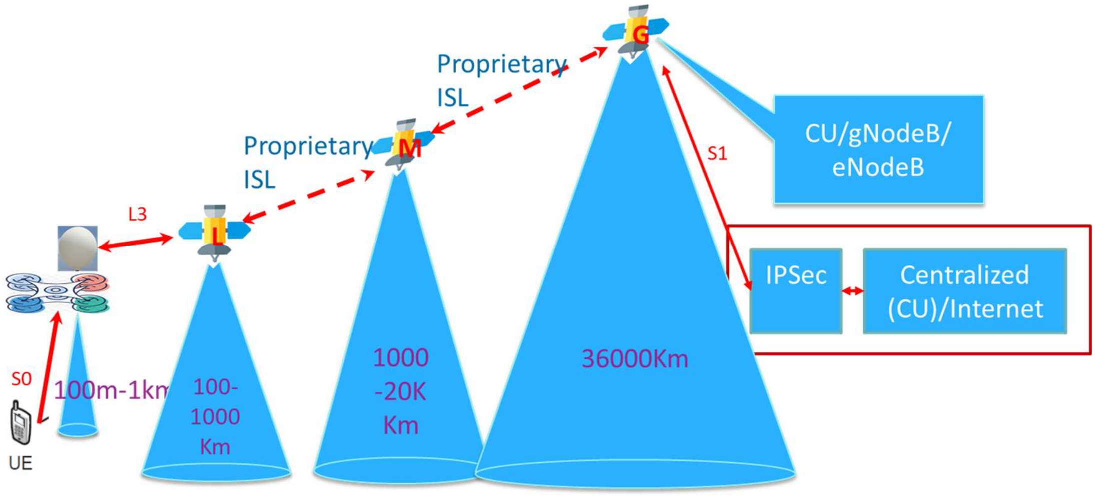


*Figure 41. Direct Access Use Case 1.g for Non-Federated Service Providers*

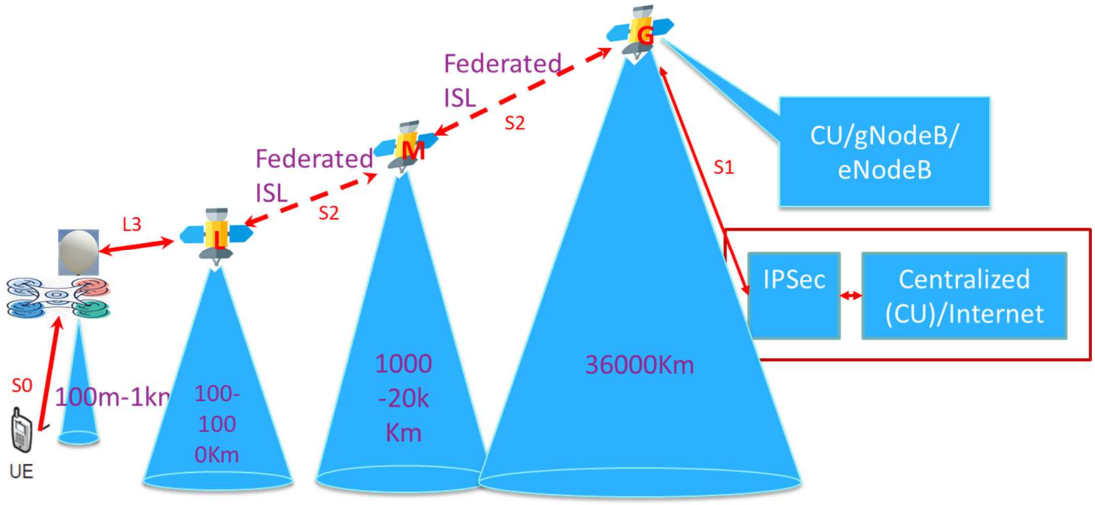


*Figure 42. Direct Access Use Case-1.g for Federated Service Providers*

### 6.2.8. Direct Access Use Case-1.h: UE to LAP → LEO → MEO → HEO → gNodeB (Non-Federated and Federated Cases)

Direct Access Use Case-1.h is similar to Direct Access Use Case-1.g. Instead of GEO satellite, HEO satellite is the last communication point between UE and CU. The interfaces are the same for non-federated and federated cases as the Direct Access Use Case-1.g. HEO satellites can be used opportunistically to reduce the latency between user UE and gNodeB / eNodeB / CU when the orbital distance is lower than the GEO satellites. Opportunistic networking aided by appropriate software-defined routing, such as that used in case [15], can be adopted in such cases with performance benefits. Figure 43 illustrates Direct Access Use Case-1.h.

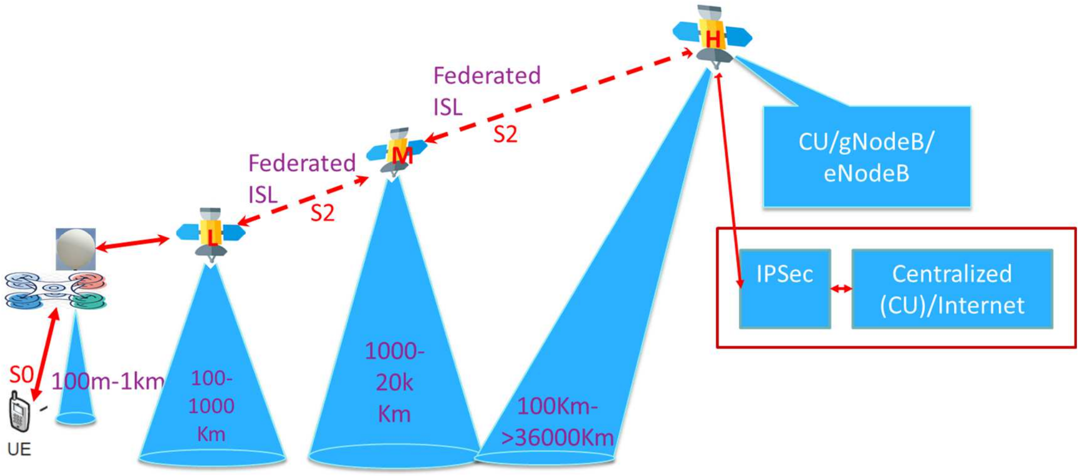


*Figure 43. Direct Access Use Case 1.h where HEO Satellites are Utilized in an Opportunistic Manner*

### 6.2.9. Direct Access Use Case-2.a: UE to HAP → gNodeB

In the Direct Access Use Case-2.a, the communication between UE and CU will be carried out through a single HAP that operates in a bent-pipe mode or 1-hop relay with regeneration capability. Further, HAPs have all the functions of a CU / eNodeB / gNodeB. The interface used for UE and HAP communication is defined as S0. Interface S1 defines the communication between HAP and CU. Figure 44 illustrates Direct Access Use Case-2.a.

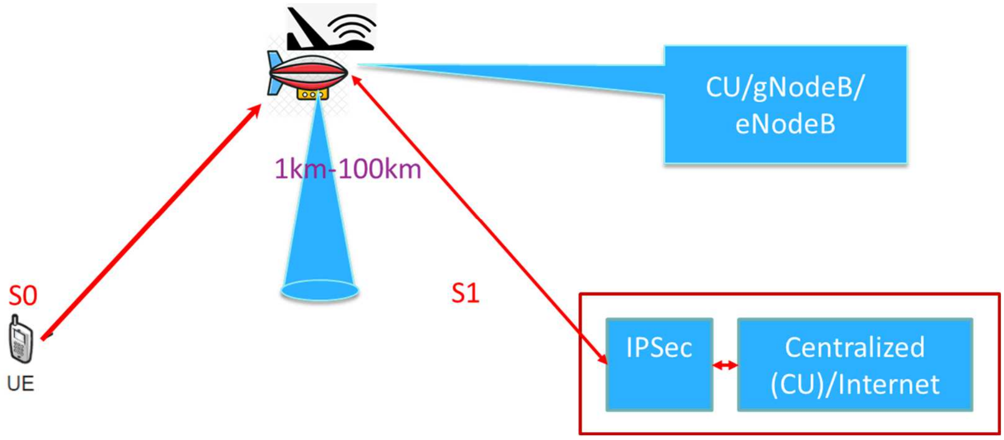


*Figure 44. Direct Access Use Case-2.a*

### 6.2.10. Direct Access Use Case-2.b: UE to HAP → HAP → gNodeB

In the Direct Access Use Case-2.b, the communication between UE and CU will be carried out through multiple HAPs that operate in a bent-pipe mode or with regeneration capability. The UE communicates with the CU through multiple HAP nodes. Further, HAPs include all the functions of an eNodeB / gNodeB. Both the HAP nodes can be non-federated or federated, where proprietary Inter HAP Link (IHL) and federated IHL are used for communications. The interface used for UE and HAP communication is denoted as S0. Interface S1 defines the communication between HAP and CU. Figure 45 and Figure 46 illustrate Direct Access Use Case-2.b for non-federated and federated cases.

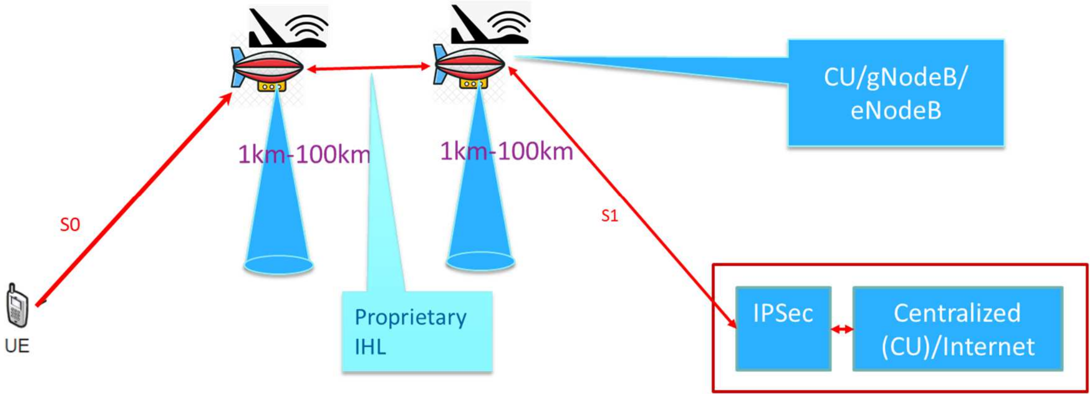


*Figure 45. Direct Access Use Case-2.b for Non-Federated Case*

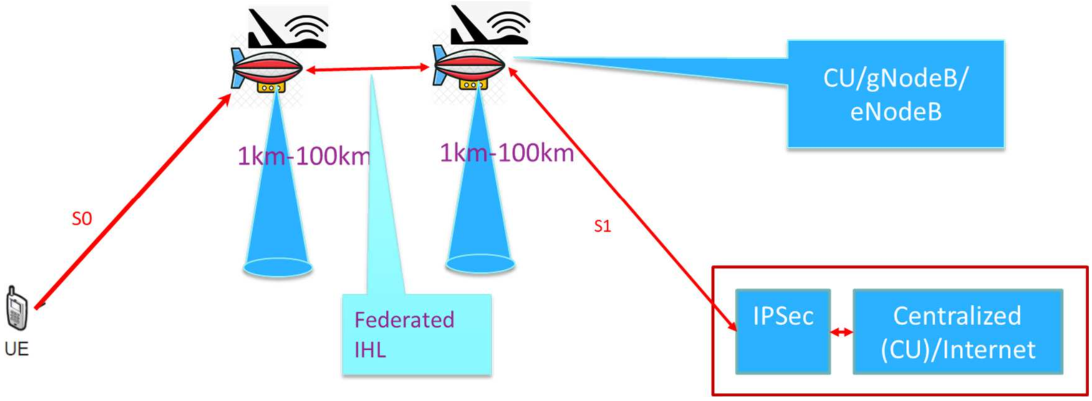


*Figure 46. Direct Access Use Case-2.b for Federated Case*

### 6.2.11. Direct Access Use Case-2.c: UE to HAP → LEO → gNodeB

In the Direct Access Use Case-2.c, the communication between UE and CU can be carried out through HAP and LEO that operate in a bent-pipe mode or with regeneration capability. The HAP and LEO nodes can belong to the same service provider (non-ice federated) or a different service provider (federated case). The L3 interface is used to communicate between HAP and LEO. Further, the HAP and LEO nodes include all the functions of an eNodeB / gNodeB. The interface used for UE and LAP communication is defined as S0. Interface S1 defines the communication between LEO and CU. Figure 47 illustrates the Direct Access Use Case-2.c.

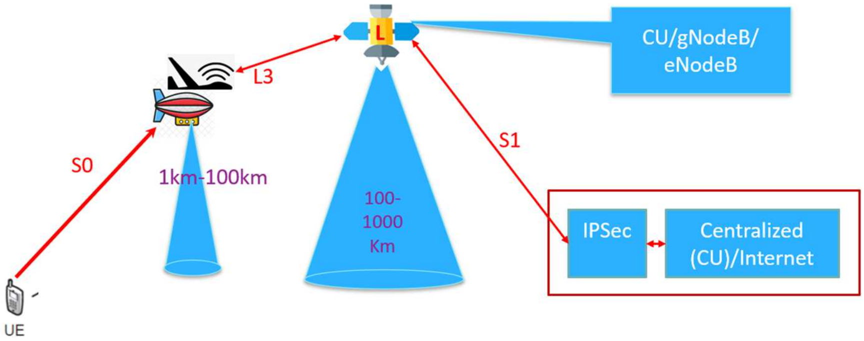


*Figure 47. Direct Access Use Case-2.c*

### 6.2.12. Direct Access Use Case-2.d: UE to HAP → LEO → MEO → gNodeB (Non-Federated and Federated Cases)

In the Direct Access Use Case-2.d, the communication between UE and CU will be carried out through HAP, LEO, and MEO, respectively. All the nodes operate in a bent-pipe mode or with regeneration capability. The LEO and MEO can belong to the same service provider (non-federated) or different service providers (federated case). In the case of non-federated, proprietary ISL is used to communicate, whereas in the federated case, S2 (federated ISL) interface is used to communicate between LEO and MEO. Further, we assume that HAP, LEO, and MEO nodes have all the functions of a CU / eNodeB / gNodeB. The interface used for UE and HAP communication is denoted as S0. Interface S1 defines the communication between MEO and CU. L3 is the interface used between HAP and LEO.

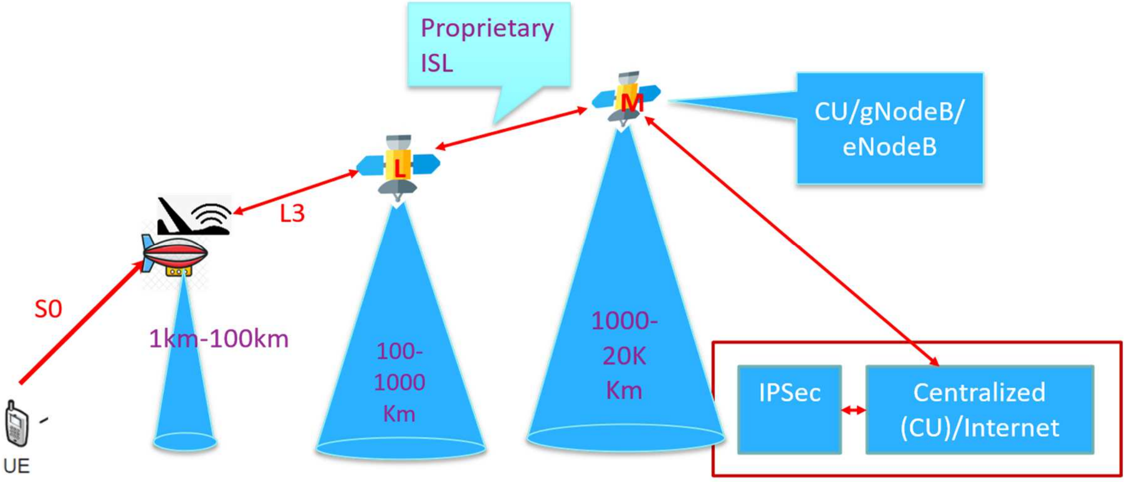


Fig. 1.

Figure 48 and Figure 49 illustrate the Direct Access Use Case-2.d for the non-federated and federated cases.

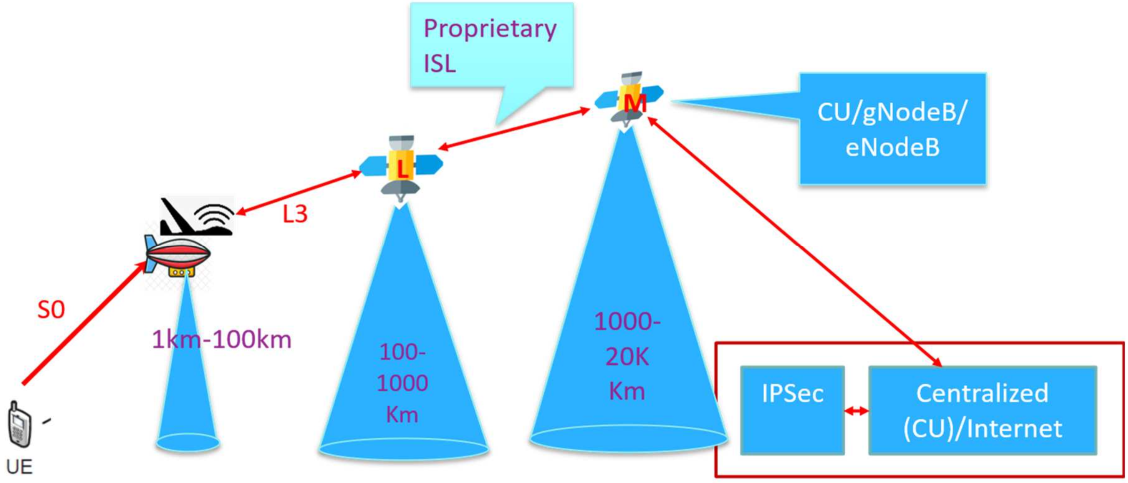


*Figure 48. Direct Access Use Case-2.d for the Non-Federated Case*

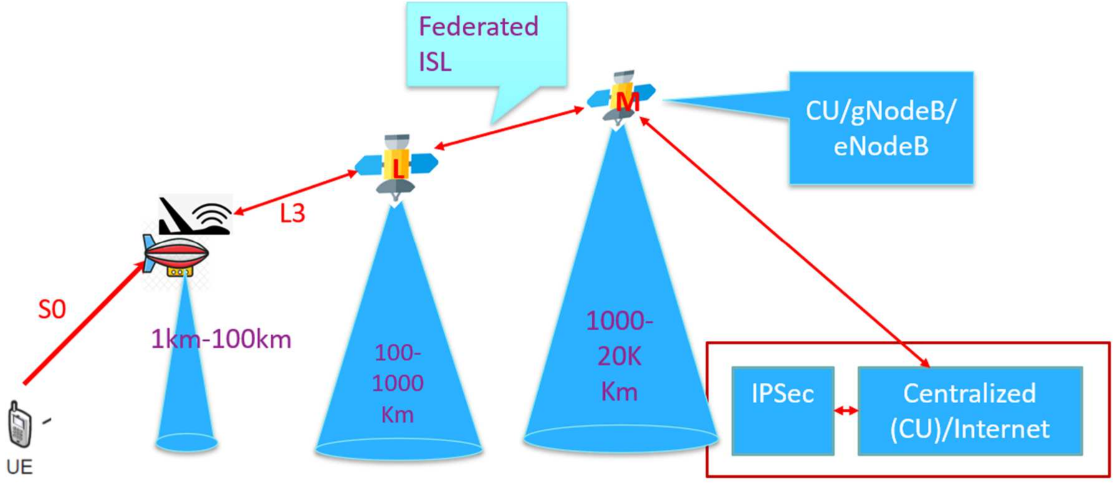


*Figure 49. Direct Access Use Case-2.d for Federated Case*

### 6.2.13. Direct Access Use Case-2.e: UE to HAP → MEO → gNodeB

In the Direct Access Use Case-2.e, the communication between UE and CU will be carried out through HAP and MEO nodes that operate in a bent-pipe mode or with regeneration capability. The HAP and MEO nodes can belong to the same service provider (non-federated) or different service providers (federated case). The L4 interface is used to communicate between HAP and MEO. Further, the HAP and MEO nodes include all the functions of an eNodeB / gNodeB. The interface used for UE and HAP communication is denoted as S0. Interface S1 defines the communication between MEO and CU.

### 6.2.14. Direct Access Use Case-2.f: UE to HAP → LEO → MEO → GEO → gNodeB (Non-Federated and Federated Cases)

In Direct Access Use Case-2.f, the communication between UE and CU will be carried out through HAP, LEO, MEO, and GEO, respectively. All the nodes operate in a bent-pipe mode or with regeneration capability. The LEO, MEO, and GEO can belong to the same service provider (non-federated) or a different service provider (federated case). In the case of non-federated systems, proprietary ISL is used to communicate between LEO, MEO, and GEO, whereas, in the case of federated systems, S2 (federated ISL) interface is used to communicate between LEO, MEO, and GEO. Further, the HAP, LEO, MEO, and GEO nodes include all the functions of an eNodeB / gNodeB. The interface used for UE and HAP communication is denoted as S0. Interface S1 defines the communication between GEO and CU. Figure 50 and Figure 51 illustrate the Direct Access Use Case-2.f for the non-federated and federated cases, respectively.

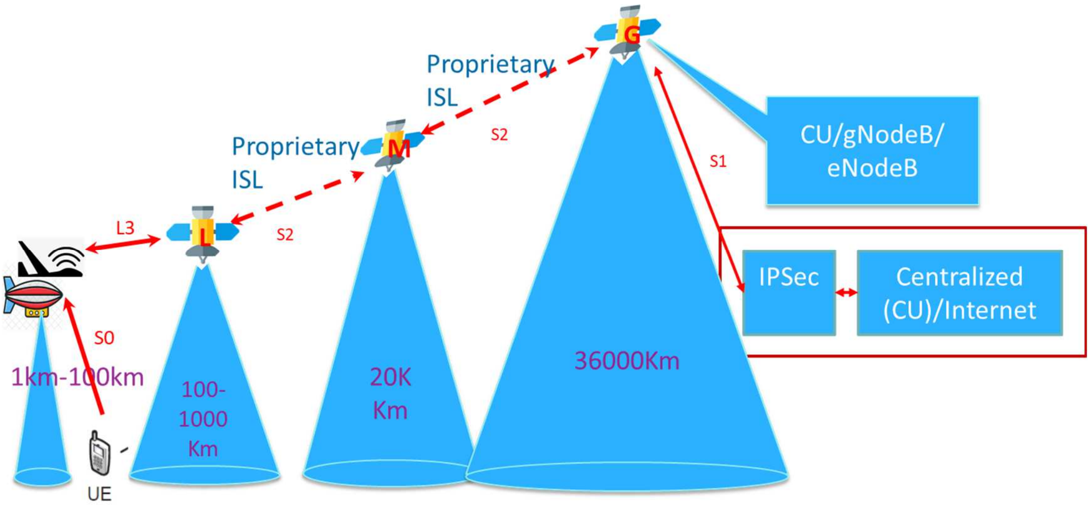


*Figure 50. Direct Access Use Case-2.f for Non-Federated Case*

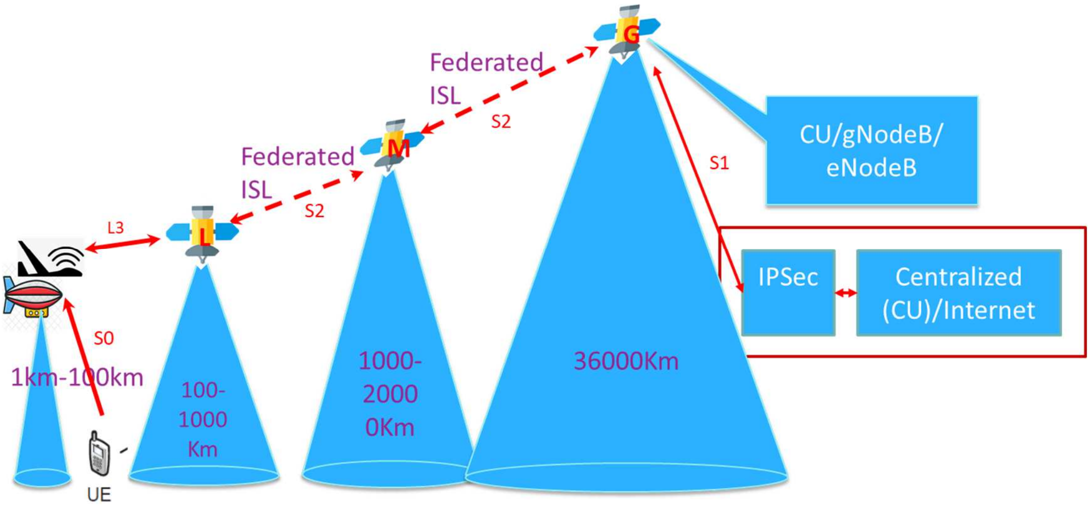


*Figure 51. Direct Access Use Case-2.f for Federated Case*

### 6.2.15. Direct Access Use Case-2.g: UE to HAP → LEO → MEO → HEO → gNodeB (Non-Federated and Federated Cases)

In Direct Access Use Case-2.g, similar to using Direct Access Use Case-1.f, instead of the GEO satellite, the HEO satellite is the last communication point between UE and CU. The interfaces are appropriately modified for non-federated and federated cases as the Direct Access Use Case-2.f. Figure 52 illustrates Direct Access Use Case-2.g.

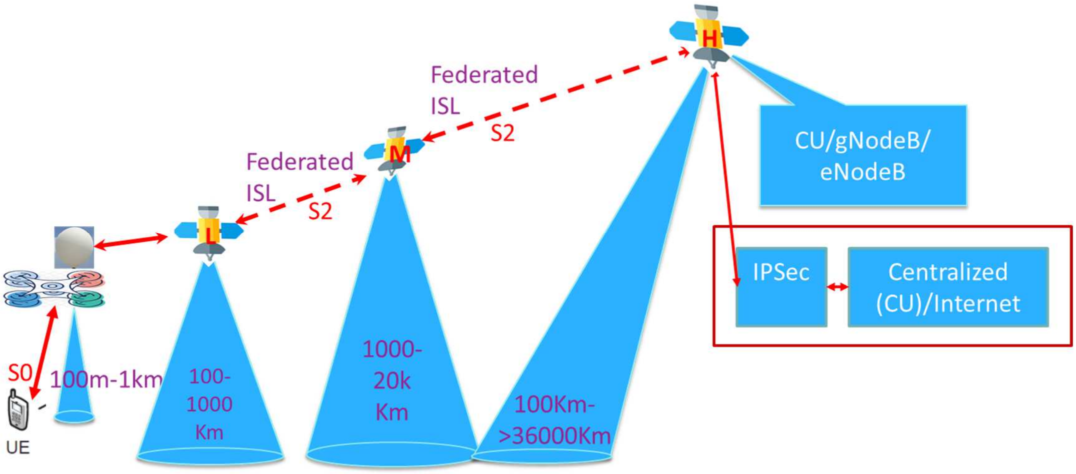


*Figure 52. Direct Access Use Case-2.g.*

### 6.2.16. Direct Access Use Case-3.a: UE to LEO → gNodeB

In Direct Access Use Case-3.a, the communication between the UE and CU will be carried out through a single LEO satellite that operates in a bent-pipe mode or 1-hop relay with regeneration capability. Further, we assume that LEO has all the functions of an eNodeB / gNodeB. The interface used for UE and LEO communication is denoted as S0. Interface S1 defines the communication between LEO and CU. Figure 53 illustrates Direct Access Use Case-3.a.

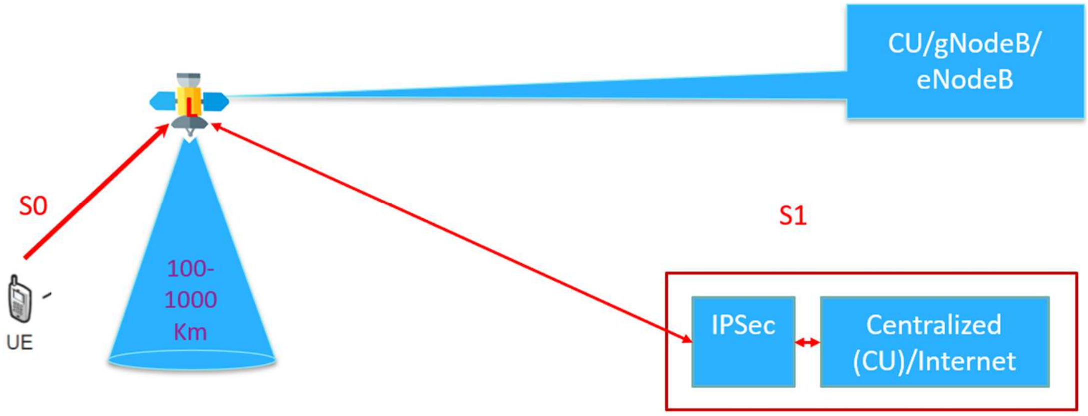


*Figure 53. Direct Access Use Case-3.a*

### 6.2.17. Direct Access Use Case-3.b: UE to LEO → LEO → gNodeB (Non-Federated and Federated Cases)

In Direct Access Use Case-3.b, the communication between UE and CU will be carried out through multiple LEO satellites that operate in a bent-pipe mode or with regeneration capability. Further, we assume that LEO satellites have all the functions of an eNodeB / gNodeB. The multiple LEO satellites can be non-federated or federated, where proprietary ISL and federated ISL are used for communication, respectively. The interface used for UE and LEO communication is denoted as S0. Interface S1 defines the communication between LEO and CU. Figure 54 and Figure 55 illustrate Direct Access Use Case-3.b, for non-federated and federated cases, respectively.

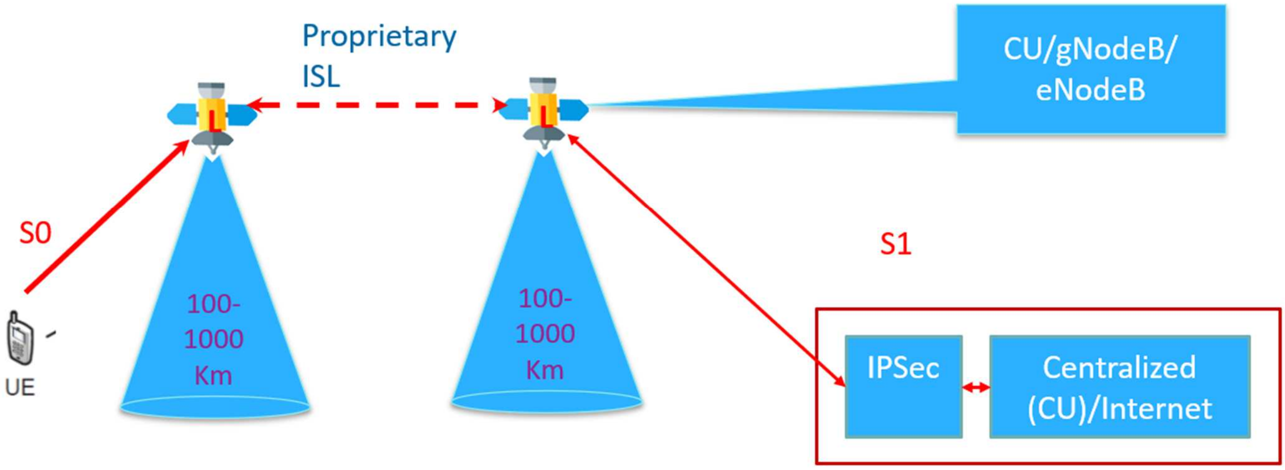


*Figure 54. Direct Access Use Case-3.b for Non-Federated Case*

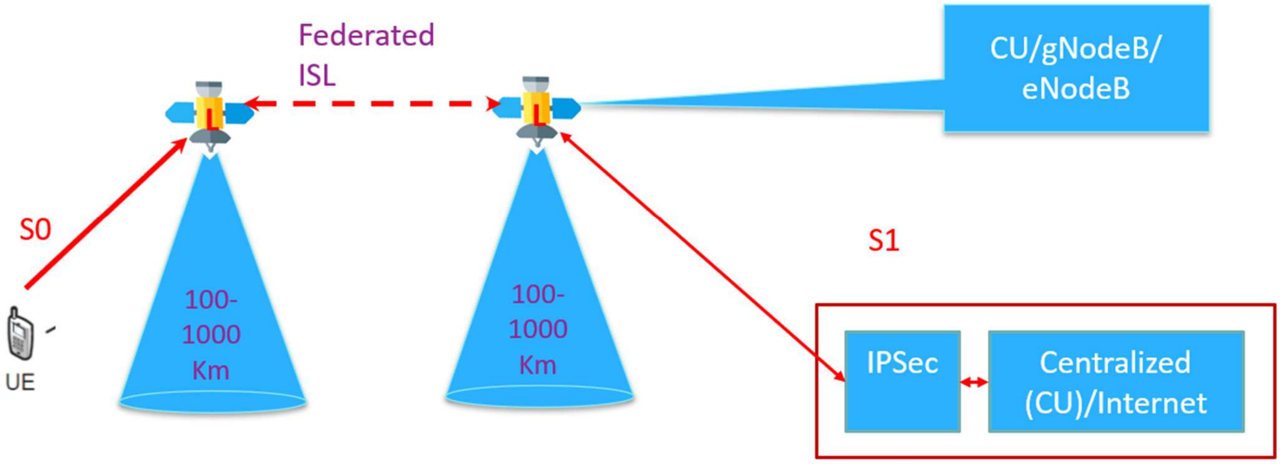


*Figure 55. Direct Access Use Case-3.b for Federated Case*

### 6.2.18. Direct Access Use Case-3.c: UE to MEO → gNodeB

In Direct Access Use Case-3.c, the communication between UE and CU will be carried out through LEO and MEO that operate in a bent-pipe mode or with regeneration capability. Further, a new case is defined where UE can directly communicate with MEO in one hop distance. The MEO and LEO nodes belong to the same company (non-federated). Further, we assume that MEO and LEO nodes have all the functions of an eNodeB / gNodeB. The interface used for UE and LEO communication is denoted as S0. Interface S1 defines the communication between MEO and CU. Figure 56 and Figure 57 illustrate the two Direct Access Use Case-3.c cases.

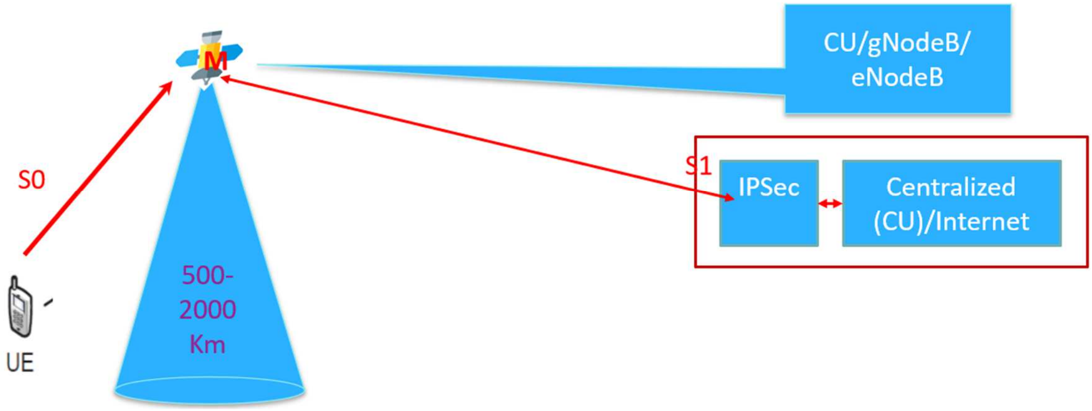


*Figure 56. Direct Access Use Case-3.c for Direct UE to MEO Communication*

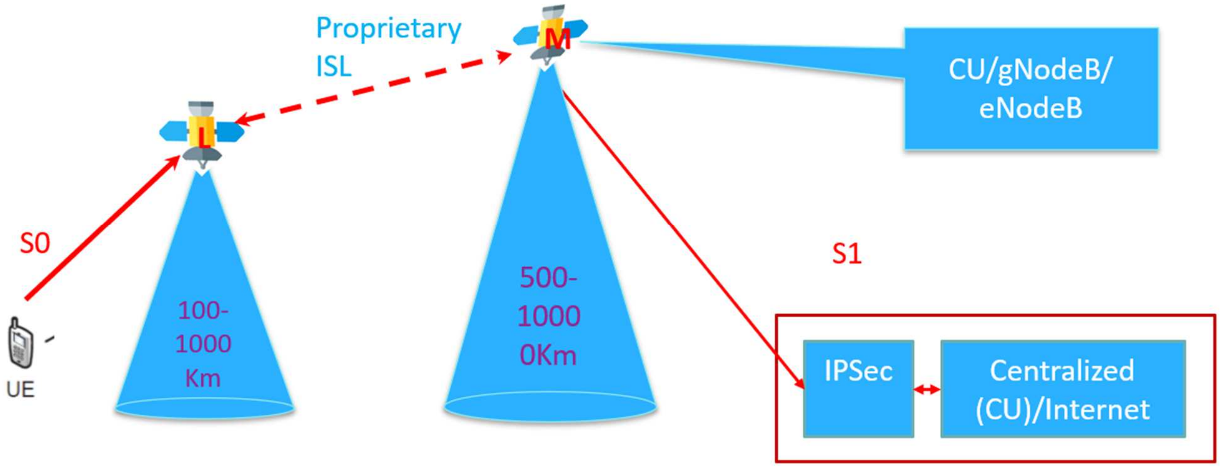


*Figure 57. Direct Access Use Case-3.c for Non-Federated Case with LEO and LEO ISL*

### 6.2.19. Direct Access Use Case-3.d: UE to LEO → MEO → gNodeB (Non-Federated and Federated Cases)

Direct Access Use Case-3.d is similar to Direct Access Use case-3.c. However, MEO and LEO nodes belong to different companies (federated). The assumption is the same as Direct Access Use Case-3.c. Figure 58 illustrates the Direct Access Use Case-3.d for the federated case with LEO and LEO ISLs.

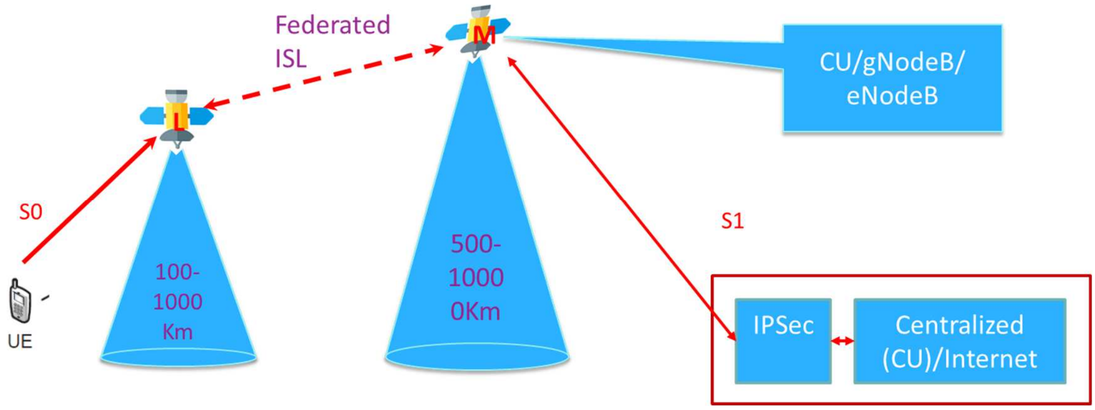


*Figure 58. Direct Access Use Case-3.d for Federated Case with LEO and LEO ISL*

### 6.2.20. Direct Access Use Case-3.e: UE to MEO → MEO → gNodeB (Non-Federated and Federated Cases)

In Direct Access Use Case-3.e, the communication between UE and CU will be carried out through multiple MEO satellites that operate in a bent-pipe mode or with regeneration capability. Further, we assume that MEO satellites have all the functions of an eNodeB / gNodeB. The multiple MEO satellites can be non-federated or federated, where proprietary ISL and federated ISL are used for communication, respectively. The interface used for UE and MEO communication is denoted as S0. Interface S1 defines the communication between MEO and CU. Figure 59 and Figure 60 illustrate the Direct Access Use Case-3.e for the non-federated and federated cases, respectively.

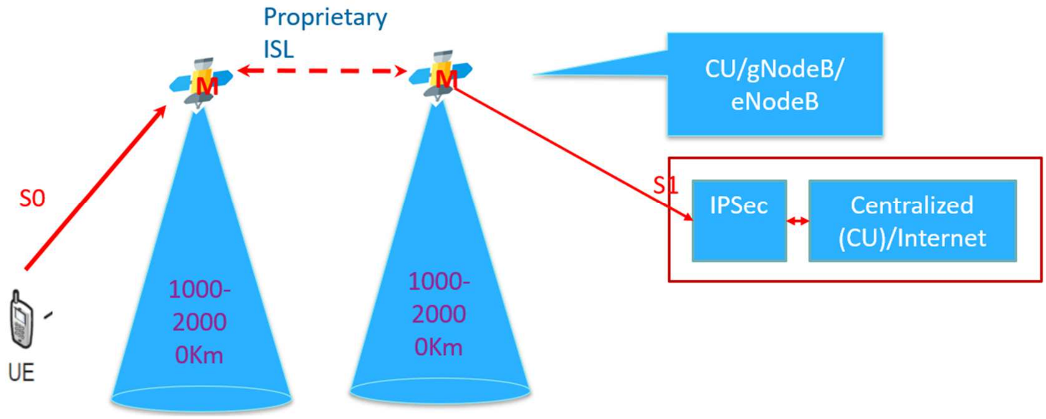


*Figure 59. Direct Access Use Case-3.b for the Non-Federated Case*

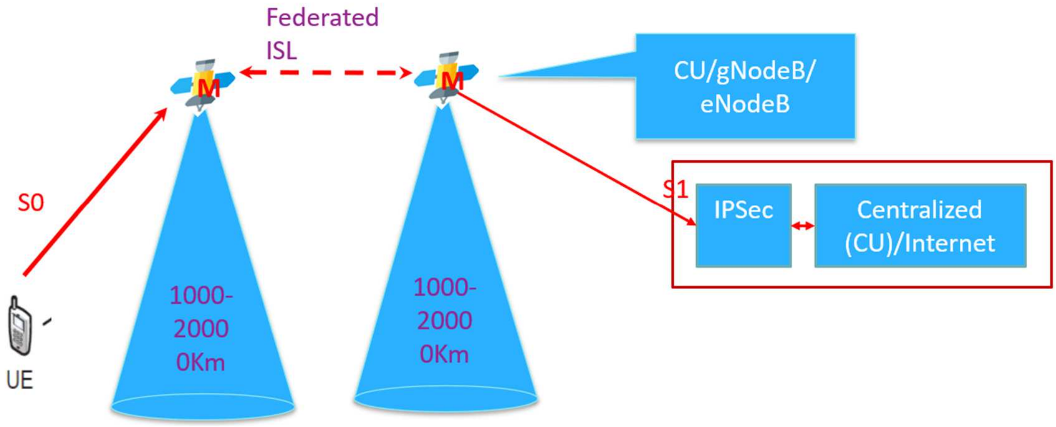


*Figure 60. Direct Access Use Case-3.b for the Non-Federated Case*

### 6.2.21. Direct Access Use Case-3.f: UE to GEO → gNodeB

In Direct Access Use Case-3.f, the communication between UE and CU will be carried out through a single GEO satellite that operates in a bent-pipe mode or 1-hop relay with regeneration capability. Further, we assume that the GEO satellite has all the functions of an eNodeB / gNodeB. The interface used for UE and GEO communications is denoted as S0. Interface S1 defines the communication between GEO and CU. Figure 61 illustrates the Direct Access Use Case-3.f.

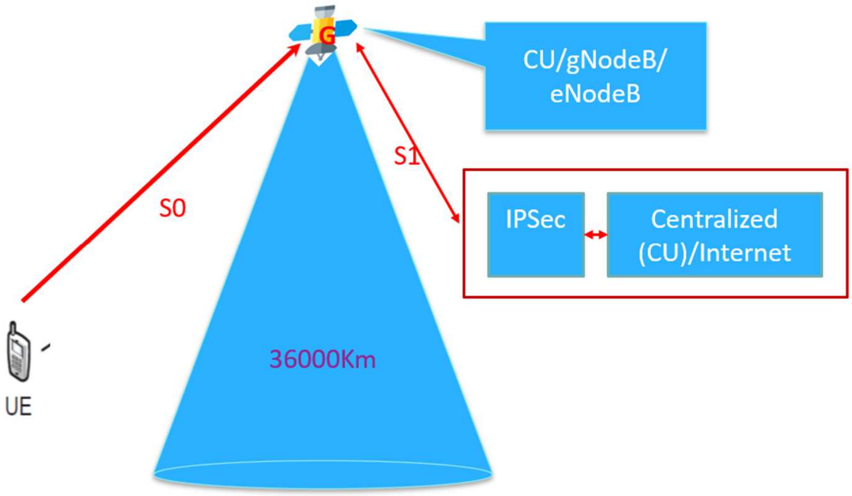


*Figure 61. Direct Access Use Case-3.f*

### 6.2.22. Direct Access Use Case-3.g: UE to LEO → MEO → GEO → gNodeB (Non-Federated and Federated Cases)

In Direct Access Use Case-3.g, UE and CU will communicate through LEO, MEO, and GEO, respectively. All the nodes operate in a bent-pipe mode or with regeneration capability. The LEO, MEO, and GEO can belong to the same company (non-federated) or different companies (federated case). In the case of non-federated systems, proprietary ISL is used to communicate between LEO, MEO, and GEO, whereas, as in the case of federated, S2 (federated ISL) interface is used to communicate between LEO, MEO, and GEO. Further, we assume that LEO, MEO, and GEO nodes have all the functions of an eNodeB / gNodeB. The interface used for UE and LEO communication is denoted as S0. Interface S1 defines the communication between GEO and CU. Figure 62 and Figure 63 illustrate Direct Access Use Case-3.g for the non-federated and federated cases, respectively.

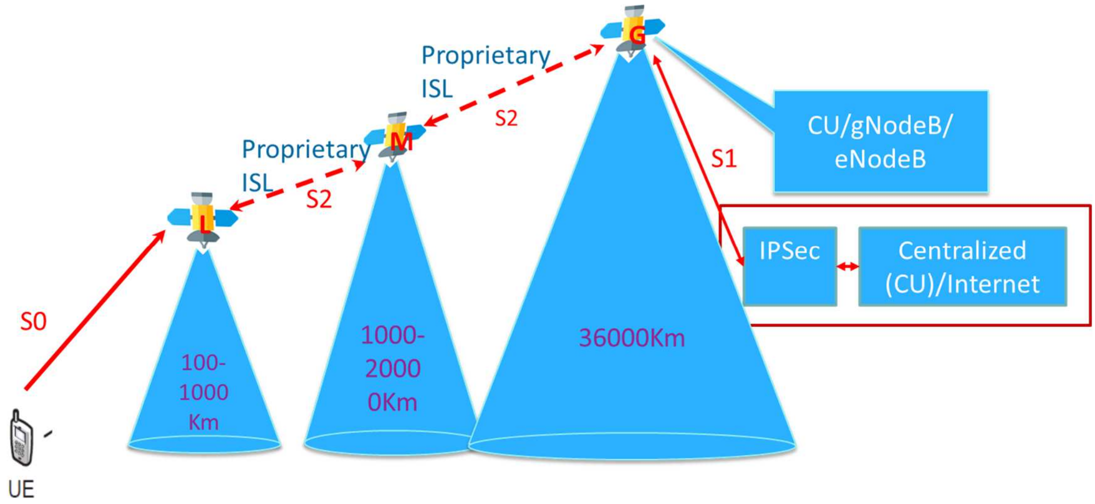


*Figure 62. Direct Access Use Case-3.g for the Non-Federated Case*

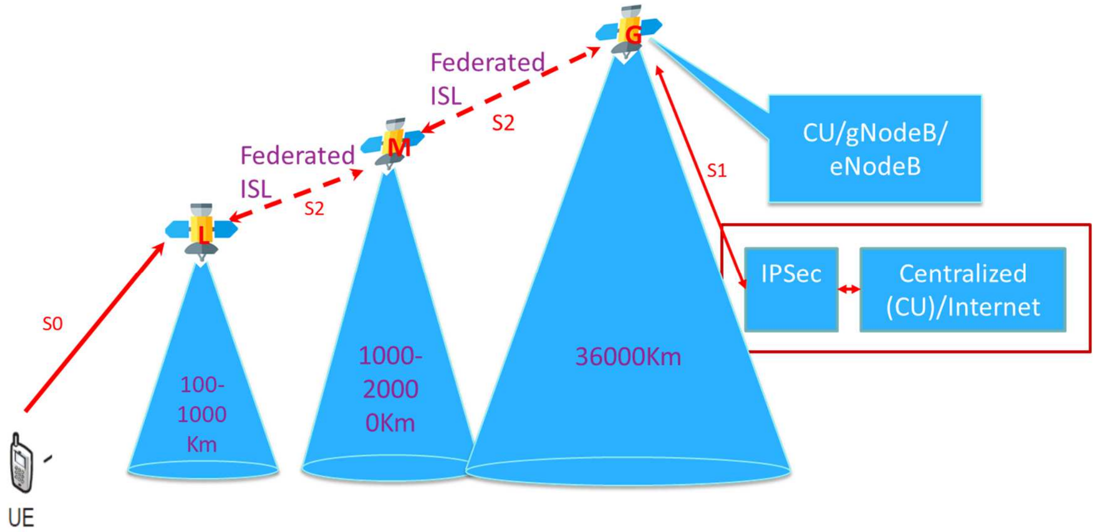


*Figure 63. Direct Access Use Case-3.g for the Federated Case*

## 6.3. Use Cases for Satellite IoT

The study under this section of the report considers the LEO non-terrestrial networks for providing services to IoT user equipment under the following physical layer reference scenarios [123]:

- Constellation of low earth orbit satellites orbiting scenarios
- Circular orbit around the earth, having a typical beam footprint of 100-1000 km.
- Transparent or regenerative payload

- No inter-satellite links
- Fixed or movable beams (moving or fixed footprint on the ground)
- Below 6 GHz frequency band
- Direct or indirect access network (indirect access via a terrestrial gateway or HAPs).

Based on the above considerations, the following reference scenarios can be formulated:

*Table 70. Satellite-IoT Physical Layer Reference Scenarios*

| ***Satellite-IoT Physical Layer Scenario*** | ***Configuration*** |
|---|---|
| **Scenario A** | LEO satellite constellation-based direct access network with fixed beams and transparent payload (amplify-and-forward) |
| **Scenario B** | LEO satellite constellation-based direct access network with fixed beams and regenerative payload (decode-and-forward) |
| **Scenario C** | LEO satellite constellation-based direct access network with steerable beams and transparent payload (amplify-and-forward) |
| **Scenario D** | LEO satellite constellation-based direct access network with steerable beams and regenerative payload (decode-and-forward) |
| **Scenario E** | LEO satellite constellation-based indirect access network supported via a terrestrial gateway with steerable beams and transparent payload (amplify-and-forward) |
| **Scenario F** | LEO satellite constellation-based indirect access network supported via HAPS with steerable beams and transparent payload (amplify-and-forward) |

Table 71 provides the reference parameters for the physical layer scenarios in Table 70.

*Table 71. Reference Parameters for Satellite-IoT Physical Layer Scenarios*

| ***Parameter*** | ***Value*** |
|---|---|
| **Frequency Range** | Sub 6 GHz |
| **Orbit** | LEO |
| **Altitude** | 600 – 1200 km |
| **Payload Type** | Transparent (amplify-and-forward) or Regenerative (decode-and-forward) |
| **Minimum Elevation** | 10° |
| **Maximum Footprint** | 1000 km |
| **End-to-End Delay** | 26 ms for 600 km and 42 ms for 1200 km altitude |
| **Maximum Doppler Shift** | 24 ppm for 600 km and 21 ppm for 1200 km altitude |
| **Device Maximum Tx Power** | 20 dBm to 23 dBm |
| **Experience Data Rate** | 2 kbps (DL) and 10 kbps (UL) |
| **Bandwidth** | 125 kHz – 500 kHz |
| **Device Density** | 400/km$^2$ |

Table 72 describes the application / use-case scenarios for satellite-IoT applications.

*Table 72. Application / Use-Case for Satellite IoT*

| ***Application / Use-Cases*** | ***Applicable Physical Layer Reference Scenarios*** |
|---|---|
| A dense network of rural and urban air quality monitoring | Scenarios A, B, C, D, E |
| Railway track condition monitoring | Scenarios A, B, C, D |
| Crowd monitoring for large gathering at open areas, stadiums, and sports events | Scenarios E, F |
| Smart agriculture applications – monitoring and actuation | Scenarios C, D, F |
| Intrusion detection or emergency (SOS) reporting | Scenarios B, D, F |

The physical layer reference architecture scenarios for satellite-IoT communications are presented in the following sub-sections.

### 6.3.1. Topology for Physical Layer Reference Scenario A

Scenario A considers LEO satellite-based constellation with multiple fixed-beam satellites in the visible range for direct access from IoT devices *(see Figure 64)*. It is suitable for large deployments of IoT networks with no scope for terrestrial gateways and applications that can withstand reasonable latencies and outages (e.g., weather monitoring). A transparent payload (amplify and forward) is assumed.

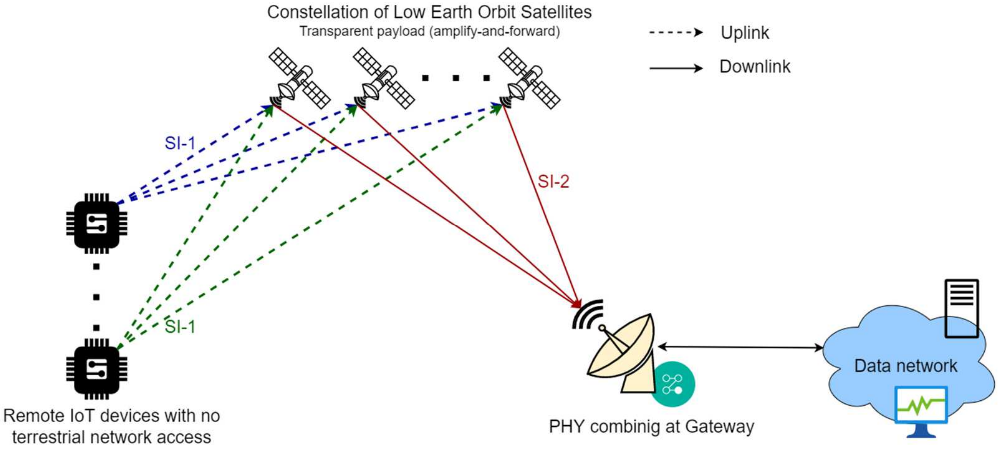


*Figure 64. Physical Layer Reference Scenario A (Direct Access, Transparent Payload)*

### 6.3.2. Topology for Physical Layer Reference Scenario B

Scenario B considers LEO satellites-based constellation with multiple fixed beam satellites in the visible range for direct access from IoT devices *(see Figure 65)*. It is suitable for large deployments of IoT networks with no scope for terrestrial gateways and applications that require greater immunity towards propagating transmission errors. A regenerative payload (decode-and-forward) is assumed.

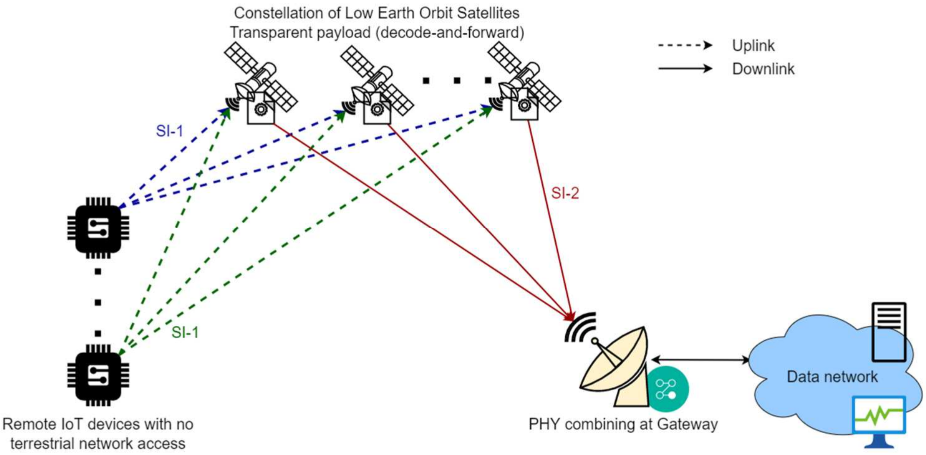


*Figure 65. Physical Layer Reference Scenario B (Direct Access, Regenerative Payload)*

### 6.3.3. Topology for Physical Layer Reference Scenario C

This Scenario C is like the topology for reference Scenario A (LEO satellite constellation-based direct access network and transparent payload) but with steerable beams.

### 6.3.4. Topology for Physical Layer Reference Scenario D

This Scenario D is like the topology for reference Scenario B (LEO satellite constellation-based direct access network and regenerative payload) but with steerable beams.

### 6.3.5. Topology for Physical Layer Reference Scenario E

Scenario E considers LEO satellites-based constellation with multiple steerable beam satellites in the visible range for IoT access via a terrestrial gateway; see Figure 66. It is suitable for IoT deployments with the feasibility of establishing terrestrial gateways and applications which require lesser latency and outages (e.g., real-time crowd monitoring in large gatherings or sports events). A transparent payload (amplify-and-forward) is assumed for this scenario.

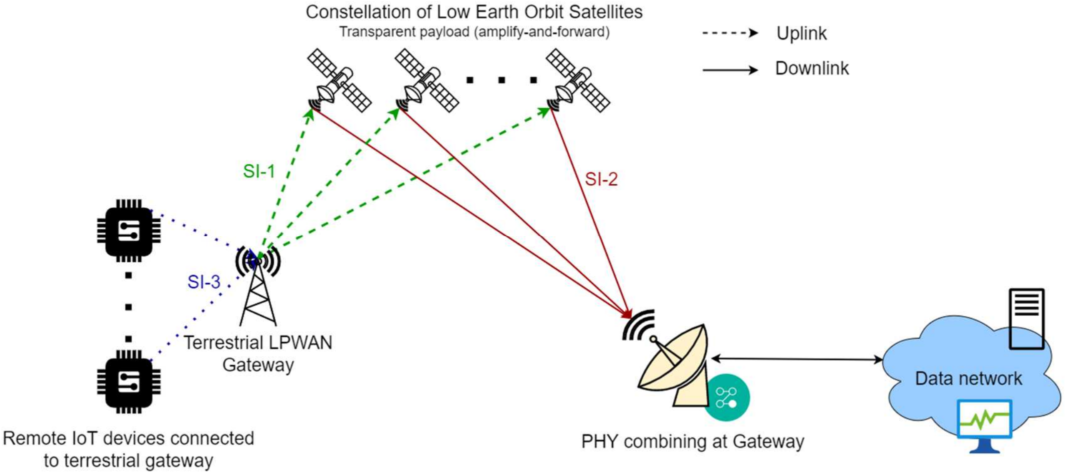


*Figure 66. Physical Layer Reference Scenario E (Indirect Access, Terrestrial Gateway, Transparent Payload)*

### 6.3.6. Topology for Physical Layer Reference Scenario F

Scenario F considers LEO satellites-based constellation with multiple steerable beam satellites in the visible range for IoT access via HAPS; see Figure 67. A transparent payload (amplify-and-forward) is assumed for this scenario. It is suitable for IoT deployments with the feasibility of coverage via drones / balloon facilities / HAPS in a limited area. It can benefit applications like crowd monitoring, smart agriculture, and intrusion detection.

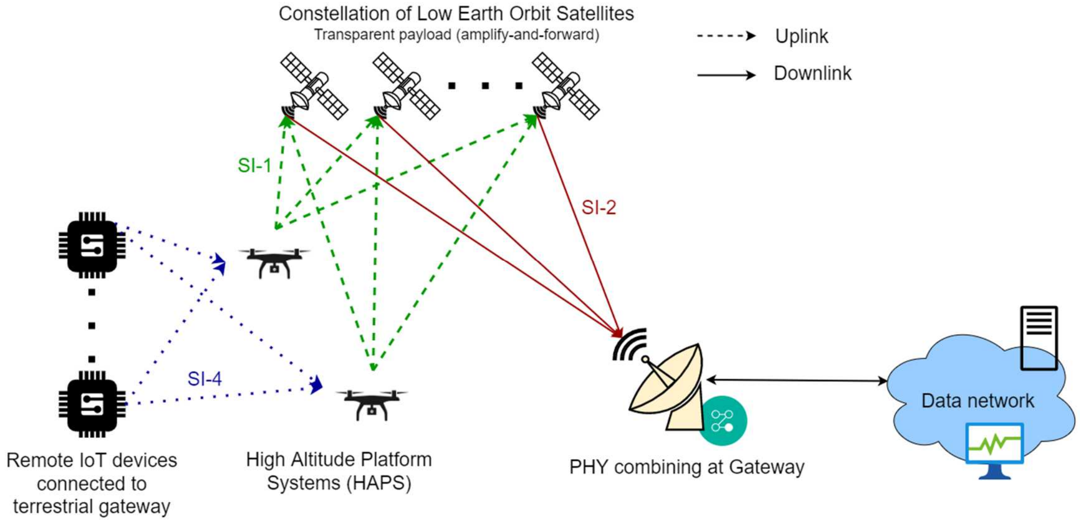


*Figure 67. Physical Layer Reference Scenario F (Indirect Access, with HAPS, Transparent Payload)*

## 6.4. Other Use Cases

Recent studies estimate that about 37% of the world's population still lacks high-speed internet access. Terrestrial networks cannot guarantee access to the internet to passengers on planes or high-speed trains, highways, and ships. However, the NTN nodes such as GEO / MEO / LEO satellites, HAPs, and UAVs can help access the internet in remote and rural areas.

While no radically new services and applications are envisaged explicitly for satellite 6G, possible areas concern vehicular communications, IoT for remote areas (agriculture, energy, and transportation), and tactile internet. Table 1 discusses the 6G verticals, drivers, and enablers. Some innovative satellite-based services are detailed in the next two sections. Table 4 explains the QoS requirements of 5G vs. 6G.

### 6.4.1. Space-Based Hosting Service (SBHS)

Traditionally, satellites are employed for broadcasting purposes. This report's first Edition considered only the satellite for back-haul purposes. However, the 2022 and 2023 Editions of the satellite roadmap focus on satellites as an access network as well and emphasize the impact of satellite broadband internet on rural and remote areas around the world with the help of the next-generation mega satellite constellations. In "A Novel Space-Based Hosting Approach for Ultra Low Latency Web Services" [124], a Space-Based Hosting Service (SBHS) approach to deploying content-server in space in LEO and GEO satellites was proposed. The new communication technologies, including 4G LTE and 5G, are not accessible in remote rural areas due to a lack of infrastructure deployment. Therefore, LEO satellite-based satellite broadband can play a vital role in connecting the digitally unconnected population by utilizing the emerging application area of SBHS.

The SBHS approach [124] suggests hosting the entire set of content servers in the LEO satellites. With the increase in the number of LEO satellites in space, the coverage of the proposed service increases. The center server placed in the satellite network stores the contents, such as multimedia files, articles, and web pages. The work is based on a dedicated satellite hosting service where the whole server provides Web services to ground-based end-users. Mathematical models concerning the computational delay and computational energy consumption are provided. Further, the authors designed an optimization algorithm for the LEO satellite queue using Markov Decision Process (MDP) to optimize queuing delay and computational energy consumption. The transmission energy required to establish the communication is analyzed through link budget analysis. The link budget analysis showed the feasibility of hosting a content server in a LEO satellite.

Using the SBHS approach, an entire English Wikipedia server is placed, as a case study, in the LEO satellites of the Iridium-NEXT satellite constellation. The simulation results showed the feasibility of hosting a content server in space and achieving ultra-low latency compared to traditional satellite-based Web services. Further, the simulation study achieved ultra-low latencies for different countries to reduce the digital divide around the world.

### 6.4.2. LEO Satellite-Based IoT Services

IoT is one of the important applications of 6G-satellite integration. Due to the large number of IoT devices, trillions of them requiring low latency, LEO satellites are particularly attractive for their services. Section 6.3 details the physical layer reference scenarios of satellite-based IoT services.

## 7. EXTERNAL OPPORTUNITIES

Potential external entities, active working groups, and conferences related to the activities of the satellite workgroup are listed below:

- Networldeurope EU platform (https://www.networldeurope.eu/)
- EU projects like 5G-STARDUST (https://www.5g-stardust.eu/), TRANTOR (https://www.trantor-he.eu/), etc.
- ESA 5G/6G hub (https://artes.esa.int/esa-5g6g-hub)
- 6G for Connected Sky (6G-SKY) project under the CELTIC-NEXT program (https://www.celticnext.eu/project-6g-sky/)
- IEEE Conferences like VTC, Globecom, ICC, Future Networks World Forum, etc.
- IEEE Low-Earth-Orbit (LEO) Satellites & Systems project (https://cmte.ieee.org/futuredirections/projects/leo-satellites-systems/)
- Consultative Committee for Space Data Systems (https://public.ccsds.org/)
- Internet Engineering Task Force (https://www.ietf.org/).

# 8. STANDARDIZATION LANDSCAPE AND VISION

## 8.1. Interaction with Standardization WG

The Satellite Working Group successfully interacted with Standards Working Group, and the following results have been identified. These topics need to be followed up to help the satellite industry in providing guidance in developing the new 5G/6G satellite systems.

1. **Reference Architectures:**

   The challenges for reference architecture include virtualized satellite networks, separately virtualized and integrated 5G, and satellite network architectures that must be further developed.

2. **QoS / QoE:**

   New QoS architecture to be developed to meet the new application-specific requirements.

3. **Edge Intelligence:**

   There is a need for a study leading to MEC standardization for NTN by 2025. Important aspects to be addressed are the scenario to be considered, reference services, the proposal for an integrated MEC-NTN architecture, overall impact of NTN peculiarities on MEC functionalities. In a broad sense, MEC-NTN will support AI techniques and deep learning approaches that will be crucial to optimize system performance and the achieved KPIs.

## 8.2. Landscape

Several mega-constellations, i.e., thousands of LEO satellites, are planned and are being designed. O3b / MEO system has already been providing services for COVID-19 health services in Peru and e-learning in Colombia. SpaceX is providing services in many parts of the world while deploying further satellites. 3GPP has frozen Release 17 and is working on Releases 18 and 19, specifically NTNs, among other standards bodies. IEEE has been developing standards for drones. The standards development is essential for successful system deployment and operations. The IEEE 5G Satellite Working Group standardization vision includes the following:

- Spectrum sharing – interference & regulation
- World-Radio Conference (WRC-19) decisions
- World Radio Conference (WRC-23) items
- Architectures and multilayer protocols and QoS framework
- Liaise with 3GPP Non-Terrestrial Network architectures, mobility management, resource management, and 5G Satellite access studies
- Continue the development of NTN, especially standards for UAV communications.

# 9. CONCLUSIONS AND RECOMMENDATIONS

## 9.1. Summary of Conclusions

5G is a new terrestrial wireless system standard designed for providing services in different contexts with unprecedented KPIs and QoS levels. As a continuation of the efforts made with the first two editions of the INGR Satellite Working Group reports, this document has raised some further challenges and presented possible solutions for the evolution of satellite systems from 5G to 6G, with particularly reference to satellites as 5G/6G back-haul and direct-access satellite services.

Recent studies estimate that about 37% of the world's population still lacks high-speed internet access. Moreover, besides urban areas, present terrestrial networks cannot guarantee access to the internet for passengers on aircraft, ships or high-speed trains, highways, and remote areas. There is a definite opportunity and need for satellite systems to complement 5G and 6G terrestrial wireless networks to satisfy all these requirements.

First of all, this report has shown different architectures and use cases where the satellite (mainly based on LEO and MEO systems), with HAPs and UAVs, can provide equivalent 5G/6G services. Moreover, different applications suitable for 5G augmentation have been presented, mainly dealing with the eMBB and mMTC cases. New applications such as space-based hosting and LEO-satellite-based services were highlighted. Further, we provided several use cases covering the following categories: (a) Use Cases for Satellite Networks as Back-haul for 6G Terrestrial Networks, (b) Use Cases with Direct Access Satellite Networks, and (c) Use Cases for Satellite IoT. We proposed three reference architectures: (i) Reference Architecture-1: non-Virtualized 5G-Satellite Networks, (ii) Reference Architecture-2: Separately Virtualized 5G-Satellite Networks, and (iii) Reference Architecture-3: Integrated Virtualized 6G-Satellite Networks, respectively for near-term, medium-term and long-term development.

PHY layer has the crucial task of achieving high performance and efficiency to maximize the air interface capacity. This can be achieved through new modulation schemes, MIMO antennas, and the adoption of mmWave communications (70 and 159 GHz), for which propagation studies have been carried out.

As for the satellite antenna system, a possible solution will be based on reconfigurable multi-feed antennas with electronic beam-steering to maximize antenna gain in the desired direction. In addition, free-space optical communications will be adopted for satellite-to-satellite links, satellite-to-ground links, and satellite-to-aerial components; this solution will tremendously increase link capacity, resilience, and security of communications. As for optical communications and security, quantum and post-quantum-based solutions must also be integrated with 6G services.

This report has also highlighted the importance of AI/ML schemes that will provide a powerful tool for real-time optimizations of many satellite system problems, like routing and path selection, handover scheme, PHY adaptation, security, etc. Mega-LEO constellations will be very complex to manage, and the adoption of AI/ML solutions is deemed essential. These new approaches will also be fundamental for 6G. Several challenges are identified, including the requirement for efficient data generation, a comprehensive comparison of centralized and distributed ML techniques, and the immediate need to standardize ML techniques to alleviate and solve several satellite problems.

MEC approaches have been presented as viable, efficient solutions for 5G/6G services. The adoption of MEC for satellite systems will make new services possible and open new markets based on IoT via satellite, and boost other services such as eXtended Reality (XR) video streaming, autonomous driving, and data analytics from space, hence contributing to the concept of satellite-as-a-service. MEC will reduce the frequency of communications via satellite hops, thus supporting critical functions for the 5G/6G satellite networking, such as offloading and caching. In the context of SDN / NFV, the orchestrator integrating the terrestrial and the satellite domain will benefit from the processing capabilities at the edge made possible by the MEC approach. Finally, the future frontier of MEC is the implementation of these concepts in space, hence leveraging on next-generation onboard processing satellite payload, which will indeed offer dedicated services from the sky.

Expected QoS requirements have been investigated, referring to the performance parameters presented in 3GPP and ITU Standards. We have shown that the QoS / QoE levels provided by satellites will be comparable with those of terrestrial 5G/6G systems due to mega LEO constellations where the satellites are much closer to the Earth. Techniques including MEC, caching, and network slicing can be used to improve QoS / QoE for satellite systems and reduce latency.

A significant emphasis in this report has been given to network management, encompassing mobility management, radio resource management, routing, softwarization, and virtualization of the satellite network, as an essential step for integrating the aerial components with 5G/6G terrestrial systems. With respect to mobility management, the challenges of maintaining a consistent addressing scheme and performing efficient and scalable handovers have been highlighted. The need to ensure QoS and avoid interference problems has been emphasized in radio resource management. The routing, softwarization, and SDN sections have addressed the issues of onboard processing, controller placement, and interoperability.

5G/6G will be based on new approaches, like MEC, SDN, NFV, and network slicing. However, many of these technologies are not yet mature when considering their security implications.

NTNs are expected to be an integral part of the 5G/6G infrastructure, and 3GPP standardization work is in progress on this subject in Release 18 and onwards. NTN includes satellites of GEO and mega-constellations of LEOs, as well as HAPs. However, the current standardization does not adequately cover mega-LEO systems, HAPs, and UAVs. An appendix has been provided surveying the status of the NTN standardization in different SDOs. It has been realized that the evolution towards SDN (and, in general, software-based solutions) will bring new threads for satellite systems and their integration with terrestrial 5G/6G systems. Security-by-design concepts must be adopted for 5G/6G developments and NTN systems. Secure communication is needed across all modes of satellite communication, whether user-driven, telemetry, satellite-to-satellite, etc. Moreover, future satellite systems must have mechanisms to manage security quickly to deal with attacks before they can cause damage.

A newer security paradigm, Zero Trust Security, is an important part of future 5G/6G security. This approach treats each network element as a potential source of attack. In doing so, trust must be developed and learned continuously to mitigate attacks before they can do significant damage. Using techniques such as machine learning and SDN in combination with real-time security information, a security architecture with situational awareness and adaptive and autonomous management can be put into place for proactive and predictive security.

All these interesting outcomes identify a clear path for the evolution of satellites from 5G to 6G systems.

## 9.2. Working Group Recommendations

According to the study carried out on the different topics and presented in the previous sections, we have identified some key recommendations, as detailed below.

- Identification of architectures with multiple connectivity types (UAVs / HAPs / MEO / LEO). GEO satellites currently have been used for the data plane, but in the future, they can also be considered for the control plane and feeding caches. Use cases and reference architectures for the near-term, medium-term, and long-term integration of satellite 6G networks have been identified.
- Efforts must be pursued to achieve system interoperability not only with the terrestrial 5G/6G, but also with the aerial components of other operators. Adopting network virtualization and softwarization with SDN / NFV and orchestrators standards (like ETSI MANO) will be essential for the future integration of satellites with terrestrial 5G/6G during the evolution process.
- MIMO communications will increase the capacity and improve the physical layer security.
- mmWave communications via satellite are possible, but solutions are needed to address the vulnerability due to weather impairments and the large Doppler shifts from LEO satellites.
- The antenna design for the satellite will be based on multi-feed antennas with electronic beam-steering.
- MEC will be an integral part of 6G-integrated NTN networks, considering the increased boost of service and functionalities at the network's edge.
- MEC success in space will be pretty much aligned with the technological advances of satellite platforms in the sense of the resources available onboard to support MEC services and eventually allow for the implementation of gNodeB and UPF functionalities in the space segment.
- Dataset generation, collection, and emulation by considering different satellite reference architectures are required for the initial investigation of ML techniques.
- A proper performance analysis of the comparison of distributed and centralized ML techniques for efficient routing, optimizing trajectory design, guaranteeing security, and better network planning is required.
- The deployment overhead for the upcoming ML algorithms in satellite and other NTN systems for training and inference must be addressed.
- Advances in virtualization and SDN techniques are the fundamental pillars to provide the flexibility, scalability, and performance demanded by the users of 5G/6G networks and required by a highly dynamic topology, such as the one provided by integrating terrestrial and non-terrestrial networks.
- Mega-LEO constellations entail a significant complexity to be managed. AI/ML can provide possible new methods to solve complex problems such as routing, resource allocation, cross-layer optimization, and handover decision in a scalable and efficient way.
- Satellite 5G/6G standards have made significant progress. Additional work is needed to address multi-layers systems, including GEO, MEO, and LEO, as well as the role of UAVs and HAPs.
- Security by design is an essential target for satellite systems. In this regard, the development of mega-satellite constellations with secure designs of the orbital planes, satellite altitudes (use of

multi-shell structures), visibility times of the satellites, etc., may help to reduce information leakage, and eavesdropping time to name a few.

- A zero-trust architecture that can work across multiple networks and service providers with open interfaces is needed to address real-time security threats.
- Integrated hybrid optical-radio systems will play a key role in providing the capacity, resilience, and security that new 6G services will demand. In this part, QKD systems can be understood as a particular use case of hybrid optical-radio systems.
- New applications and services have been identified for the integrated 6G-satellite networks.

### 9.2.1. Future Work

Future work on using satellite systems for mobile communications will be needed to address specific 6G requirements [125], following and adapting the solutions considered for terrestrial systems. In the future, there will be thousands of satellites around the earth, where each can play the role of a terminal, a router, or a base station. Traditional network management approaches are unsuitable for such a complicated and dynamic environment. In this regard, scalable and distributed mobility management is essential for efficient network operation. This will require studying multipath routing schemes and the possibility of adopting sophisticated routing protocols capable of routing data packets through satellites belonging to constellations managed by different operators. In this way, user requirements of QoS / QoE can be met while efficient network performance and resource utilization can be achieved.

The reference architecture's scalability is needed to accommodate several thousands of satellites in orbit. Seamless handover between terrestrial and satellite segments needs new solutions. Identifying interface standardization, operation guidelines, traffic management, shaping, and other similar solutions are essential to achieve federated satellite and opportunistic services. One another area that raises future research opportunities is the utilization of highly elliptical orbits for low-latency services.

Optimization of the MEC services still needs to be further researched concerning the evolution of satellite systems and the integration with 3GPP standards. This study may culminate with implementing gNodeB (fully or with the CU / DU splitting option) to assess the feasibility of such a concept in space. Dedicated concepts such as edge-to-edge, edge discovery, distributed learning towards optimal edge service placement, and task atomization require additional investigation for possible exploitation in NTN domains. This approach will become even more compelling according to the current view of 6G as a 3D network of networks, where the space segment will consist of a multi-layer multi-orbit NTN part, whereby the actual resource allocation across space will be a very challenging job in the overall MEC concept design.

To boost the integration of NTNs with 6G, a change in the AI paradigm is required to move from network-centric AI to user-centric AI. The former analyzes information from network entities to make more informed decisions on optimizing network resources. The second is focused on understanding individual users' needs and preferences to provide personalized recommendations and satisfactory experiences. Furthermore, AI as a service must be integrated to automate various processes in developing NTN infrastructure. This automation process can lead to increased efficiency and reduced development time. From the algorithmic point of view, new applications of upcoming AI tools, including generative AI and Deep Reinforcement Learning (DRL), should be further investigated for the satellite systems.

Space IoT scenarios will need to be further investigated for their implications regarding system multi-layer architecture and how to achieve cooperation of the different layers and KPIs. Edge intelligence's impacts (including MEC and AI/ML) on future satellite 6G systems must be further investigated to highlight the implications on system architecture, protocols, and services.

Future work will be needed to address space communications as a possible evolution and extension of the work made on satellite communications. Space communications will become increasingly important with the progress in space exploration. Some of the most recent projects, namely LCE, GeoLITE, SILEX, ALEX, etc., have demonstrated the feasibility of high data rate for near-earth communications of 5 – 6 Gbps involving LEO, MEO, and GEOs[110]. The use of mmWave for near-earth communications is a key enabler for 6G era communication[111] that can offer much higher bandwidth and support enhanced mobile broadband communications. Similarly, optical communications are an interesting technology that may help provide services requiring large bandwidth. Furthermore, optical links are the basis of QKD strategies, which enable perfect security and robustness to quantum computer attacks. In the future, it is expected that: (i) hybrid optical-radio systems will be pushed as a strategy to increase the capacity and robustness against channel impairments and high demands of service, (ii) the combination of quantum-security (e.g., QKD) with post-quantum techniques to increase the security. In this latter case, advanced strategies for increasing the key generation rate of QKD schemes are a real need. Joint designs of the data and quantum channel may also be a strategy for aligning the demands of 6G, the security capabilities of QKD, and strategies of security-by-design of the satellite constellations. The definition of the use cases of eavesdropping in non-terrestrial networks also needs to be targeted in the future. In the former case, the size of the optical beams is much smaller than the radio ones. So, multi-beam optical satellite strategies and larger beam sizes for the optical links should be researched for smooth switching between the optical and radio links.

Future space missions should perform studies to realistically evaluate their telecommunication needs while considering that missions will not rely solely on optical communication but some combination of optical and RF communication. For example, future optical services on deep-space missions will include access links for the Moon, Mars, and other planetary missions. In combination with an augmented Mars-to-Earth (trunkline) optical data-rate capability, imagery from the surface could be streamed up to an orbiter for relay back to Earth in near real-time. While the basic building blocks for many of the communications links are available to support deep-space communications, various networking challenges need to be researched [126].

Methods to obtain the security state of the network need to be investigated to support real-time proactive security. Potential types and data sources are necessarily based on the different network elements. In a 5G/6G NTN environment, these can include satellites, IoT devices, and more. Additionally, open interfaces are needed to disseminate such information to determine whether the network element meets trust conditions. Trust conditions should be dynamic and be learned by computing the "trust score" of the entity based on that element's data, as described.

# 10. CONTRIBUTOR BIOS

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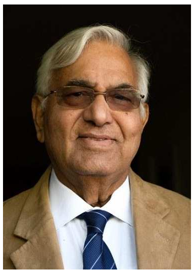

Dr. Kota is the President of SoHum Consultants and an Adjunct Professor at the University of Oulu, Finland. He held technical and management positions at Harris, Loral Space, Lockheed Martin, SRI International, MITRE Corp, Xerox Corp. and Computer Science Corp. He contributed to satellite and wireless communication network systems, digital video broadcasting, mobile communications, broadband internet, and hybrid networks for commercial and defense programs. He provided leadership in the international standardization of broadband satellite networks as head of the U.S. delegation and the U.S. chair of the ITU-R Working group on FSS, MSS, and BSS. Dr. Kota He has authored and co-authored 200 papers in conference proceedings and journals and five books. Dr. Kota conducted a lecture series and tutorials on computer networking, broadband satellite networks, and digital video broadcasting at MILCOM, IEEE, AIAA conferences, the University of Oulu, Finland, LNMIT, and MNIT, Jaipur, India. He was a lecturer for five years at IIT, Roorkee, India. Dr. Kota served as a guest editor of special issues for IEEE Communications, Wireless, VTS, International Journal of Satellite Communications and Networking, and Space Communications. Dr. Kota was a keynote speaker at conferences and symposiums and served as an Unclassified Technical Program Chair / Executive Member of MILCOM 2007, 2004, and 1997. He received the IEEE Communications Society, Satellite and Space Communications Technical Committee Distinguished Service Award. He was a Fulbright Specialist by the U.S. Department of State and received the Golden Quill Award from Harris Corporation for Project Leadership in Broadband Satellite Communications for Internet and Assured Communications. Dr. Kota holds a Ph.D. from the University of Oulu, Finland, an Engineer's Degree from Northeastern University in Boston, Massachusetts, and an MSEE from IIT in Roorkee, India. He is a Life Senior Member of IEEE and an Associate Fellow of AIAA.

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Giovanni Giambene received a Dr. Ing. degree in Electronics in 1993 and a Ph.D. in Telecommunications and Informatics in 1997, both from the University of Florence, Italy. From 1994 to 1997, he was with the Electronic Engineering Department of the University of Florence, Italy. He was the Technical External Secretary of the European Community COST 227 Action ("Integrated Space / Terrestrial Mobile Networks"). He also contributed to the SAINT Project ("Satellite Integration in the Future Mobile Network," RACE 2117). From 1997 to 1998, he worked on a GSM development program with OTE (Marconi Group) in Florence, Italy. In 1999, he joined the Department of Information Engineering and Mathematical Sciences of the University of Siena, Italy. Currently, he is an associate professor, teaching the first-level course on Fundamentals on Telecommunications and the advanced course on Networking at the University of Siena. He was vice-Chair of the COST 290 Action (2004-2008), entitled "Traffic and QoS Management in Wireless Multimedia Networks" (Wi-QoST). He participated in the projects: (i) the SatNEx I & II network of excellence (EU FP6, 2004-2009) and SatNEx III&IV (ESA 2010-2018) as work package leader on radio access techniques, cross-layer air interface design, and network coding techniques for satellite systems; (ii) the EU FP7 Coordination Action "Road mapping technology for enhancing security to protect medical & genetic data" (RADICAL) as work package leader on security and privacy; (iii) the COST Action IC0906 (2010-2014) "Wireless Networking for Moving Objects" (WiNeMO) as national representative; (iv) the EU FP7 Coordination Action RESPONSIBILITY. At present, he is involved in the ESA SatNEX V project. Giambene is IEEE senior member and has been nominated IEEE Comsoc distinguished lecturer 2021-2023. Since 2015, he has been an IEEE Transactions on Vehicular Technology editor. Since 2019, he has been an editor of IEEE Wireless Communications Magazine.

**Mohammed Abdelsadek**

Mohammed Y. Abdelsadek received the B.Sc. (with honors) and M.Sc. degrees from Assiut University, Assiut, Egypt, in 2011 and 2014, respectively, and his Ph.D. degree from the Memorial University of Newfoundland, St. John’s, NL, Canada, in 2020, all in electrical and computer engineering. He is currently a Postdoctoral Fellow at Carleton University, Ottawa, ON, Canada. Before joining Carleton University, he was a Sessional Instructor at the Memorial University of Newfoundland. Earlier, he was an Assistant Lecturer at Assiut University. His current research interests include satellite communication networks, ultra-reliable low-latency communications, radio resource management, and AI/ML for wireless networks. He has served as a Reviewer and TPC member for several IEEE journals and conferences. He is an IEEE Member.

**Mohamed-Slim Alouini**

Mohamed-Slim Alouini was born in Tunis, Tunisia. He received a Ph.D. degree in Electrical Engineering from the California Institute of Technology (Caltech) in 1998. He served as a faculty member at the University of Minnesota and then at the Texas A&M University in Qatar before joining in 2009 the King Abdullah University of Science and Technology (KAUST), where he is now a Distinguished Professor of Electrical and Computer Engineering. Prof. Alouini is a Fellow of the IEEE and Optica (Formerly the Optical Society of America (OSA)). He is currently particularly interested in addressing the technical challenges associated with the uneven distribution, access to, and use of information and communication technologies in far-flung, rural, low-income, disaster, and/or hard-to-reach areas.

**Marc Amay**

Marc Amay is a Ph.D. Researcher at the Space and Resilient Communications and Systems (SRCOM) Research Unit of Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) in Barcelona, Spain. His research area of interest is on i) Quantum Satellite Communications, ii) Integrated Terrestrial-Non-Terrestrial Networks (3D Networks), and iii) Hybrid Radio-Optical Wireless Communications, all to serve the paradigm of 6G communications. He received his Bachelor of Science degree in Electronics and Communications Engineering from New Era University, Philippines, with one year spent at the University of the Philippines to major in Mathematics. In 2021, he obtained his Double Master’s degree with distinction (cum laude) from Aston University, United Kingdom (Master of Science in Smart Telecom and Sensing Networks) and Telecom Paris, France (Master of Electrical Engineering in Optical Networks and Photonics Systems). He was a research intern at Laboratoire d’Ingenierie des Systemes de Versailles (LISV), France, working on Channel Modelling of Indoor Optical Wireless Communications, then a Research Fellow at Scuola Superiore Sant’Anna Pisa, Italy working on Visible Light Positioning for industrial use cases. Before his master’s, he worked in a start-up company as a Communication Systems Engineer, participating in government- and private-funded projects. He led the implementation of Remote-sensing and Telemetry Infrastructure Projects for verticals such as environmental monitoring and energy management. He has travelled across Europe, Asia, and North America to undertake training, conferences, and seminars. He is an active member of European Consortiums such as CostAction NewFocus, CostAction Interact, and IEEE Future Networks Society.

**Sarath Babu**

Sarath Babu (Member, IEEE) received his Ph.D. from the Indian Institute of Space Science and Technology, Thiruvananthapuram, India, in 2021. He completed his master's degree in Computer Science and Engineering (Information Security) from the National Institute of Technology, Calicut, India, and his bachelor's degree in Information Technology from Mahatma Gandhi University, Kottayam, India. He is currently working as a Research Scientist at the Department of Electrical and Computer Engineering, Iowa State University, USA, and affiliated with the Center for Wireless, Communities, and Innovation (WiCI). His primary focus is on the project ARA-Wireless Living Lab for Smart and Connected Rural Communities, a part of the NSF Platforms for Advance Wireless Research program. His research interests include next-generation wireless infrastructures, software-defined networks, complex networks, systems security, and intelligent transportation systems.

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Dr. Joan Bas received the M.Sc and Ph.D. (cum laude) in Electrical Engineering from the Universitat Politècnica de Catalunya (UPC) in 1998 and 2004, respectively. While pursuing his Ph.D., he was the recipient of a 1998-2000 fellowship of the UPC's Communication Signal Processing Group and a 2000-2004 Ph.D. scholarship granted by the Spanish Ministry of Science and Technology. As a postdoctoral researcher in March 2005, he joined the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC). In 2008 he was granted a Leonardo Torres Quevedo fellowship from the Spanish Government to join CTTC as a permanent staff. Currently, he holds at CTTC the position of Research Associate in the Space and Resilient Communication Systems (SRCOM) department. He has published +40 conference papers, journal papers, and a book chapter, supervised Msc. and post-doc students, and participated in +30 research projects and +10 technological transfer ones. He is also serving as a reviewer of +15 journals. He has also participated in the organization of national and international conferences (e.g., ICASSP2020, GLOBECOM2021, Satellite Workshop on ICC 2022). His main research areas of interest are: the improvement of the spectral and energy efficiency of satellite communications, indoor monitoring, optical wireless communications and their integration with RF systems, security on IoT systems, and the design of integrated 6G Terrestrial and Non-Terrestrial Networks. He has coordinated the physical layer activities for the second, third, and fourth satellite roadmap of the IEEE International Network Generations Roadmap (INGR) from the IEEE Future Networks Society.

**Pietro Cassarà**

Pietro Cassarà received his M.Sc. degrees in Telecommunication and Electronic Engineering from the University of Palermo in 2005 and his Ph.D. degree in 2010, jointly with the State University of New York. Nowadays, he is a permanent staff member of the Institute of Science and Information Technologies (ISTI) at the National Research Council (CNR) and a permanent member of the National Inter-University Consortium for Telecommunications (CNIT), Pisa, Italy. Since 2017 he has been a temporary staff member of the CMRE lab at the NATO of La Spezia. His research interests include optimized automatic controls and machine learning theory for wireless sensor networks, distributed cyber-physical systems, and distributed learning architectures for networking. As part of his research activities, he has had the opportunity to participate in and coordinate activities in European and European Space Agency and Nationally funded projects. He is Co-Chair of the National IPv6 Council and a referee at the European Telecommunications Standards Institute for the IPE and NTI activities. He has been involved in many activities, organizing conferences, workshops, round tables, and activities as an editor. He has been participating in the IEEE ComSoc and VTS committees and is involved in the IEEE Machine Learning for Communications ETI activities.

**Sachin Chaudhari**

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**Debabrata Dalai**

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## Tasneem Darwish

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## Tomaso de Cola

Tomaso de Cola was born in Manosque, France, on April 28, 1977. He received the “Laurea” degree (with honors) in telecommunication engineering in 2001, the Qualification degree as a Professional Engineer in 2002, and the Ph.D. in Electronic and Computer Engineering, Robotics and Telecommunications in 2010 from the University of Genoa, Italy. From 2002 until 2007, he worked with the Italian Consortium of Telecommunications (CNIT), University of Genoa Research Unit, as a scientist researcher. Since 2008, he has been with the German Aerospace Centre (DLR), where he is involved in different European Projects focusing on different aspects of DVB standards, CCSDS protocols, and testbed design. He is a co-author of more than 50 papers, including international conferences and journals. His main research activity concerns: TCP/IP protocols, satellite networks, transport protocols for wireless links, interplanetary networks as well as delay-tolerant networks. Dr. de Cola has served on the technical program committee at several IEEE International Conferences. He is a member of the IEEE Communications Society.

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Thomas Delamotte (Member, IEEE) received a master’s degree in communications and network engineering from the National Polytechnic Institute of Toulouse, Toulouse, France, in 2009 and a Ph.D. degree (summa cum laude) in communications engineering from the Bundeswehr University Munich, Munich, Germany, in 2019. He was a Research Fellow with the Department of Electrical Engineering and Information Technology, Bundeswehr University Munich. Since 2016, he has been coordinating the Research Group Digital Satellite Payloads and Satellite Monitoring from the Chair of signal processing at the same university. He is currently engaged in several national and international research projects focusing on applying advanced signal processing techniques and waveform designs for next-generation high-throughput satellite systems. He is a member of the satellite expert working groups from the NetworldEurope European Technology Platform and the IEEE Future Networks initiative.

**Ashutosh Dutta**

Ashutosh Dutta is currently Chief 5G Strategist and JHU / APL Sabbatical Fellow at Johns Hopkins University Applied Physics Labs (JHU / APL), USA. He also serves as Chair for Electrical and Computer Engineering for Engineering Professional Program at JHU. His career, spanning more than 30 years, includes Director of Technology Security and Lead Member of Technical Staff at AT&T, CTO of Wireless at a Cyber security company NIKSUN, Inc., Senior Scientist in Telcordia Research, Director of Central Research Facility at Columbia University, adjunct faculty at NJIT, and Computer Engineer with TATA Motors. Ashutosh is the author of over 100 technical papers and 31 patents. Ashutosh co-authored the book, "Mobility Protocols and Handover Optimization: Design, Evaluation and Application" published by IEEE and John & Wiley. As a Technical Leader in 5G and security, Ashutosh has been the founding Co-Chair for the IEEE Future Networks Initiative, focusing on 5G standardization, education, publications, testbed, and roadmap activities. Ashutosh is IEEE Communications Society's Distinguished Lecturer for 2017-2020 and an ACM Distinguished Speaker (2020-2022). Ashutosh is the founding co-chair of IEEE Future Networks Initiative and Member-At-Large of IEEE Communications Society. Ashutosh has served as the general Co-Chair for the IEEE STEM conference for the last 10 years. Ashutosh served as the Director of Industry Outreach for IEEE Communications Society from 2014-2019. He was the recipient of 2009 IEEE MGA Leadership Award and 2010 IEEE-USA professional leadership award. Ashutosh currently serves as Member-At-Large for the IEEE Communications Society for 2020-2022. Ashutosh has served as the general Co-Chair for the premier IEEE 5G World Forums and has organized 75 5G World Summits around the world. Ashutosh currently serves as the Chair for IEEE Industry Connection's O-RAN activities. Ashutosh is a Distinguished Alumnus of NIT Rourkela with BS in Electrical Engineering, MS in Computer Science from NJIT, and a Ph.D. in Electrical Engineering from Columbia University under the supervision of Prof. Henning Schulzrinne. Ashutosh is a Fellow of IEEE and a Distinguished Member of ACM.

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Ayush Kumar Dwivedi received a B.Tech. Degree in Electronics and Communication Engineering from Jawaharlal Nehru Technological University Hyderabad, India, in 2017. He is currently pursuing his doctoral research under Dr. Sachin Chaudhari at the International Institute of Information Technology Hyderabad, India. His areas of interest are in the fields of next-generation wireless communication, satellite communications for Internet-of-Things, and Internet-of-Things for smart cities. From Dec 2015 – Jan 2016, he was an intern at the Electronics Corporation of India Limited. He also contributes to discussions at the Telecommunication Standards Development Society of India (TSDSI) for a study item on rural broadband services and architectures. He is also active in operationalizing the Center of Excellence (CoE) research on IoT for Smart Cities at IIITH.

**Michael Enright**

Dr. Michael A. Enright is the CEO and President of Quantum Dimension, Inc. and has 30 years of experience in security, Artificial Intelligence (AI) and Machine Learning (ML), embedded computing, image and video processing, RF communication, and more. Dr. Enright has a Ph.D. in Electrical Engineering from the University of Southern California (USC) thru his work with the Signal and Image Processing Institute (SIPI) at USC, an M.S. in Electrical Engineering from the Illinois Institute of Technology, an M.S. in Mechanical Engineering from the University of Missouri-Columbia and a B.S.

in Aeronautical and Astronautical Engineering from the University of Illinois at Champaign-Urbana and is a Senior Member of the IEEE. For the past 15 years at Quantum Dimension, he has led a team of engineers in the company's technology developments, including AI/ML, RF communication, software-defined radio, and navigation using advanced embedded technologies, including digital signal processing, graphics processor unit, and FPGA. Before founding Quantum Dimension, Dr. Enright was a researcher with the Signal and Image Processing Institute (SIPI) and the Integrated Media Systems Center (IMSC) at USC, where he worked on multimedia cross-layer communication techniques. Further back, Dr. Enright: led the development of the video compression architecture for Boeing Digital Cinema with MPEG-2, MPEG-4, and JPEG2000 coding algorithms, acted as an information security lead for network security, and was responsible for the design and development of a space-based phased-array antenna subsystem at Hughes Space and Communication. Before Hughes, Dr. Enright worked at Motorola Cellular on the handset design for the Iridium satellite system. He began his signal processing career at AT&T Bell Laboratories in Naperville, Illinois, where he developed DSP software for AT&T's 5ESS telephone switching systems. Dr. Enright has been an Adjunct Professor in the Electrical Engineering Department at USC, where he taught both undergraduate and graduate courses in image and signal processing, digital communications, and wireless communication systems design.

**Marco Giordani**

Marco Giordani received his Ph.D. Degree in Information Engineering from the University of Padova, Italy, in 2020, where he is now a Postdoctoral Researcher and Adjunct Professor. During his Ph.D., he visited NYU and TOYOTA Infotechnology Center Inc., USA. He has been collaborating with several academic and industrial research partners, including InterDigital, NYU, TOYOTA, NIST, the US Army Research Office, Orange, Huawei, King's College, and KAUST. He co-authored 50+ published articles in the area of millimeter wave wireless networks, two of which have received Best Paper Awards. He is a recipient of several awards, including the IEEE Daniel E. Noble Fellowship Award from the IEEE Vehicular Technology Society, the Francesco Carassa Prize from the Italian Telecommunications and Information Theory Group (GTTI), and the IEEE ComSoc Outstanding Young Researcher Award for EMEA. He serves as Associate Editor for the "Aerial and Space Networks" section of the Frontiers in Communications and Networks Journal. He also serves as Guest Editor for several Special Issues of the Sensors Journal (MDPI). His research focuses on protocol and architecture design for 5G/6G cellular and vehicular networks.

**Alberto Gotta**

Alberto Gotta is a staff member of the Information Science and Technologies Institute (ISTI) of the Italian National Research Council since 2005. He has been the research leader of the "Communication Protocols and Architectures" section of the Wireless Network Laboratory at ISTI since 2015. From 2002 to 2005, he has been with the National Inter-University Consortium for Telecommunications at the Research Unit in Genoa, at the Politecnico School of the University of Genoa. He is also a project reviewer for the Italian Ministry of Economic Development since 2013. He is a member of the ISTI-IIT CNIT Research Unit. He is a member of the Italian Group of Telecommunications and Information Technologies (GTTI). He is also a ComSoc Satellite & Space Communications Technical Committee member and of the Machine Learning for Communications and Aerial Communication Emerging Technologies Initiatives. He has been participating in the IEEE International Network Generations Roadmap (INGR), belonging to the INGR Satellite Working Group.

His primary research interests include dynamic bandwidth allocation, admission control, multiple access protocols, error recovery techniques, and fade countermeasure control systems in wireless and satellite multi-service networks. He has been participating in several projects funded by the European Community (FP6, FP7, H2020), in National Industrial Innovation / Operation Plan projects (PII / PON), in Regional projects (POR / FAR FAS), and in European Space Agency projects (ARTES).

**Eman Hammad**

Dr. Eman Hammad is a cyber security professional & interdisciplinary professional focusing on trustworthy & resilient complex systems and emerging technologies. She obtained her Ph.D. in Electrical & Computer Engineering from the University of Toronto. Eman combines practical experience and theoretical research to shape her vision for resilient-by-design solutions in the connected world. She is the director of the innovations in Systems Trust & Resilience (iSTAR) lab. Eman's work has been published in more than 50 papers and was recognized with merit awards (best paper award, best poster award) and has been featured on multiple outlets. Most recently, she was honored as one of Canada's Top 20 Women in Cybersecurity. Eman is a senior IEEE member currently serving as Toronto ComSoc chair and the co-chair of the IEEE 5G Security working group for the International Network Generations Roadmap (INGR). She delivered numerous invited talks at academic and industrial conferences, chaired and co-chaired several conferences and workshops, and participated in several panels. She serves on the advisory board of several initiatives. Eman is an active advocate for diversity and inclusion in STEM and Cybersecurity. Her service has been recognized by IEEE exceptional, chapter achievement, and exemplary service awards.

**Tamer Khattab**

Tamer Khattab (M' 94, SM' 18) received the B.Sc. and M.Sc. degrees in electronics and communications engineering from Cairo University, Giza, Egypt, and a Ph.D. in electrical and computer engineering from the University of British Columbia (UBC), Vancouver, BC, Canada, in 2007. From 1994 to 1999, he was with IBM wtc, Giza, Egypt, as a development team member, then a development team lead. From 2000 to 2003, he was with Nokia (formerly Alcatel Canada Inc.), Burnaby, BC, Canada, as a senior member of the technical staff. From 2006 to 2007, he was a post-doctoral fellow at the University of British Columbia, where he was involved in prototyping advanced Gbits/sec wireless LAN baseband transceivers. He joined Qatar University (QU) in 2007, where he is currently a Professor of Electrical Engineering. He is also a senior member of the technical staff with Qatar Mobility Innovation Center (QMIC), a research and development center owned by QU and funded by Qatar Science and Technology Park (QSTP). His research interests cover physical layer security techniques, information-theoretic aspects of communication systems, radar and RF sensing techniques, and optical communication. Dr. Khattab is an editor of the IEEE Communications Letters and the IEEE Open Journal of the Communications Society. In addition to more than 150 high-profile academic journals and conference publications, Dr. Khattab has several published and pending patents.

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Pablo G. Madoery received a B.S. in telecommunication engineering from the National Defense University, Argentina, in 2015 and a Ph.D. in engineering sciences from the National University of Cordoba, Argentina, in 2019. He is a postdoctoral fellow at Carleton University on a MITACS fellowship and an assistant professor of Computer Science at the National University of Cordoba, Argentina. He has co-authored 10 articles in international journals and 20 in leading conferences in communication protocols and routing algorithms for delay-tolerant satellite networks. He is researching AI/ML-assisted routing and transport solutions applied to satellite mega-constellations.

**B. S. Manoj**

B. S. Manoj (Senior Member, IEEE) received a Ph.D. in computer science and engineering from the Indian Institute of Technology Madras in 2004. He was an Assistant Research Scientist and a Lecturer with the Electrical and Computer Engineering Department, University of California at San Diego. He is currently a Professor with the Department of Avionics, Indian Institute of Space Science and Technology, Thiruvananthapuram, India. His research interests include complex networks, ad hoc wireless networks, delay tolerant networks, next-generation wireless architectures, wireless sensor networks, wireless mesh networks, satellite networks, and 6G-satellite integration.

**Jean-Daniel Medjo Me Biomo**

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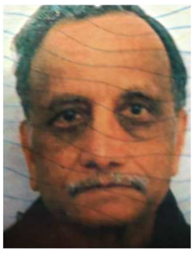
**Prashant Pillai**

Prof Prashant Pillai (Senior Member, IEEE) is an award-winning academic leader and visionary who has over 19 years of UK Higher Education experience. He is a globally renowned scholar and outstanding university educator who provides academic direction and leadership to research, business engagement, and education. He is currently Associate Dean for Research and Knowledge Exchange for the Faculty of Science and Engineering at the University of Wolverhampton, UK. He was previously a Professor of Cyber Security and Director of the Wolverhampton Cyber Research Institute. Before that, he was a Reader in Cyber Security and the Head of the Cyber Research Group at Oxford Brookes University, UK. Over the years, Prof Pillai has led several national / international research projects in networking protocols and cyber security. He has been invited for talks at various international conferences and has published 100 papers in peer-reviewed journals and conferences. With an educational background in Electronics and IT security and an avid interest in Artificial Intelligence, Prof Pillai has a passion for researching complex issues that lie in the interaction of these areas. His current research interest lies in applying AI and developing novel security solutions for safety critical systems (like smart grids, autonomous cars, aeronautical systems, and robotics). He is the current Chair of the IEEE UK and Ireland Blockchain Group and Chair of the Innovation Alliance West Midlands Cyber Working Group. He was Co-Chair of the 5G-Satellite subgroup of the IEEE 5G Technology Roadmap Working Group, a founding member of the IEEE special interest group on Big Data for Cyber Security and Privacy, and an Associate Editor of IEEE Transaction on Aerospace and Electronic Systems.

**Pramud Rawat**



During the last 15 years Dr. Rawat's 65-year-long career culminated in Program Office support for CBP-DHS in US. It involved performance evaluation of just released border control software packages and, simultaneously, looking at the technologies in the pipeline through the 3GPP releases with the potential to meet the pressing needs of the multiple missions that are involved in preserving homeland security. Satellites (especially the constellations of low-earth-orbit satellites now coming online), UAVs, tethered balloons, cloud-edge architecture, and AI/ML for information acquisition and processing. After retirement, he is actively engaged in research in these areas.

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Dr. Paresh Saxena is an Assistant Professor in the Dpt. of Computer Science & Information Systems, BITS-Pilani, Hyderabad, India. He is currently leading a project MUT-DROCO (Multipath Networking Testbed for Drone Communications), funded by DST-SERB, Govt. of India, and a project NANCY (Neural Adaptive Network Coding for video transmission over wireless networks) funded by TCS, India. Previously, he has been involved as a work package leader in two European Space Agency (ESA) funded projects: SatNetCode and HENCSAT, along with a work package member in the European H2020-funded project Geo-Vision. He was a European COST action IC1104 member from 2013–2016 and worked on a project funded by MITACS, Canada, in 2008. He was a visiting researcher at SFU, Vancouver, Canada, in 2008 and Telecom ParisTech, Paris, in 2010. During his Ph.D. from UAB, Barcelona, Spain, he was awarded UAB Doctoral Fellowship Grant (P.I.F) from 2011–2015. Post-Ph.D., he was fortunate to spend a few years at AnsuR Tech., Oslo, Norway as a Senior researcher. His primary research focuses on designing and implementing reliable and robust data transfer protocols for terrestrial and non-terrestrial networks.

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Pat Scanlan is a Product Technology Manager with Cubic Telecom Ltd, a leader in providing globally connected software solutions and analytics services to the automotive, transport, and agricultural sectors. He has over 35 years of professional experience across a wide spectrum of technologies and business propositions; he is a recognized domain expert in Mobile Telecommunications, Core, Radio, OSS and BSS, IoT, Industry 4.0, 5G-NR, NFV, SDN, AWS / Azure systems with acknowledged expertise in the area of R&D, Software Practice, Telecoms (mobile in particular), Customer Experience Management, and Big Data Analytics.

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Ray Sperber is a semi-retired satellite engineer with 44 years in the space business, of which 40 have been in satcoms. Most, but not all, of his work, has been for communications satellite operator SES, but he has also worked for satellite manufacturers and on special space-related projects. Currently, he is a consultant. He has a BS in Physics and a MS in Aeronautics and Astronautics, both from MIT and an MBA from Sacred Heart Luxembourg. His primary technical interests are applied physics, electromagnetics & optics, space technology, and communications.

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**Daniele Tarchi**

Daniele Tarchi was born in Florence, Italy, in 1975. He received his M.Sc. degree in Telecommunications Engineering and a Ph.D. in Informatics and Telecommunications Engineering from the University of Florence, Florence, Italy, in 2000 and 2004, respectively. From 2004 to 2010, he was a Research Associate at the University of Florence, Italy. From 2010 to 2019, he was an Assistant professor at the University of Bologna, Bologna, Italy. Since 2019 he has been an Associate Professor at the University of Bologna, Italy. He is the author of more than 130 published articles in international journals and conference proceedings. His research interests are Wireless Communications and Networks, Satellite Communications and Networks, Edge Computing, Fog Computing, Smart Cities, and Optimization Techniques. He has been involved in several national and international research projects and collaborates with several foreign research institutes. Prof. Tarchi has been an IEEE Senior Member since 2012. He is an Editorial Board member for IEEE Wireless Communications Letters, IEEE Transactions on Vehicular Technology, and IET Communications. He has been a symposium co-chair for IEEE WCNC 2011, IEEE Globecom 2014, IEEE Globecom 2018, and IEEE ICC 2020, and a workshop co-chair at IEEE ICC 2015.

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**Seema Verma**

Professor Seema Verma, a Scholar in the Electronics & Communication stream, is working as the Dean of the School of Aviation, Banasthali Vidyapith, India. She is associated with various scientific / professional societies, such as a Fellow of IETE, a Life Member of the Indian Science Congress, a Life Member of the Indian Society for Technical Education (ISTE), and member of the International Association of Engineers (IAENG). She has produced 25 Ph.Ds. Currently, 5 students are working on their doctoral work under her supervision in wireless sensors and ad-hoc networks (aircraft ad-hoc networks). She has authored close to 100 papers in various peer-reviewed journals & conferences. She has authored 6 books and has been granted 4 fully funded projects from DST, UGC, & AICTE. She has been granted with two Indian patents, has published 8 patents, and received 15 copyrights. She is a member of the expert committee of the National Board of Accreditation (NBA) & NAAC. She has been an expert in the Evaluation of research (Ph.D.) theses of various Indian

Universities. She is a recipient of the Young Professional Award by Govt. of Telangana, IBM Mentor Award, Certificate of Appreciation from Texas Instruments, Certificate of Excellence in Education, Digital Seal from Institute of Women of Aviation Worldwide[iWOAW], Global Education Excellence Awards, 2017, “Most Innovative Female Teacher of Electronics and Telecommunications in Rajasthan” by Prime Time news channel.

**Simon Watts**

Simon Watts is an experienced and commercially astute telecommunications system engineering / architecture leader with standards, project, and product management experience. Simon regularly presents and participates in discussion panels and has supported multiple technical papers at Avanti. He leads Avanti’s 5G and beyond technical activities and is the Avanti representative on GSOA’s 5G Standards Working Group; he attends the ETSI / SES / SCN working group, some 3GPP SA meetings, the IEEE INGR meetings, and others. He is a principal consultant at Avanti, working on EC, ESA, and national research and innovation projects covering many aspects of satellite communications. Before joining Avanti, he worked as Chief Engineer – Europe at Hughes and started his career at BT International.

**Halim Yanikomeroglu**

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# 12. ACRONYMS / ABBREVIATIONS

Table 73 contains acronyms and abbreviations. Please refer to the link below for a detailed glossary of satellite-related terms. Moreover, Table 74 lists the frequency bands the satellite community uses.

Daniel Minoli. "APPENDIX B: GLOSSARY OF KEY SATELLITE CONCEPTS AND TERMS" in the book Innovations in Satellite Communications and Satellite Technology, The Industry Implications of DVB-S2X, High Throughput Satellites, Ultra HD, M2M, and IP, pp.367-411, [Online] https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118984086.app2

*Table 73. List of Acronyms*

| ***Term*** | ***Definition*** |
|---|---|
| 1G-4G | First Generation to Fourth Generation |
| 3GPP | Third Generation Partnership Project |
| 5G | Fifth Generation |
| 5GAA | 5G Automotive Association |
| 5QI | 5G-QoS Identifier |
| A3C | Asynchronous Advantage Actor Critic |
| AAE | Adversarial AutoEncoders |
| AAU | Active Antenna Unit |
| ACK/NAK | Acknowledgment / Negative Acknowledgment |
| ACM | Adaptive Coding and Modulation |
| AE | AutoEncoders |
| AI | Artificial Intelligence |
| API | Application Programming Interface |
| AN | Access Network |
| ANN | Artificial Neural Network |
| ATD | Average Traffic Density |
| B2B | Business to Business |
| B2C | Business to Consumer |
| B5G | Beyond 5G |
| BS | Base Station |
| BSS | Business Support System |
| CAPEX | CAPital EXpenditure |
| CCN | Content-Centric Networking |
| CCSDS | Consultative Committee for Space Data Systems |
| CDMA | Code Division Multiple Access |
| CDN | Content Delivery Networks |

| ***Term*** | ***Definition*** |
|---|---|
| CN | Core Network |
| CNN | Convolutional Neural Network |
| COTS | Commercial Off-The-Shelf |
| CP | Control Plane |
| CO-OFDM | Coherent Orthogonal – Optical Frequency-Division Multiplexing |
| COTS | Commercial On The Shelf |
| CP-OFDM | Cyclic Prefix - Orthogonal Frequency-Division Multiplexing |
| CSI | Channel State Information |
| C/U | Control Plane / User Plane |
| CU | Centralized Unit |
| D2D | Device to Device |
| DAVID | DAta and Video Interactive Distribution |
| dB | deciBel |
| DevOps | Development and information technology operations |
| DFT | Discrete Fourier Transform |
| DFT-s-OFDM | Discrete Fourier Transform spread Orthogonal Frequency Division Multiplexing |
| DISA | Defense Information Systems Agency |
| DL | Deep Learning |
| DNN | Deep Neural Network |
| DoS | Denial of Service |
| DR-COOP | Disaster Recovery and Continuity of Operations |
| DRB | Data Radio Bearers |
| DU | Distributed Unit |
| DVB-S2 | Digital Video Broadcasting – Satellite – Second Generation |
| E2E | End-to-End |
| EAP | Edge Automation Platform |
| EHF | Extremely High Frequencies |
| EIVE | Exploratory In-Orbit Verification of an E/W band Satellite Communication Link |
| EM | Expectation Maximization |
| eMBB | enhanced Mobile BroadBand |
| eNB / eNodeB | evolved Node B (base station) |
| EPC | Evolved Packet Core |
| EPFD | Effective Power Flux Density |
| ESA | European Space Agency |

| ***Term*** | ***Definition*** |
|---|---|
| ESIM | Earth Stations In Motion |
| ETSI | European Telecommunications Standards Institute |
| EU | European Union |
| FCC | Federal Communications Commission |
| FDD | Frequency-Division Duplexing |
| FDMA | Frequency Division Multiple Access |
| FL | Federated Learning |
| FMIPv6 | Fast Mobile IPv6 |
| FPGA | Field Programmable Gate Array |
| FSO | Free Space Optics / Optical |
| GaN | Gallium Nitride |
| GBR | Guaranteed Bit Rate |
| GEO | Geostationary Earth Orbit |
| GFBR | Guaranteed Flow Bit Rate |
| GHz | GigaHertz |
| gNB / gNodeB | Next-generation NodeB (5G base station) |
| GMM | Gaussian Mixture Model |
| GNSS | Global Navigation Satellite Systems |
| GSMA | GSM (Groupe Speciale Mobile) Association |
| GSO | Geosynchronous Orbit |
| HAPs | High Altitude Platforms |
| HEO | Highly Elliptical Orbit |
| HIR | Heterogeneous Integration Roadmap |
| HTS | High Throughput Satellite |
| IEEE | Institute of Electrical and Electronics Engineers |
| IETF | Internet Engineering Task Force |
| IFFT | Inverse Fast Fourier Transform |
| IM/DD | Intensity Modulation / Direct Detection |
| IS | IP multi-Media Subsystem |
| INGR | IEEE International Network Generation Roadmap |
| IoT | Internet of Things |
| IP | Internet Protocol |
| IRDS | International Roadmap for Devices and Systems |
| ISA | Italian Space Agency |

| ***Term*** | ***Definition*** |
|---|---|
| ISG | Industrial Specification Group |
| ISL | Inter-Satellite Link |
| ISP | Internet Service Provider |
| ITALSAT | Italian Satellite |
| ITS | Intelligent Transport System |
| ITU | International Telecommunication Union |
| ITU-T | ITU Telecommunication Standardization Sector |
| km | Kilometers |
| KNN | K-Nearest Neighbor |
| KPI | Key Performance Indicator |
| LAA | Licensed Assisted Access |
| LEO | Low Earth Orbit |
| LDPC | Low-Density Parity-Check |
| LoS | Line-of-Sight |
| LR | Logistic Regression |
| LSM | Least Mean Square |
| LTE | Long-Term Evolution |
| M2M | Machine to Machine |
| MAC | Medium Access Control |
| MANO | Management and Network Orchestration |
| MEC | Mobile Edge Computing or Multi-access Edge Computing |
| MEMs | MicroElectroMechanical systems |
| MEO | Medium Earth Orbit |
| MFBR | Maximum Flow Bit Rate |
| MIMO | Multiple-Input, Multiple-Output |
| MIPv6 | Mobile IP version 6 |
| MitM | Man in the Middle |
| ML | Machine Learning |
| MLP | Multilayer Perceptron |
| mMIMO | Massive MIMO |
| mMTC | massive Machine-Type Communication |
| mmWave | Millimeter-Wavelength |
| MOS | Mean Opinion Score |
| MR | Merged Reality |

| ***Term*** | ***Definition*** |
|---|---|
| MTC | Machine Type Communication |
| MU | Multi-User |
| MVNO | Mobile Virtual Network Operator |
| mWT | Millimeter-Wave Transmission |
| NaaS | Network as a Service |
| NASA | National Aeronautics and Space Administration |
| NF | Network Function |
| NFV | Network Function Virtualization |
| NGMN | Next Generation Mobile Network |
| NGC | Next-Generation Core |
| NGEO | Non-Geostationary earth orbit |
| NGSO | Non-Geosynchronous Satellite Orbit |
| NIN | Non-IP Networking |
| NOMA | Non-Orthogonal Multiple Accesses |
| NR | New Radio |
| NS | Network Slicing |
| NSA | Non-Stand Alone |
| NTN | Non-Terrestrial Networks |
| OAM | Optical Angular Momentum |
| OEC | Orbital Edge Computing |
| OFDM | Orthogonal Frequency-Division Multiplexing |
| OIPLL | Optical Injection Phase-Lock Loop |
| OPEX | OPerational EXpenditure |
| OPNFV | Open Platform Network Function Virtualization |
| OSS | Operational Support System |
| OTA | Over The Air |
| OTFS | Orthogonal Time-Frequency Space |
| OTT | Over The Top |
| PAPR | Peak-to-Average Power Ratio |
| PAT | Pointing, Acquisition, and Tracking |
| PDB | Packet Delay Budget |
| PEP | Performance Enhancing Proxy |
| PGW | Packet GateWay |
| PHY | PHYsical layer |

| ***Term*** | ***Definition*** |
|---|---|
| PMIPv6 | Proxy Mobile IP version 6 |
| PoC | Proof of Concept |
| QFI | QoS Flow Identifier |
| QKD | Quantum Key Distribution |
| QoE | Quality of Experience |
| QoS | Quality of Service |
| RA | Reference Architecture |
| RAN | Radio Access Network |
| RCC | Root Raised Cosine |
| RE | Range Extension |
| RL | Reinforcement Learning |
| RF | Radio Frequency |
| RIS | Reconfigurable Intelligent Surface |
| RRM | Radio Resource Management |
| RSRP | Reference Signal Received Power |
| RSS | Received Signal Strength |
| Rx | Receiver |
| SATCOM | Satellite Communications |
| SBS | Small Base Station |
| SCaN | Space Communications & Navigation (NASA's testbed) |
| SCN | Satellite Communications and Navigation (ETSI working group) |
| SDN | Software-Defined Networking |
| SDGs | Sustainable Development Goals |
| SDO | Standards Developing Organization or Standards Development Organization |
| SDF | Service Data Flow |
| SDR | Software-Defined Radio |
| SEC | Satellite Edge Computing |
| SEF | Satellite Edge-computing Function |
| SES | Satellite Earth Station (ETSI working group) |
| SFC | Service Function Chaining |
| SIC | Successive Interference Cancellation |
| SIM | Subscriber Identification Module |
| SISO | Single Input - Single Output |
| SLA | Service Level Agreement |

| ***Term*** | ***Definition*** |
|---|---|
| SNF | Satellite Network Federation Function |
| SNR | Signal-to-Noise Ratio |
| SNS | Satellite Network Service |
| SON | Self-Optimizing Network |
| SU | Single User |
| SVM | Support Vector Machine |
| SVNO | Satellite Virtual Network Operator |
| SWaP | Size, Weight and Power |
| SWOT | Strengths, Weaknesses, Opportunities, Threats |
| TCP/IP | Transmission Control Protocol / Internet Protocol |
| TDD | Time-Division Duplexing |
| TDMA | Time Division Multiple Access |
| TSBS | Terrestrial Small Base Station |
| TSDSI | Telecommunications Standards Development Society India |
| TTI | Transmission Time Interval |
| TWTA | Travelling Wave Tube Amplifier |
| Tx | Transmitter |
| UAV | Unmanned Aerial Vehicle |
| UE | User Equipment |
| UP | User Plane |
| UPF | User Plane Function |
| URLLC | Ultra-Reliable Low Latency Communications |
| V2I | Vehicle to Infrastructure |
| V2V | Vehicle to Vehicle |
| vEPC | virtual Evolved Packet Core |
| VHTS | Very High Throughput Satellite |
| VLEO | Very-low-Earth-Orbit |
| VNF | Virtual Network Function |
| W-Cube | CubeSat-based W band channel measurements |
| WAVE | W band Analysis and Verification |
| WDM | Wavelength Division Multiplexing |
| WG | Working Group |
| WGS | Wideband Gapfiller Satellite |
| WR12 | Waveguide Rectangular 12 waveguides |

| ***Term*** | ***Definition*** |
|---|---|
| WRC | World Radiocommunication Conferences |
| WEP | Wired Equivalent Privacy |
| WG | Working Group |
| WPA | Wi-Fi Protected Access |

*Table 74. Radio Frequency Band Definitions (as Used by the Satellite Community)*

| ***Band*** | ***Frequency Range*** |
|---|---|
| S | 2 to 4 GHz (= IEEE definition, accepted in satellite work) |
| C | 3.6 to 7 GHz |
| X | 7 to 10.7 GHz |
| Ku | “K-under” = 10.7 to 18.3 GHz |
| Ka | “K-above”= 18.3 to 40 GHz (encompasses IEEE K band) |
| Q | 33 to 50 GHz (Near 40 GHz, overlaps adjacent bands) |
| V | 40 to 75 GHz (= IEEE definition, accepted in satellite work) |
| W | 75 to 110 GHz (= IEEE definition, accepted in satellite work) |

# APPENDICES

## Appendix A. 5G/6G Application for Border Control

The term “border control” is used in this section to imply activities carried out by governments to prevent illegal entry of people and cargo into the country, drug traffic, terrorism, transnational crime, and transportation of asylum seekers across national borders for profit. This is a vast set of activities involving multiple government agencies (e.g., agencies that conduct intelligence operations, screen visa applicants, interrogate travelers, inspect cargo arriving at ports, track drug traffickers, detect attempts to dig tunnels, etc.). They are making increasing use of smart sensors and surveillance devices. They are almost certain to become major users of tools for data mining, complex event processing, and natural language processing within this decade.

The flow of information, which means acquiring and processing intelligence data in our case, is a critical factor in the border control operations sketched out above. Most of the unfortunate events that have occurred in the recent past could have been avoided by adopting the 5G/6G technology with suitable use cases also supported by ITU-R in IMT-2020[A1].

### Primary Challenge

In the case of border control, an alliance of agencies responsible for border control in countries worldwide, like the 5G Automotive Association[A2], is missing. It is necessary to form such an alliance, develop the concept of operations, determine the need for frequency allocations to meet the QoS requirements, and identify critical areas for R&D.

### Secondary Challenge

Most of the border areas, farms cultivating drugs, training camps for terrorists, and paths followed by aircraft and boats for drug smuggling, lie in areas that are not covered by terrestrial communication systems. For these, it makes sense to adopt UAVs, HAPs, and LEO satellites providing 5G connectivity in these areas to support agencies’ activities.

### Solution to the Primary Challenge

The system architecture has to be built around:

- A cloud federation at the core containing private clouds belonging to individual agencies and public clouds
- Edge clouds can support low latency applications at the frontline and condense information generated by sensors before it is sent to the core, conserving bandwidth and maintaining the security
- Back-haul system suitable for the required QoS
- Application packages needed to provide customized reports for situational awareness to decision-makers and lookout lists to frontline staff
- Analytical tools for performance evaluation
- Data archival for use in future forensic analyses and process improvement

### Solution to the Secondary Challenge

5G LEO satellites, linked with commercial cloud services, can provide a fast and cost-effective connection to law enforcement agencies in any country with information sources worldwide for monitoring events. Information sources include international agencies like Interpol *(see Figure 68)*.

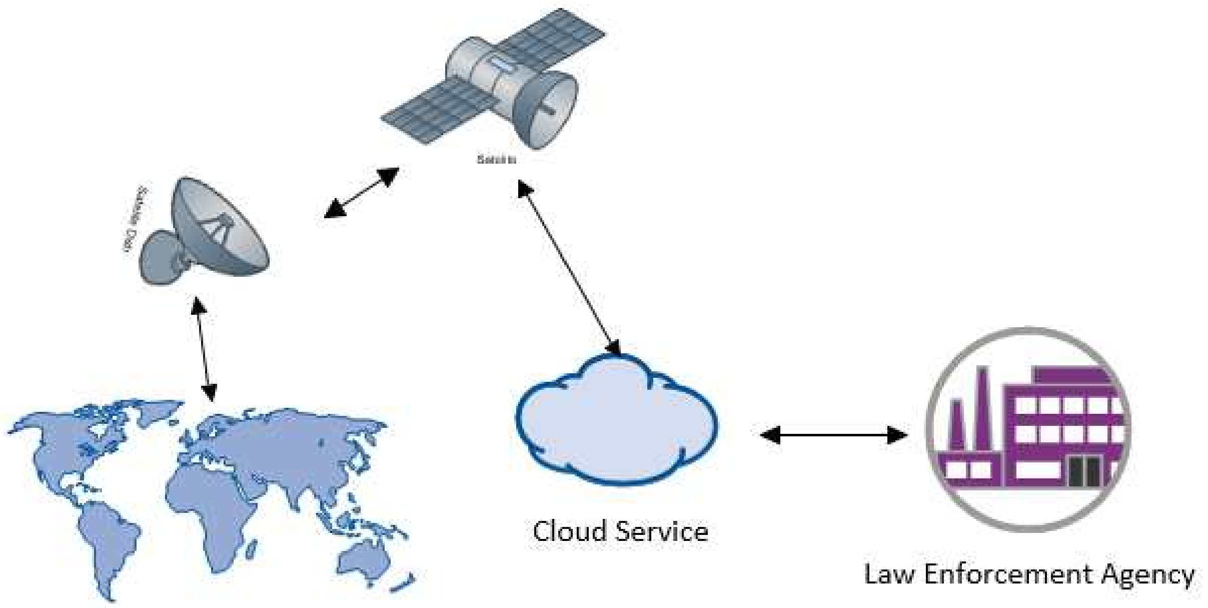


*Figure 68. Use of 5G LEO Satellites and Cloud Service*

### References for Appendix A:

[A1] Recommendation ITU-R M.2083-0, “IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond,” September 2015.

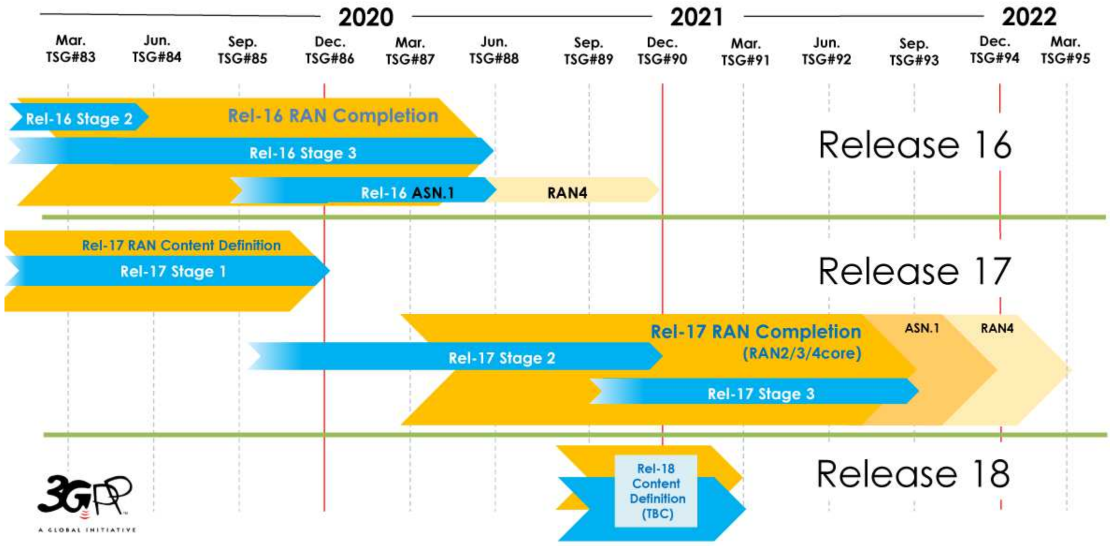
[A2] 5GAA Vision and Mission, https://5gaa.org/about-5gaa/vision-mission/

# Appendix B. Standardization

This section briefly summarizes 5G and B5G standards activities, specifically referring to Non-Terrestrial Networks (NTN) by organizations like 3GPP, IEEE, ITU, 5GPP, and ETSI.

## B-1 3GPP Activities

Release 17 has addressed NTN for 5G systems, which adopt satellites to support under-served areas (e.g., isolated / remote areas, onboard aircraft, or vessels). Figure 69 shows the 3GPP plan for standards development. The status of the 5G standardization of 3GPP can be monitored in the reference[B1].



Source: 3GPP TSG SA#87e, 17-20 March 2020, e-meeting document SP-200222

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*Figure 69. Evolution of 3GPP Standardization in Releases*[B2]

The most important 3GPP WGs that deal with SATCOM technologies are RAN1 (Layer 1), RAN3 (Interfaces), SA1 (Services), and SA2 (Architecture). During Releases 15 and 16, 3GPP studied the feasibility and standard adaptations needed to enable NR communication over satellite systems (NTN), as shown in Table 75.

*Table 75. 3GPP TR Documents on SATCOM*[B3]

| *Technical Report ID* | *Impacted Specification* | *Title* | *WG, Release #* |
|---|---|---|---|
| TR 23.737 | N/A | Study on architectural aspects of using satellite access in 5G | SA2, Rel 17 |
| TR 38.811 | N/A | Study on NR to support non-terrestrial networks | RP/RAN1, Rel 15 |
| TR 22.822 | TS 22.261 (Rel 18) | Study on using satellite access in 5G | SA1, Rel 16 |
| TR 38.821 | N/A | Solutions for NR to support non-terrestrial networks | RAN2/3, Rel 16 |
| TR 22.829 | N/A | Enhancement for UAVs | SA, Rel 17 |
| TR 22.819 | N/A | Feasibility study on maritime communication services over 3GPP system | SA1 |

NTN Release 17 was frozen on June 2022. It envisages a transparent satellite architecture (both GEO and LEO). Use cases are eMBB (5G-NR) and IoT (eMTC and NB-IoT). The UE will have GNSS capabilities. GNSS positioning will help synchronize and estimate Timing Advance, mobility, etc., but may not always be available, e.g., for IoT-oriented lower-cost devices. The UE will have FDD mode using the frequency range 1 below 6 GHz. The tracking area is earth-fixed. The radio cells from the satellite can be both earth-fixed or earth-moving. The target of Release 17 has been to achieve a minimum set of modifications for NTN to address long propagation delays, large Doppler effects, and moving NTN radio cells. Release 17 also covers NG-RAN architecture enhancements, related procedures, and service continuity from TN to NTN and NTN to TN systems. The satellite is transparent in Release 17 with two possible architectures: direct satellite access and satellite back-haul. NG-RAN architecture enhancements are envisaged to support NT. The radio part (satellite and UE) specifications are for S-/L bands.

TR 23.737, TR 38.811 (NR for NTN), and TS 22.261 describe architectural and service requirements. The following Release 17 documents describe satellite-related activities.

- 5GSAT_ARCH, "Integration of Satellite Components in the 5G Architecture," whose outputs can contribute to documents (TR/TS) 23.501, 23.502, 23.503, and 23.737.
- FS_5GSAT_MO, "Study on Management and Orchestration Aspects with Integrated Satellite Components in a 5G Network," whose outputs can contribute to documents (TR/TS) 28.808 and 28.805.

The 3GPP working groups involved are 5GSAT_ARCH (SA2), IoTSAT_ARCH (SA5), 5GSAT_ARCH_CT (CT1), NR-NTN-solutions (RAN), and LTE_NBIOT_eMTC_NTN (RAN).

Highlights from the five technical reports mentioned in Table 75 are provided below:

- **TR 22.822:** Provides 12 use cases for 3 service categories of 5G SATCOM, namely service continuity, service ubiquity, and service scalability. It recommends functional requirements for each use case, including, e.g., latency issues.
- **TS 22.261:** Adapts 5G SATCOM requirements as part of overall 5G system requirements. It includes 11 Change Requests (CRs) from 5GSAT WG.
- **TR 38.811:** Provides the first comprehensive technical study on the feasibility of 5G NR for 3GPP non-terrestrial networks. The evaluation includes, e.g., Doppler shifts, delays, antenna patterns, and channel models. For instance, the one-way delay can be up to 270 ms for GEO systems while as low as about 1-2 ms for a HAP system. It recognized key impact areas on 5G NR to support non-terrestrial operation are related to propagation channels, frequency planning, power limitations, network cell pattern modeling, delay characteristics, mobility of users and infrastructure, service continuity, and radio resource management with minimal response time.
- **TR 38.821:** This report (Release 16) addresses how 5G can be adapted to use satellite. It is a comprehensive document that addresses aspects such as architectures, layer 1 issues, random access protocols, mobility management, regulatory issues (interference), satellite orbital aspects, and RAN recommendations. The following architecture alternatives are considered for NTN:
  - Direct access / transparent satellite / GW + gNodeB
  - Direct access / regenerative satellite + gNodeB / GW
  - Direct access / regenerative satellite + gNodeB-DU / GW + gNodeB-CU

    - Multi-connectivity with terrestrial path and satellite one or two satellite paths
- **TR 23.737**: It provides reference satellite integration scenarios and architectural assumptions, with terrestrial and satellite core networks and satellite back-haul scenarios. Challenges and solutions are investigated in the following aspects:
    - Mobility management with large satellite coverage areas
    - Mobility management with moving satellite coverage areas
    - Delay in satellite
    - QoS with satellite access: what are the impacts on the QoS of a 5GS system when introducing satellite access
    - RAN mobility with non-geostationary regenerative-based satellite access
    - Multi-connectivity with satellite access
    - The role of satellite link in content distribution towards the edge
    - Multi-connectivity with hybrid satellite / terrestrial back-haul (multi-homing)
    - Regulatory services with super-national satellite ground station.
- **TR 22.819**: It considers maritime communication services as one of the 3GPP vertical applications and proposes a use case on satellite access to support maritime communication services over a 5G system.

3GPP is progressing in standardizing 5G and beyond [B4]. This will be carried out not simply as interworking, intended as independent cellular and satellite networks can exchange information through standardized interface with/without interworking function. We are considering a real integration, where mobile networks and satellite networks can be combined to achieve a common goal (e.g., seamless global coverage). The target users are handsets, IoT devices, vehicles, drone-mounted devices, vessels, and aircraft-mounted devices. Integration of satellite with mobile systems is now possible with 3GPP Release 17 NTN standard: the same stack protocol can handle both the satellite access (NTN) and the terrestrial access (TN). This standard results from a joint effort between stakeholders of both the mobile and satellite industries, who both find benefits. Satellite helps terrestrial mobile in providing global service continuity and resiliency. Terrestrial mobile systems enable satellites to access a unified and large ecosystem and drive down costs.

### B-1.1 Next Releases 18 and 19

Release 18 works on NTN in two WGs as follows[B4]:

- SA2 WG:
    - eMBB (5G-NR):
        - Network verified UE location
        - Support of a back-haul with changing delay
        - Support of UPF on GEO satellite
    - IoT (4G eMTC/ NB-IoT)
        - Discontinuous coverage (e.g., paging enhancements, UE wake-up, power saving)

- RAN WGs:
    - eMBB (5G-NR):
        - Coverage enhancements
        - NR-NTN deployment in above 10 GHz bands and support for VSAT / ESIM
        - NTN-TN and NTN-NTN mobility and service continuity enhancements
        - Network verified UE location
    - IoT (4G eMTC / NB-IoT)
        - Disabling HARQ feedback
        - Mobility enhancements
        - Discontinuous coverage enhancements
        - Improved GNSS operations

The detailed time plan for Release 18 is shown in Figure 70. NTN Release 18 is expected to be completed by the first quarter 2024.

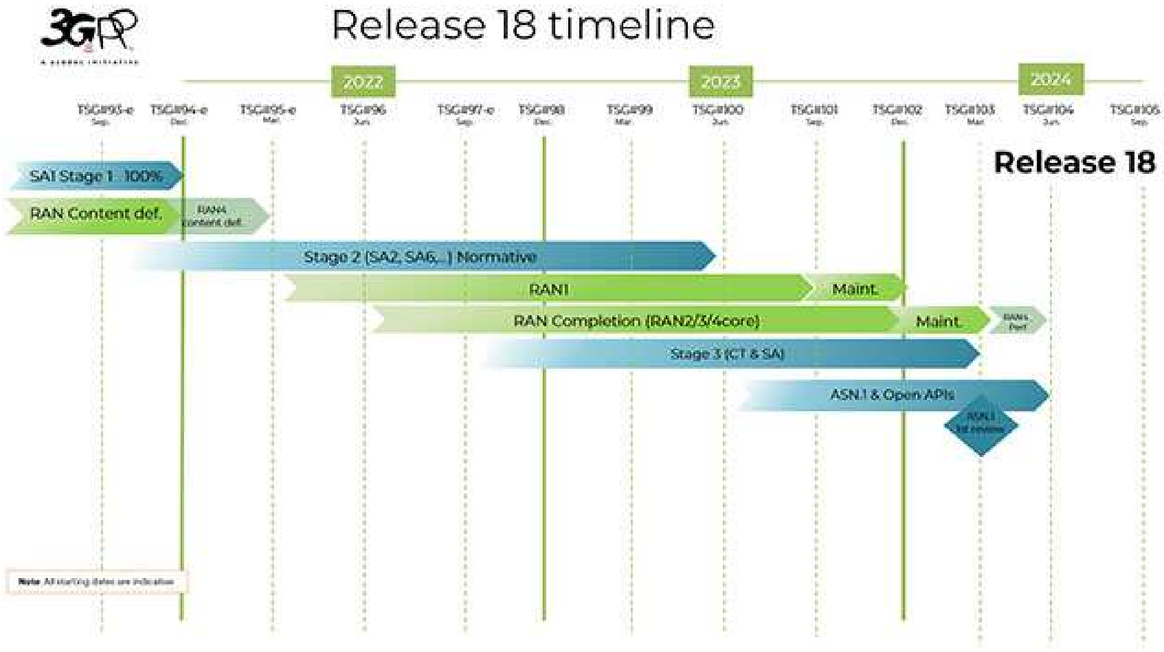

*Figure 70. Release 18 Schedule*

Release 18 will also address the radio part (satellite and UE) specifications for >10 GHz bands.

Release 19 and beyond will cover satellite 6G, which is intended as a unified system with terrestrial and satellite parts. 6G is meant for the unification with native support of multi-connectivity and mobility across TN / NTN access technologies. The NTN will be multilayer multi-orbit multi-band (UAVs, HAPS, LEO, MEO, GEO). In Release 19, the satellite will have a regenerative payload with onboard edge computing to support Artificial Intelligence and Machine Learning.

The ESA Alix project[B5] project has established a Satellite Standardization Interest Group (SSIG) working with 3GPP and ETSI toward future satellite systems. SSIG aims to allow stakeholders to exchange information about satellite-related standards activities for integrating satellites into the 5G ecosystem to improve mutual understanding and collective effectiveness. SSIG has more than 50 participants, including industries, operators, universities, and research institutions. The SSIG vision is that satellite networks have specific characteristics with respect to capacity, reliability, availability, resiliency, and broadcast / multicast capabilities. Satellite technologies have also evolved to significantly reduce the cost of satellite systems and increase flexibility in using their resources. Standards play an important role in achieving this integrated network vision. As such, there are significant benefits in aligning satellite technologies as appropriate with relevant (terrestrial) network standards (including, but not limited to, 3GPP). The SSIG activities aim to develop a standardization plan supporting the integration of satellites in 5G and beyond 5G setting out relevant groups and their key objectives and milestones. In particular, it will provide strategic guidance to relevant standardization activities in 3GPP and related standardization groups.

## B-2 IEEE Standards Activities on UAVs / Drones

The current standards in progress in IEEE on UAVs / drones are detailed below.

- IEEE P1936.1 - Standard for Drone Applications Framework

  This standard establishes a framework for the support of drone applications. It specifies drone application classes and application scenarios and the required application execution environments.

- IEEE P1937.1 - IEEE Draft Standard Interface Requirements and Performance Characteristics for Payload Devices in Drones

  This standard presents general interface requirements and performance characteristics of payload devices in drones. It describes the drone payload interfaces in three categories: Mechanical, electrical, and data. A mechanical interface is used to fix the payload to the drone. The electrical interface is an electromechanical device used to join electrical terminations. The electrical interface includes the power supply interface and the two-way communication interface. The data interface refers to the communication protocol. This standard defines interfaces, performance metrics, provisioning, operation control, and management for drone payload devices. This standard mainly specifies payload interface requirements for small and light drones.

- IEEE P1937.3 - Protocol for the Flight Data Transmission of Civil Unmanned Aerial Vehicle Based on BeiDou Short Message

  This standard specifies the general requirements for the content of flight data and transmission protocol of civil unmanned aerial vehicle systems based on the BeiDou short message protocol. No draft is available for this standard.

- IEEE P1939.1 - Standard for a Framework for Structuring Low Altitude Airspace for Unmanned Aerial Vehicle (UAV) Operations

  This standard defines a structure for low-altitude airspace that enables safe and efficient UAV traffic management. It defines UAV capabilities and related infrastructure for UAVs to comply with low-altitude air space regulations.

## B-3 ITU Standardization

According to ITU, the 5G system is called IMT-2020. The IMT-2020 network architecture is envisioned to be access network-agnostic and with a core network common to Radio Access Technologies (RATs) for IMT-2020 and existing fixed and wireless networks. The IMT-2020 core network should be accompanied by common control mechanisms that are decoupled from the access network technologies. The IMT-2020 network should support new RATs for IMT-2020, evolved IMT-advanced RATs, wireless LAN (WLAN) access networks, fixed broadband network access, and satellite networks.

ITU-R has determined those candidate technology submissions assessed by ITU-R to be the qualified IMT-2020 technologies and meet the key technical criteria underpinning the IMT-2020 Vision and global 5G. In July 2020, 3GPP 5G was formally endorsed as ITU IMT-2020 5G Standard. ITU-R Recommendations of the M family refer to 5G systems. The first release of IMT 2020 by ITU-R WP 5D will be provided in a new ITU-R Recommendation, "Detailed specifications of the radio interfaces of IMT-2020", ITU-R M. IMT-2020.SPECS.

A series of ITU-R Recommendations (standards) for the satellite component of IMT has already been developed, including the integration of the terrestrial and satellite mobile communication systems[B6]:

- Rec. ITU-R M.818 – "Satellite Operation within International Mobile Telecommunications-2000 (IMT2000)"
- Rec. ITU-R M.1167 – "Framework for the Satellite Component of International Mobile Telecommunications-2000 (IMT-2000)"
- Rec. ITU-R M.1182 – "Integration of Terrestrial and Satellite Mobile Communication Systems"
- Rec. ITU-R M.1850 – "Detailed Specifications of the Radio Interfaces for the Satellite Component of International Mobile Telecommunications-2000 (IMT-2000)"
- Rec. ITU-R M.2014 – "Global Circulation of IMT-2000 Satellite Terminals"

## B-4 World Radio Conference (WRC-19)

WRC-19 took place in Sharm El. Sheikh, Egypt, Oct 28 - Nov 22, 2019, and 3540 delegates from 165 countries attended. The members have taken the following decisions:

- 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 station within the frequency band 17.7-19.7 GHz (space to earth) and 27.5-29.5 GHz (earth to space).
- Allocation to the fixed service in the bands 31-31.3 GHz, 38-39.5 GHz identified for worldwide use by HAPs. Confirmed the existing bands 47.2-47.5 GHz and 47.9-48.2 GHz are available for worldwide use of HAPs.
- Regulatory frameworks for sharing between GSO and non-GSO satellite systems in the 50/40 GHz range.
    - 37.5 - 42.5 GHz (space-to-earth)
    - 47.2 - 50.2 GHz (earth-to-space)

  - 50.4 - 51.4 GHz (earth-to-space)
- Sharing between GSO FSS, BSS & MSS, and non-GSO FSS satellite systems
- Milestone-based deployment process to avoid spectrum warehousing by large non-GSO satellite filings
- New regulation adopted: non-GSO systems have to deploy 10% of the constellation within 2 years, 50% within 5 years and complete the deployment within 7 years.

### B-5 Preparation of World Radio Conference (WRC-23)

The following aspects will be discussed at WRC-23 as a prosecution of related work in WRC-19:

- The use of HAPS as IMT Base Stations (HIBS) for the mobile service in certain frequency bands below 2.7 GHz already identified for IMT on a global or regional level;
- To harmonize the use of the frequency band 12.75-13.25 GHz (earth-to-space) by earth stations on aircraft and vessels communicating with GEO space stations in the fixed-satellite service globally;
- To study regulatory measures to facilitate the use of the frequency bands 17.7-18.6 GHz, 18.8-19.3 GHz and 19.7-20.2 GHz (space-to-earth) and 27.5-29.1 GHz and 29.5-30 GHz (earth-to-space) by NGSO FSS ESIM, while ensuring due protection of existing services in those frequency bands;
- To determine the appropriate regulatory actions for the provision of inter-satellite links in specific frequency bands or portions thereof by adding an inter-satellite service allocation where appropriate;
- To consider studies relating to spectrum needs and potential new allocations to the mobile-satellite service for future development of narrowband mobile-satellite systems.

### B-6 ETSI Activities

ETSI is interested in 5G, even if not directly related to the satellite components[B7]. ETSI is investigating several component technologies that will be integrated into future 5G systems, such as NFV, MEC, Millimeter Wave Transmission (mWT), and Non-IP Networking (NIN).

In particular, as for NFV, ETSI has currently provided Release 4, including NFV-MANO, power management, and an orchestration tool that can facilitate network slicing, an interesting option for the satellite 5G.

Within ETSI, the Alix project consortium has led the development of TR 103.611 “Satellite Earth Stations and Systems (SES); Seamless integration of satellite and/or HAPS (High Altitude Platform Station) systems into 5G system and related architecture options” in TC-SES / SCN WG (SCN TC-SES DTR / SES-00405 ETSI TR 103 611, December 2018). Moreover, Alix is leading the development of a TR “Satellite Earth Stations & Systems (SES); DVB-S2x / RCS2 versus 3GPP New Radio protocol technical comparison for broadband satellite systems”- as part of DTR / SES-00456 work item in TC-SES / SCN WG.

Other ETSI documents:

- ETSI, “Edge Delivery in 5G through Satellite Multicast,” ETSI TR TBD, SCN TC-SES DTR / SES-00447, June 2019.
- ETSI, “Reference Virtualized Network Functions Data Model for Satellite Communication Systems,” ETSI TR TBD, SCN TC-SES DTR / SES-00446, March 2019.

### B-7 5G PPP

The 5G PPP is a joint initiative between the European Commission and the European ICT industry. The 5G PPP will deliver solutions, architectures, technologies, and standards for the ubiquitous 5G communication infrastructures. Within the 5G-PPP, many cross-project working groups identify shared issues and develop supported program-level positions on technical and strategic items. Among the currently active working groups, there is one “Pre-Standardization” to identify standardization and regulatory bodies to align with, e.g., ETSI, 3GPP, IEEE, and other relevant standards bodies.

5G PPP has elaborated a white paper. We refer here to version 3 of June 2019 [B8]. This document is based on 3GPP Releases 15 and 16. 5G PPP adopts a programmable network, according to ETSI MANO. Architecture options are discussed. As for the satellite, it is said that “… we consider the use of satellite communications as part of the 5G network acting as a transport network that provides connectivity between areas.” In particular, four use cases only based on satellite back-haul for 5G are provided as follows and based on the SaT5G H2020 EU project’s outcome.

- Use Case 1: “Edge delivery & offload for multimedia content and MEC VNF software”
- Use Case 2: “5G fixed back-haul”
- Use Case 3: “5G to premises”
- Use Case 4: “5G moving platform back-haul”

### References for Appendix B:

[B1] 3GPP Work Program, Web page with URL: http://www.3gpp.org/DynaReport/GanttChart-Level-2.htm#bm

[B2] 3GPP, Releases, Web page with URL: https://www.3gpp.org/specifications/67-releases

[B3] A. Anttonen, P. Ruuska, M. Kiviranta, “3GPP Non-Terrestrial Networks: A Concise Review and Look Ahead,” VTT Technical Research Centre of Finland. VTT Research Report, No. VTT-R-00079-19, January 2019.

[B4] N. Chuberre, “3GPP NTN Standardization: Past, Current and Future,” Presentation at the INGR satellite WG meeting of November 24th, 2021.

[B5] ALIX Project “Support to Standardisation of Satellite 5G Component,” with URL https://artes.esa.int/projects/alix

[B6] ITU-R Recommendations (M-series); Web site with URL: http://www.itu.int/ITU-R/go/rec-m

[B7] ETSI, 5G, Web page available at the following URL: https://www.etsi.org/technologies/5g

[B8] 5G PPP, “View on 5G Architecture,” white paper Version 3.0, June 2019; Online with URL: https://5g-ppp.eu/wp-content/uploads/2019/07/5G-PPP-5G-Architecture-White-Paper_v3.0_PublicConsultation.pdf

## ANTITRUST STATEMENT

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