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ABSTRACT

The fifth generation (5G) Wireless Communication systems development has brought out a paradigm shift using advanced technologies e.g., softwarization, virtualization, Massive MIMO, ultra-densification and introduction of new frequency bands. However, as the societal needs grow, and to satisfy UN's Sustainable Development Goals (SDGs), 6G and beyond systems are envisioned. Non-Terrestrial Networks including satellite systems, Unmanned Aerial Vehicles (UAVs) and High-Altitude Platforms (HAPs) provide the best solutions to connect the unconnected, unserved and underserved in remote and rural areas in particular.

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, there is a considerable renewed interest in planning and developing non-GSO satellite systems. Within the next few years several thousands of Low Earth Orbit (LEO) satellites and mega LEO constellations will be ready to provide global Internet services.

This report is the 2022 Edition of the INGR Satellite Working Group Report, subsequent to the previous two editions [1] [2]. The topics considered in this INGR Satellite WG 2022 Edition of the roadmap are the following taking 6G systems into account: applications and services, reference architectures (both backhaul and direct access), satellite IoT, mmWave use for satellite networks, machine learning and artificial intelligence, edge computing, QoS/QoE, security, network management and standardization. The work on the roadmap will continue towards the next edition of the roadmap addressing new challenges and potential solutions for future networks.

Key words
Satellite Communications, Satellite Networks, Waveforms, MIMO, mmWave, OFDM, QoS, QoE, Security, Network Architecture, LEO, MEO, GEO, HAP, UAV, MEC, AI/ML, IoT

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INGR ROADMAP

1. INTRODUCTION

Numerous applications and verticals including machine-to-machine communications, mobile broadband, virtual and augmented reality demonstrated the vast potential of fifth generation (5G) wireless communications, and it is in full swing around the world. The emerging applications such as precision agriculture, health care and autonomous cars dictate the research of 6G and beyond to provide global connectivity and satisfying the UN's Sustainable Development Goals (SDGs). Recent ITU estimates consider that 2.9 billion people are still offline (37% of the world's population) showing an important recent boost caused by the COVID emergency, but still having world's poorest left far behind. Non-Terrestrial Networks (NTN) including satellite systems, Unmanned Aerial Vehicles (UAVs) and High-Altitude Platforms (HAPs) provide the best solution to connect the unconnected, unserved and underserved in remote and rural areas. These systems play a significant role in 5G and 6G as a complementary solution for ubiquitous coverage, broadcast, multi-cast provision, emergency and disaster recovery.

This is the 2022 Edition of the IEEE International Network Generation Roadmap (INGR). This edition describes various needs, challenges in achieving these needs and the potential solutions towards 6G satellite systems. This satellite roadmap 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 11.

1.1. 2022 Edition Update

The 2022 Edition of the satellite roadmap has been revised, updated and improved in all its parts. The most significant updates are provided in Sections 4, and 5. In particular, we would like to highlight the modifications as follows:

- In Section 4.2, we have studied the satellite use case scenario considering satellite backhaul access, satellite direct access and satellite IoT.
- Section 5.4 contains a new study focusing on mmWave adoption in satellite systems.
- A complexly revised part on security for satellite 5G/6G systems has been provided in Section 5.9
- Section 5.10.17 addresses management issues for software-defined satellite networks.
- In Section 7.2.1, mmWave-band space communications are considered an important future direction in the study of satellite 6G systems.
- Appendix B contains an update overview of the current standardization progress of satellite 5G systems including the most recent works in 3GPP Releases 17 and 18.

All the aspects included in this 2022 Edition of the satellite report are very strategic for the satellite industry.

2. WORKING GROUP VISON

During the past several decades, Geostationary Earth Orbits (GEO) and Geosynchronous Orbits (GSO) satellites have been launched supporting broadband Internet, disaster recovery and backhauling services. A few Low Earth Orbit (LEO) satellite systems like Skybridge, Teledesic, Iridium, Globalstar and Odyssey were developed and only some of them have been survived today. However, nowadays there is a tremendous, renewed interest and demand for global Internet connecting the unconnected, in planning several of LEO satellites systems called Mega Constellations or in general non-GSO systems. As per the vision of successful technology within the next 10 years with high bandwidth, low latency and dense connectivity, results in the following verticals shown in Table 1.

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

Verticals	***Drivers***	***Enablers***
Healthcare	• Remote and Rural diagnosis • Surgery and treatment	• Video streaming • VR/AR/Mixed Reality • Advanced Robotics • THz band communications
Autonomous Cars	• Advanced sensors • Laser scanners • THz arrays for 3D images	• Terrain mapping • Route optimization • Safety
Manufacturing	• Intelligent industrial automation • Novel sensing	• Autonomous equipment • Data analytics • Massive IoT
Precision Agriculture	• Non-Terrestrial Networks • Ubiquitous wireless access	• Soil moisture measurements • Precise monitoring of plant illness, temperature, humidity
Education	• Remote access • Imaging processes	• Video streaming • AR/VR/XR
Smart Infrastructure	• Intelligent communications • Powerline communication	• IoT sensor networks • Pervasive AI • Automation
Non-Terrestrial Networks	• MEO/LEO Constellation • UAV, HAP • Navigation systems	• Space IoT • Terrestrial off loading • AI/ML
Space based Hosting Services	• Ultra-low latency web services • Rural access to global knowledge base	• Emergence of high bandwidth satellites • Deployment of Ultra-Dense LEO/MEO satellite networks • Enhanced computing and storage capability of various types of satellites platforms

Satellite-based IoT Services	• Low latency satellite-based IoT service provisioning • Low-cost low delay operations • Rural and suburban coverage	• Agricultural sensor networks • Marine sensor networks • Remote monitoring

To make both GSO and non-GSO systems successful in the next 10 years, new satellite components will be implemented. Note that the evolution of satellite technology is commonly slower than the terrestrial because of the spatial constraints for building the satellite so that the life cycle of the satellite technology is longer than that of terrestrial wireless technologies.

The satellite industry must address the following issues to make the planned systems successful.

- New innovation business models for 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 considering atmospheric attenuation at high frequency bands
- Performance and cost tradeoffs for the intersatellite 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
- Integration of the terrestrial and satellite networks using the Software Defined Networking and Network Function Virtualization
- Integrated network architecture to meet the new service needs with the 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 (resource, routing, handover, and mobility) and mobile edge computing and their impact on system design

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

The application areas where current satellite communication networks play a key role are illustrated in Figure 1 below. One may expect these uses to continue and even be augmented in the Beyond 5G (B5G) era [3].

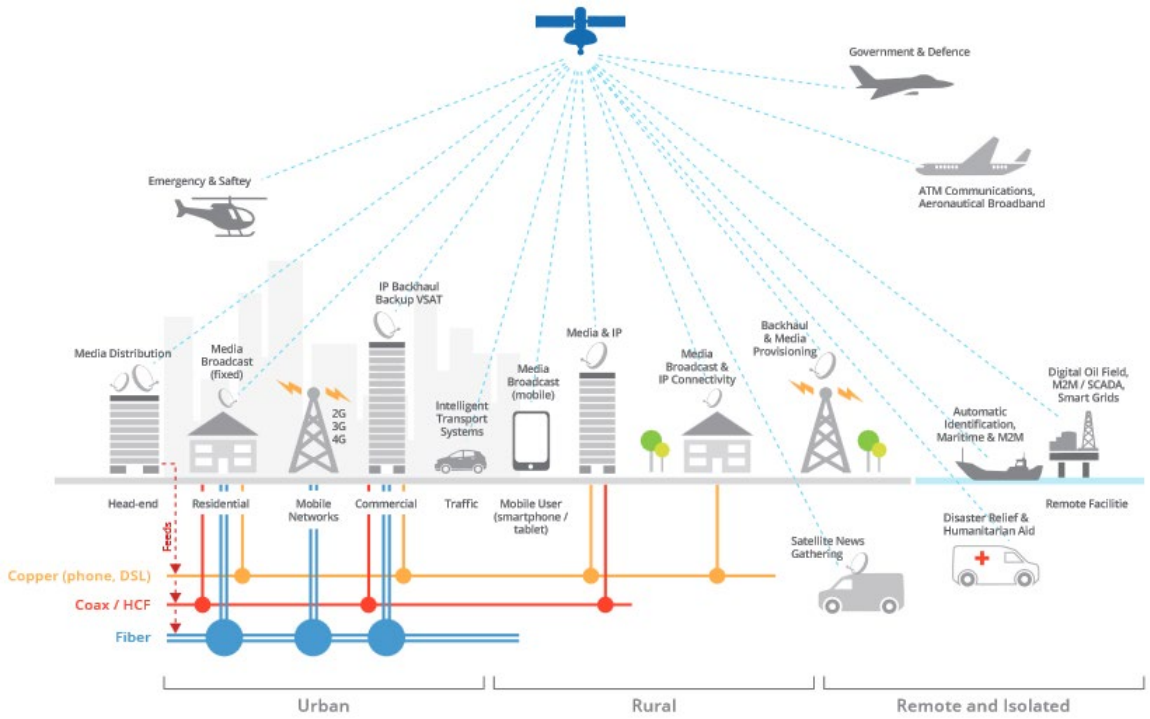


Figure 1. Communications application domains typically addressed by satellite networks.

Reference: ESOA 5G White Paper [3]

ITU (and others) have categorized wireless communication services with the use case triangle illustrated below in Figure 2 [4].

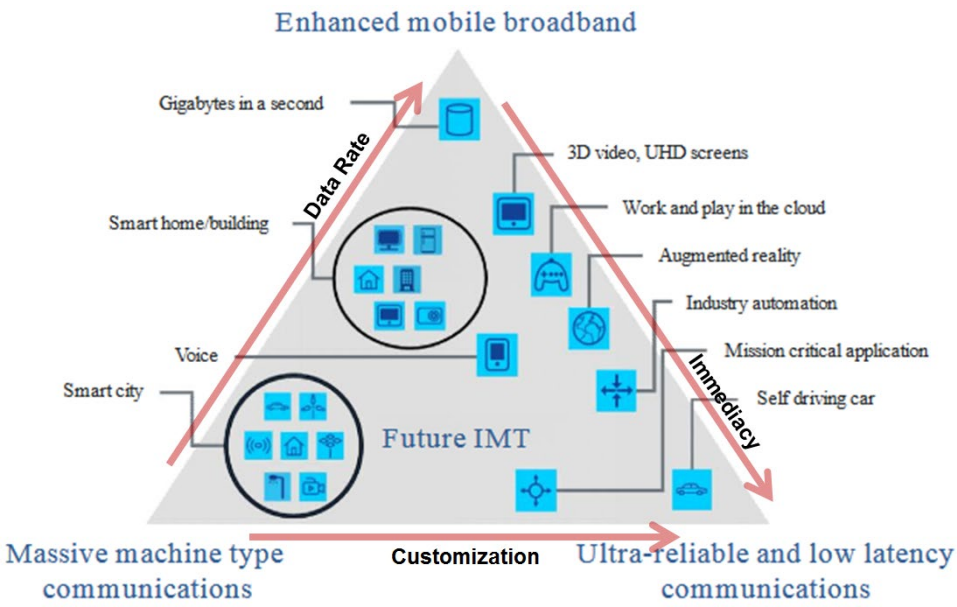


Figure 2. Modern Wireless Use Cases. Reference: IMT-2020/1-E, enhanced by present authors [4]

Note that along each edge of Figure 2's triangle, a general characteristic change as one gets closer towards a vertex of the triangle. When users are remote, moving or have otherwise challenged terrestrial connectivity (for instance, needing simultaneous broadcast to millions), satellite communications provide a suitable solution.

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 coverages. Thus, the improvement of 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.

2.1. Scope of Working Group Effort

Table 2 describes various topics covered in this 2022 Edition and their scope is briefly described.

Table 2. Topics and Descriptions

Topic	*Scope*
Applications & Services	5G/6G satellite applications for urban, rural and remote areas. Need to expand for the current 5G to the future 6G applications and services. New services such as Space-based Hosting Services can be considered or lowering the latency of web services over Non-Terrestrial Networks
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 near-

	term (3 years), separate virtualized for mid-term (5 years) and integrated virtualized for 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 UE to satellite propagation delay and access delays, also QoS requirements and architecture are discussed
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. Also, SDN and NVF are discussed
Standardization	Current status on 3GPP, ITU, ETSI, IEEE standardization activities on 5G satellite and NTN networks is discussed. WRC-19 decisions & WRC-23 plans are discussed

2.2. Linkages and Stakeholders

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

- Industry manufacturers, e.g., SpaceX, TeleSat, O3B, One Web, CubeSat, Lockheed Martin, Loral Space, ViaSat, iDirect
- User communities
- Regulators – Federal Communications Commission (FCC)
- Space Agencies – e.g., NASA, ESA, ISRO, DLR, JAXA
- Governments – Defense Information Systems Agency (DISA)
- Standard Development Organization (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), Research Institutions and Laboratories.

The satellite working group interacts with other areas in INGR as shown in Figure 3 by cross-cut matrix for the 2022 Edition of this report.

	1. Massive MIMO	2. mmWave & Signal Processing	4. Energy Efficiency	5. Edge Services	6. Satellite	7. Optics	8. Standardization Building Blocks	9. Testbed	10. System Optimization	11. Deployment	12. Applications & Services	13. Security and Privacy	14. Connecting the Unconnected	15. Artificial Intelligence/ Machine Learning
INGR Working Group Name	**ACCESS**			**NETWORKS**			**SYS. & STANDARDS**			**ENABLERS & USERS**				
ACCESS														
1. Massive MIMO		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
2. mmWave & Signal Processing	✓		✓		✓		✓	✓		✓	✓	✓		
4. Energy Efficiency	✓	✓			✓		✓		✓	✓	✓		✓	✓
NETWORKS														
5. Edge Services	✓				✓	✓	✓	✓			✓	✓	✓	✓
6. Satellite	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓
7. Optics	✓			✓	✓		✓			✓	✓	✓		✓
SYS & STANDARDS														
8. Standardization BB	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
9. Testbed	✓	✓		✓	✓		✓		✓	✓	✓	✓	✓	✓
10. System Optimization			✓				✓	✓			✓	✓	✓	✓
USERS & ENABLERS														
11. Deployment	✓	✓	✓		✓	✓	✓	✓			✓	✓		✓
12. Applications and Services	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
13. Security and Privacy	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
14. Connecting the Unconnected			✓	✓	✓		✓	✓	✓		✓	✓		
15. AI/ML			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

Figure 3. Cross-cut matrix (blue color cells refer to meetings carried out this year for the 2022 edition of the report)

3. TODAY'S LANDSCAPE

3.1. Current State of Technology and Research

Geostationary satellites at 36,000 km above the earth currently used as High Throughput Satellite (HTS). A HTS provides a capacity (throughput) that is many times that of a traditional satellite system (up to 200 Gbps satellite capacity). A HTS can provide more than 10 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 on 2017) : Ka-band GEO satellite, 40 gateways (GWs), 300 Gbps total network capacity
- Viasat-3 (expected in 2022): Three Ka-band GEO satellites, More than 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, 6 fully steerable beams to point at traffic hotspots. GX5 will allow download speeds more than 60 Mbps with a latency of around 600 ms.

However, non-GSO such as Medium Earth Orbits (MEO) and LEO systems have become the recent innovation in satellite systems. This potential 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 digital economy is in demand. Currently operating and planned non-GSO systems are shown in Table 3.

Table 3. Current and Planned non-GSO Systems [5]

Characteristics	'Other 3 billion' O3b (SES)	Starlink (SpaceX)	Lightspeed (Telesat)	Amazon (Kuiper)	OneWeb
Data Rate	1 Gbps	Tests Q2 2021: Download 100 Mbps (median); Upload 14 Mbps (median) Expectations: Download 10 Gbps	Download (min, req.): 50 Mbps Upload (min, req.): 10 Mbps	Download: 400 Mbps (prototype 2021)	Download up to 200 Mbps (tests 2021); Upload up to 40 Mbps (tests 2021)
No. of Satellites	12 (a second mPOWER system to start to deploy with 24 MEO and 16 LEO on inclined orbit)	1844 as of November 2021. Planned to 12000 (extension to 42000)	Planned to 298	Planned to 3236 (possibly upgraded to 7774)	358 as of October 2021. Planned to 648.
Latency	140 ms	Tests Q2 2021: 35-45 ms	Expected 30 to 50 ms	Low latency	Below 70 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 220 inclined orbit satellites (1325 km)	LEO/590-630 km (3 shells)	LEO near-polar circular orbits/1200 km / no ISLs
Frequency Band	Ka	Ku, Ka	C, Ka, Ku	Ka	Ka/Ku
Scheduled Status	2013-2019	2020	2023	2026-2029	End of 2021

The current landscape is not only non-GSO systems, but also includes Non-Terrestrial Networks (NTNs), that are composed of UAVs and HAPs. There currently exist several case studies of non-terrestrial connectivity deployments in different countries. Recently, HAPs technology is acquiring an important role in 5G-satellite integration. HAPs should have a long endurance and are as such designed to stay aloft for months using either drones with relatively big wings in the case with the Airbus Zephyr project [6] or balloons like in the case with the Alphabet's Loon [7] initiative. The HAPs can be solar or hydrogen-powered [8] and fly in an energy-efficient fashion in order to lift the heaviest possible payload carrying on the top of telecom equipment, a variety of other tools such as cameras, radar, etc. for suitable applications

3.2. Drivers and Technology Targets

MEO satellites between 8,000-20,000 km altitude and LEO satellites between 400-2,000 km altitudes provide latencies of 5-50 ms for LEO, 100-150 ms for MEO, respectively. 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.

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

HAPs can be used to provide both fixed broadband connectivity and mobile user connectivity for backhauling traffic. HAPs normally are at an altitude of 20-50 km and provide broadband connectivity and telecommunication services particularly in communities, rural and remote areas that are underserved. This use of HAPs has become more viable due to technology evolution through 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 5 of the report.

3.3. Satellite 5G Deployment Challenges/Bottlenecks/Barriers from the Market Standpoint

After ten years of commercial LTE use globally, 5G rollout is now proceeding with haste. However, "networks in space" are now also playing a critical role in a different kind of connectivity landscape – the rise of LEO satellite providers.

SpaceX, NASA, Amazon and OneWeb are each investing billions in satellite offerings. Couple this with the slew of other new options like 5G and neighborhood Wi-Fi via offerings like Amazon Sidewalk, secure access options when working from home, and private enterprise networks. If we have a hard time moving simply between Wi-Fi and cellular now, what does that mean for our future with the satellite connectivity completing a unified connectivity ecosystem for global access?

Are we at the start of a race between ground and satellite communications networks? It is an excellent question for commercial use cases. Cooperation Strategies and Alliances are already forming as we see the accelerated performance and connectivity innovations in HAP & LEO's while 5G and 6G evolutions occur in tandem. There is now absolutely no commercial doubt that market share of communications traffic involving satellites is likely to grow significantly thanks to 5G/6G inter-domain connectivity, with over-satellite communications filling a vacuum currently unserved for remote connectivity for personal, maritime, commercial, logistics, education, agriculture, exploration and industrial use cases.

Spectrum allocation to satellite players is of course a similar challenge as is the spectrum allocation to 5G operators. Alliances need to be sorted out to be truly integrated. So, is this "Pie in the Sky"? Indeed not, though there are winners and losers as commercial objectives test out technology challenges as well as environmental and legal barriers. Time will tell who the real winners and losers will be. But a lot of hurdles need to be jumped yet.

The following part of this section reviews the most recent updates from the market standpoint, also including some indication of new technological opportunities.

Satellite Industry Consolidation

In July 2021, Amazon has acquired a team of employees from Facebook focused on delivering internet connectivity from LEO satellites. This team will join Amazon to work on Project Kuiper. The move brings an end to Facebook's efforts to provide internet connectivity to remote areas via its satellites.

In November, there were eight major acquisitions. The biggest was the announced US$ 7.3 Billion purchase of Inmarsat by ViaSat. The combination of the two companies creates a powerhouse in key

vertical markets such as mobile services, aeronautical and maritime, among others. The combined company will have spectrum licenses in Ka-, L-, and S-bands and a fleet of 19 satellites currently in service, with an additional 10 satellites planned in the next three years. ViaSat previously acquired Rignet, a major service provider in the oil and gas business.

Nearly 3 Billion Still Have No Internet Access

In November, the International Telecommunications Union (ITU) released a report that revealed that an estimated 37% of the world's population–or 2.9 billion people–still never used the Internet. This bodes well for satellite companies, especially the new NGSO constellations aiming to bridge the digital divide. It also presents a challenge since 97% of those with no Internet access are in developing countries. What is significant about this figure is that it had not changed much since the early 2000s, when a certain satellite startup called the "Other 3 Billion" (O3b) aimed to close the gap.

Some satellite operators have made it their mission to connect the unconnected. Satellite operator Kacific has made some inroads in the Asia-Pacific region with their all Ka-band satellite Kacific-1 and another satellite planned in the next three years. But with nearly three billion unconnected people, clearly much more needs to be done to bridge the digital divide,

New Technologies

In April this year, a seven-company consortium led by Airbus Defense and Space announced a plan for an in-orbit satellite factory that will assemble a satellite in space. This manufacturing in space concept follows many other innovations introduced in the last few years, such as in-orbit servicing and software-defined satellites, which will fundamentally change how satellites are manufactured, launched, and operated.

Current mega-LEO systems are basically providing access via VSATs, not direct access to the satellites. This is because of the size of the terminal antenna and the link budget needs. The Starlink terminals consist of a Wi-Fi router and a small satellite dish which the company's official installation guidelines call "Dishy McFlatFace".

However, 3GPP standardization is already addressing direct satellite access. Moreover,

Lynk has filled in May this year a license with FCC to operate a constellation of 10 small satellites expected to increase to 5000 with the scope to provide 'cell towers in the space'. Lynk uses LEO satellites, just like Starlink and OneWeb, but the difference is that it establishes a direct connection straight to devices, as opposed to using a terrestrial hub

Space Tourism Takes Off

The high-profile space flights carrying media-savvy Billionaires generated widespread interest in space among the general public. In July 2021, Virgin Galactic launched its first commercial sub-orbital flight with Billionaire founder Richard Branson and five other passengers on board. This was followed by Blue Origin's successful flight with Billionaire Jeff Bezos just nine days later. SpaceX, meanwhile, sent four civilians on a three-day orbital mission in September. By the end of the year, there were several other sub-orbital flights that followed, making it seem that it will be a regular occurrence in the coming years. It certainly is an interesting time to be in the space and satellite industry.

Various Headlines

July '21 Hybrid Satellite System - Inmarsat announced plans to create a 'multi-orbit' constellation called Orchestra, intensifying competition in an increasingly crowded market in space. The UK-based satellite operator aims to add a terrestrial 5G network and a small constellation of LEO satellites to its existing and planned group of satellites in geostationary orbit. The primary ambition of the new hybrid network is to increase Inmarsat's ability to provide low-latency, high-bandwidth connectivity, especially in congested network hotspots around the world, such as airports and ports.

Aug '21 Speeds - Starlink's overall speeds continue to outpace those of fellow satellite broadband services ViaSat and HughesNet, but its median download speeds in the US are starting to enter the neighborhood of fixed-line broadband networks according to Ookla's latest round of Speedtest data. Ookla's data for Q2 2021 found that Starlink's median download speeds in the US climbed to 97.23 Mbps, up from 65.72 Mbps in Q1 2021. By comparison, HughesNet's median download speed in the US clocked in at 19.73 Mbps in Q2 2021 (up from 15.7 Mbps in Q1 2021), while Viasat's was 18.13 Mbps in Q2 2021 (up from 17.67 Mbps) in the prior quarter. Then, Starlink's overall speeds continue to outpace those of other satellite broadband services, starting to approach the performance of fixed-line broadband networks.

Aug '21 IoT & Satellite - SpaceX has acquired a startup called Swarm Technologies (Palo Alto, California) that is targeting the Internet of Things (IoT) sector with similar technology. This acquisition appears to be a move by SpaceX to add IoT expertise to its team.

Sept '21 Satellite providing complementary coverage - OneWeb has secured a key customer for its emerging LEO satellite broadband platform, announcing that AT&T will use it to provide satellite-based connectivity to business customers and government customers in Alaska and states in the northern continental US. This way, AT&T intends to extend its reach in hard-to-serve areas that fall outside of AT&T's fiber footprint or are beyond the reach of AT&T's network of cell towers. OneWeb's satellite-based platform will effectively "complement" AT&T's existing access technologies.

ESA has recently launched the initiative "Space for 5G and 6G" based on the 5G/6G Hub at Harwell in the UK. This Hub is a place for collaboration and innovation, where industry will take advantage of the immense potential of converged satellite and terrestrial telecommunications networks to create advanced applications that benefit society and the environment.

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. Machine to machine communication will have a dramatic impact on QoS requirements for satellite 6G.

4. Future State (2032)

4.1. Vision of Future Technology

The vision of 6G will be that of enabling new societal needs as per the UN’s SDGs, which cannot be fully satisfied by the 5G. The 6G network is envisioned to be pervasively intelligent, reliable, scalable, terrestrial network and providing global broadband connectivity integrating terrestrial networks, NGSO, UAVs, and HAPs.

Future 6G systems, will adopt new technologies as:

- Mega constellations
- 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.

Table 4 provides key performance indicators, comparing 5G and 6G (referring to terrestrial systems)

Table 4. Key Performance Indicators (Reference: N. Rajatheva et.al, White Paper on Broadband Connectivity in 6G)

KPI	5G	6G
Peak data rate	20 Gbps	1Tbps
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

4.2. Architectural Framework, Use Cases, and Reference Architecture

Table 5 provides reference architectural framework for near-term (3 years), mid-term (5 years), and long-term (10 years). These are further detailed in Section 4.2.3.

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 works as a traffic carrier or tunnel for the UE/SBS traffic to the rest of the 5G infrastructure	Satellite networks and 5G terrestrial networks are virtualized separately.	Satellite networks and 5G terrestrial networks are virtualized and integrated.

4.2.1. Non-Terrestrial Elements Considered

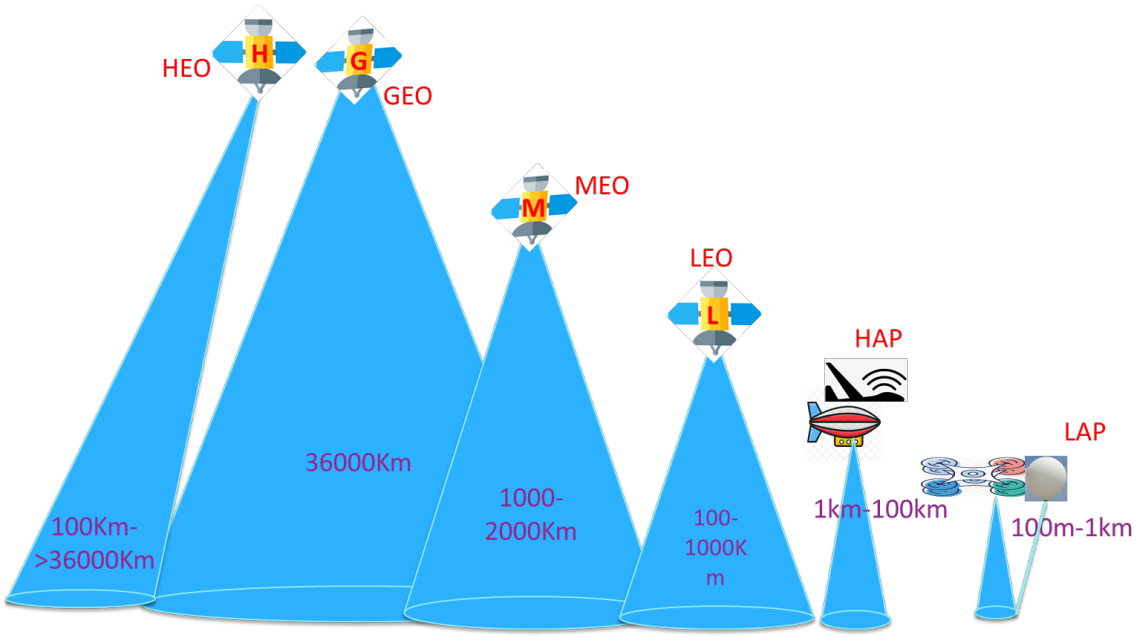


Figure 4. Non-Terrestrial Network elements considered in this report

The 2022 Edition of the satellite roadmap focuses 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 4 illustrates the NTN elements. Table 6 represents the approximate orbital altitude.

Table 6. NTN Elements and Altitude Range

Type of NTN	**Name**	**Approximate orbital altitude**
LAP	Low Altitude Platforms	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 5 illustrates all the cases studies which 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.

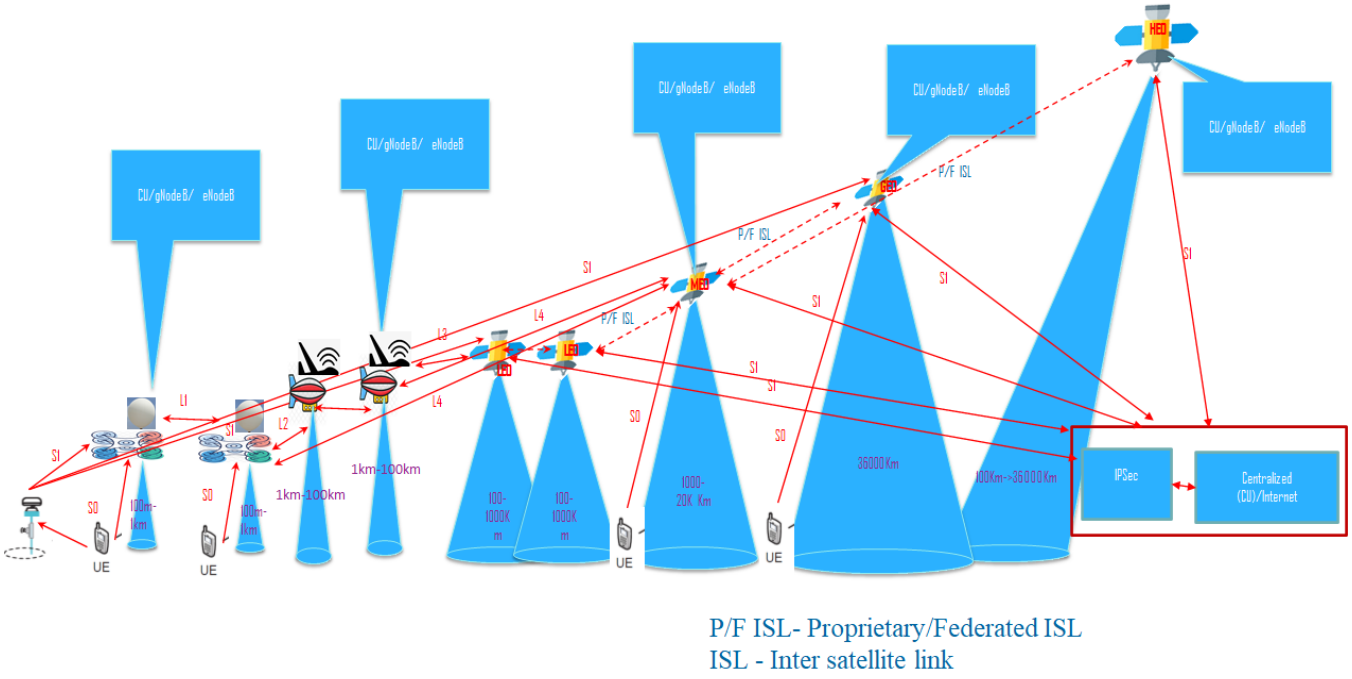


Figure 5. Representation of all use cases that will be addressed in the next sub-sections

4.2.2. Use Cases for Satellite Networks as Backhaul for 6G Terrestrial Networks

The 2021 Edition (Edition 2) of the satellite chapter focuses on the use of satellite network infrastructure as backhaul infrastructure for 5G terrestrial networks. This section further enhances the 2021 Edition to suit the 6G requirements. The potential use cases where the satellite networks or UAVs can be used for direct access are also included in the 2022 Edition.

The following use cases are identified for satellite networks as backhaul:

1. **Use Case-1:** DU to CU Bent Pipe/1-hop relay over a LEO satellite
2. **Use Case-2:** DU to CU over Multi-hop LEO non-federated Network
3. **Use Case-3:** DU to CU over Multi-hop Federated Network
4. **Use Case-4:** bent pipe/1-hop relay to DU to Gateway
5. **Use Case-5:** DU to Gateway backhaul over multi-hop LEO non-federated network
6. **Use Case-6:** DU to Gateway backhaul over multi-hop federated LEO network

7. **Use Case-7:** Terrestrial SBS to LEO bent-pipe/1-hop relay To eNodeB/eNodeG
8. **Use Case-8:** Terrestrial SBS to eNodeB/eNodeG over LEO multi-hop non-federated network
9. **Use Case-9:** Terrestrial SBS to eNodeB/eNodeG over LEO multi-hop federated LEO
10. **Use Case-10:** UAVs as bentpipe/single-hop relay
11. **Use Case-11:** UAV multi-hop backhaul
12. **Use Case-12a-b:** UAV-LEO Integrated multi-hop backhaul

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

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

In the 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 6 illustrates the Use Case-1.

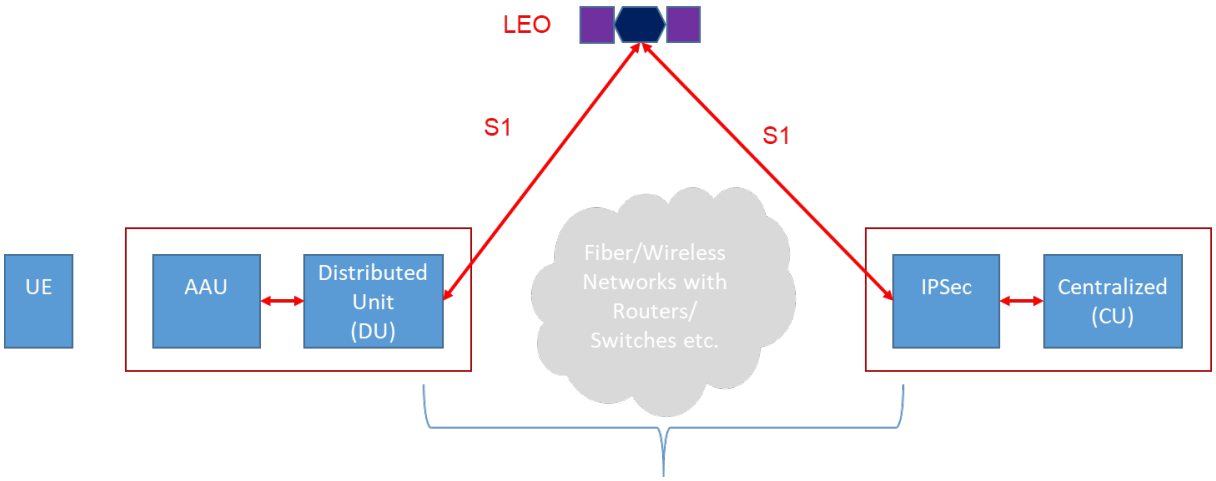


Figure 6. Use Case-1

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

The use case-2 considers the communication between DU and CU through multi-hop LEO satellite network where the inter-satellite links are proprietary, and, therefore, the satellite segment is considered as a non-federated satellite network. Figure 7 illustrates Use Case-2. The interface required or DU-Satellite and Satellite-CU communication is S1.

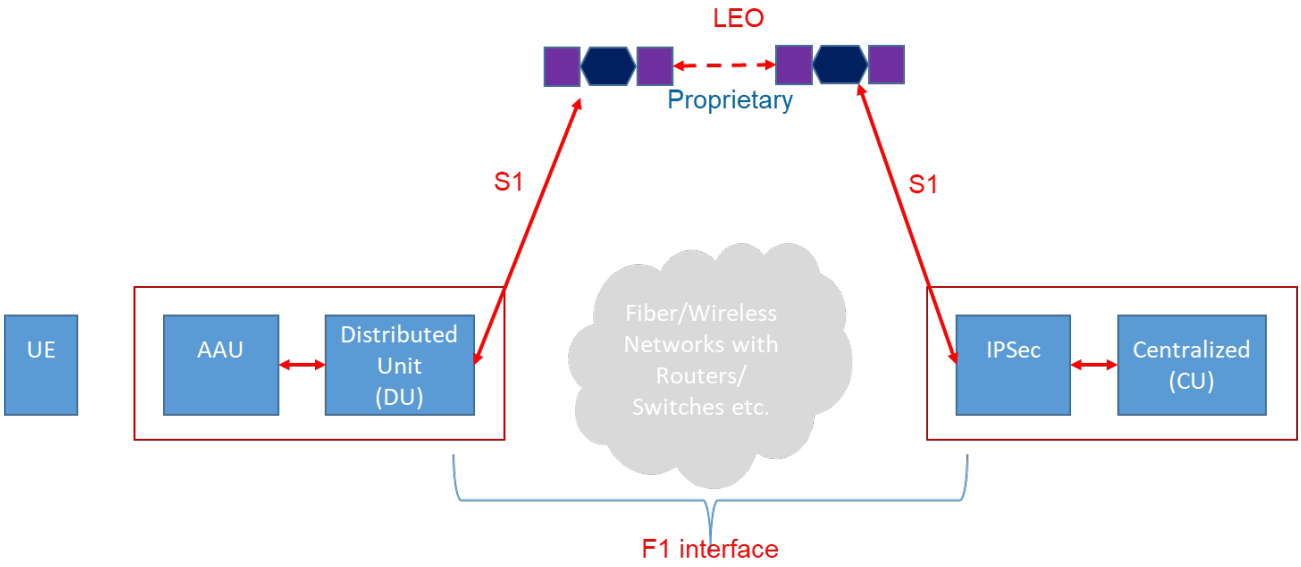


Figure 7. Use Case-2

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

The 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. The interface S2 shall be defined as a standard interface in order to ensure the communication between satellite networks owned and operated by multiple service providers. Figure 8 illustrates Use Case-3.

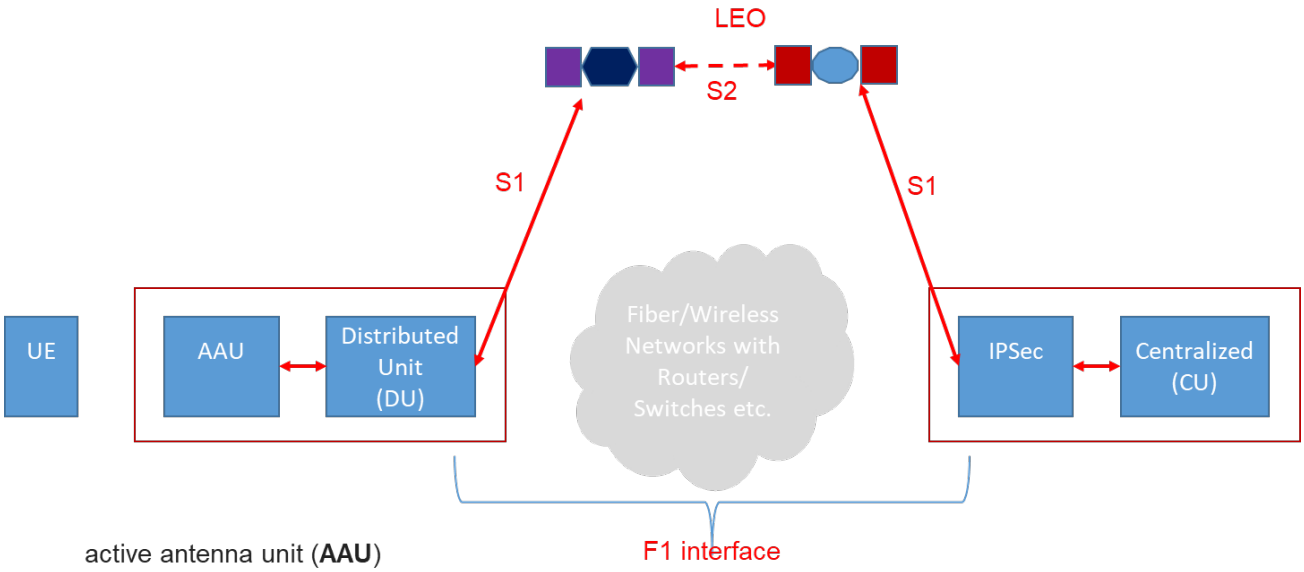


Figure 8. Use Case-3

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

Use case-4 considers the bent pipe/1-hop communication between the DU to CU through the Satellite Network Service (SNS) provider's gateway infrastructure and the wired network. Figure 9 illustrates Use Case-4. Here the bandwidth requirements of the communication session between the DU and CU will be considered in order to transfer the data between the gateway and the CU effectively.

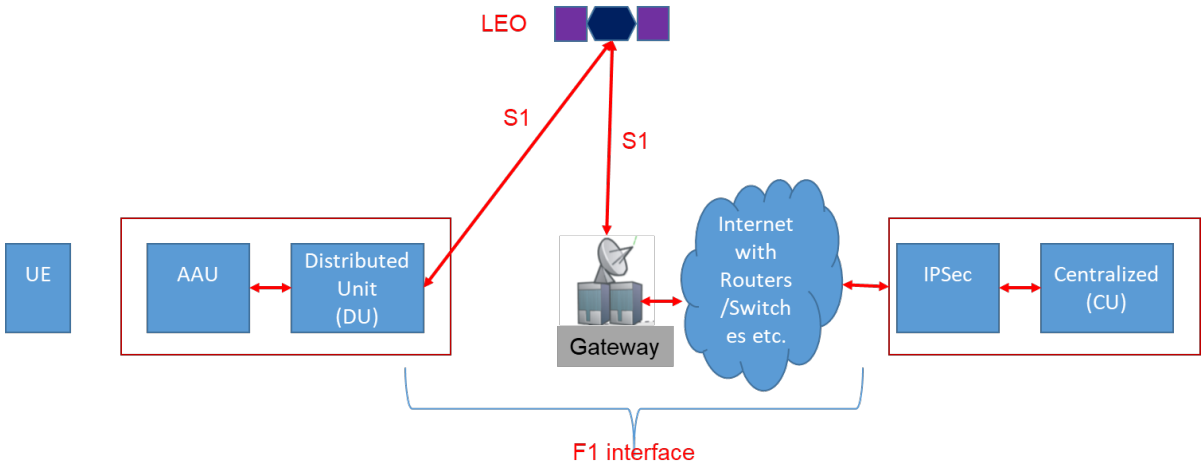


Figure 9. Use Case-4

4.2.2.5. Use Case-5: DU to Gateway backhaul over multi-hop LEO non-federated network

The 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. Figure 10 illustrates Use Case-5. 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.

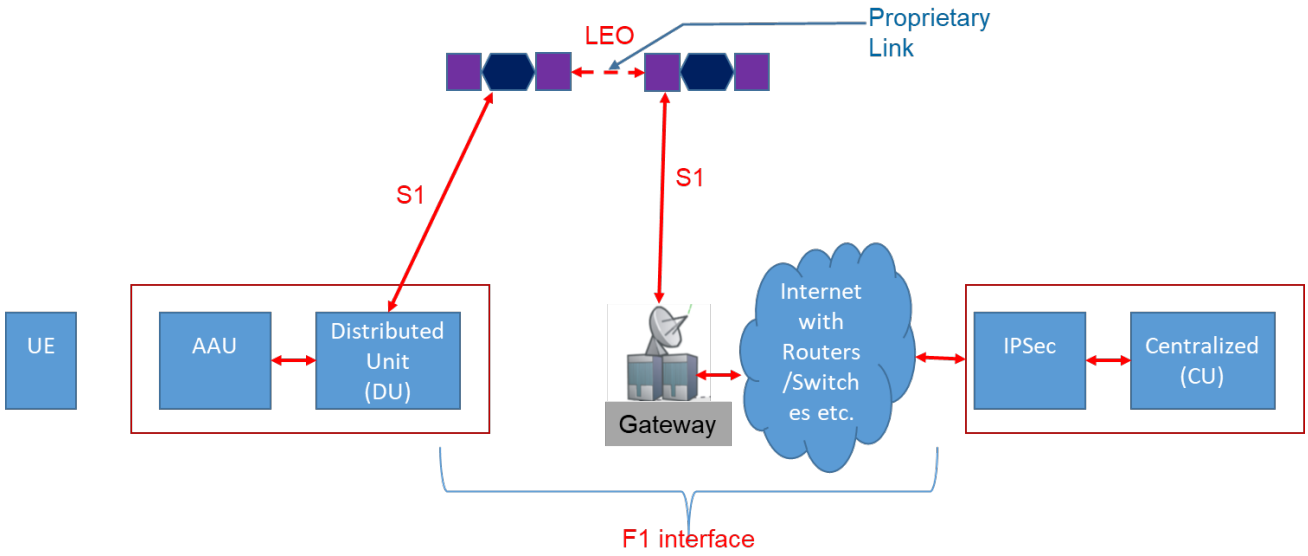


Figure 10. Use Case-5

4.2.2.6. Use Case-6: DU to Gateway backhaul over multi-hop federated LEO network

Use case-6 refers to the multi-hop communication between the DU and CU through the federated LEO satellite networks and through 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 in order to achieve federated communication between the satellite networks belonging to multiple satellite service providers. Figure 11 illustrates Use Case-6.

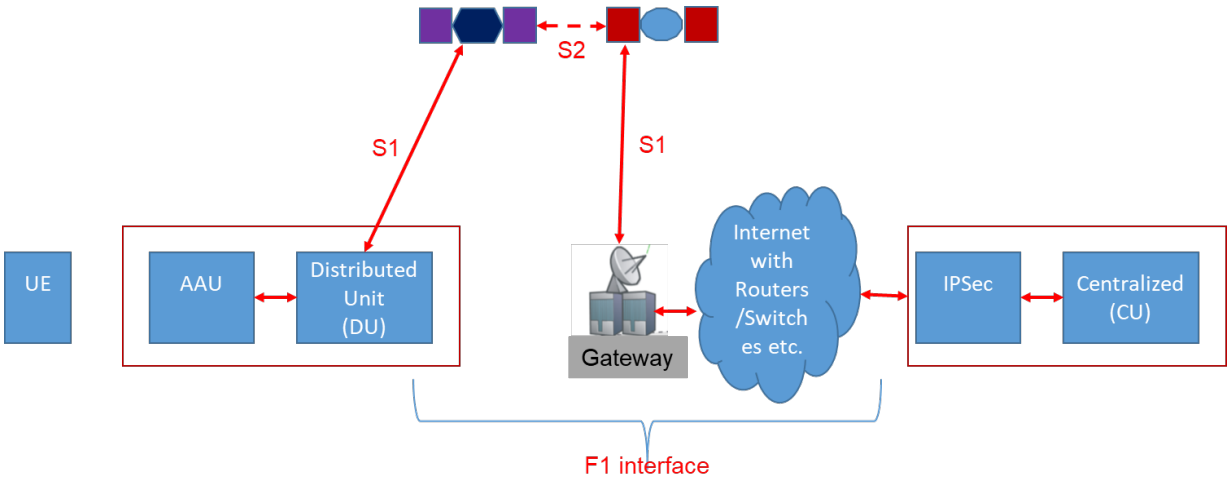


Figure 11. Use Case-6

4.2.2.7. Use Case-7: Terrestrial SBS to LEO bent-pipe/1-hop relay To eNodeB/eNodeG

Use case-7 involves the communication between the Terrestrial Small Base Station (TSBS) and eNodeB/eNodeG over a single satellite operating in bent-pipe or 1-hop relay mode. The TSBS and the eNodeB/eNodeG shall use the S1 interface for communication. Figure 12 illustrates Use Case-7.

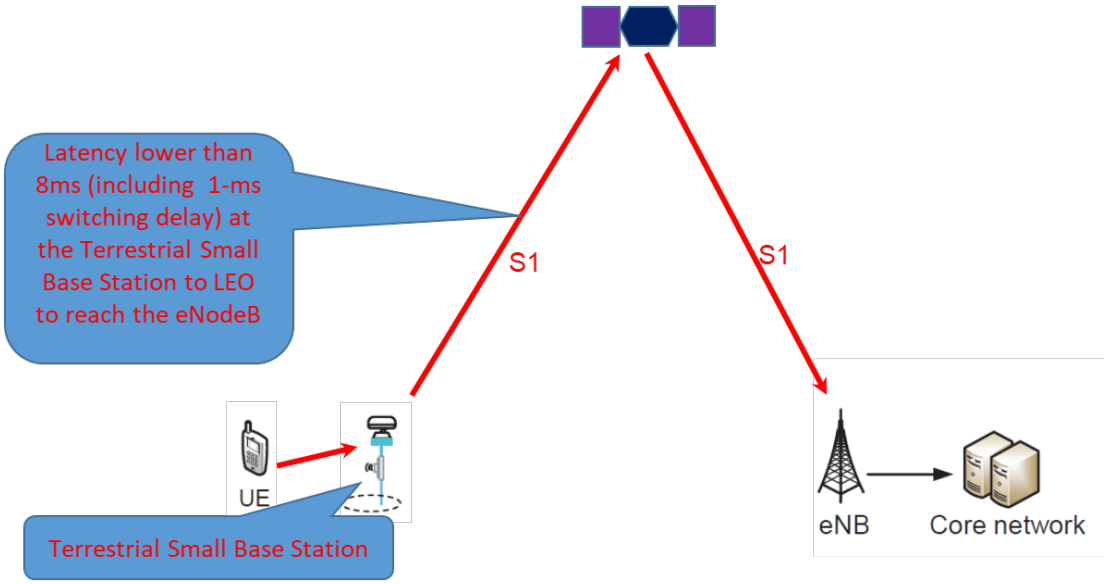


Figure 12. Use Case-7

4.2.2.8. Use Case-8: Terrestrial SBS to eNodeB/eNodeG over LEO multi-hop non-federated network

Use case-8 considers the multi-hop communication between the TSBS and eNodeB/eNodeG over a non-federated LEO satellite network. Figure 13 illustrates Use Case-8.

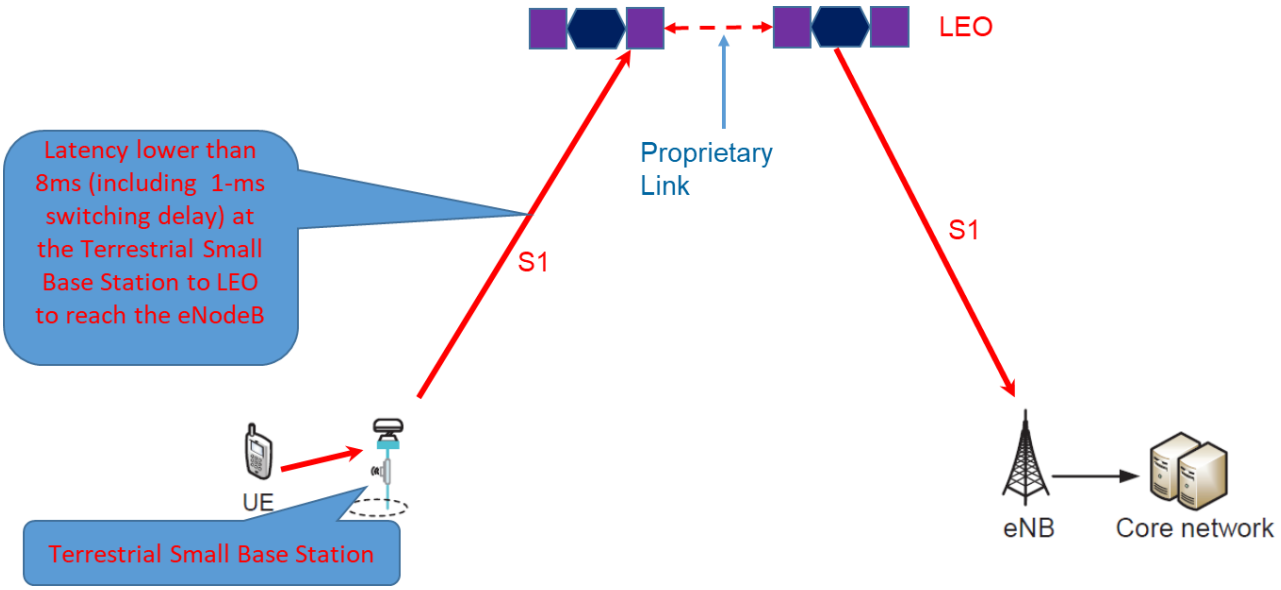


Figure 13. Use Case-8

4.2.2.9. Use Case-9: Terrestrial SBS to eNodeB/eNodeG over LEO multi-hop federated LEO

Use case-9 considers the multi-hop communication between the TSBS and eNodeB/eNodeG over a federated LEO satellite network involving multiple satellite network service providers. Figure 14 illustrates Use Case-9.

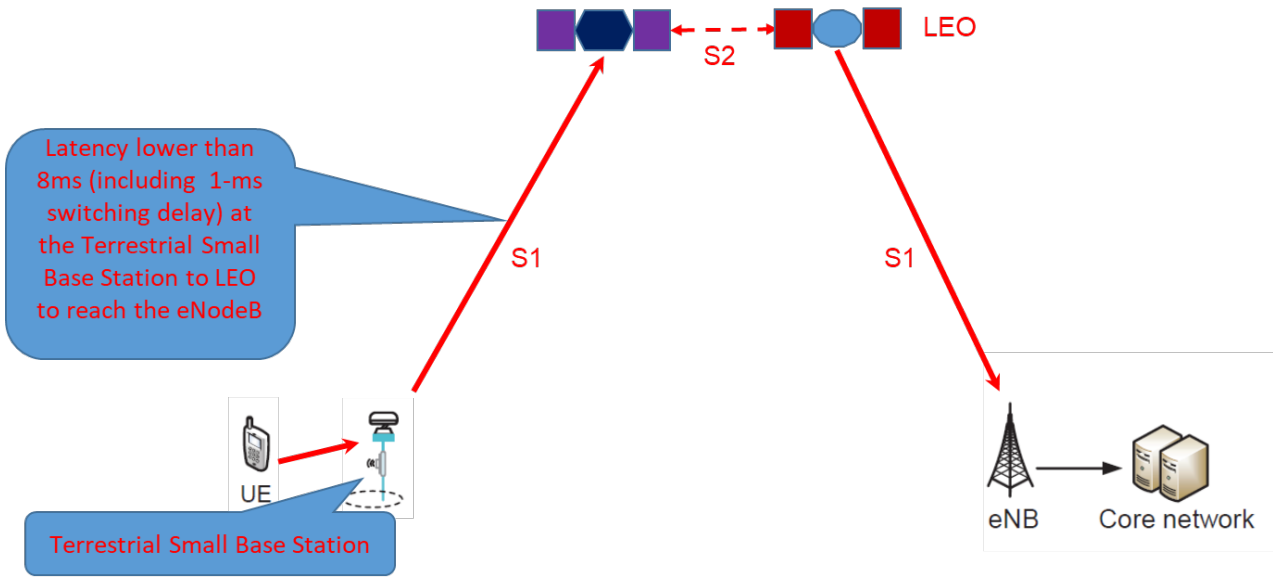


Figure 14. Use Case-9

4.2.2.10. Use case-10: UAVs as bentpipe/single-hop relay

Use case-10 considers UAVs and HAPs to provide a 1-hop relay/bent pipe communication between the TSBS and eNodeB/eNodeG. The HAPs can be used as flying airborne base stations in order to connect the unconnected or the under-connected [9]. The HAPs can be integrated to the backbone network. The HAPs are considered up to 30 km [10] altitude and can provide round-trip latency of the order 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 one-hop relay, a single HAPs functions as a "tower-in-the-air" relaying data between the TSBS and eNodeB/eNodeG where either mobile UEs or access points are located in underserved regions [11]. Figure 15 illustrates Use Case-10.

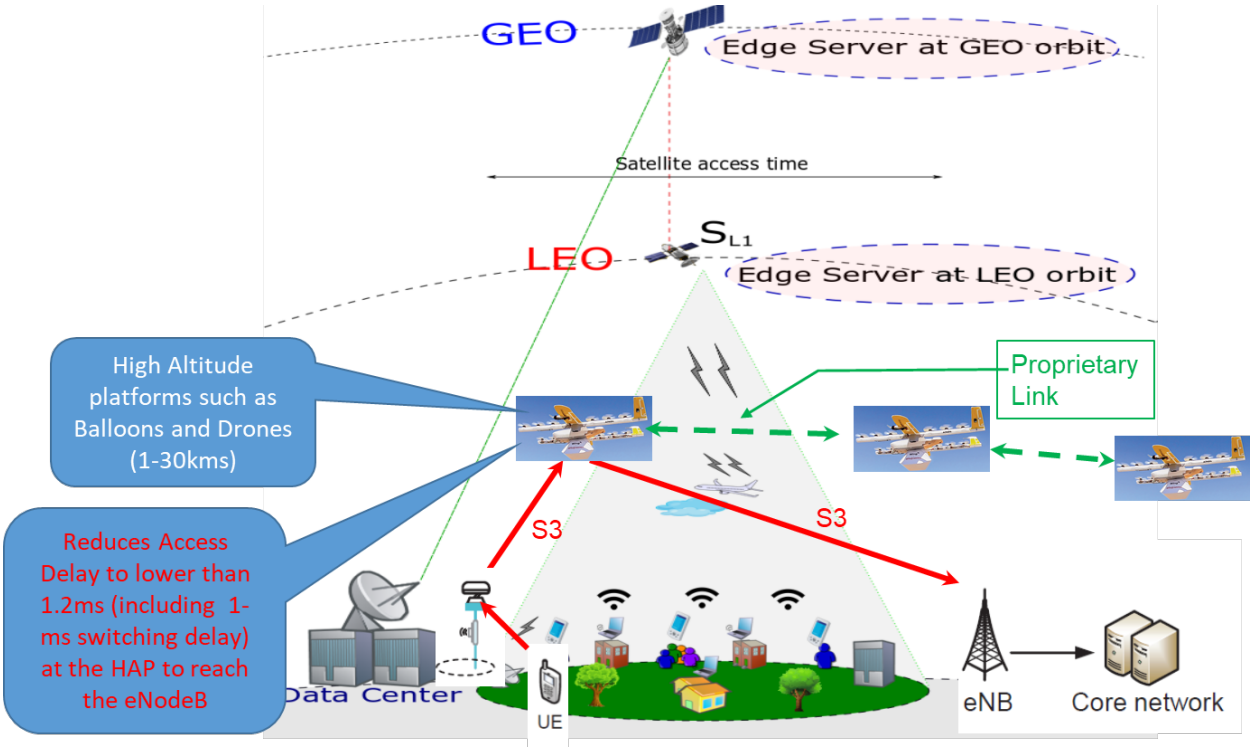


Figure 15. Use Case-10

4.2.2.11. Use case-11: UAV multi-hop backhaul

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/eNodeG communication. Figure 16 illustrates use case-11. Inter-UAV links can be proprietary. In this configuration, a swarm/cascade of HAPs are used to form a stratospheric integrated access backhaul network for the underneath local users in large, underserved regions [11].

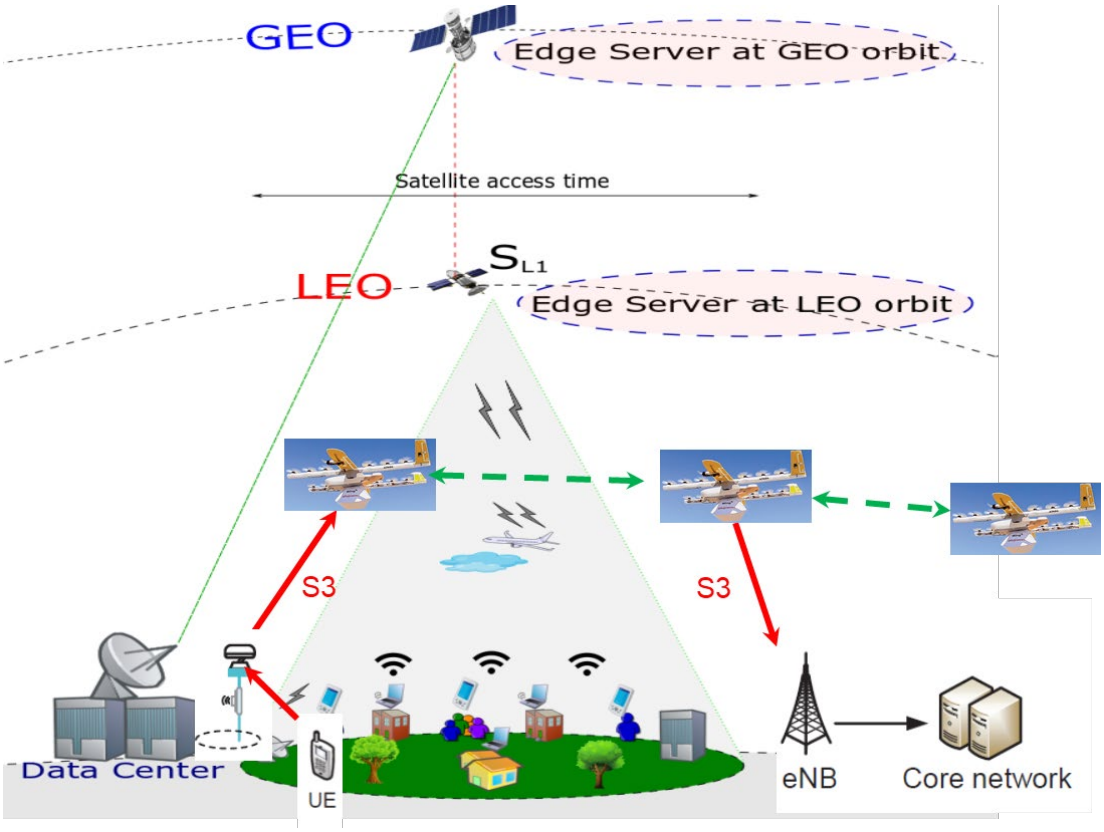


Figure 16. Use Case-11

4.2.2.12. Use case-12a-b: UAV-LEO Integrated multi-hop backhaul

Use case-12a deals with the integration of UAV/HAP-LEO-MEO-GEO satellite integration where the TSBS communicates with the UAV/HAP over S3 interface. Figure 17 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 to satellite involves UAV/HAP in a hierarchical manner. On the downlink communication between the LEO/MEO/GEO satellite to eNodeB/eNodeG, the satellite communicates directly with the eNodeB/eNodeG through S1interface.

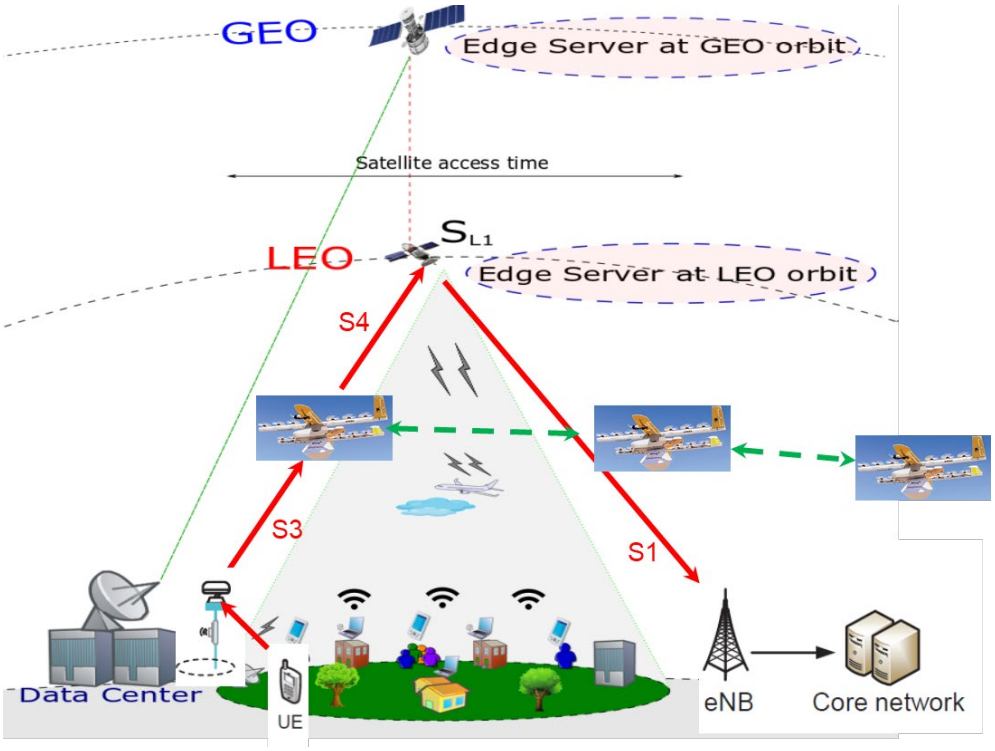


Figure 17. Use Case-12a

Use case-12b deals with the hierarchical communication on both the uplink and downlink communications. That is, uplink communication in use case-12b is like the 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 18 illustrates Use Case-12b.

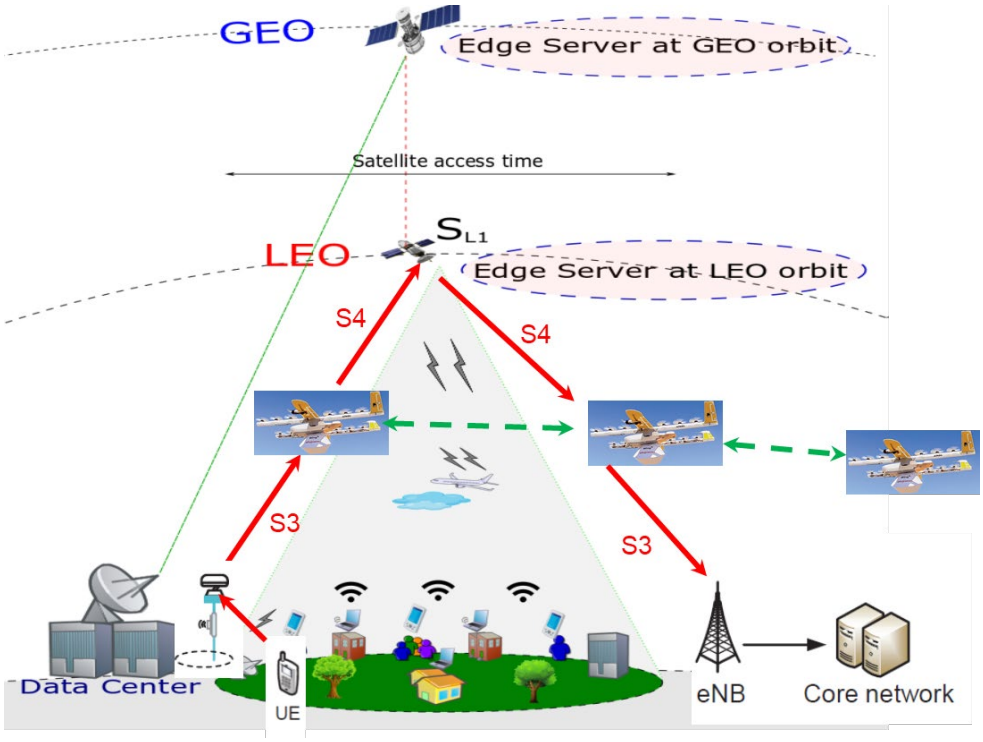


Figure 18. Use Case-12b

4.2.1. Use Cases with Direct Access Satellite Networks

Together with the NTN backhaul services scenarios described in the previous sections; the 2022 Edition of the satellite report also considers the use of the satellite network infrastructure as direct access. These new use cases for the direct access to satellite network 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 (backhaul 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.

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 are discussed briefly in the following sections.

4.2.1.1. 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 defined as S0. The communication between LAP and CU is defined by the interface S1. Figure 19 illustrates Direct Access Use Case-1.a.

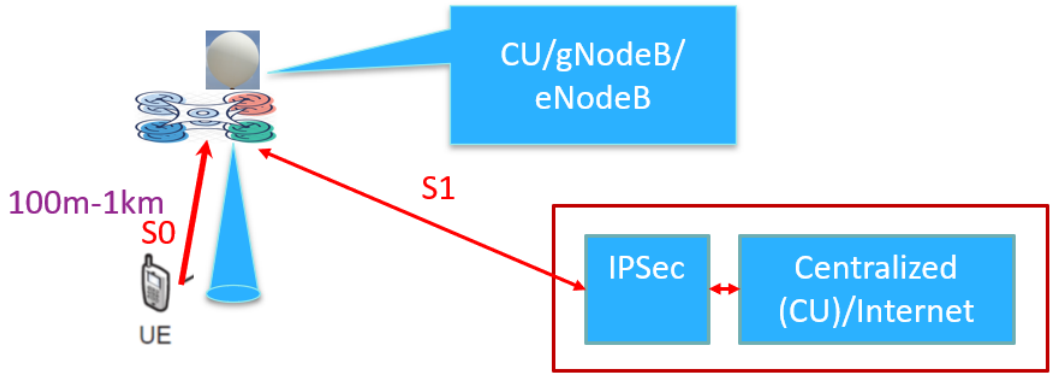


Figure 19. Direct Access Use Case-1.a

4.2.1.2. 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. The communication between LAP and CU is defined by the interface S1. The interface used for communication between two LAP nodes is defined as L1. Figure 20 illustrates Direct Access Use Case-1.b.

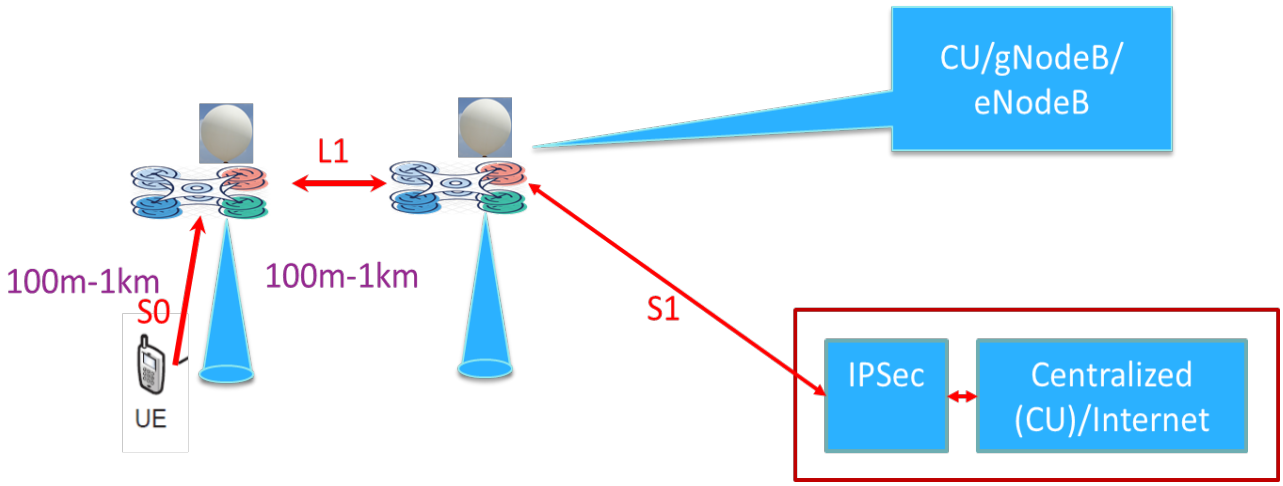


Figure 20. Direct Access Use Case-1.b

4.2.1.3. 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 same service provider (non-federated) or 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 defined as S0. The communication between HAP and CU is defined by the interface S1. Figure 21 illustrates Direct Access Use Case-1.c.

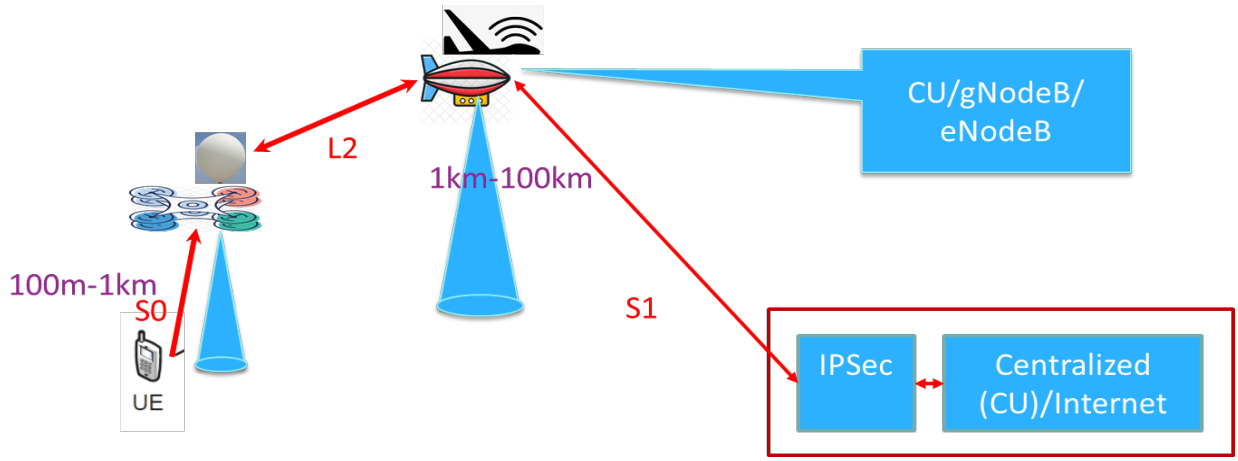


Figure 21. Direct Access Use Case-1.c

4.2.1.4. 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 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 defined as S0. The communication between LEO and CU is defined by the interface S1. Figure 22 illustrates Direct Access Use Case-1.d.

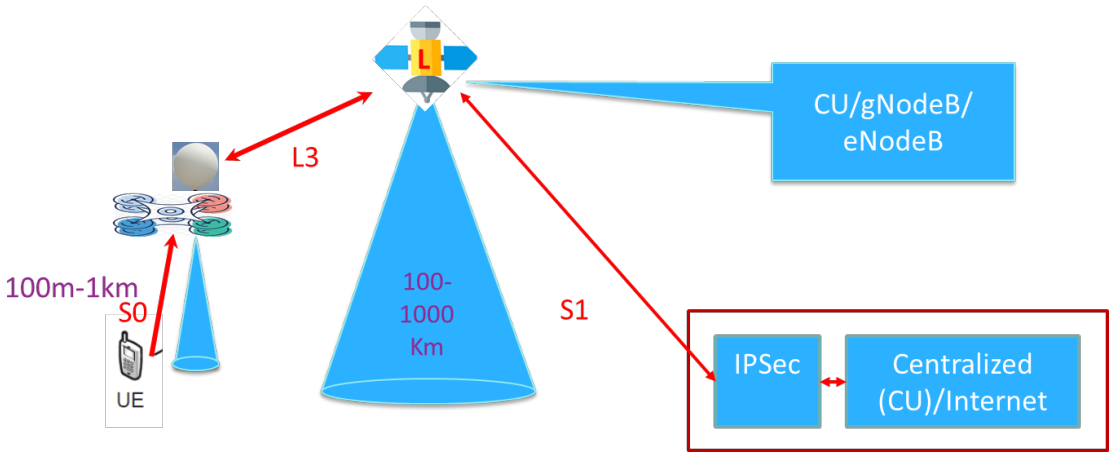


Figure 22. Direct Access Use Case-1.d

4.2.1.5. 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. The communication between MEO and CU is defined by the interface S1. Figure 23 illustrates Direct Access Use Case-1.e.

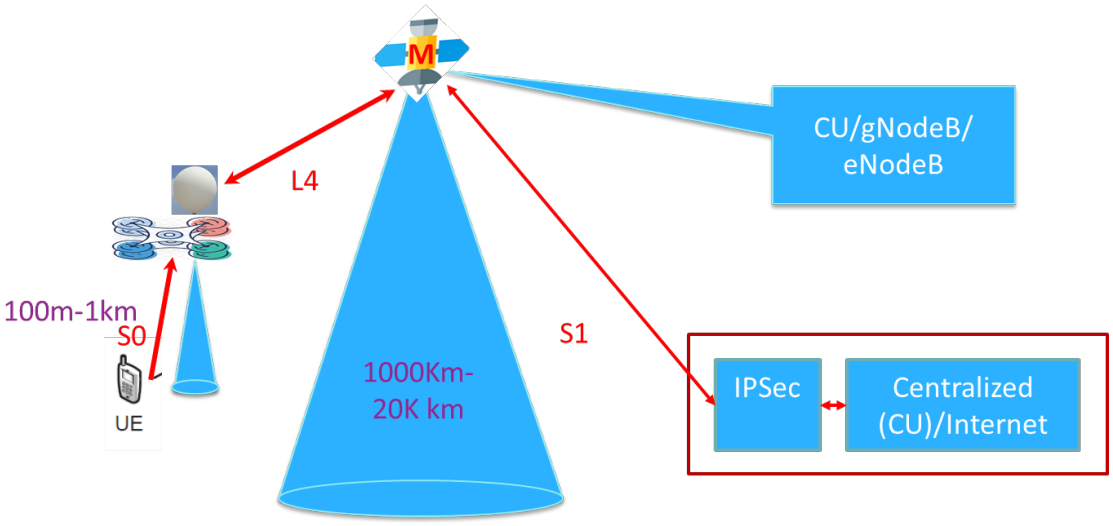


Figure 23. Direct Access Use Case-1.e

4.2.1.6. Direct Access Use Case-1.f: UE to LAP → LEO → MEO → gNodeB (non-federate 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 case, proprietary ISL is used to communicated 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 defined as S0. The communication between MEO and CU is defined by the interface S1. Figure 24 illustrates Direct Access Use Case-1.f.

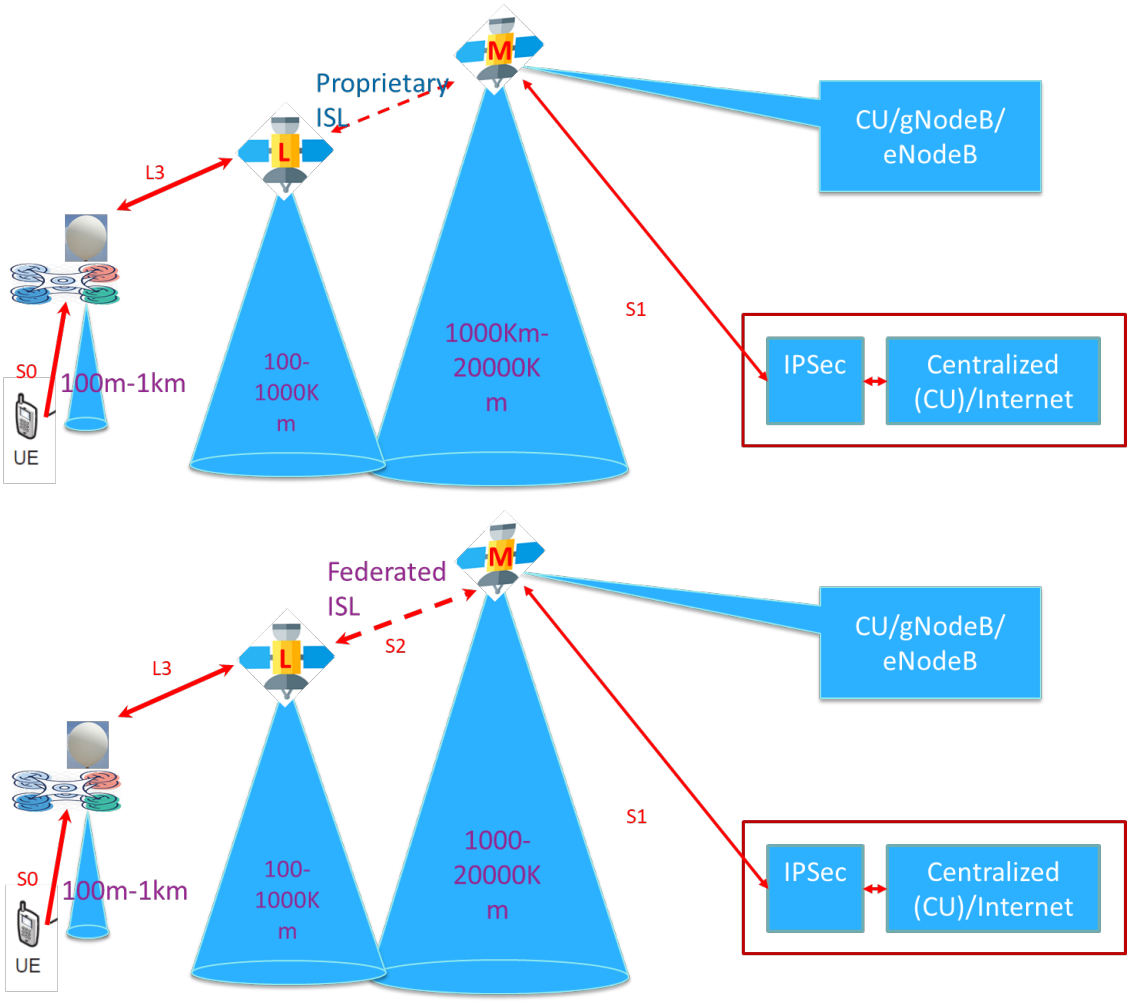


Figure 24. Direct Access Use Case-1.f (top and bottom figures illustrate the non-federated case and federated cases, respectively)

4.2.1.7. 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 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 defined as S0. The communication between GEO and CU is defined by the interface S1. Figure 25 and Figure 26 illustrate Direct Access Use Case-1.g for non-federated case and federated cases, respectively.

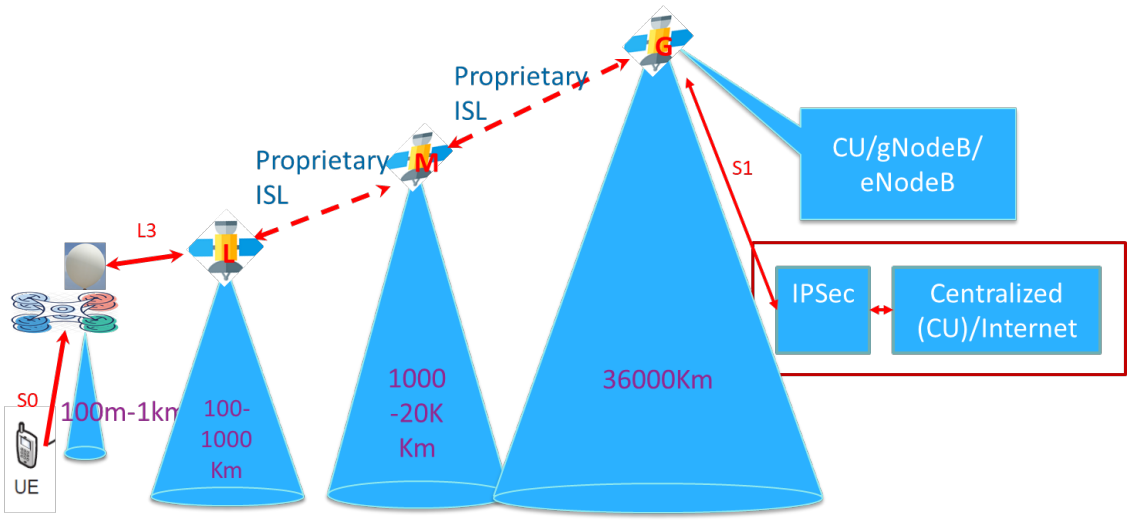


Figure 25. Direct Access Use Case 1.g for non-federated service providers

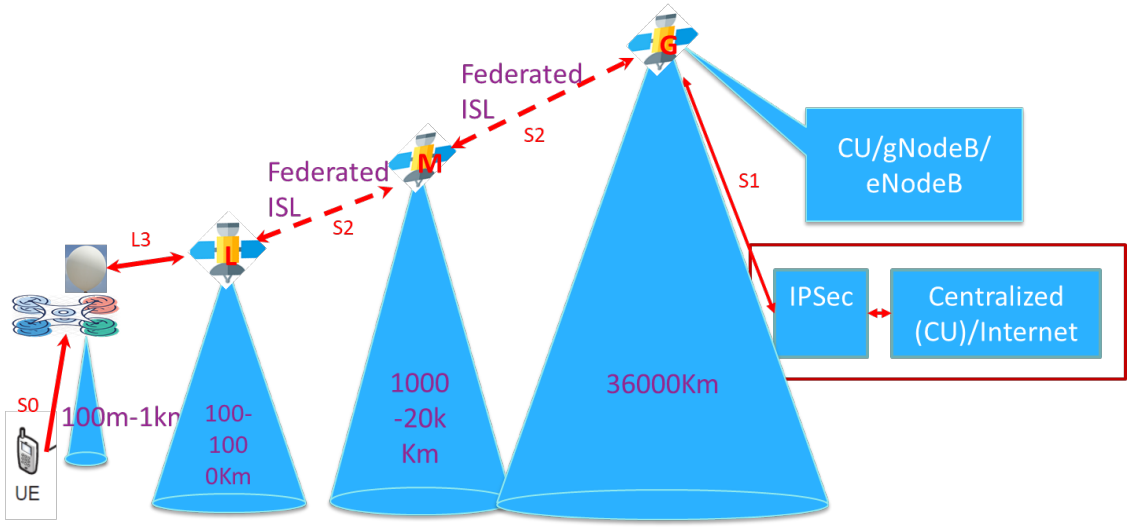


Figure 26. Direct Access Use Case-1.g for federated service providers

4.2.1.8. 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 used as a last communication point for communication 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 in an opportunistic manner 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 [12] can be adopted in such cases with performance benefit. Figure 27 illustrates Direct Access Use Case-1.h.

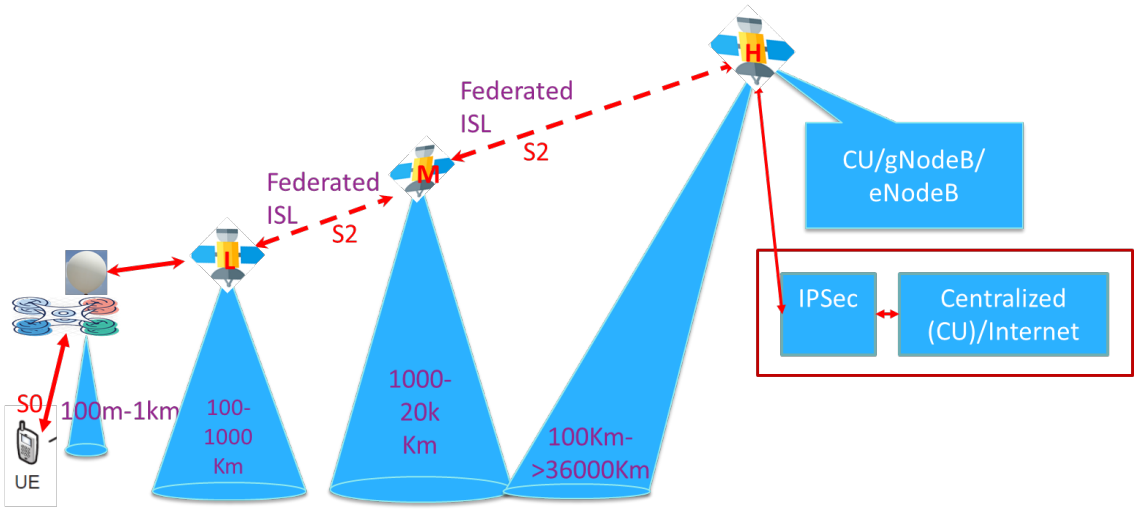


Figure 27. Direct Access Use Case 1.h where HEO satellites are utilized in an opportunistic manner

4.2.1.9. 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. The communication between HAP and CU is defined by the interface S1. Figure 28 illustrates Direct Access Use Case-2.a.

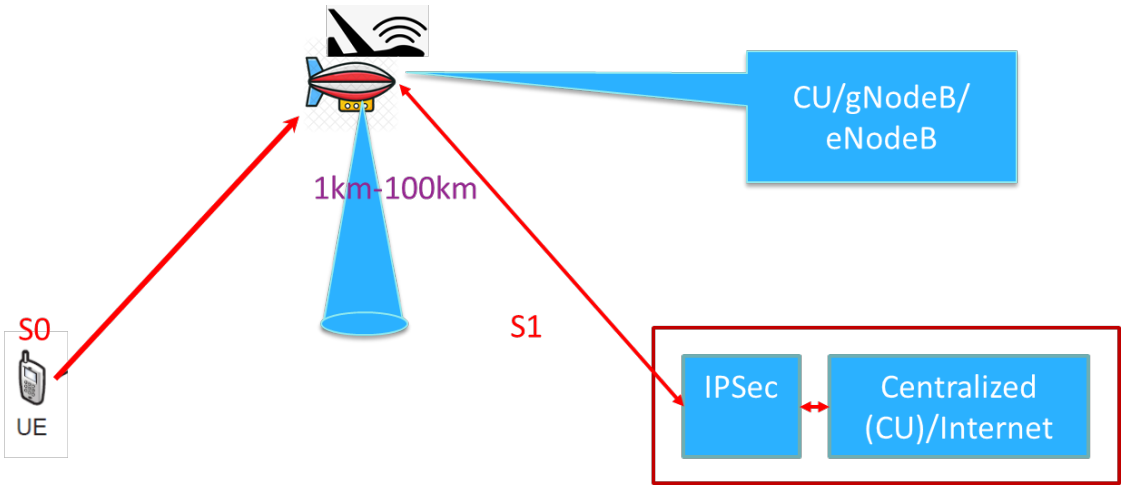


Figure 28. Direct Access Use Case-2.a.

4.2.1.10. 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 communicate 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 defined as S0. The communication between HAP and CU is defined by the interface S1. Figure 29 and Figure 30 illustrate Direct Access Use Case-2.b for non-federated and federated cases, respectively.

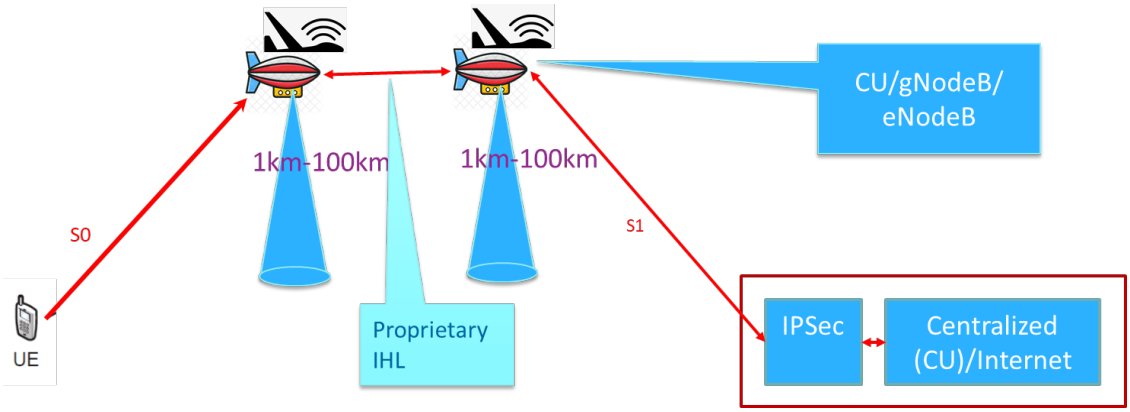


Figure 29. Direct Access Use Case-2.b for non-federated case

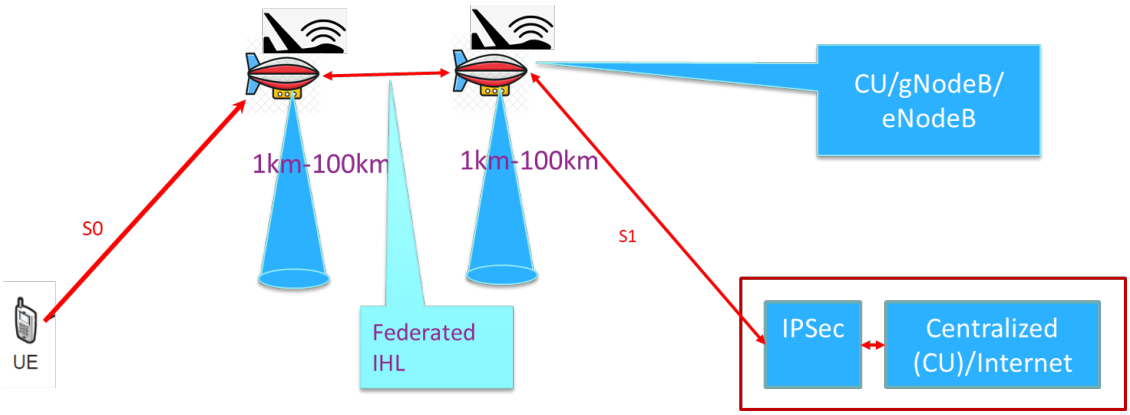


Figure 30. Direct Access Use Case-2.b for federated case

4.2.1.11. 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 same service provider (non-ice federated) or 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. The communication between LEO and CU is defined by the interface S1. Figure 31 illustrates the Direct Access Use Case-2.c.

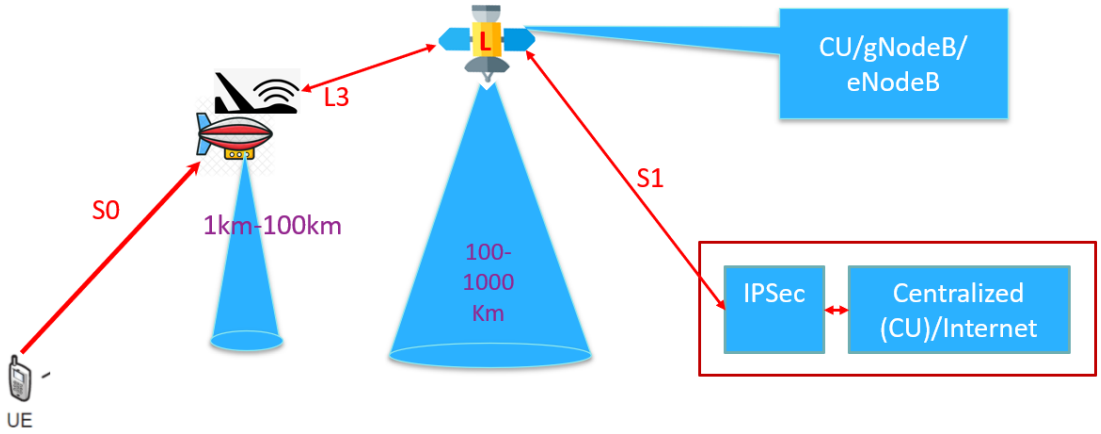


Figure 31. Direct Access Use Case-2.c

4.2.1.12. 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 operates in a bent-pipe mode or with regeneration capability. The LEO and MEO can belong to 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 an CU/eNodeB/gNodeB.

The interface used for UE and HAP communication is defined as S0. The communication between MEO and CU is defined by the interface S1. L3 is the interface used between HAP and LEO. Figure 32 and Figure 33 illustrate the Direct Access Use Case-2.d for the non-federated and federated cases, respectively.

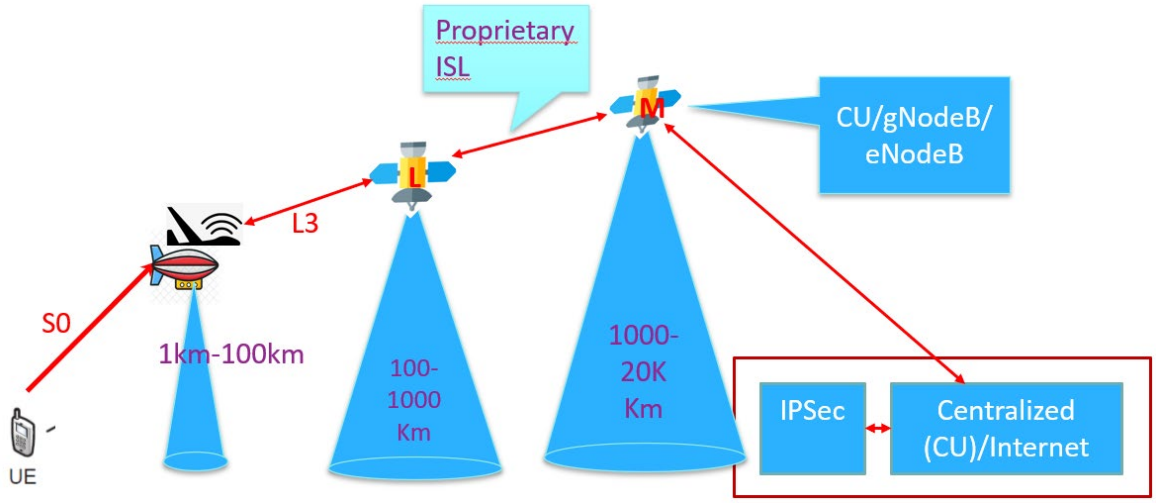


Figure 32. Direct Access Use Case-2.d for the non-federated case

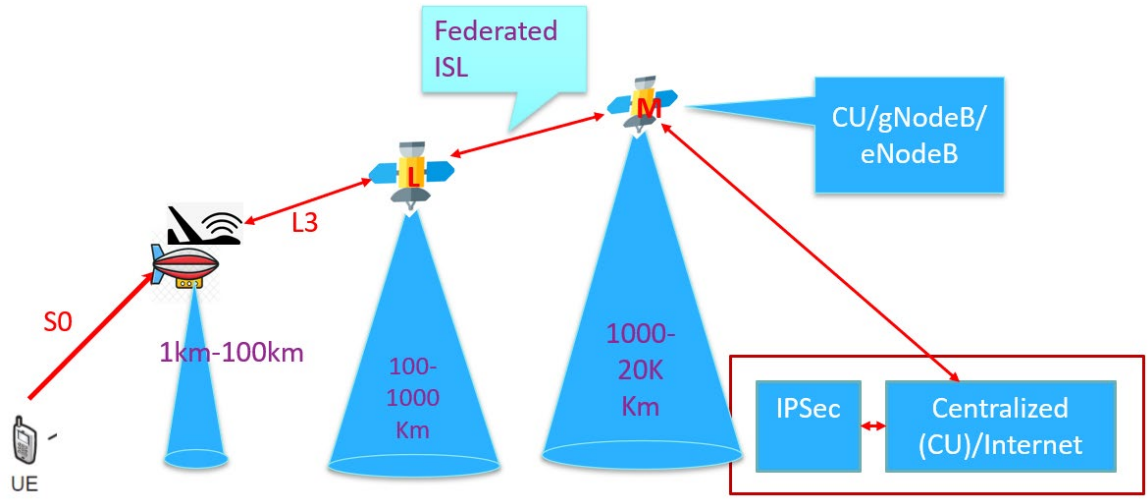


Figure 33. Direct Access Use Case-2.d for the federated case

4.2.1.13. 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 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 includes all the functions of an eNodeB/gNodeB. The interface used for UE and HAP communication is defined as S0. The communication between MEO and CU is defined by the interface S1.

4.2.1.14. 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 same service provider (non-federated) or different service provider (federated case). In the case of non-federated systems, proprietary ISL is used to communicated 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 defined as S0. The communication between GEO and CU is defined by the interface S1. Figure 34 and Figure 35 illustrate the Direct Access Use Case-2.f for the non-federated and federated cases, respectively.

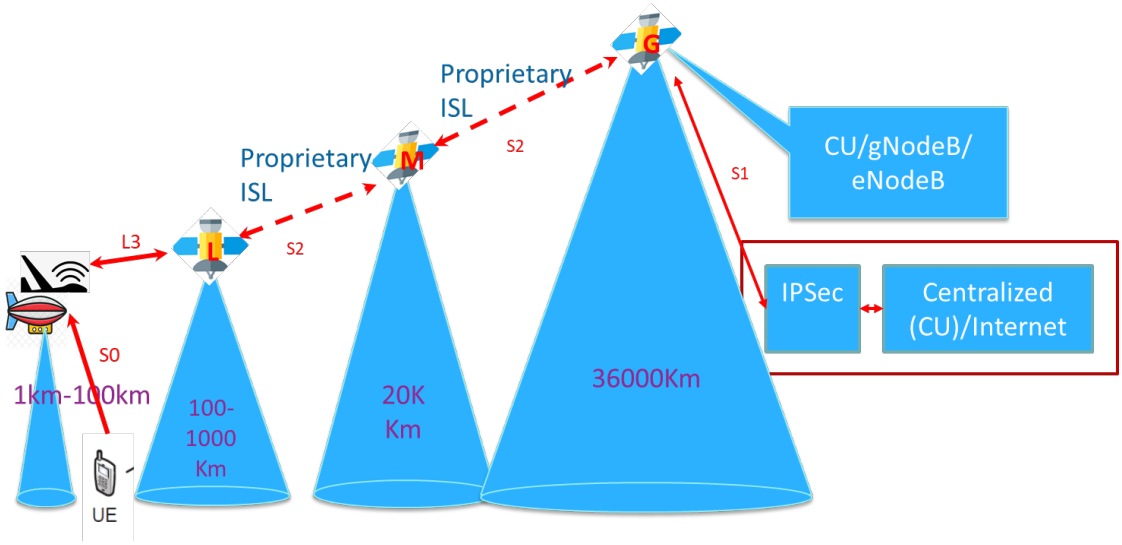


Figure 34. Direct Access Use Case-2.f for the non-federated case

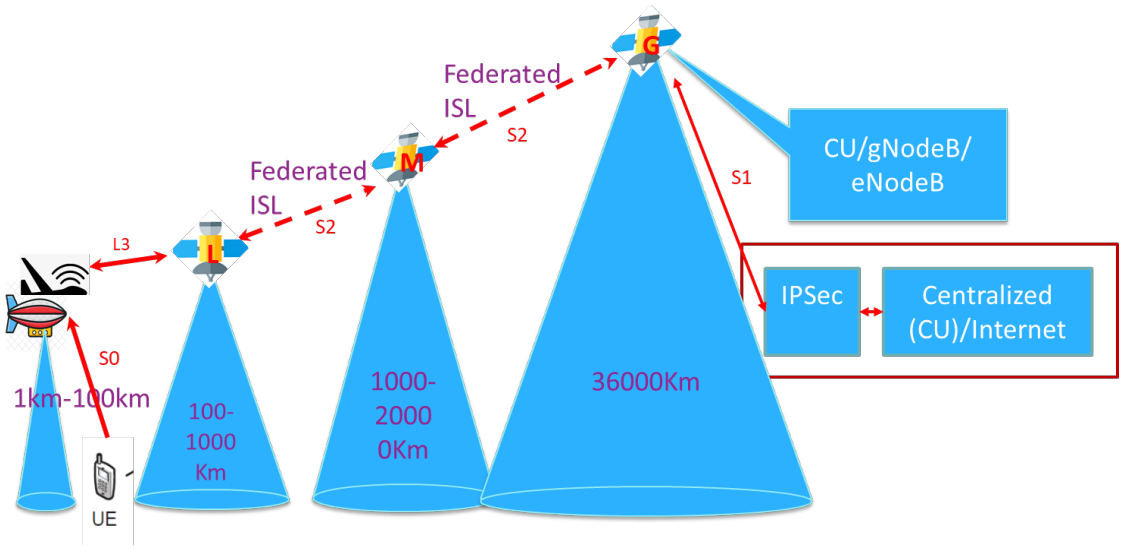


Figure 35. Direct Access Use Case-2.f for the federated case

4.2.1.15. 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 use Direct Access Use Case-1.f, instead of GEO satellite, HEO satellite is used as a last communication point for communication between UE and CU. The interfaces are appropriately modified for non-federated and federated cases as the Direct Access Use Case-2.f. Figure 36 illustrates Direct Access Use Case-2.g.

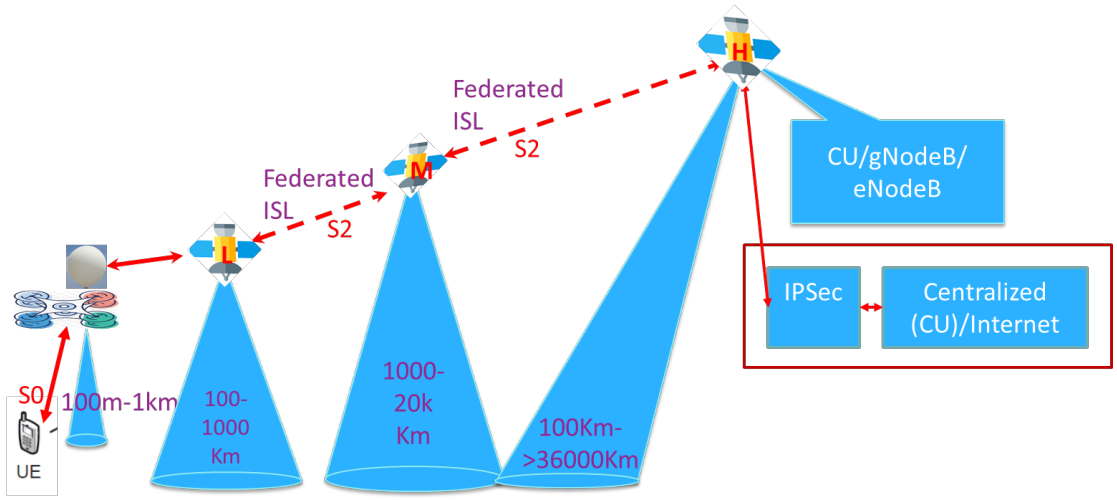


Figure 36. Direct Access Use Case-2.g.

4.2.1.16. 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 defined as S0. The communication between LEO and CU is defined by the interface S1. Figure 37 illustrates Direct Access Use Case-3.a.

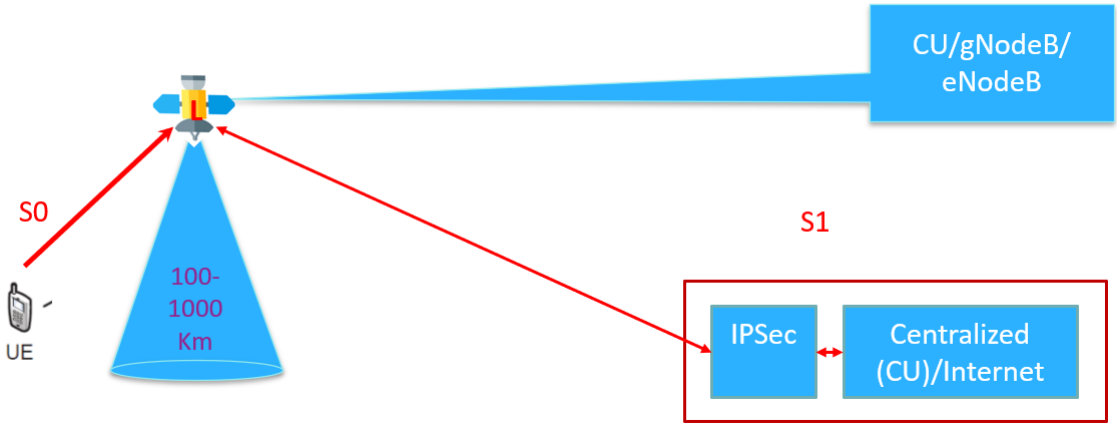


Figure 37. Direct Access Use Case-3.a

4.2.1.17. 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 defined as S0. The communication between LEO and CU is defined by the interface S1. Figure 38 and Figure 39 illustrate Direct Access Use Case-3.b, for non-federated and federated cases, respectively.

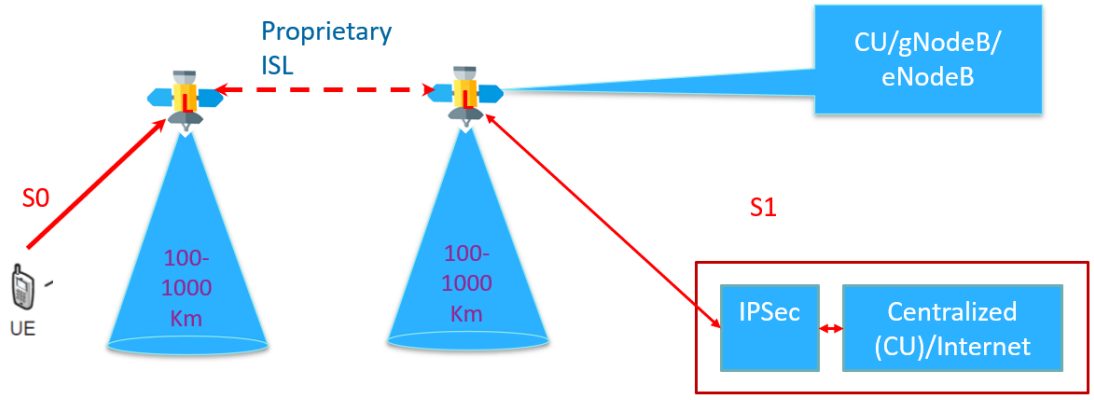


Figure 38. Direct Access Use Case-3.b for the non-federated case

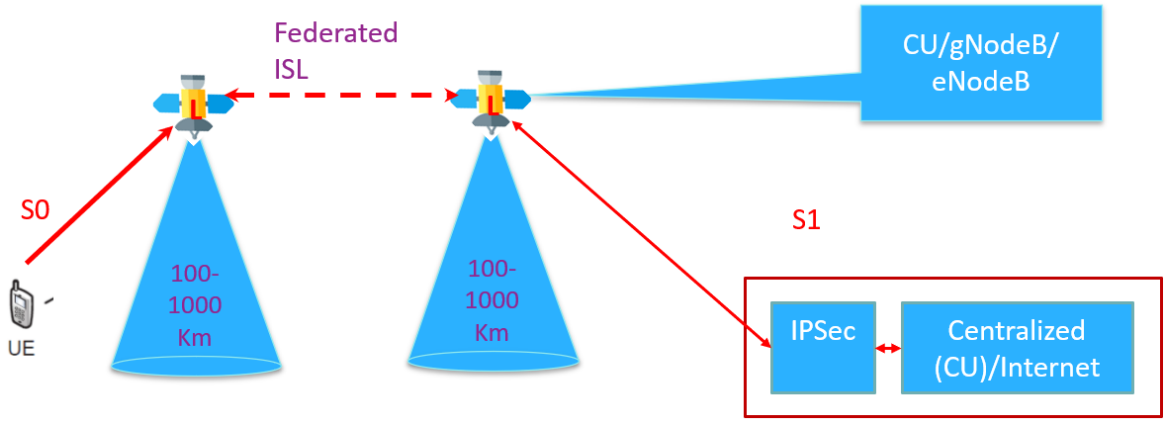


Figure 39. Direct Access Use Case-3.b for the federated case

4.2.1.18. 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 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 defined as S0. The communication between MEO and CU is defined by the interface S1. Figure 40 and Figure 41 illustrate the two cases of Direct Access Use Case-3.c.

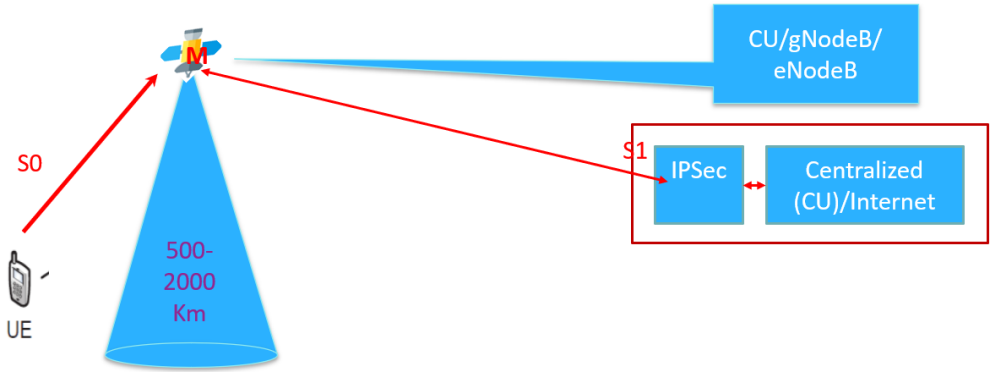


Figure 40. Direct Access Use Case-3.c for the direct UE to MEO communication

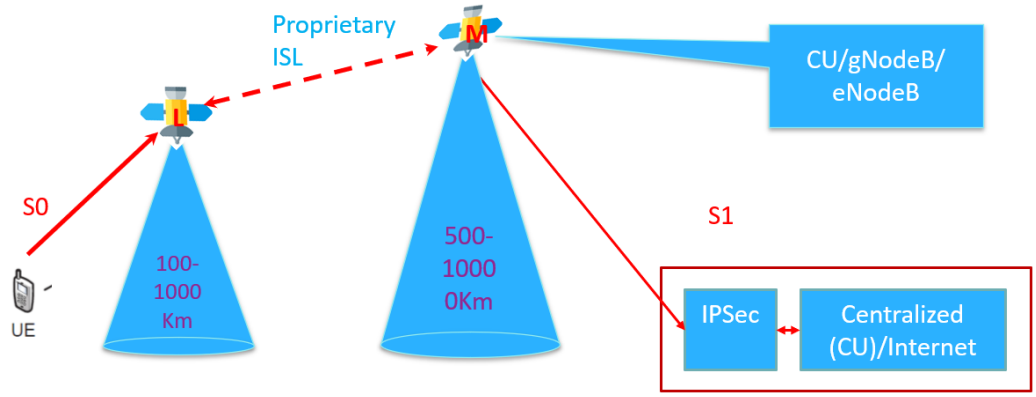


Figure 41. Direct Access Use Case-3.c for the non-federated case with LEO and LEO ISL

4.2.1.19. 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). Further, the assumption is the same as Direct Access Use Case-3.c. Figure 42 illustrates the Direct Access Use Case-3.d for the federated case with LEO and LEO ISLs.

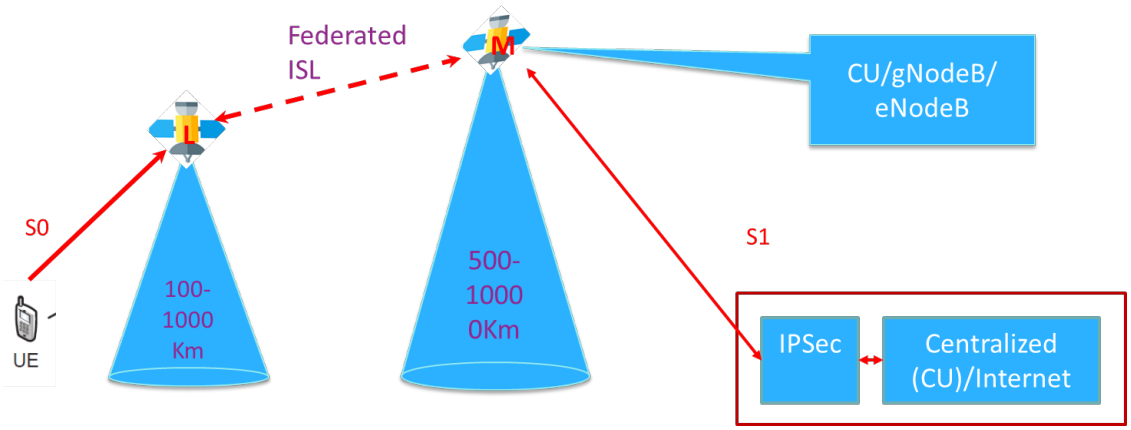


Figure 42. Direct Access Use Case-3.d for the federated case with LEO and LEO ISL

4.2.1.20. 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 defined as S0. The communication between MEO and CU is defined by the interface S1. Figure 43 and Figure 44 illustrate the Direct Access Use Case-3.e for the non-federated and federated cases, respectively.

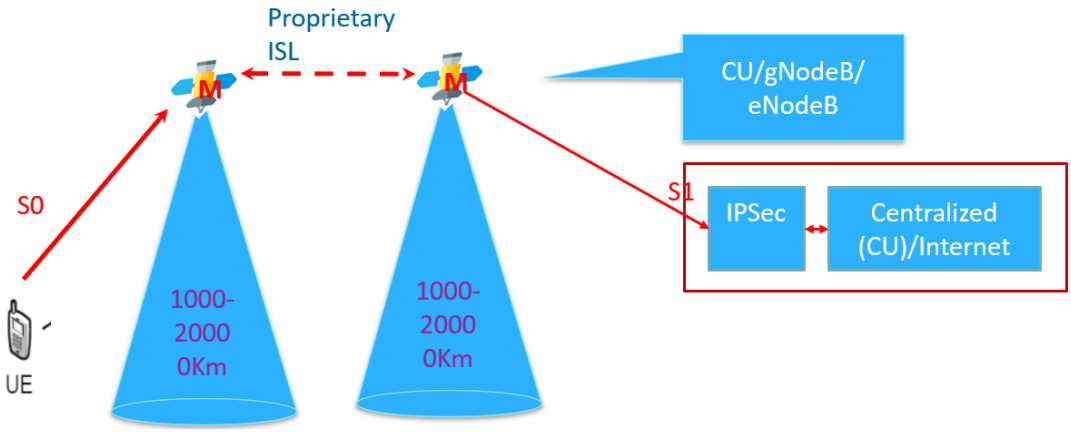


Figure 43. Direct Access Use Case-3.b for the non-federated case

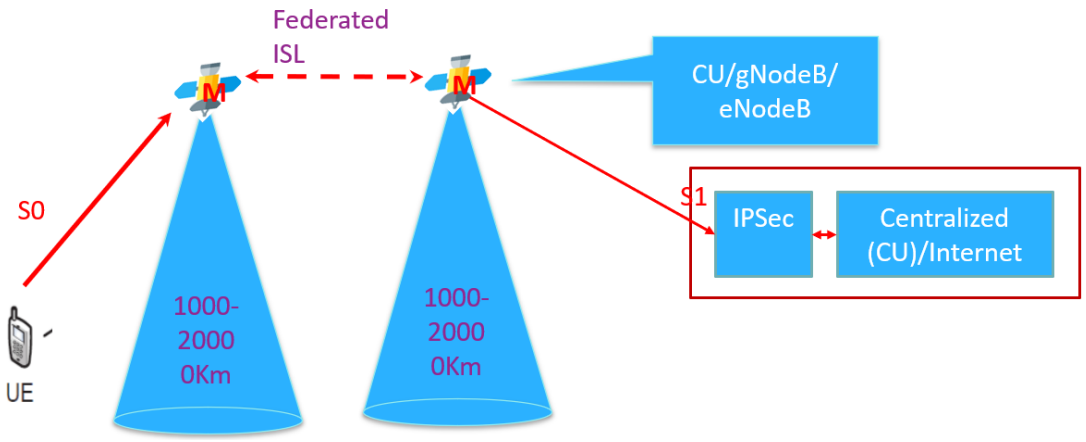


Figure 44. Direct Access Use Case-3.b for the non-federated case

4.2.1.21. 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 defined as S0. The communication between GEO and CU is defined by the interface S1. Figure 45 illustrates the Direct Access Use Case-3.f.

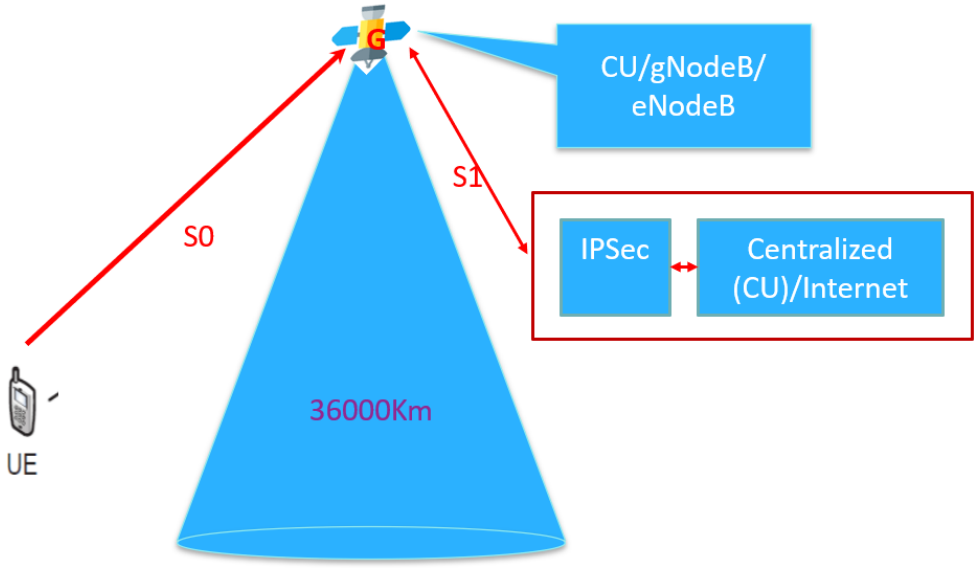


Figure 45. Direct Access Use Case-3.f

4.2.1.22. Direct Access Use Case-3.g: UE to LEO → MEO → GEO → gNodeB (non-federated and federated cases)

In Direct Access Use Case-3.g, the communication between UE and CU will be carried out through LEO, MEO, and GEO, respectively. All the nodes operates in a bent-pipe mode or with regeneration capability. The LEO, MEO, and GEO can belong to same company (non-federated) or different companies (federated case). In the case of non-federated systems, proprietary ISL is used to communicated between LEO, MEO, and GEO where, 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 defined as S0. The communication between GEO and CU is defined by the interface S1. Figure 46 and Figure 47 illustrate Direct Access Use Case-3.g for the non-federated and federated cases, respectively.

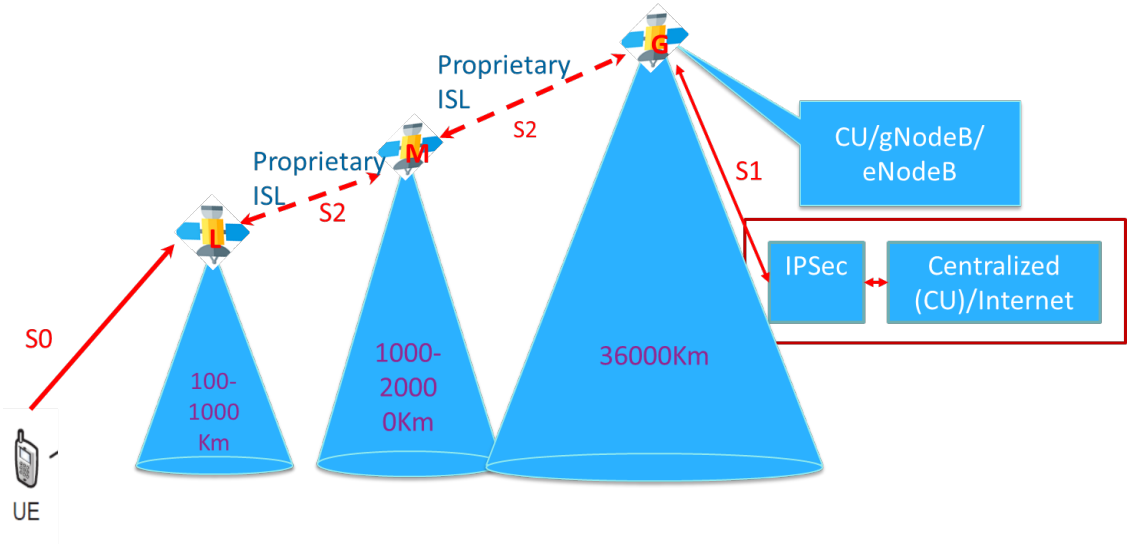


Figure 46. Direct Access Use Case-3.g for the non-federated case

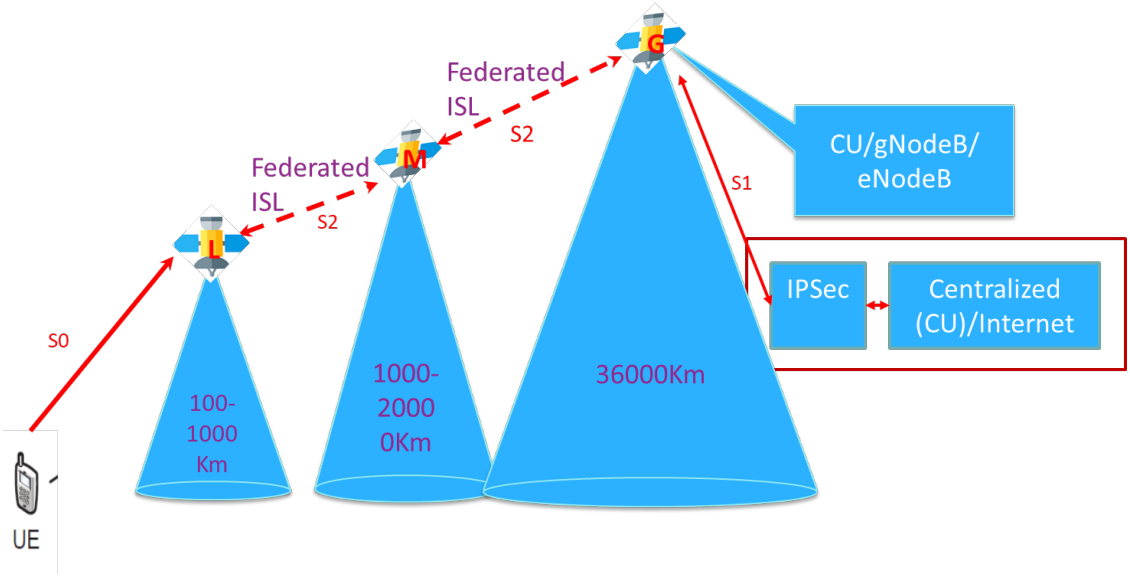


Figure 47. Direct Access Use Case-3.g for the federated case

4.2.2. 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 [13]:

- 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 intersatellite 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 terrestrial gateway or HAPs)

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

Table 7. 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 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 8 provides the reference parameters for the physical layer scenarios in Table 7.

Table 8. 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 9 describes the application/use-case Scenarios for satellite-IoT.

Table 9. 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, sport 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.

4.2.2.1. Topology for Physical Layer Reference Scenario A

Scenario A considers LEO satellites-based constellation with multiple fixed beam satellites in the visible range for direct access from IoT devices; see Figure 48. A transparent payload (amplify-and-forward) is assumed for this scenario. It is suitable for large deployments of IoT networks with no scope for terrestrial gateways and applications which can withstand reasonable latencies and outages (e.g., weather monitoring).

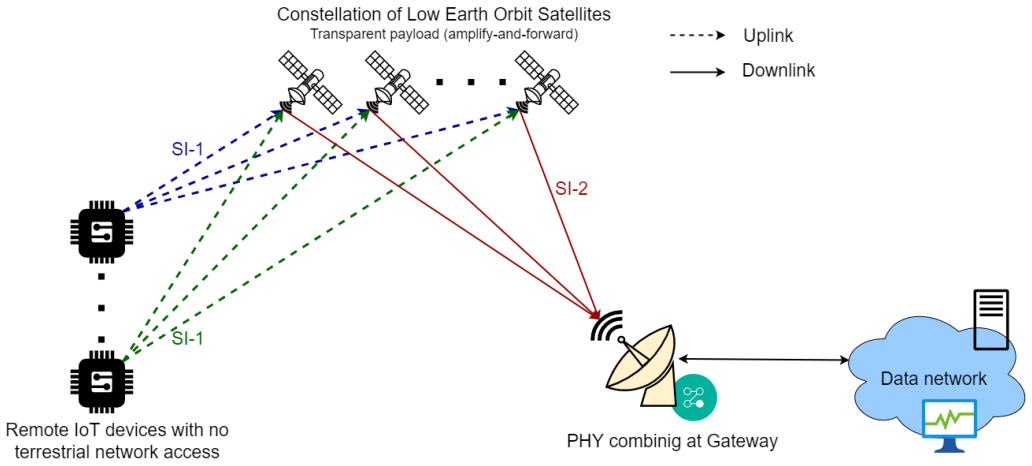


Figure 48. Physical layer Reference Scenario A (direct access, transparent payload)

4.2.2.2. 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 49. A regenerative payload (decode-and-forward) is assumed for this scenario. It is suitable for large deployments of IoT networks with no scope for terrestrial gateways and applications which require greater immunity towards propagating transmission errors.

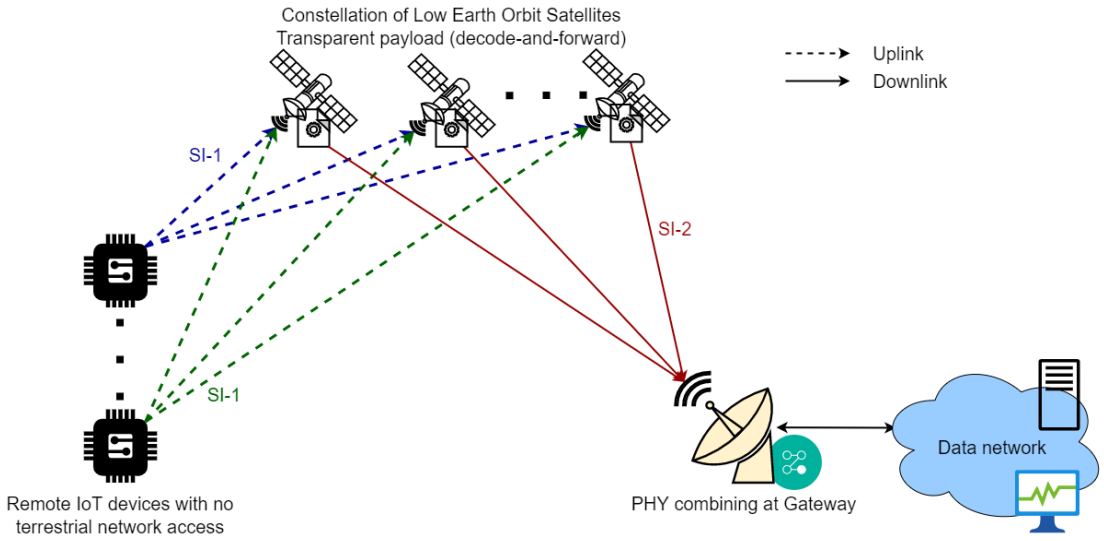


Figure 49. Physical layer Reference Scenario B (direct access, regenerative payload)

4.2.2.3. 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.

4.2.2.4. 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..

4.2.2.5. 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 50. A transparent payload (amplify-and-forward) is assumed for this scenario. 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 sport events).

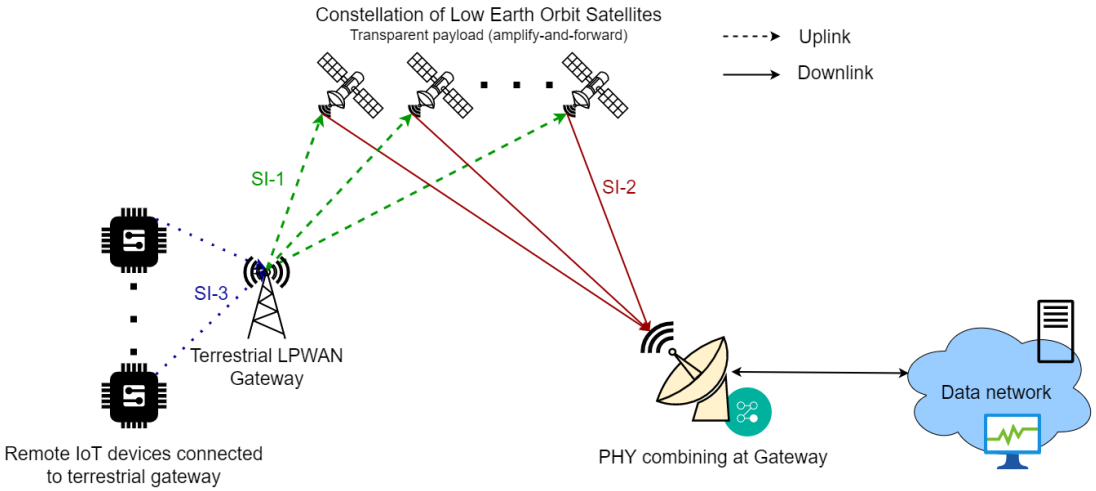


Figure 50. Physical layer Reference Scenario E (direct access, terrestrial gateway, transparent payload)

4.2.2.6. 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 51. 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, intrusion detection.

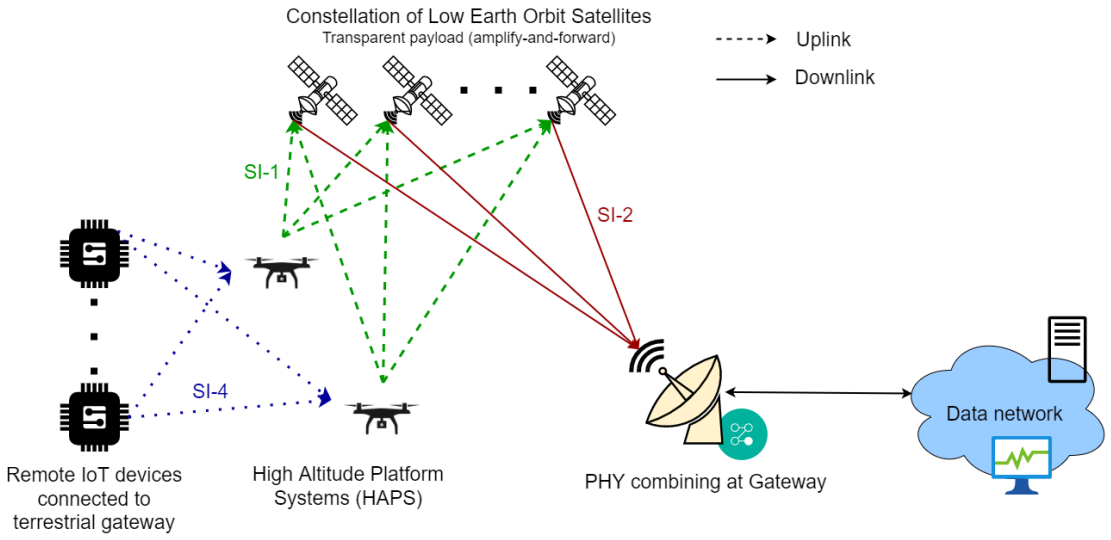


Figure 51. Physical layer Reference Scenario F (direct access, with HAPS, transparent payload)

4.2.3. Reference Architectures

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

Moreover, we provide below Table 10 showing the relation between the satellite 5G interfaces defined in TR 38.821 Rel. 16 and those considered in this document.

Table 10. Interface Equivalence between this Satellite Roadmap and 3GPP 38.821 Rel. 16 for 5G-Satellite Integration

No.	Interface defined in this INGR Satellite WG Edition 2 document (Sx: S stands for interfaces relevant for 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	Closest interfaces are NR-Uu, N_G, NGU, and F1 over SRI, which run over the S1 interface of this document transparently. Satellite Radio Interface (SRI) is used in 3GPP TR 38.821 Rel 16 in place of S1.	Equivalent standard 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 in order 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 in order to enable standardization 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 in order to enable standardization of DU to HAP link, enabling industry, and lowering the cost of operation. 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 this interface specs.

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

Figure 52 and Figure 53 depict RA-1, where the existing satellite networks are used by the 5G terrestrial networks as a traffic tunnel or bent-pipe scheme for carrying the traffic. As shown in the figure, the control and 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. All the use cases mentioned above (Use case-1 to Use case-12b) are applicable for the RA-1.

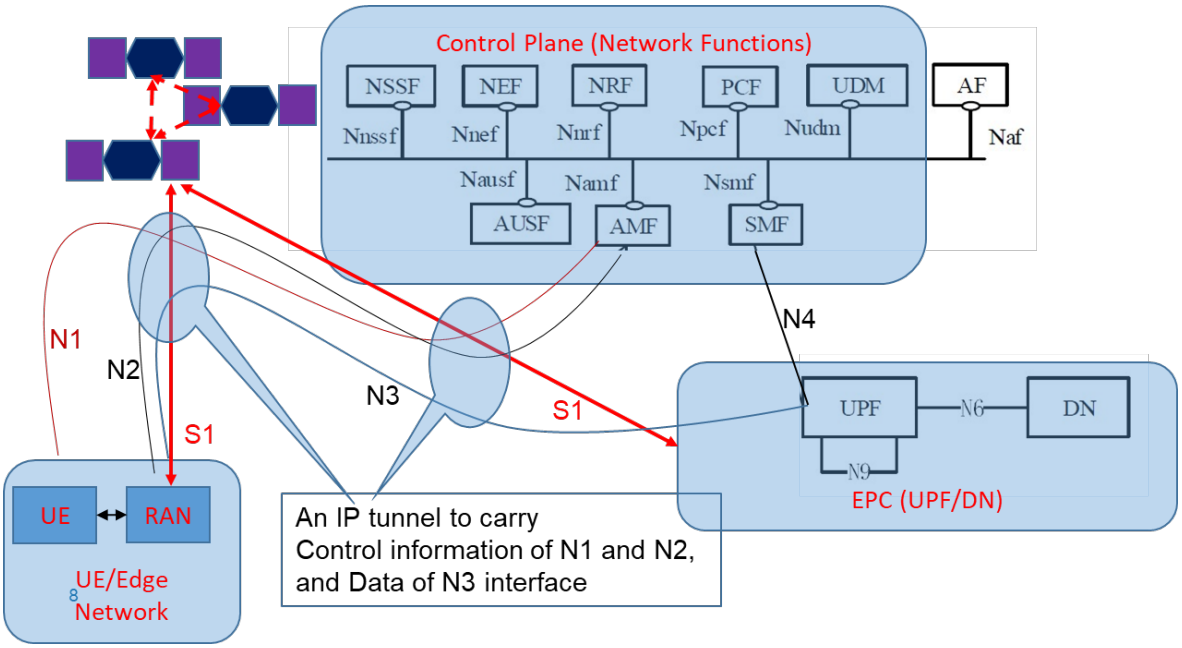


Figure 52. Reference Architecture-1: Non-virtualized 5G-Satellite Networks

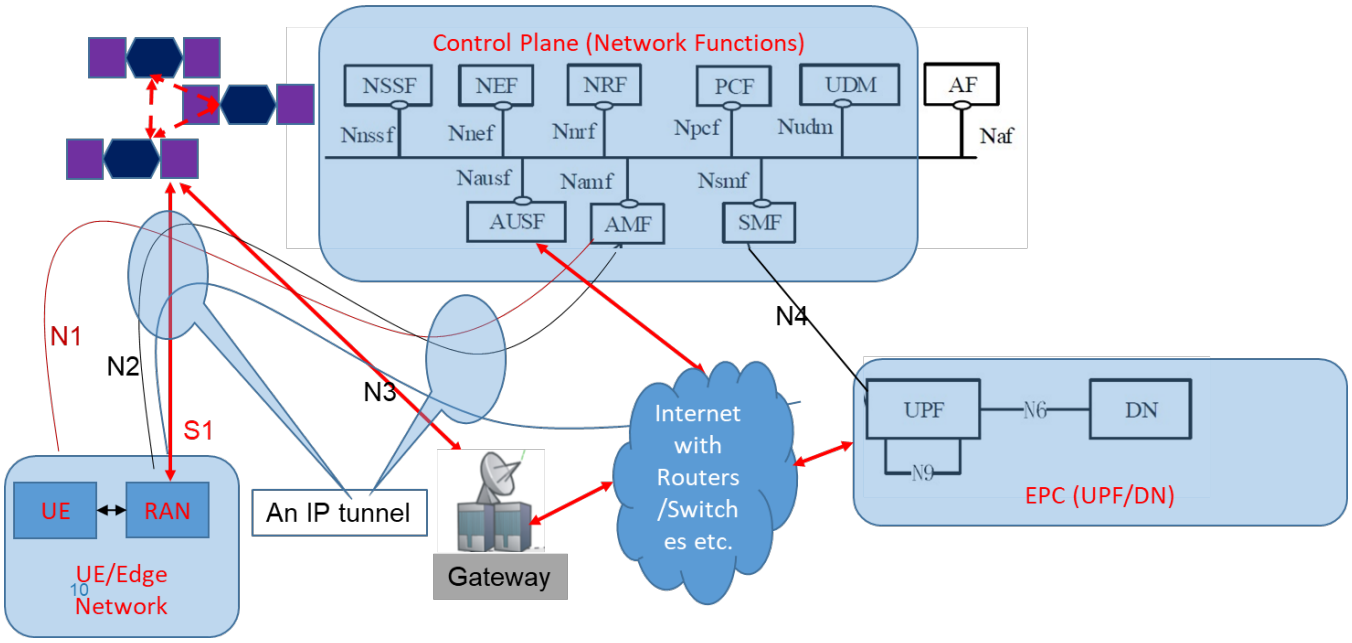


Figure 53. Another depiction of Reference Architecture-1

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

In Figure 54, the RA-2 is depicted where the satellite network is a virtualized network infrastructure similar yet separated from the terrestrial 5G virtualized network. The satellite network virtualization characteristics can also face different networking challenges, network function requirements, and implementation scenarios. It is likely that the evolution of today's non-virtualized, non-federated

satellite networks can lead to a virtualized satellite network with federation capability that is different from the existing terrestrial 5G networks within the next 3-5 years. The control plane design, control operations, network slicing, network functions, network interfaces, network orchestration approaches, and all such network functional aspects are not necessarily matching between the virtualized satellite and virtualized terrestrial 5G networks. In such a medium-term development of satellite networks, RA-2 suits best for 5G-satellite integration.

We define two additional network functions: Satellite Edge-computing Function (SEF) and Satellite Network Federation Function (SNF) in addition to the functions defined as part of 3GPP network functions. A part of SEF is considered in the work [14] where Satellite Edge Computing (SEC) framework for 5G satellite integration enabling multi-layer caching as well as intersatellite cache exchange is described. Each of the separately virtualized networks (i.e., satellite and terrestrial 5G) maintains separate MANO modules for their respective 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 of the data and control information carried over the interfaces N1, N2, and N3, as per the definition of 3GPP standard TS 23.501, will be 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 [12].

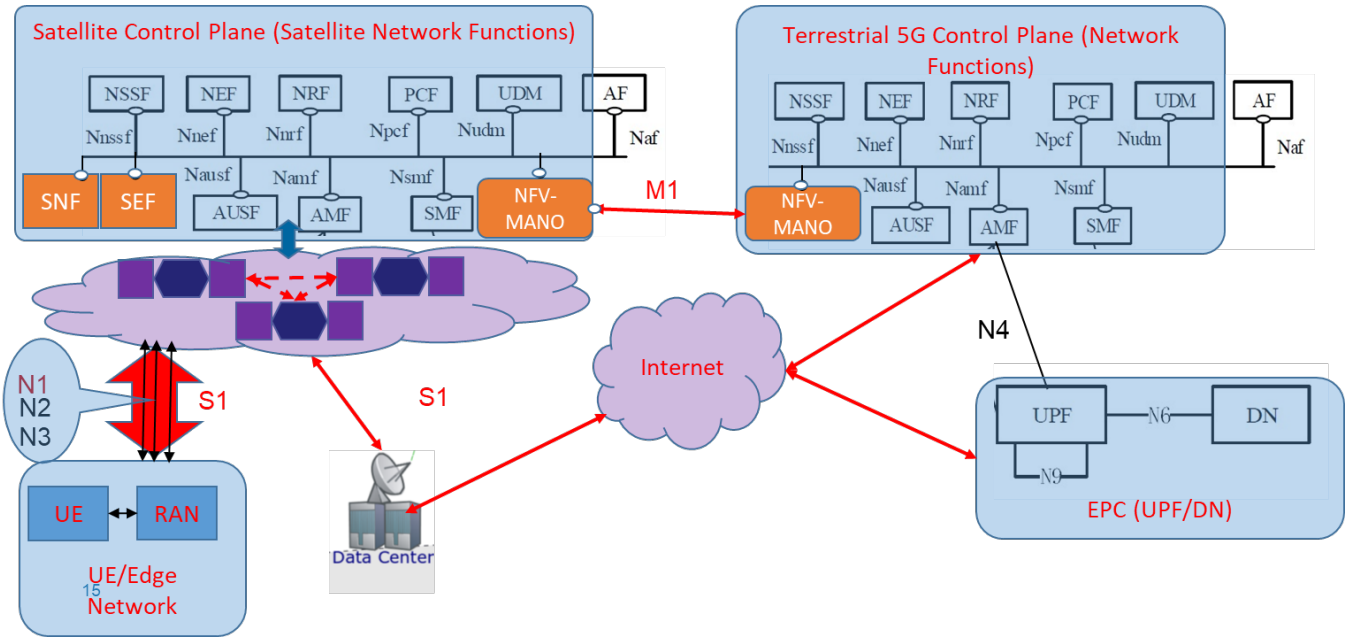


Figure 54. Reference Architecture-2

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

In the long-term future of satellite and 5G evolution, an integrated virtualized 5G-satellite network system is anticipated as per the consideration of the RA-3 shown in Figure 55. 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 responsibility to carry out resource management, routing of packets, channel management, slice

management, edge computing decisions, and federation functions rests with the integrated MANO module of the network.

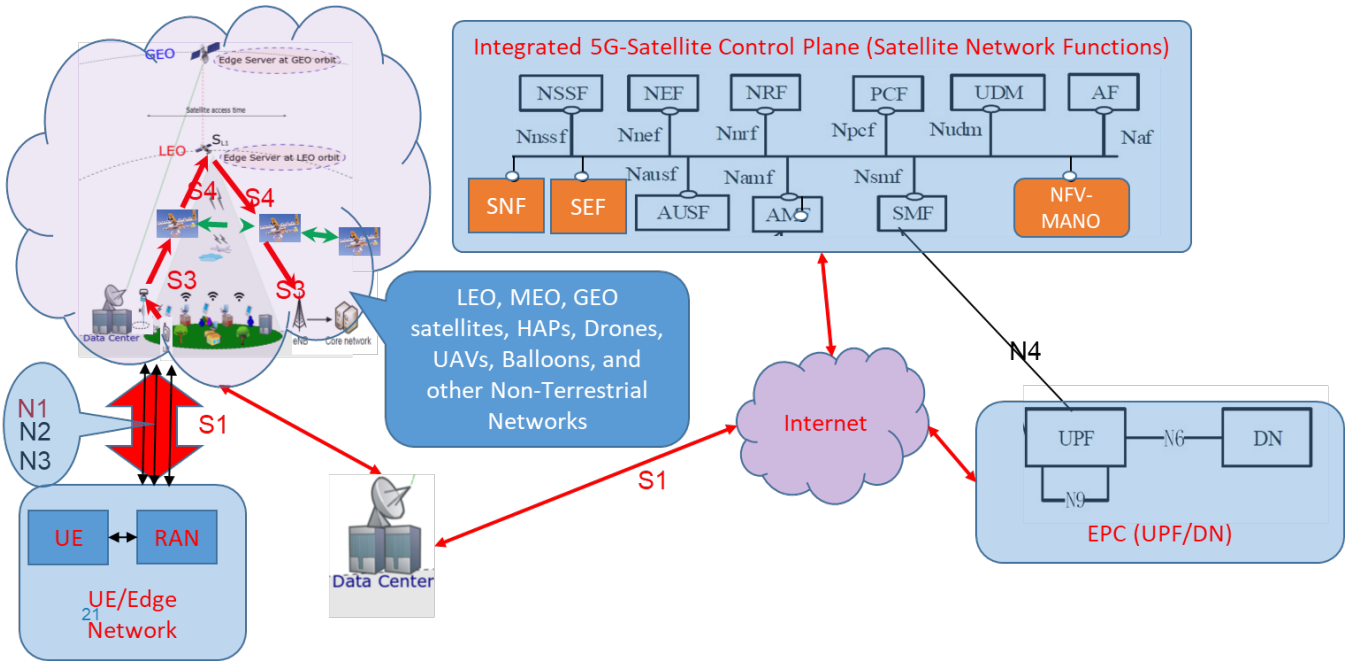


Figure 55. Reference Architecture-3

5. Needs, Challenges, and Enablers and Potential Solutions

5.1. Summary

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

5.2. Applications and Scenarios

5.2.1. 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 aircrafts or high-speed trains, highways, and ships. However, the NTNs nodes such as GEO/MEO/LEO satellites, HAPs, and UAVs can help to give access the Internet to remote and rural area population.

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

5.2.1.1. Space Based Hosting Service (SBHS)

Traditionally, satellites are employed for broadcasting purposes. However, the 2022 Edition of the satellite roadmap focuses on satellites as an access network as well and emphasizes 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 [15]," 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 lack of infrastructure deployment. Therefore, LEO satellite-based satellite broadband can play a vital role in achieving the goal of connecting the digitally unconnected population by utilizing the emerging application area of SBHS.

The SBHS approach [15] suggests hosting the entire set of content-servers in the LEO satellites. 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. 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 the traditional satellite-based web services. Further, the simulation study achieved ultra-low latencies for different countries to reduce the digital divide around the world.

5.2.1.2. 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 5.2.2 details the physical layer reference scenarios of satellite-based IoT services.

5.2.2. Challenges

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

One can envisage a wide range of scenarios for what happens next. While it is not possible to elaborate on all of them here, one may elucidate several bounding outcomes for them.

The first bounding outcome is that growth in data demand (driven largely by video customized to individual users, steered by analytics) is so extreme (current growth rates exceeding 30%/year) as to render it unacceptable to not be connected, even when remote or moving. We may call this the "broadband" scenario; the "High Throughput Satellites" and upcoming large (> 100's of satellites) constellations address this scenario. Most of the uses cases defined by ITU belong to the enhanced Mobile Broadband (eMBB) scenario.

A second bounding outcome is the mMTC (massive Machine-Type Communications) "Internet of Things" where ultimately nearly everything has a small radio periodically sending data (i.e., status or readings), resulting in large volumes across large areas such 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 when it comes to types of devices, data, and location. For instance, one might 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 is critical as the number of desired truly remote connections grows.

All people with smartphones are already connected in that they 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.

A final bounding outcome, not necessarily exclusive from those above, is a "broadcast resurgence" scenario. 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 keep delivering compelling high-quality program content to mass markets broadly segmented by language and geography. Broadcast resurgence could be motivated in part by user privacy concerns and (governmental and/or commercial) motivations to enhance social coherence with similar content for everybody. The broadcast resurgence can augment eMBB content choices, but is fundamentally a different mode of delivery, providing different user experiences. Broadcast resurgence is challenged once entire countries are connected via fiber but will still be an important and quite likely scenario in lesser-developed regions where fiber to the home may still be decades away.

Latency is often considered to be a major drawback for satellite links. This is certainly true for links of broadband geostationary satellites (their double hop being almost 0.5 s), but much reduced for the mega-constellations now being launched, which can offer below 10 ms single hops. Further, since the speed of light in a fiber is about 2/3 that of in free space, 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 satellite "sweet spots" in the 5G ecosystem. Mobile Edge Computing (MEC) at these cache sites is a natural adjunct.

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

Table 11. 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

5.2.3. Potential Solutions

Table 12. Solutions Associated with "Applications and Scenarios"

Near-term Challenges: 2020-2023	*Potential Solutions to Near-Term Challenges*
Satellite for eMBB	Linear video often license content for eMBB also
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 13. Overall Needs

Needs	*Description*
Need 1: Architecture for 5G-satellite integration	5G-satellite integration requires new integration architectures in order to meet the traffic performance requirements as well as the objectives of integrated network.
Need 2: To achieve federated satellite networks	Federated networking among multiple satellite network service providers can help lower the costs and improving 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 or 5G-satellite integration. The S1 interface defined for UE and LEO satellite 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 to LEO satellite, S4, needs to be developed.

5.3.1.1. Challenges

Table 14. 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 interfaces 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. Potential Solutions

Table 15. 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 Reference Architecture-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 Reference Architecture-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 Reference Architecture-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 5.2.3.
- 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. It is also possible to use the LEO network in conjunction with the UAVs, HAPs, and drones to ensure the latency is within acceptable limits. The use of 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 or not.
- 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 5.2.3.
- Solution to challenge 6: See the description of Reference Architecture-3 in Section 5.2.3.
- 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 16 provides the challenges associated with Satellite-IoT architecture and scenarios.

Table 16. Challenges Associated with "Satellite-IoT"

Near-term Challenges: 2020-2023	*Description*
Challenge 1	Low processing capability at 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 17 provides potential solutions for the challenges described in Table 16.

Table 17. 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 of information received from multiple satellites of the constellation, use 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. mmWave through Satellite Networks

5.4.1. Introduction

In the second edition of the Satellite Roadmap of the IEEE International Network Generations Roadmap (INGR), the physical layer issues were devoted to MIMO and RF-Optical systems. These strategies were proposed to support the following satellite needs: capacity, robustness, and security from the physical layer point of view. However, new generation of satellite networks will be also equipped with inter-satellite, and satellite-UAV links to deploy the future 3D satellite networks to provide global coverage with the lowest possible latency and, will be integrated with terrestrial networks. Moreover, it is expected that new applications such as the ones based on augmented reality and/or the ones related to climate change monitoring will play a key role in 6G systems. In this latter case, hybrid constellations that permit to combine Earth Observation and Communications may emerge. In practical terms, it means that 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 2022 edition of the IEEE INGR explores the use of the mmWave band as one of the potential ways to cope with the spectrum demand of the next generation of satellite networks. Toward this regard, this section is divided as follows. First, the frequency range that encompasses the mmWave band, the sub-bands that it has, 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.

5.4.1.1. Definition of the mmWave band

The mmWave band groups all frequencies which wavelength 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 ranged from 30 GHz to 300 GHz. This EHF band can be subdivided in the following sub-bands: Q (33-50 GHz), V (50-75 GHz), W (75-110 GHz), D (110-170 GHz) and mm or G (170-300 GHz). Note that the Ka band goes from 26.5 to 40 GHz. So, part of the Q band is included in the Ka

band since ITU-R nor IEEE officially recognize the Q band, but ISO does it. If it is used the ISO notation then the definition of the mmWave bands is aligned with the set of frequencies that have a wavelength on millimeters. Consequently, it means that part of Ka band, i.e., 26.5-30 GHz, is outside from the mmWave region. That is why there is an "overlapping" with Ka band. Furthermore, IEEE defines the V band in the range 40-75 GHz whereas ISO considers the range of V-band between 50 and 75 GHz. However, not all available spectrum of these bands is dedicated to satellite communications. Specifically, Table 18 shows the allocated frequencies for the uplink and downlink satellite transmissions as well as their available spectrum. Note that from the initial 270 GHz spectrum of the mmWave band only 10 GHz are available for satellite communications. Nevertheless, in the D and G bands there is no spectrum assigned for satellite communications yet. Finally, after showing the definition of the mmWave band the following section details its channel characteristics.

Table 18. Uplink, Downlink and Available Spectrum for the mmWave through Satellite according to ITU-R regulations

Frequency Band	Uplink	Downlink	Available Uplink Spectrum	Available Downlink Spectrum
Q	42.5-43.5 GHz 47.2-50.2 GHz	37.5-42.5 GHz 47.5-47.9 GHz 48.2-48.54GHz 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

5.4.1.2. Channel Characteristics at the mmWave Bands

As it is well-known the higher the frequency, the larger the path losses. Nonetheless, it is also important to take the atmospheric effects into account since the wavelength of these bands is very small. Toward this regard, Figure 56 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 57 shows the rain attenuation in dB/km in terms of the frequency for different rain fall rates. These attenuations are extracted from ITU-R [18]. From Figure 56 it is possible to observe that in Q band for frequencies ranged between 33-47 GHz, the main 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. On the contrary, the V band is practically dominated by the attenuation of the Oxygen. Only the set of frequencies comprised between 71 to 76 GHz is dominated by the water vapor attenuation. In this band the attenuation that introduces the Oxygen has a different behavior with the increase of the frequency. From 50-61 GHz, the attenuation of the Oxygen increases with the frequency but from 61-75 GHz reduces its attenuation with the augment of the frequency (see Figure 56). In fact, the range from 53-67 GHz have an attenuation larger than 10 dB/km, which is quite high for being used in satellite communications. So, it means that in this band is better to use its lower and upper frequencies instead 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 the 71-75 GHz. The frequencies in the range from 51.4-71 GHz at these moments are not used due to the large attenuation by Oxygen. In the W band the water vapor attenuation increases with the frequency. On the contrary, the Oxygen attenuation decays until the 94 GHz and from that to 110 GHz rises with the frequency. For that reason, the band of 94 GHz is considered as an atmospheric transparent window

which attracts applications for mmWave radar, astronomy, and defense. Currently the band from 77-81 GHz is used by the automotive radar.

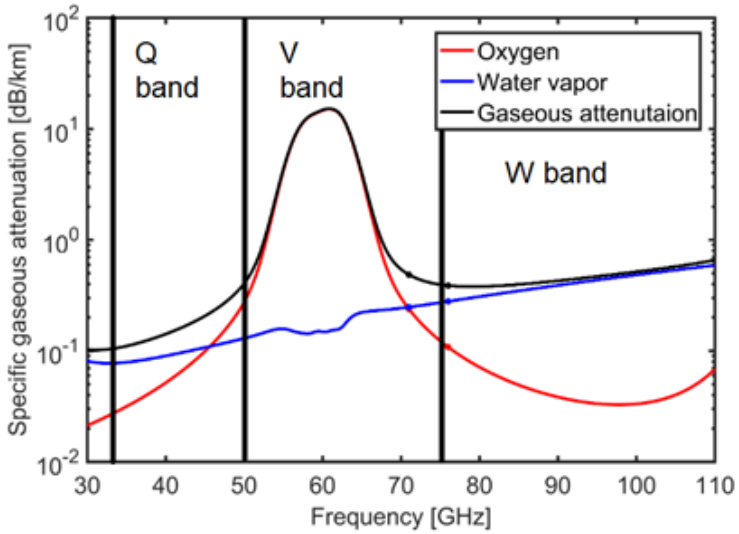


Figure 56. Attenuation in dB/km of the atmospheric gases: oxygen, water vapor and total. Pressure = 1 013.25 hPa; Temperature = 15°C; Water vapor density = 7.5 g/m^3

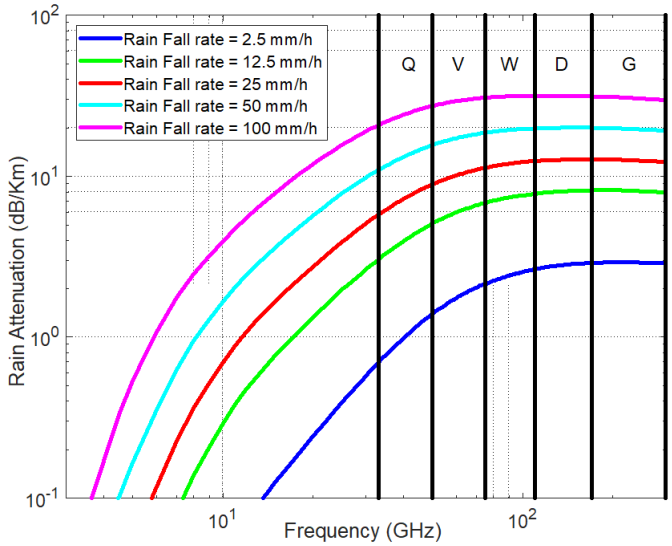


Figure 57. Rain attenuation in dB/km across frequency for the rain fall rates of 2.5 mm/h (light rain in blue), 12.5mm/h (medium rain in green), 25 mm/h (heavy rain in red), 50 mm/h (Downpour in cyan) and 100 mm/h (tropical in magenta). Horizontal polarization antenna [18]

From Figure 57, 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 sensible to the attenuation that introduces the rain. The attenuation for all rainfall rates has a similar pattern with the frequency. Initially, the attenuation increases notably with the frequency but from a certain value of frequency it turns a flat shape with independence of the rain fall 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 rainfalls that fade the downloading/uploading data process to the satellite, ii) large

power amplifiers to have a large margin to close the link budgets in case of rain, iii) use robust channel coding schemes to overcome as much as possible atmospheric effects, and iv) dynamic link layer adaptation that depends on meteorological information. From other side, these bands are quite interesting for being used as intersatellite, Moon to Satellite or inter-planetary communications in general due to their large available bandwidth and the absence of the rainfall effects and clouds.

5.4.1.3. Commercial Interest in mmWave

Although mmWave bands have larger propagation losses, it is also true that these bands are less used and so the larger will be the available spectrum for satellite communications. Then, it means that by resorting to these bands, the number of gateways will be lower and so the cost of the ground segment will be reduced. As these frequency bands are new for mmWave communications through satellites, they open new business opportunities to satellite operators [19]. Recently, the past 3rd November 2021, FCC approved the broadband satellite constellation of Boeing. Specifically, it will work in the following bands 37.5-40 GHz, 40-42 GHz, 47.2-50.2 GHz, 50.4-51 GHz band as well as in the 65-71 GHz for Inter Satellite Links (ISL) [20]. So, in the communications from 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 follows OneWeb constellation, which also received in August 2020, FCC approval for a 2000 non-Geostationary-satellite orbit (NGSO) broadband satellite constellation. 720 at 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]. SpaceX has also been approved by FCC 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 that they will operate are: 37.5-42 GHz (space-to-Earth), and 47.2-50.2 GHz, and 50.4-51.4 GHz (Earth-to-space). Thus, it complements its existing 4425 NGSO satellites that use both Ku and V spectrum for user links and Ka and V band for gateway links and telemetry. Recently, Astra has also filled to FCC to use a constellation of 13620 LEO satellites at an altitude of 700 km in V-Band [24]. Similarly, other satellite companies such Amazon, Inmarsat, Intelsat, Hughes, Telesat to name a few of them have requested to FCC to use V-Band. On the GEO side, EUTELSAT will launch on May 2022 its KONNECT VHTS satellite which will use Q/V band feeder links to provide fixed broadband and mobility connectivity across Europe [25]. So, this band and mmWave in general have attracted the commercial interest of the satellite companies to deploy new satellites or expanding their current constellations. At this point, it is necessary to point out that previous frequency margins for the V-band follow the FCC criteria (40-75GHz).

5.4.1.4. State-of-the-Art on mmWave Band through Satellite

Theoretical Studies

The interest of using mmWave bands to maximize the data rates in very/ultra-high throughput systems has been investigated from a theoretical point of view. In particular, the impact of receive power limitations on the achievable system performance has been analyzed. The studies in [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 for example 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 clouds attenuation. Whereas 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 further results [29]. This supports the interest of using the Q/V/W-bands for feeder links in GEO systems. Thanks to the larger available bandwidth in the Q/V/W-bands, the number of ground stations needed to support a target sum data rate can indeed be significantly reduced compared to a similar GEO system with only Ka-band feeder links. A system with an aggregated bandwidth of 350 GHz would for example necessitate 70 Ka-band feeder links (2.5 GHz of uplink bandwidth/2 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 [30], these conclusions cannot be generalized to feeder links for LEO mega-constellations. The results [30] show that a typical mega-constellation with satellites able to connect with two gateway stations at the same time can support higher data rates with links in the W- or the Q/V-band than in the Ka-band. However, a 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.

In terms of 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 [32] have validated the feasibility of establishing mmWave connections to provide access connectivity to terrestrial nodes using non-terrestrial stations and shed light on the research challenges associated to non-terrestrial networks. The same conclusions were obtained [33] in which a terrestrial terminal was deployed to communicate with a satellite placed at different altitudes, elevation angles and propagation scenarios. The authors [33] 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 elevation, compared to an urban scenario.

While the adoption of the mmWave spectrum for non-terrestrial networks seems promising, solutions are being proposed towards the development of new waveforms and modulation schemes, e.g., impulse-based Ultra-WideBand (UWB) modulation where 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.

Some 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 practical fields in future networks, including control and emergency communication in rural area [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 reported 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, the authors in [33] demonstrated via simulations that better wireless coverage can be provided when a standalone space layer is assisted by HAPs operating in the stratosphere. In fact, 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 spaceborne stations.

Measurements Campaigns

Regarding the missions on the mmWave bands, i.e., Q, V and W, all of them were dedicated to study the propagation conditions of these bands. 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 the ITALSAT one. It was devoted to characterize 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, 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, it was conducted the propagation experiments in the Q/V Bands by means of 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 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]. It simultaneously transmits from a LEO satellite at an altitude of 530 km a beacon at 75 GHz (W-band) and other one at 37.5 GHz (Q-Band). Thus, 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 one which is an ARTES project from ESA [42]. In this case, it is desired to test 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 WR12 encompasses the range of frequencies 60-90 GHz.

Hardware Development

Regarding the commercial solutions on the mmWave band, currently it is only possible to obtain limited COTS for the Q band and specific purpose subsystems in the Q and V bands for scientific missions

(e.g., [43] [44] [45]). On the contrary for the W band, it is not possible to obtain in the satellite field any commercial product yet. Note that the first satellite transmission on this band was conducted the past 21st September 2022 in the W-CUBE mission. This is not the case of terrestrial communications since the band 77-81 GHz is used for automotive radar in Advanced Driver Assistance Systems (ADAS). Departing from this knowledge, it is expected that there will be in a short time commercial hardware in this band. Basically, this band requires to develop high power amplifiers for the transmitter at the W-band with high DC-RF efficiency, and low noise amplifiers for compensating the large propagation loses at the W-band [46].

5.4.2. Challenges

The mmWave for satellite faces several challenges. We have distributed them in three parts: Near-term, Mid-term, and Long-term. The Near-term changes are the ones that can be adopted in the framework 2020-2023. The Mid-term ones they will be adopted in 2024-2025. Finally, the long-term ones will be introduced in the 2026-2030 temporal period.

At the near-term the challenges that mmWave through satellite have to face are following. First harmonization the frequency range and nomenclature of the mmWave bands. Thus, it will be possible speed up the standardization of new components, obtain affordable equipment (really needed), and increase its adoption by satellite industry. In second term, introduce the results of the satellite missions at the W-Band into the current models for predicting channel loses. As a third stage improve the efficiency of the power amplifiers and obtain mmWave equipment at an affordable cost. This is valid for all bands of interest. This would permit to extend the coverage of mmWave signals to larger distances and increase its adoption.

At the mid-term, the challenges that mmWave should consider to face are the next. In a first approach, fade mitigation techniques should be developed and implemented. The higher the frequency band that it is used the larger the attenuation from path, rain, and clouds. In second term, the use of 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 permit to increase the multiplexing gain of mmWave systems is of interest. Thus, it will be possible to extend the use of other band of mmWave for satellite (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 that they can transmit and the physical area in which the antennas can be placed are quite reduced.

Finally at the long-term, is assumed that mega-satellite constellations will be operating. Consequently, in this stage is desired that the resulting satellite networks provide the requirements of 6G systems. In particular, the capacity and latency constraints. Towards this regard, the challenge will consist of supporting multi-beam satellite architectures with fast handovers.

Table 19. Challenges Associated with "Capacity"

Near-term Challenges: 2020-2023	*Description*
Harmonization of its frequency bands	It would be necessary to harmonize the nomenclature and range of the mmWave bands to speed up the standardization of its commercial products, reduce its costs which will help to obtain 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 to name a few of them).
Efficiency of the power amplifiers	The use of mmWave increase by the facto the channel propagation losses. Consequently, it requires to use large arrays and high-power amplifiers to transmit the data. However, the transmitted power is limited by the efficiency of the amplifies. Then it will be necessary to increase the efficiency of them to increase the performance of beamforming techniques. Solutions to obtain affordable equipment cost would help to spread the adoption of the mmWave band.
Mid-term Challenges: 2024-2025	*Description*
Fade Mitigation Techniques	At this stage fade mitigation techniques have to be devised and implemented to cope with the mmWave channel impairments. Note that the higher the frequency band the larger the attenuation from 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 constellation will combine multi-orbit satellites, HAPs, and terrestrial infrastructure in a transparent way. In order to increase the capacity frequency reuse schemes will be used. Then, it is key that signals from satellites at different orbits be received correctly although they use the same resources at the same time.
Antenna solutions that reduce the channel propagation loses	As it is well known the higher the frequency, the larger are the propagation loses. In this case, new antenna solutions that permit to reduce this effect would permit to relax the requirement of power amplifiers with a very large efficiency and/or the use of a very large number of antennas. This is critical in small satellites such as the nanosat ones since the power and space of the antennas is limited.
Long-term Challenges: 2026-2030	*Description*
Fast Satellite Architectures of High Capacity	In this scenario, mega-constellation of satellites will be operating. In order to increase their capacity multi-beam architectures will be supported. However, if 6G requirements have to be fulfilled, it is required that fast beam management techniques be implemented.

5.4.3. Potential Solutions

As in the previous section, the potential solutions to the challenges that have to face mmWave through satellite are also classified in the following categories: Short-term (2020-2023), Medium-term (2024-2025) and Long-term (2026-2030).

Table 20. 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 the standardization, adoption, implementation of a technology are aligned, its adoption is speed up. This should be the case for the mmWave band since there exists multiple definitions for the same band, different classification of the mmWave bands. So, cross-cooperation to have a uniform definition of the mmWave band would be desirable in the next years.
Updating Channel Models	The current channel loses at high frequency from ITU-R are the result of theoretical models. So, it would be interesting that the results from real satellite transmissions in mmWave, such Alphasat, W-Cube and EIVE to name a few be integrated in the next versions of ITU-R channel models.
Efficiency of the power amplifiers	In order to increase the efficiency of the power amplifiers and electronic hardware in general when they work at very large frequencies, it is recommended to use the Gallium Nitride (GaN) since it permits to obtain smaller form factors and larger efficient components compared to the silicon-based ones.
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. In order 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. Then, it will be required to use interference cancellation techniques to remove the interference from different satellites. Toward this regard artificial intelligence will be key to recognize the interference and remove it. Finally, new waveforms such as the OTFS could be also 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 loses	In mmWave is used an array of beamformed antennas to obtain a multiplexing gain that permit to cope the channel loses. In this situation, the increase of the effective area of the antennas by resorting to new materials with appropriate conductivities and dielectric constants may also contribute to 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, optical bands to increase their capacity but also to augment their robustness to the channel impairments. Then, a potential solution to support multiple transmission bands consists in using automatic beam switching strategies guided by artificial intelligence.

5.4.3.1. Solution to Harmonization of the mmWave Frequency Bands

The adoption of a technology by the industry is key by its success. In this case, if the definition of the bands in mmWave was homogenous for all different key actors, it will speed up its global adoption. In this case, cross-communication among the different institutions will be key in the next years.

5.4.3.2. Solution to Updating mmWave Channel Models

As it has previously commented, mmWave band spans from 30 to 300 GHz frequency range. However, only exists commercial solutions for the Q (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. In 2022, it is expected that the mission EIVE will test the E-Band too. Although ITU-R provide results for the channel losses for frequencies up to 1000 GHz they are only estimations. Then, the results from the mmWave channel measures of these missions have to be compared with the theoretical ones provided by ITU-R models [17],[18] and introduced in the next versions of such documents.

5.4.3.3. Solution to Efficiency of the power amplifiers

At high frequency, the mmWave hardware is typically associated with severe power utilization for electronic components like DACs, phase shifters and combiners, and power amplifiers, which are required to process a large number of antenna outputs and very wide bandwidths. In this context, the adoption of the Gallium Nitride (GaN) technologies on satellites 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 [47] [48].

5.4.3.4. Solution to Fade Mitigation Techniques

As it has been previously stated, the mmWave signals can suffer a large attenuation from propagation path and atmospheric channel. In this case fade mitigation techniques have to be conducted. From the physical layer point of view, the following ones can be introduced: i) site diversity, ii) develop 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). In this latter case, the RIS bypass the blockage situation by generating multiple-line-of-sight (LoS) links.

5.4.3.5. Solution to Interference Mitigation Techniques

Future satellite networks will combine multi-orbit satellites and will be integrated with the terrestrial networks in a transparent way. In order to increase the capacity of the satellite networks frequency reuse schemes will be used. Then, it means that interferences among satellites may exists. Specially 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 one. In this case, interference mitigation techniques may help to cope with this issue. For instance, the use of narrow band interference schemes in which the interference is detected by using artificial intelligence strategies. Note that apart from removing the interference, it is of utmost interest to recognize the existence of an interference, determine its typology and adapt the canceller by appropriate learning strategy. Furthermore, next generations of satellite networks will combine communication and Earth observation systems. Toward this regard the use of new waveforms that permit to combine both worlds such as the OTFS ones may help to reduce interferences between different typologies of satellite networks.

5.4.3.6. 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 compared to mechanical products, and reduced size, weight and power challenges 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 [48] [49]. Furthermore, new achievements in the satellite industry simplify the deployment of flexible payloads, allowing services to autonomously adapt to evolving requirements, after launch and throughout the satellite lifetime, and support 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 a plurality of 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 permit to obtain additional gain. Thus, it would be increased the transmit EIRP and received power. In this case, new materials with appropriate dielectric constants may help to increase the resulting effective area [49].

5.4.3.7. 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 their connectivity and reduce latency. Thus, if one link from one technology does not work, it will be used another one or in case of high-capacity demand will be used several technologies 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 to

increase its response when the signal bandwidth is large. However, in this case techniques to compensate the deviation of the components with the time should be considered.

5.5. Antennas & Payload

Satellites are an integral part of today's communications network first in the provision of 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 in the future sophisticated antenna & payload systems will support reliable and robust communications.

Table 21 shows the three main technical needs of the satellite industry today that have implications on antenna and payload technologies.

Table 21. Overall Needs

Needs	*Description*
Capacity	Higher communications capacities are required, both per-user and on aggregate
Robustness	The antenna system needs to be reliable and interoperable with other satellite provider assets under all conditions
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 far distance between the ground and the satellite and are typically mechanically steered via gimbals. These ground antennas can be used judiciously in an array configuration to support higher data rate links [50].

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

For the space-to-Earth links, future antennas may migrate from a single reflector-type high gain antenna operating over a narrow frequency band to an antenna system with intelligence, with the ability to reconfigure its parameters to optimize link performance. This will especially be a primary requirement for the successful operation of mega-constellations in LEO orbit. Satellites in GEO orbit will also benefit from this flexibilization to easily adapt to the evolution of the market during their 15-year lifetime. Parameters such as frequency bands, polarization, beam and null-steering, 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, the use of optical links, to support a very high-date rate and secure transmissions will become part of satellite payloads, supporting both space-to-space and space-ground links.

For the sake of a clear 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 22. Current and Future Antenna Technologies

	Today	**Future**
Ground stations (Gateways)	Large C/X/Ku/Ka-band reflector antennas	Large Q/V/W reflector antennas

		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 Telescope (optical links)
Satellite – User links	Multi-beam reflector antennas with multiple feed per beam architecture	Multi-band active antennas supporting flexible beamforming (phased arrays with hybrid architectures, meta surfaces, …) Large-scale arrays using satellite swarms
Satellite – Intersatellite links	Medium-gain antennas such as S-band patch antennas	Small reflector antennas Telescope (optical links)
End users	Reflector antennas	Multi-band active antennas (phased arrays, meta surfaces, etc.) with a limited complexity and a low-power consumption

5.5.1. Challenges

Capacity needs

System capacity can only be raised by higher capacity links (typically, needing more bandwidth as there are practical power limits) and by having more available network paths, as would be available if there was interoperability.

Interoperability between satellites and ground stations needs to be addressed early on in order to avoid the mistakes of terrestrial early 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 especially rely on the deployment of active antennas able to support large bandwidths of potentially several GHz. For antennas deployed at the user side, the major challenge will be to reduce the costs such that a large consumer base can be reached. This will especially 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 be focused on finding the best trade-off between the flexibility of the antennas and their 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 23.

Table 23. Challenges Associated with "Capacity Needs"

Near-term Challenges: 2020-2023	*Description*
Frequency bandwidth	Operation over a wide frequency bandwidth in order to maximize capacity and interoperability
Processor constraints	For flexibility, digital processors are required, 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 deployment of technologies needed to advance satellite communications
Mid-term Challenges: 2024-2025	*Description*
Tracking and frequency bandwidth	Tracking satellites either 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 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, the ability to configure the payload to operate over multiple frequency bands can be used to mitigate weather events using a lower frequency band.

First, the ability to change its beam shape to optimize coverage based on capacity or emergency, and during spacecraft maneuvers is key. Second, with the increase in satellites, the likelihood of unwanted interference can be mitigated by beamforming. 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 57). 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 kind of innovative approach can only be efficiently included in future satellite networks if the antenna and payload subsystems are able to cooperate and exchange information with other entities (e.g., interferers in terrestrial networks).

Table 24. 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, the prevention and mitigation of unwanted interference will require the antenna system to detect where the interference is coming from and reconfigure the beam pattern to null the interferers while still maintaining communications within the main beam. Similarly, in order 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 mitigates interference via its filtering and level control functionality. Unless the repeater demodulates & 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. Our table below addresses this.

Table 25. Challenges Associated with "Security"

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

5.5.2. Potential Solutions

The tables below address potential solutions for the challenges associated with capacity, robustness, and security, respectively.

Table 26. 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 do it
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 offered by 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 will allow for a flexible and robust implementation of multiple channels, multiple 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 Signal processing hardware/algorithms

Table 27. 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 be able to survive the environments encountered in space. The use of GaN devices allows to implement 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 & 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 unit and antenna designs can allow efficient allocation of onboard resources. The same applies for gateway electronics.
Attenuation due to rain in higher frequency bands (e.g., Q/V band)	For the feeder links, the use of larger Q/V-band antenna reflectors will enable to increase the link margins and hence the robustness against rain fades. Antennas with a diameter of up to 10 m at the gateway side [8] and 2,4 m at the satellite side [9] can be envisioned.
Long-term Challenges: 2028-2032	*Description*
Cognitive capability	Self-configuring, self-repairing antenna & payload subsystems

Table 28. 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 be able to 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/AI have been widely explored for mobile and wireless networking. It is now being considered as a key 6G enabler as described in the recent white paper on ML in 6G wireless communication networks by S. Ali *et al.* [51]. 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 [52] [53] [54]. In order to achieve higher data rates, global coverage, higher reliability, better security, etc., it is required to use ML tools with non-terrestrial networks instead of traditional fixed rules based on certain heuristics. AI encapsulates ML, i.e., the way that a computer can learn to perform a task 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 and there is enough labeled data to explore. Some key concepts include classification and regression techniques, understanding of training and generalization errors, underfitting and overfitting models and dataset shifts. Some learning models include linear regression, statistical logistic regression, supervised classifier, Support Vector Machines (SVMs), Artificial Neural Networks (ANNs) and Deep Neural Networks (DNNs). Some related work on the application of supervised learning for non-terrestrial networks is covered in [55] [56].

- In unsupervised learning, data is available for training, but output is not labeled. Hence, subgroups are discovered with similar characteristics among the variables without any guidance. Some learning models include Gaussian Mixture Model (GMM), Expectation-Maximization (EM), Hierarchical clustering, K-means clustering, unsupervised soft-clustering, AutoEncoders (AE) and Adversarial AutoEncoders (AAE), etc.
- Reinforcement learning (RL) is different from supervised and unsupervised, where, in RL, an agent learns from interaction with an environment to achieve some long-term goal. The goal is usually to maximize the reward. The agent should be able to partially or fully sense the environment state and take actions to influence the environment state. RL is very useful in unknown environments, especially, for non-terrestrial networks [57] [58], where often the network conditions are not known.

These three categories and their learning models are used in several applications of ML for non-terrestrial networks. Specifically, the application of ML can be classified into six different "needs" as shown in Figure 58 and listed below.

- **Need #1:** AI-driven network planning and routing, including reducing handover costs and efficient multiple access
- **Need #2:** ML for positioning, including path selection, trajectory design and mobility
- **Need #3**: ML for applications including image/video delivery, situational awareness, traffic prediction, etc.
- **Need #4**: AI-driven enhanced security, including applications in public safety networks
- **Need #5:** ML for resource management, including energy power management and data caching
- **Need #6:** AI-driven physical layer communications including channel modeling, spectrum allocation, adaptive configurations of coding schemes, etc.

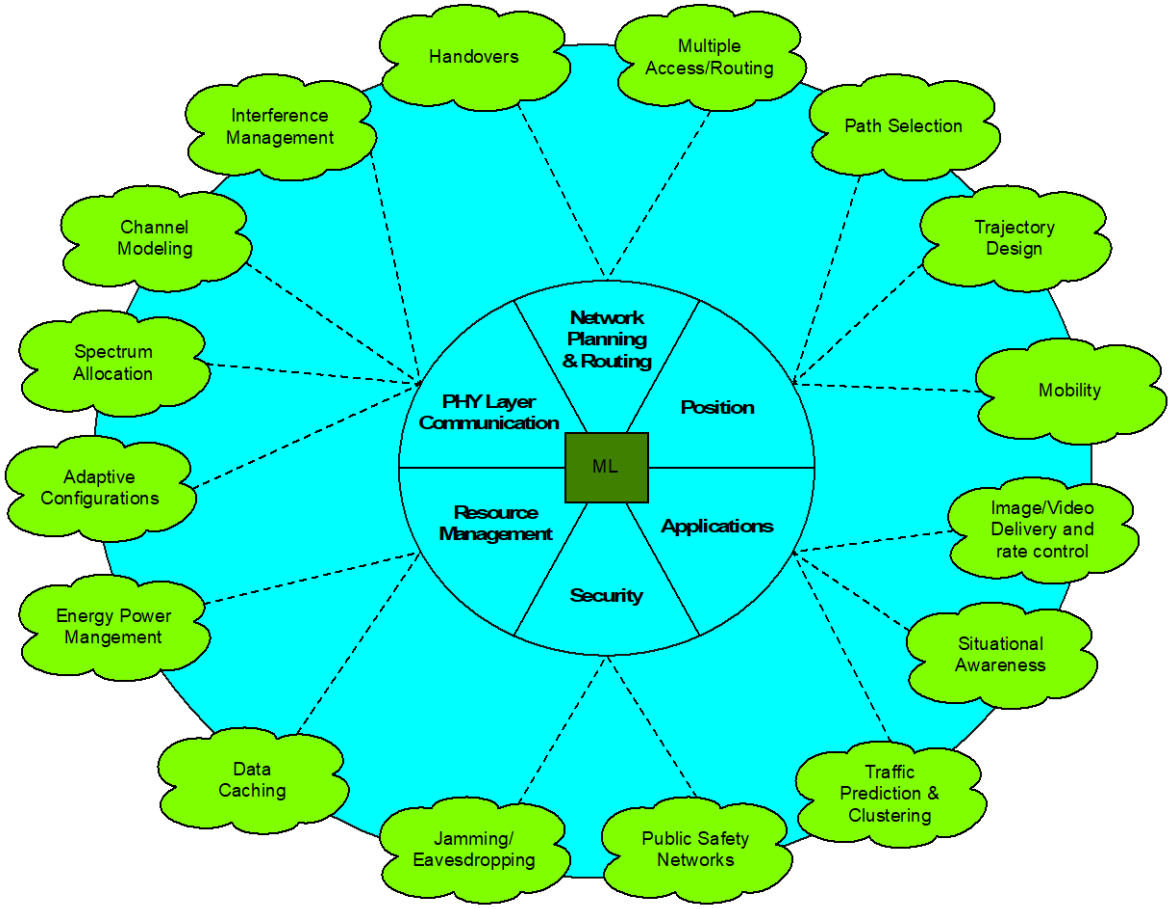


Figure 58. Classification of ML applications for Non-Terrestrial Networks

5.6.1. Challenges

In the previous section, we have identified 6 "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 29. Challenges Associated with all "Needs"

Near-term Challenges: 2022-2025	*Description*
Challenge #1: Efficient Dataset Generation	Several applications of ML for non-terrestrial networks are in unknown territories where the dataset may not be available. For such scenarios, the challenge is to generate and provide an efficient dataset. The other challenges, including training data, splitting data, training intervals, accuracy of predictions, etc. should be addressed.
Challenge #2: Learning Efficiency	The three major ML techniques are supervised, unsupervised and RL. However, there are several algorithms that 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	Both central and distributed networked systems have their pros and cons. With respect to ML techniques, there has been a lot of focus on Federated and Distributed learning. On the other hand, wrt technologies, MEC, content delivery network, D2D and blockchain are being considered for the future. The applications and tradeoff between centralized

	and decentralized ML approaches for non-terrestrial networks should be measured and compared.
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 is essential for the performance of wireless networks. On a similar note, 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 the area of ML application for non-terrestrial networks is still disordered. To advance technologies for future networks, it is critically important to standardize AI/ML applications and methods to measure the performance and to create benchmarks for these strategies. This is a long-term challenge, and the other near-term challenges are required to address to complete the scandalization.

5.6.2. Potential Solutions

In previous sections, we have identified "needs" and "challenges" for machine learning and artificial intelligence application with non-terrestrial networks. In this section, we present tables where each table describes the solutions corresponding to each "need."

Table 30. Potential Solutions to Address "Need #1: AI-driven network planning and routing"

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 path route for the traffic dissemination.
Challenge #2: Learning Efficiency	Learning efficiency and accuracy of deep learning (DL) techniques to distribute traffic with reduced computational cost using distributed training.
Challenge #3: Centralized vs Distributed ML techniques	Analysis and comparison of distributed and centralized routing techniques especially in case of hierarchical architecture with UAVs, LEO, MEO, GEO satellites and HAPs.
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).
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.
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.

Table 31. Potential Solutions to Address "Need #2: ML for positioning"

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Challenge #1: Efficient Dataset Generation	Efficient data generation by taking in consideration the proper horizontal and/or vertical placements for HAPs and UAVs, 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 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	Performance analysis of centralized and distributed ML techniques for proper detection and localization and optimal trajectory design.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Challenge #4: Deployment Overhead	Identification of deployment locations, including the integration of ML at edge/cloud/source and evaluation of deployment overhead.
Challenge #5: Cross-layer cooperation	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	Proper standardization process to be followed addressing challenges for efficient data generation and learning efficiency.

Table 32. Potential Solutions to Address "Need #3: 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 data generation. Specific video factors including frame rate, resolution and bitrates should be taken into consideration.
Challenge #2: Learning Efficiency	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 should be compared.
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, exploring ML implementations at both server and clients.
Challenge #5: Cross-layer cooperation	This need is specific to application layer, but network feedback, including packets 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 33. Potential Solutions to Address "Need #4: 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, 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 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), Wi-Fi Protected Access (WPA) to the non-terrestrial application integrated with ML algorithms.

Table 34. Potential Solutions to Address "Need #5: ML for resource management"

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Challenge #1: Efficient Dataset Generation	Selection of efficient data generation for resource management targets such as spectrum allocation and caching, network coordination, multi-modal multi-task offloading, 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, improving 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 for optimizing energy efficiency and recharging of 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 35. Potential Solutions to Address "Need #6: 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 taking into account the application of ML at 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). In fact, the MEC market has been growing dramatically in the last 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, hence possibly opening new market opportunities. However, the peculiarities of the satellite environment coupled with the MEC service requirements introduce important challenges (threats). From this standpoint, it is of paramount importance to stress the value brought by MEC-enabled satellite systems in terms of KPI to the B5G ecosystem. In particular, such a concept can help distribute the necessary resources to perform computing in the network, hence reducing the overall energy consumption. Moreover, the use of a satellite has inherently a large coverage capability, which will help simplify the access to computing and caching facilities from many users, independently of their specific position (i.e., also in rural and unconnected areas). Finally, the combination of AI concepts together with (v)LEO satellite systems may help further reduce the perceived latency to more easily achieve the concept of perceived zero latency, which B5G ecosystem alone (i.e., without support from NTN segments) can hardly achieve on all possible use cases (i.e., multi-connected or unconnected scenarios).

As to the main identified opportunities for the satellite industry, they 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 either at the edge node or at the central location. In order 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 the satellite hop. Edge placement will incur the deployment of more network functions – when the function is placed at the edge, this function must be managed in order to assure 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 functioning of the system, such as user profiles or user credentials, should not be placed at the edge.

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

Computation Offloading

Computation offloading techniques have been introduced for allowing 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 research [59] where multiple challenges are illustrated. Among others, computation offloading is considered for reducing the latency with respect to legacy data center-based solutions. The authors consider an integrated Satellite and terrestrial network for IoT applications [60], where an incentive mechanism is proposed for optimally selecting the destination of the task offloading. A game-theoretic approach is considered [61] 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 source of data. In some applications, data to be processed could be on the ground, while in some other cases 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 that of exploring a distributed computation approach where multiple devices collaborate. To this aim, when considering satellites as devices, the distributed approach could become very challenging.

Satellite MEC Caching

In Integrated Satellite-Terrestrial networks, MEC caching services can be deployed in the satellite orbital constellations or a single satellite to store the useful data in order to improve the secure level 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 [62]. The LEO satellites are treated as cloud data storage centers instead of the relay nodes, in which the data servers are deployed on the satellites. With the aim to reduce the downlink and uplink bandwidth consumption, a two-layer caching model is also introduced to support the content delivery service, in which the satellite layer and the ground station layer perform the joint caching [63]. Within a similar architecture, the work [64] 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 [65]. In addition, to improve the file distribution performance, the authors [66] propose an on-path caching-enabled fetching strategy by considering the spatial-temporal changing of the satellite and the ground stations.

Caching in satellites is needed to store the data, which can be used repeatedly, but the satellite has only limited storage space. It is very challenging to determine the caching data by utilizing the limited storage size and analyzing the data. On the other hand, the availability of on-board caching coupled to AI mechanisms can be leveraged to predict data request and hence possibly meet the stringent requirements from URLLC services. There are however still several challenges to realize the satellite MEC caching. We will only list the main ones as follows. First, the mobility of the satellite should be considered as 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 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 be guaranteed when the potential data amount and types can be extremely massive in the reference scenario.

Orbital Systems

MEC services when employing satellites should consider the satellite orbital constellations due to their impact on the service continuity and delay on the ground. The authors [67] consider the scenario that MEC platforms with computation and storage resources are deployed on LEO satellites, called "LEO-MEC". The authors [68] propose the Orbital Edge Computing (OEC) system as an approach for including CubeSat as part of the edge computing facility in a space-based architecture.

Within this context, it will be of paramount importance to integrate a dense vLEO and LEO orbital system with a distributed approach, especially by exploiting intersatellite 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 gNB 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 computation resource level, especially in terms of power and computation budget as well as in terms of cache, so that the possible tradeoff with the corresponding implementation on ground should be considered too.

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 [69] 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 [70] propose a protocol for supporting the distributed k-nearest service discovery, demonstrating that it allows scalable and locality-aware, name-based service discovery. It also allows routing for the target nodes avoiding redundant lookup message exchanges across the edge networks.

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 in 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.

Deployment and Orchestration

When facing a distributed scenario, it becomes of paramount importance to deploy and orchestrate efficiently the different resources and services. While deployment entails efficiently deploying the

different applications, orchestration involves their joint management with the available physical resources. The authors [69] consider jointly the service discovery with their optimal placement in a terrestrial network. The authors [71] 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 [72], where the TALENT platform is presented. The authors [73] survey 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 that a service can be effectively used if it is placed in the correct position. This is even more important in the case of a satellite system that considers different constellations impacting the 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. As an example, ETSI MANO is proposed for managing and orchestrating different functions. Its extension to edge computing and satellite could surely be of interest.

Based on the peculiarities identified for each of the aforementioned scenarios and use cases, it is possible to identify some key challenges, especially with respect to 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 36. Challenges Associated with "MEC"

Near-term Challenges: 2022-2025	*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.
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 have to be jointly coordinated.
Mid-term Challenges: 2026-2027	*Description*
Service Discovery	To discover the specific availability of a service in the network, which in the case of satellite systems is quite unexplored.
Long-term Challenges: 2027-2032	*Description*
Satellite MEC caching	To define the content or information what could be cached onboard satellite and to investigate which platforms should better used to this aim. An additional challenge is represented by the typical limited onboard storage available in space platforms.

5.7.2. Potential Solutions

Table 37. 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 special 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.
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. Obviously, in the case of

	multi-asset (e.g., multi-band, multi-orbit, multi-platform) satellite system, a more dynamic approach has to be taken.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Service Discovery	According to the current 3GPP specification (i.e., TS 23.748), discovery could be done either central or in a distributed manner, the latter benefiting from the availability of ISLs.
Long-term Challenges: 2027-2032	*Potential Solutions to Long-term Challenges*
Satellite MEC caching	To take advantage of space/time correlation between satellites and use of artificial intelligence schemes to better predict content requests and accordingly place contents by also exploiting power-efficient caching schemes.

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 at the terrestrial side or on-board the satellite. When considering terrestrial data sources, the possible solutions could consider the role of the satellite as a remote processing node or acting as a relay toward a ground station. While the first solution aims at reducing the offloading delay, the second one involves a higher delay. As a counterpart, onboard processing is usually very limited, allowing this solution as feasible in very few spacing use cases (e.g., IoT). Still considering terrestrial generated data, energy consumption is a figure of merit, where the satellite orbital system could impact on 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 intersatellite links for deploying tasks to be processed. The second would involve ground stations acting as a data sink for processing satellite-generated data.

5.7.2.2. Solution: Orchestration and Deployment

In contrast with service discovery, deployment and orchestration aim to proactively deploy and then orchestrate the MEC services in a given scenario. While deployment can leverage on NFV principles by flexibly managing the different functions in a satellite environment, the orchestration seems to be 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 as well as different demands for ground users could impact on dynamic service deployment policies.

5.7.2.3. Solution: Service Discovery

When facing MEC service discovery the main issue is that of identifying which services are involved and where they are deployed in a given satellite network. By resorting to 3GPP TR 23.748, which aims at defining the procedure for Edge Application Service Discovery, we can define two main solutions. 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 intersatellite 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. To realize the MEC caching in satellites, the following aspects have to be property taken into account. 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 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 the conditions of the limited caching space on satellites.

5.8. QoS/QoE

5.8.1. Challenges

The term QoS is extensively used today. It is not only used in analogue and digital transmission in telephony networks but also in broadband networks, wireless networks, multimedia services and even the Internet. Networks and systems are gradually being designed with consideration of the end-to-end performance required by user applications. Most traditional Internet applications such as email and ftp are sensitive to packet loss but can tolerate delays. For multimedia applications (voice and video) this is generally the opposite. They can tolerate some packet loss but are sensitive to delay and variation of the delay. Therefore, networks should have mechanisms for allocating bandwidth resources to guarantee a specific QoS for real-time applications. QoS can be described as a set of parameters that describes the quality of a specific 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 survey.

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 59, 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.

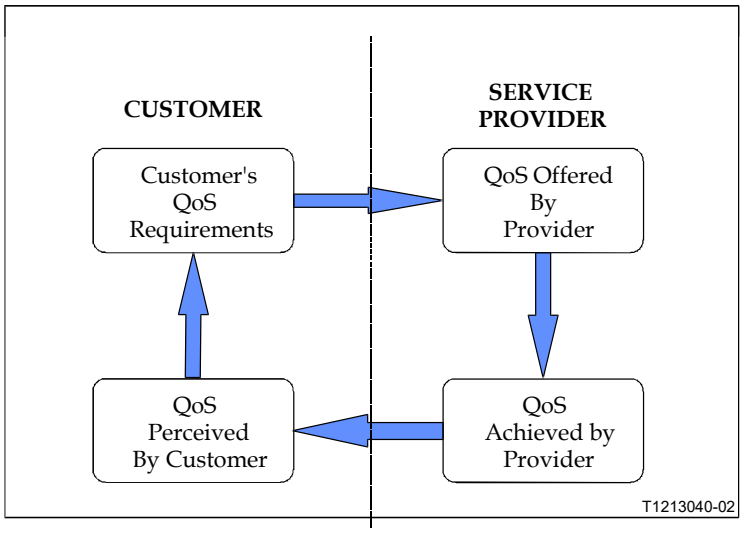


Figure 59. The four viewpoints of QoS (ITU-T G.1000)

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 following 3GPP reports [74] [75] [76].

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 not only satellites at different altitudes but also HAPs and UAVs. This system will allow multiple layers of connectivity (3D space networks). These different layers have a distinct impact on the system latency [please refer to Section 4.2 on "Reference architectures (LEO/MEO/GEO, aerial platforms, UAVs, and drones)" 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 60 that the end-to-end measurements can be carried out for the terrestrial networks and satellite network separately.

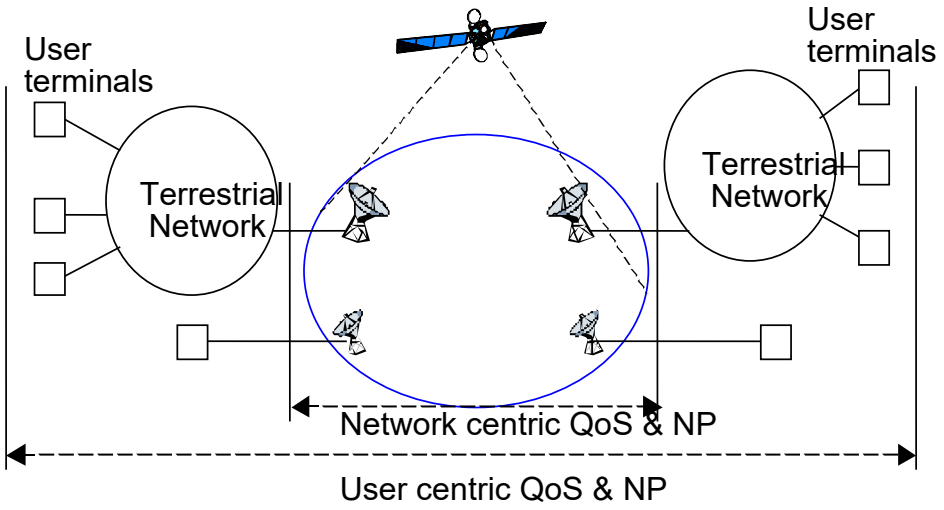


Figure 60. User- and network-centric views of QoS and Network Provision (NP) concepts

The one-way propagation delay between a UE and a satellite may range between 1 ms and 140 ms depending on the satellite 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 actual location of the communication endpoints [77]. On the other hand, it is expected that 5G - B5G - 6G will support new and extremely challenging services from the latency standpoint, such as augmented reality / virtual reality, gaming, in addition to streaming and other intensive traffic classes. A survey of innovative 5G use cases is provided in Section 5.2; further interesting examples involving the aerial component with HAPs, UAVs, and LEO satellites are provided [78].

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 [79]. This multipath peculiarity will have an impact on QoS requirements.

The full QoS model of 5G is detailed in 3GPP TS 23.501 [80] [81]. This specification applies to terrestrial 5G connections and the satellite ones that are compliant with the 5G standard (i.e., direct connectivity). However, 3GPP TS 23.501 does not explicitly mention the satellite case: all the 5G QoS Identifiers (5QI) specified in 23.501 are quite general. In 3GPP, QoS is at the flow level concerning the treatment of traffic flows between the UE and the User Plane Function (UPF) in terms of 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, resource efficiency, including the case of the satellite access [82]. TS 22.261 provides the following Table 38 on the propagation delay. These propagation delays impose some key constraints for services and protocols, as discussed below.

Table 38. UE to satellite propagation delay (Reference: TS 22.261 [82])

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

Still, the 3GPP specification TS 22.261 provides the following QoS Table 39 for satellite access.

Table 39. QoS requirements for satellite access (Reference: TS 22.261 [82])

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 kbit/s/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
Narrowband IoT connectivity	2 kbit/s	10 kbit/s	8 kbit/s/km^2	40 kbit/s/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 pictorial format as shown in Figure 61 below.

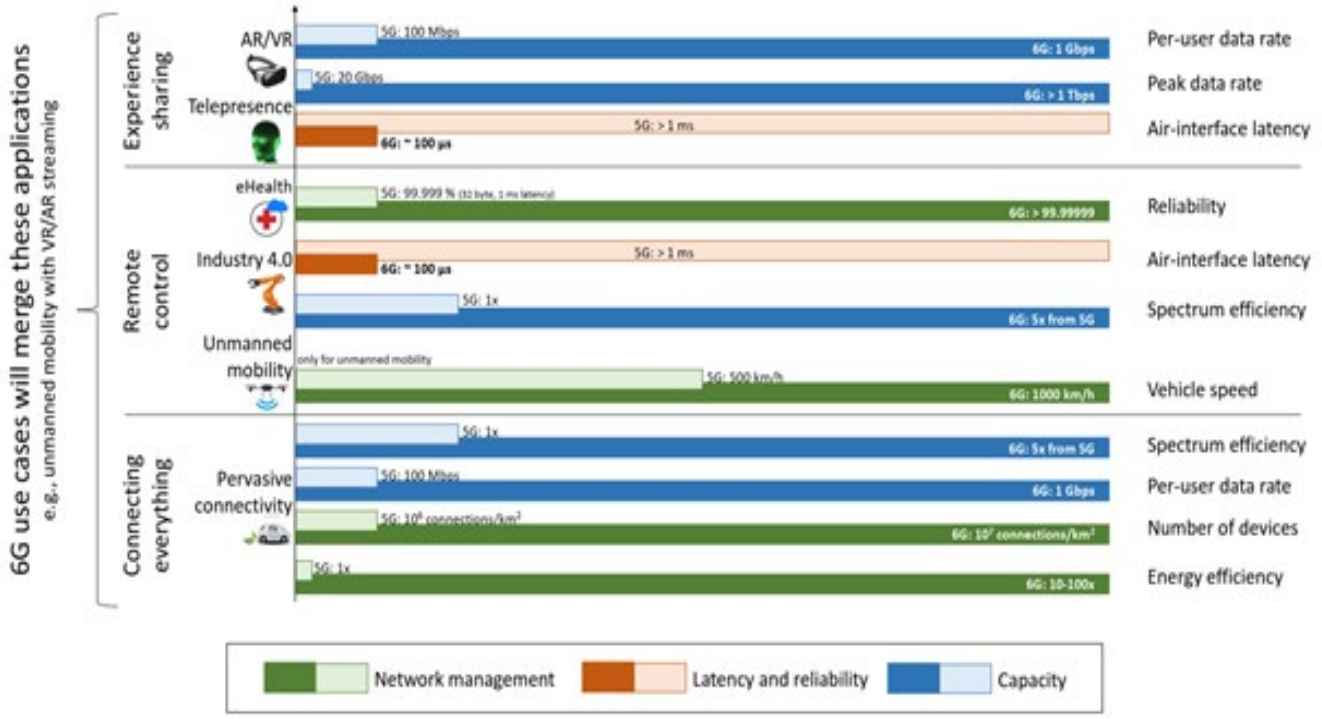


Figure 61. 5G QoS requirements [83].

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 [77]. For instance, URLLC may require a PDB of 5 ms, 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 in 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 attain 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) but rather MEC and AI/ML concepts should be envisioned. Likewise, large user data rates are not always achievable, depending on the specific propagation characteristics and the overall considered environment.

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

QoS architecture and function virtualization for 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 just to transmit information. Newly emerging applications require the network operators to redefine the functions of communication systems to include caching, computing, and retrieving resources with intelligence regarding context around users.

With the advent of 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 [84]. Such integration will create significant new opportunities for both 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, in the satellite domain, there is not a clear programming model. The overall integrated satellite-terrestrial ecosystem will be based on the current 5G design architecture, hence massively building on SDN/NFV, network slicing, MEC, and Service Function Chaining (SFC) concepts. The proper configuration and placement of such functions will be of paramount importance to meet the verticals' QoS requirements concerning bandwidth and computation demand and delay constraints to cite a few.

QoS architecture and function virtualization for 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. A full mesh network in the 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 to this, coordination between scheduling and resource allocation policies will be needed across multiple layers. In this respect, the main challenge will be to provide a suitable and flexible design concept able

to scale correctly in multi-tenant networks. To this end, proper instantiation of network slices and the related dimensioning will be pivotal to meet 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 40. 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 on 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 also LEO constellations provided with the networking capabilities (routing, SDN, MEC, etc.) needed for meeting 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 making use of different frequency bands to enable effective data communications. In this context, it is expected that a 3D satellite network will appear as a mesh system extending the terrestrial infrastructure implementing B5G and 6G technologies.

5.8.2. Potential Solutions

Table 41. 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 with respect to 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 to allow 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 where needed very 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.

5.8.2.1. 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 has to be co-located with storage or deployed in the very proximity to address low latency targets and reliability. However, for constrained IoT devices with satellite direct access capabilities, the closest hardware that could embed computing power is the satellite itself.

Today 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 OEC that co-locates computing hardware with high-data-rate in small, low-cost satellites [85].

5.8.2.2. Potential solutions to challenges #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, responsible for acquiring signal samples
- A baseband unit, 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, 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 that is a communication protocol enabling SDN operations), and the possibility of executing software-defined network 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 some 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 be of great value to make the overall network operations more flexible. However, this might come with the penalty of additional processing delay.

5.8.2.3. Potential solutions to challenges #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 [86].

The User Plane Function (UPF) is a fundamental component of 3GPP 5G core infrastructure system architecture (see Figure 62). According to 3GPP TS 23.501 [80], 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 [77]. 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. Other signaling between the access part and the control plane is via N1 and N2 interface. Please refer to our reference architecture in Section 5.2.3 (see also Figure 62 below).

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

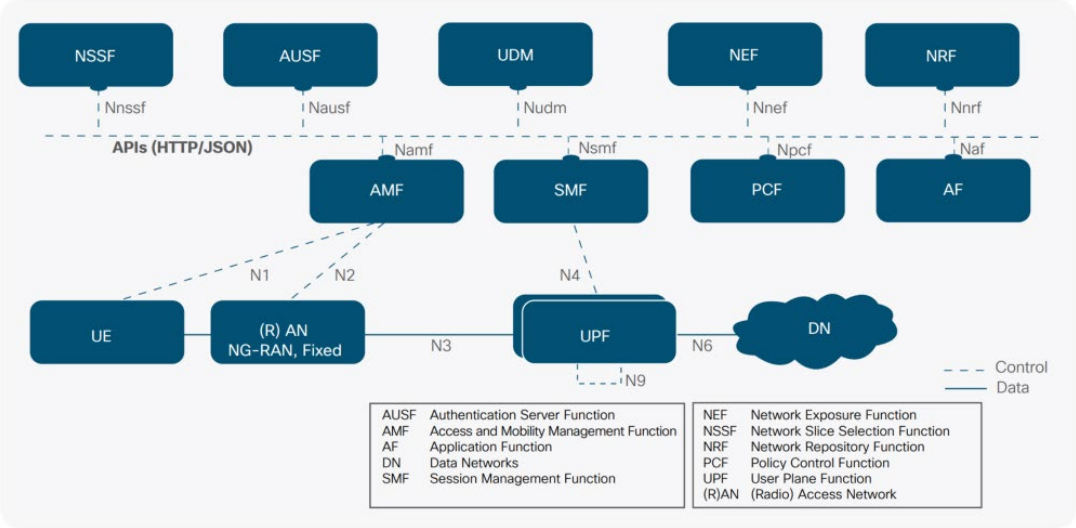


Figure 62. 5G network functions architecture, including User Data Management (UDM) in the core.

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 [87].

5.9. Security

The integration of 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 to 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 and 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 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 [88] [89].

Security has always been considered as an afterthought for most technology developments and hence always tends to be breached, as the underlying technology was never designed to be secure. Hence it is important that security-by-design concepts are adopted for 5G development, such that greater levels of security and protection can be achieved [90] [91].

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 [92] [93].

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 also within the non-terrestrial network across the orbital applications.

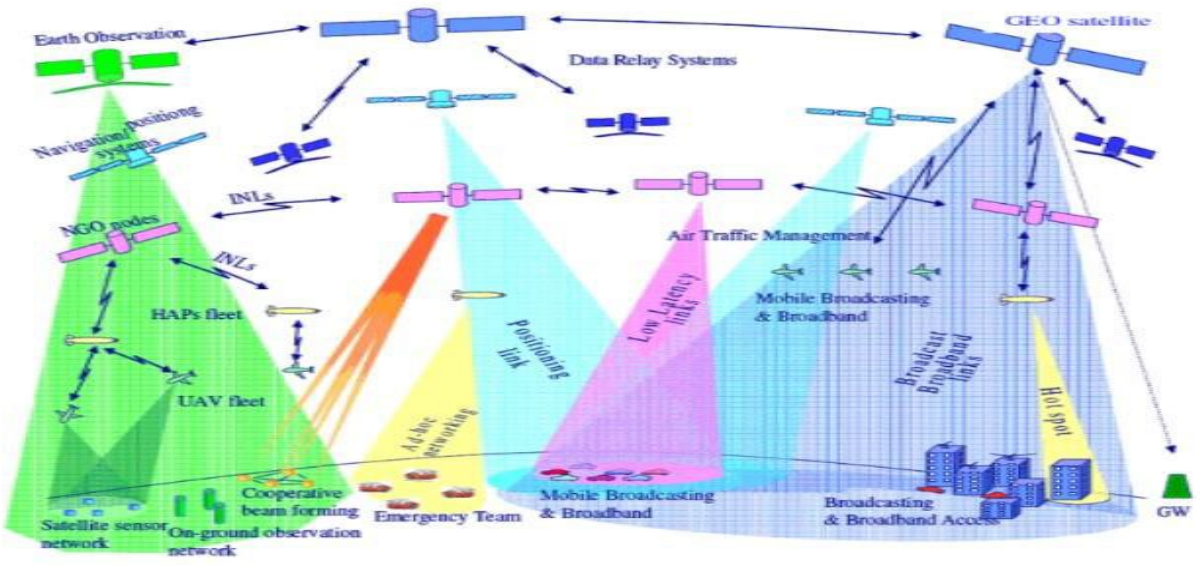


Figure 63. GEO (Geosynchronous Orbit), HEO (Highly Elliptical Orbit), MEO (Medium Earth Orbit), LEO (Low Earth Orbit), and HAP (High Altitude Platforms) [1]

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 63, 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].

It is clear that the emerging LEO satellite mega-constellations have a high potential to address global connectivity problems in rural areas and densely populated metropolitan centers [94]. The designs of these networks will be challenging as they introduce new constraints in terms of their integration to 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 actually far beyond cyber-security challenges that are solely related to the communication environment. The cyber-physical security perspective should be considered as in a holistic manner [95]. 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 it can command maneuver. Maneuver decisions are mainly given by the Telemetry, Tracking, Command, and Monitoring system (TTC&M) at the ground station. TTC&M systems sustain 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, so the security aspects of these emerging networks are of paramount importance.

5.9.1.2. Secure Air Interface

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 even jamming attacks. Signals received from the GEO satellite are usually very weak and could be overridden with another signal stream and vulnerable to illegal interception. Data confidentially (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, malicious insider attacks [96]. Typically, satellites can serve as 5G core or 5G user end point (UE). When satellites are used as 5G UEs these can be potential source of attacks due to botnets or infected malware. These can then contribute to flooding of interface or crashing of various network functions in the core network. Eavesdropping and data leakage could lead to loss of confidentiality that are caused by 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 flaw 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 the user traffic and control traffic. At the same time, it is important to implement secure monitoring tools to detect any types of attacks in the data plane and control plane and then apply any further mitigation techniques. Some of the mitigation techniques could include, beamforming, access class barring, encryption of data at rest and data in transit, multi-factor access control among others.

5.9.1.3. Secure 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 particular application vertical 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 challenges associated with it. Also combining these together in the same network gives rise to further 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 threat taxonomy to study the threats associated with each of these enablers and devise mitigation techniques for each of the threats.

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 for preventing 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 denial of service to other slices, slide channel attacks across slices, sealing between slices when UE is connected to multiple slices, impersonation attacks against a network slice during 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 capping of resources of individual, authentication of individual slices, ring fencing of individual slices.

It is highly likely that MEC concepts would be adopted in a 5G satellite architecture to move functionality to the edge of the network 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. Some of the mitigation techniques could include access control, authentication, proper encryption mechanism for the security context at the edge, IDS/IPS for proper security monitoring.

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

5.9.1.4. Trust Management

Current trust management protocols do not account for the diversity to be found in the 5G infrastructure with new devices, new actors and roles, new types of operators and new types of users. Trust management protocol must consider the vertical application domain and then slicing between the domains and layers simultaneously. The use of satellites within this complicated 5G arena further brings in new dimensions to the equation. Designing a trustworthy network and making informed trust decisions are both challenging in a 5G satellite environment. 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 take into account 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, risk factors associated with various types of threats. It is also important to develop Zero trust model to take care of zero-day type of attacks and assuming that there is no trust existent in the network.

5.9.1.5. Delay and Energy-Aware Algorithms

5G presents stringent latency requirements as a key priority. Security always increases delays and 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 that also consider 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 do not only provide adequate security but also are not energy-hungry and slow.

It is imperative that quantum resistance cryptographic algorithms are developed as the current standard algorithms may not remain secure when quantum computers will come into production. It is also important to make sure that security is not compromised at the expense of supporting ultra-low latency applications. In order to support ultra-low latency applications, in most cases security context is stored at the edge cloud giving rise to additional vulnerability. Thus, care must be taken to ensure that proper security mechanism is in place 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 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 their security services (more at layer 2) to protect the data it carried across its networks that were locally managed by the satellite operator. Mobile networks whose data was carried over the satellite backhauls did not have a view of this security and hence 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. It is imperative that 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.

In order to maintain confidentiality and integrity of the data traffic and control traffic at the RAN, Edge and Core, it is important make sure proper encryption and integrity keys are derived as a result of EAP-AKA or 5G-AKA mechanism during authentication process. End-to-end security may need to take into account security requirements in multiple roaming domains, Each operator domain may have different security mechanism. Hence, care needs to be taken into account to avoid threats due to 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 of packets in data plane and user plane to make sure proper quality of service is maintained. It is important to make sure that these markings are properly maintained across service provider domains.

5.9.1.7. Security Management Automation and Orchestration

While it is very important to have security-by-design concepts in the development of 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 that can 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 actors in the network to make sure 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 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, there are open-source orchestration tools such as OpenStack that can be used for network automation. With this perspective, tools and techniques for management and orchestration of the security architecture are also needed in order to secure satellite networks. Whereas a cloud computing system tend to be homogeneous, satellite networks can be much more complex and involve not only a single satellite but may contain multiple satellites that communicate over a very large distance. When one considers the B5G architecture with satellite components, as in Figure 63, it is apparent that in order to secure the entire network, an advanced architecture that is comprised of multiple systems and vendors is needed. 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. 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. In order to avoid the compromise of these APIs, it is important to authenticate the APIs and encrypt the communication.

In "Secure federated learning for cybersecurity by virtue of network cooperation, [97]" 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 64. 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 distributed 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 that may occur in one component of the network to be detected and disseminated to other regions of the network. 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 meta data or alerts to Policy Control Function (PCF) that could be part of distribution layer or management layer. PCF in turn can communicate with Policy Control Enforcement Function to mitigate the attacks. In a distributed satellite architecture, Policy Control Functions can be distributed across the network. Also, the enforcement points could be at the routers or switches that can be controlled by the respective SDN controllers. These enforcement points can also be distributed and will be controlled by respective SDN controllers. Hence, the communications among the Data Analytics Engine, Policy Control Functions and Policy Control Enforcement points need to be secured. 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.

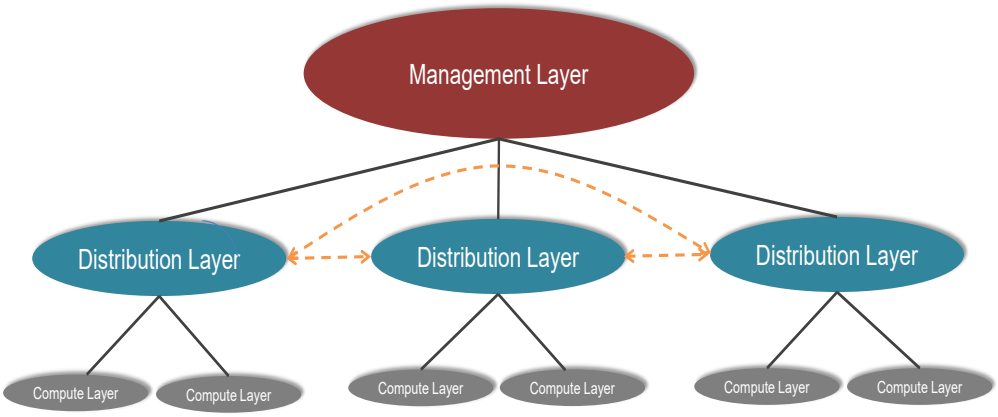


Figure 64. Hierarchical Layered Security Architecture

The research in this paper was targeted towards 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 cybersecurity information is shared across networks to ensure security, which in fact, is in everyone's best interest.

5.9.1.8. Realtime Security Monitoring

Realtime security monitoring is needed to understand the security state of the network. In Figure 64, 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 take place across the compute elements, regardless of whether they are on one or more satellites. While compute system attacks may have commonality with traditional terrestrial network attacks, the satellite has many subsystems that are unique. For example, command and control, telemetry, power and communication systems have must be protected and monitored in a manner that is different than computer networks.

Today, digital forensics are common practice in law enforcement investigations. Some of the tools that are used, including file and memory analysis, may be able to determine whether an attack is underway or imminent. Unlike forensics, these functions need to be performed in real-time in order to provide an effective security view of the network. Realtime monitoring of compute 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.

5.9.2. 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 42 based on near-term, mid-term and long-term challenges.

Table 42. 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 capability, e.g., spacecraft power, bus, etc. It is important to design satellite subsystems with cybersecurity as a core component.
Mid-term Challenges: 2026-2027	*Potential Solutions to mid-term challenges*
Challenge #2: Fast Trust Management	Methods to implement Zero Trust into single and multiple satellite systems is needed to provide the best level of security. This must take place in a timely manner to ensure that significant delays are not introduced into the security system.
Challenge #3: Development of Autonomous Security Management and Orchestration	Future satellite systems must be able to have mechanisms to manage security quickly to deal attacks before they can cause damage. If the systems can detect threats in a timely manner and rapidly instantiate defense mechanisms, damage can be reduced. To achieve this 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 #4: 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, including (a) mobility management, (b) radio resource management, and (c) routing.

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). Basically, the satellites' locations need to be handled with low signaling cost and high accuracy. The fast handover of the satellite from one gateway to another should be addressed to guarantee soft and seamless handover. In addition, when a user is forced to switch to another satellite due to satellites 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 at the same time or within a short period of time. This might congest the communication links with handover signaling and location updates. A new method to efficiently handle group handover with low cost is required.

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. In order to keep the communication with satellites their location and addresses need to be managed while they are moving from one network or domain to another. 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 satellite (both as a terminal and mobile BS) is very important to support the S1 interface of the use cases mentioned in Section 5.2. However, there are several challenges to overcome. The following table summarizes the challenges related to the need of "**Support Satellite Location Management**".

Table 43. 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 singling 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, 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) are the two main challenging issues in distributed location management.

5.10.2.2. Support Satellite Location Management - Potential Solutions

To support satellite location management, this section describes several potential solutions which address the challenges in Table 43. First, to handle the frequent IP address change, the Earth surface can be divided into clusters and each cluster covers the area of multiple satellite footprints. A satellite moving in the same cluster do 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 needs to change without affecting the local address. Third, to overcome the drawbacks of centralized location management, the concept of SDN-based distributed mobility management [98] can be exploited with some modifications in satellite networks. However, one of the critical issues that need to be considered is the distribution and placement of the controllers (e.g., on earth or in space). Table 44 summarizes the potential solutions of the challenges of the first need for satellite mobility management "**Support Satellite Location Management"**.

Table 44. 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 surface can be divided into clusters that cover the area of multiple satellites footprint. A satellite moving in the same cluster does not have to change its IP address. When a satellite moves from one cluster to another, then the IP address needs to be changed.
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 Terminal Handover – Challenges

LEO satellite footprints (coverage areas) might overlap. When terminals (users) are moving near the edges of satellites 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 a large number of satellites available in the sky, selecting the best satellite as the handover target might not be an easy process especially with the consideration of certain QoS levels and the competition among many users. Table 45 summarizes the challenges related to the third need "**Support Terminal Handover"**.

Table 45. Challenges Associated with "Support 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 an easy process considering certain QoS and the competition among many users.

5.10.3.2. Support Terminal Handover – Potential Solutions

To support terminal handover in satellite networks, several challenges need to be addressed. This section provides potential solutions for the three challenges mentioned in Table 45. 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, satellites 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 then 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 5.2. Table 46 summarizes the

potential solutions of the challenges of the third need of satellite mobility management **"Support Terminal Handover"**.

Table 46. Potential Solutions to Address "Support 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, satellites 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 to evaluate the available satellite options then select the best satellite that satisfies the user QoS requirements.

5.10.4. Mobility Management in Satellite Networks - Need #3

5.10.4.1. Support Group of Terminals Handover – Challenges

The challenges related to the fourth need **"Support Group of Terminals Handover"** are summarized in Table 47. When a large number of users in a satellite footprint have to go through connection handover within a short time period due to satellite movement, this may create a storm of location updates and handover signaling when the large group of users are triggering handover in almost the same time. 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 the handover delays. As FMIPv6 protocol was not designed for group handovers, implementing such protocol for group handover scenario requires some enhancements. In future satellite networks with mega-constellations, there will be several satellites as available options for handover target. One satellite might not be able to serve all users and satisfy all their QoS requirements.

Table 47. Challenges Associated with "Support Group of Terminals Handover"

Near-term Challenges: 2022-2025	*Description*
Challenge 1 (Handling the location update and handover signaling of large number of users triggering handover in 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 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 target, 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. Thus, users need to be grouped into clusters where each cluster can be served with a specific satellite.

5.10.4.2. Support Group of Terminals Handover – Potential Solutions

Table 48 summarizes the potential solutions of the challenges of the fourth need for satellite mobility management "**Support Group of Terminals Handover"**. First, to handle the location update and handover signaling of many users triggering handover at almost the same time, terminals prioritization can be a potential solution. Second, to implement FMIPv6 for a group of users' handovers, a representative user should be elected. The elected representative can obtain a network address prefix from the next satellite and distribute the address prefix among the group of users [99]. Third, when the group of users have different QoS requirements and they need to be handed over to a group of satellites because they cannot be served by one satellite, this can be managed in a similar way to the multiple producers - multiple consumers problems.

Table 48. 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 in almost the same time)	To handle many users without degrading their QoS, users should be prioritized based on their position, movement pattern, and required QoS level.
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 in a similar way to the multiple producers' multiple consumers problem.

5.10.5. 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 5.2. 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, due to the deployment of many satellite systems, e.g., dense LEO constellations and the massive number of connected users/devices, high interference is inevitable. Therefore, interference coordination and mitigation in satellite networks is crucial to utilize the limited frequency and power resources efficiently.

5.10.6. Radio Resource Management in Satellite Networks - Need #1

5.10.6.1. Optimized Resource Management – Challenges

To optimize the resource allocation process in future satellite networks, several challenges need to be addressed. First, the long propagation delay associated with satellite communications directly impacts the QoS of the users, which makes it difficult to fulfill the end-to-end QoS requirements of some users. Second, the high mobility of Non-GEOstationary (NGEO) 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. In addition, due to the increasing number of satellite users, the scalability of the resource allocation techniques should be taken into consideration. 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. Table 49 summarizes the associated challenges to realize an optimized resource allocation in future satellite networks.

Table 49. Challenges Associated with "Optimized Resource Allocation"

Near-term Challenges: 2022-2025	*Description*
Challenge 1: High propagation delay	Cannot support low latency requirements of the users.
Challenge 2: High mobility of NGEO 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 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 due to very large number of different systems, e.g., tens of thousands of LEO satellites.

5.10.6.2. Optimized Resource Management – Potential Solutions

To address the challenges associated with resource allocation, numerous potential solutions can be employed. 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 the 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 antennas technology. Table 50 summarizes the potential solutions for every discussed challenge.

Table 50. 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 through 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 NGEOs	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. Optimizing admission control procedures to guarantee QoS satisfaction of admitted users.
Challenge 4: High interference	Exploiting the spatial dimensions utilizing phased array antennas technologies. 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. Optimizing admission control procedures to guarantee QoS satisfaction of admitted users.
Challenge 6: Much higher interference	Exploitation of spatial dimensions utilizing more advanced phased array antennas technologies. More coordination and interoperability between different systems and centralized management approaches.

5.10.7. Radio Resource Management in Satellite Networks - Need #2

5.10.7.1. 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 different 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 are characterized by their low data rate transmissions and delay-tolerance. Besides, the IoT devices are generally low-cost, low-power devices. Therefore, they require energy-efficient services. This 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 51 summarizes these challenges from the near-term, mid-term, and long-term points of view.

Table 51. 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.

5.10.7.2. 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 the 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 utilizing the virtualized reference architectures RA-2 and RA-3, as discussed in Section 5.2.3. These potential solutions are summarized in Table 52.

Table 52. 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 flexibly adapt and re-define the. network slices. 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.

5.10.8. Radio Resource Management in Satellite Networks - Need #3

5.10.8.1. 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 is of utmost importance to satellite networks. The challenges of efficient interference management and spectrum utilization are summarized in Table 53.

Table 53. 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 NGEO satellites coexist with GEOs, HAPs/UAVs, and terrestrial.

5.10.8.2. Efficient Interference Management and Spectrum Utilization – Solutions

To overcome the challenge of limited spectrum resources, dynamic spectrum access utilizing cognitive radio technology can be employed. In this regard, 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 5.2.3), can play a vital role in interference mitigation and avoidance. Table 54 summarizes the potential solutions for every discussed challenge.

Table 54. 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 the interference between systems.

5.10.9. 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 for 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 both 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). To ensure that such routing becomes a reality in satellite networks, we identify key needs (requirements), challenges, and potential solutions.

5.10.10. Routing in Satellite Networks - Need #1

5.10.10.1. Intersatellite Links – Challenges

Inter-Satellite Links (ISLs) are essential to fully harness the benefits of LEO satellite networks. These links are presented in the use cases of Section 5.2 as proprietary links or interface S2 links. A configuration where pairs of LEO satellites only communicate using ground relays or GEO relays would be very expensive and counterproductive for the latency. ISLs can be either RF-based or FSO-based. The latter is more appealing as it is conducive to higher data rates and has no interference to deal with. As of today, even though projects like Starlink already have hundreds of LEO satellites in orbit, ISLs are yet to become a reality. Ground relays are still being used at this early stage of the project. But the expectation is that, as the FSO technology on LEO satellites matures, we will see ISLs implemented substantially within the next 5 years. Table 55 summarizes these challenges and their anticipated timeline.

Table 55. Challenges Associated with "Intersatellite Links"

Near-term Challenges: 2022-2025	*Description*
Infancy of long-range laser links	The laser link technology for LEO-to-LEO communication (long-range) is still maturing. Traditionally, laser links have been used for very short-range communications. RF is still the go-to for all radio communications, including satellites, as it has a proven record. Most existing transceiver models are RF by default.
Pointing, Acquisition, and Tracking (PAT)	Maintaining very accurate PAT in the context of highly mobile LEO satellites is an immense effort.
Mid-term Challenges: 2026-2027	*Description*
Standardization	Bringing all the different flavors of laser links together. They will have been developed independently in non-collaborative groups/operators.
Long-term Challenges: 2028-2032	*Description*
None anticipated	The laser link technology for LEO-to-LEO communication should be fully mature at this point.

5.10.10.2. Intersatellite Links – Potential Solutions

The solutions to the above-mentioned challenges mainly reside in increased research (academic and industry) and collaboration between the parties for agreed-upon techniques. This is necessary for the maturity of laser links in ISLs. At this early stage of these constellations and for the next couple of years, there is still a heavy reliance on ground relays. GEO-LEO ISLs have been demonstrated [100]. Still missing are the LEO-LEO ISLs represented as interface S2 in the use cases of Section 5.2. Table 56 summarizes these potential solutions.

Table 56. Potential Solutions to Address "Intersatellite Links Challenge"

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Infancy of long-range laser links	Increasing the funding for academic research will inevitably lead to the quick maturity of laser links for long-range usage.
Pointing, Acquisition, and Tracking (PAT)	More academic research, aligned with the need of the main operators, shall also help here, as it is related to the maturity of this technology. Due to the speed of the satellites, and the relative speed between satellites, maintaining accurate PAT is going to be challenging.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Standardization	More collaboration between the players will result in agreements for standardization.
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
None anticipated	N/A, since no challenge is anticipated at this point.

5.10.11. Routing in Satellite Networks - Need #2

5.10.11.1. On-Board Processing – Challenges

Without onboard processing, routing cannot take place. On-board processing will ensure that each satellite fully recovers the received packet, 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 the ones 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.

5.10.11.2. On-Board Processing – Potential Solutions

At this juncture, on-board processing is already available either in the form of digital transparent processing (no demodulation and no decoding) or in the form of full regenerative processing (demodulation and decoding included) [101]. But it is not yet used/tested for LEO-LEO routing decision making. To reduce the expensiveness of full regenerative processing, one solution would be to use partial regenerative processing instead whereby only the header packet is regenerated, which would be enough for routing purposes. 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 whereby 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.

5.10.12. Routing in Satellite Networks - Need #3

5.10.12.1. Dual RF/FSO – Challenges

The RF/FSO dual functionality is important because a) any given LEO satellite needs to be able to communicate with a ground station (vertical link) and with other LEO satellites (horizontal link); and b) the atmosphere makes it such that the conditions (losses, impairments) on a vertical link are very different from the conditions on a horizontal link. The atmosphere has very adverse effects on Extremely High Frequencies (EHF), making the usage of FSO impractical on top of the fact that laser links could potentially trigger health concerns for ground users. With the dual RF/FSO operation, vertical links would operate in RF, whereas horizontal links would operate in FSO. These vertical links are the interface-S1 links, and the horizontal links are the interface-S2 links, both presented in the use cases of Section 5.2. Amongst the challenges associated with this dual RF/FSO operation, we can name once again the PAT. We can also name the Doppler effect that would change the received frequencies. Table 59 summarizes these challenges.

Table 59. Challenges Associated with "Dual RF/FSO"

Near-term Challenges: 2022-2025	*Description*
Coupled functionality	Current studies that have explored hybrid RF/FSO systems only focus on FSO augmenting RF when the latter becomes temporarily inefficient, or vice versa. Commercially available hybrid RF/FSO products (like fSONA and MRV products) use the RF link just as a back-up channel [102].
Pointing, Acquisition, and Tracking (PAT)	Due to the speed of the satellites, and the relative speed between satellites, maintaining accurate PAT is going to be challenging.
Mid-term Challenges: 2026-2027	*Description*
Doppler Effect	Due to the relative speed between satellites, the received signal frequency is going to be changed. This will be true for both ISLs (FSO) and ground satellite (RF). We rank this as a mid-term challenge because it is expected that we will have more inter-orbit ISLs, and these will be more affected by Doppler.
Long-term Challenges: 2028-2032	*Description*
None anticipated	We should have dual RF/FSO transceivers on satellites at this point.

5.10.12.2. Dual RF/FSO – Potential Solutions

Some techniques have been proposed in the literature [103] [104] to curb the Doppler effect. Also, in the literature [105] [106] are other techniques to tackle the PAT challenge. What is needed is to test those in the context of satellite mega-constellations. Potentially, some modification and fine-tuning will be needed. Table 60 summarizes these potential solutions.

Table 60. Potential Solutions to Address "Dual RF/FSO Challenges"

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Coupled functionality	Explore concurrent operation of RF and FSO, each targeting its clientele: RF for satellite to ground and vice versa; and FSO for ISLs. This could mean using two transceivers (One for RF, one for FSO) on the satellite.
PAT	For the ground-satellite links, use a hybrid pointing architecture that uses inertial sensors, a celestial reference, and an uplink beacon. For the ISLs, use beaconless pointing that only needs a celestial reference source [105] [106].
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Doppler Effect	Using techniques such as the optical injection phase-lock loop (OIPLL) technique [90] or a Doppler shift compensator as proposed in [104], or develop new techniques of accurate location estimation.
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
None anticipated	N/A, since no challenge is anticipated at this point.

5.10.13. Routing in Satellite Networks - Need #4

5.10.13.1. Routing Protocols – Challenges

Once we have intersatellite links, on-board 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 5.2. 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 the 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 61 summarizes some of the expected challenges.

Table 61. 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, is going to be the main attraction and advantage of satellite networks over terrestrial networks. Table 62 summarizes the potential solutions.

Table 62. 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 networks. 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 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, the notion of network virtualization focuses on the concept of a software-based representation of both 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 the concept of 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 as well as physical separation of network resources [107]. 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, the adoption of SDN/NFV and NS is a necessary step in the evolution of satellite-terrestrial networks. This 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) [108]. 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 63 summarizes the satellite network function virtualization challenges.

Table 63. 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 satellite networks will be operated by multiple operators, 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 needs to be able to create /remove network functions in an automated way.

5.10.15.1. Network Function Virtualization – Potential Solutions

There are some possible solutions to the above-listed challenges, which are summarized in Table 64.

Table 64. 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 65 summarizes some important challenges related to network slicing in satellite networks.

Table 65. 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	In satellite networks, NS might involve multiple operators and resources from different networks. Also, the integration with terrestrial and aerial networks may necessitate to create 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. It is more challenging to automate the creation and management of network slices across different types of integrated networks (i.e., satellite, aerial, terrestrial).

5.10.16.2. Network Slicing – Potential Solutions

Some possible solutions to the above-listed challenges are summarized in Table 66.

Table 66. 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 67 summarizes some important challenges related to network slicing in satellite networks.

Table 67. 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 the 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 68.

Table 68. 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 satellite might reduce the overhead of creating new tables. Intelligent predictions may play 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. Hierarchical structure of controllers, which can be across integrated networks, should be adopted to reduce the load on controllers and reduce controller 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

Standardization activities for 5G and beyond 5G for Non-Terrestrial Networks are in progress in different organizations like 3GPP, IEEE, ITU, ETSI and others. There are several challenges to be addressed for the planned and future mega-constellations of non-GSO satellites, UAVs and HAPs

systems to serve the unserved and underserved remote and rural areas. A standardization work is needed to identify the role of the different layers in a multi-layer NTN taking into account, routing, distributed intelligence, joint resource management (including traffic offloading) and network management.

The challenges for near-term (2020-2023), mid-term (2024-2025) and long-term (2026-2030) and possible solutions are discussed below. Appendix B provides a description of the current state of standardization 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 69.

Table 69. Needs for Standardization

Need 1	**Reference Architecture** 5G Satellite network architecture requires integrated architectures to meet the traffic performance requirements
Need 2	**Spectrum Sharing** 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** New resource allocation, routing protocols, mobility management, and hand over algorithms for 5G LEO satellite networks
Need 4	**Multilayer Network Protocols** New protocols for multi-layer networks to support 5G and B5G services and applications
Need 5	**QoS/QoE** New QoS framework supporting performance requirements, e.g., high bandwidth, low latency for different applications
Need 6	**Edge Intelligence** There is the need to identify the distribution of edge intelligent tasks within the NTN architecture with changes to current MEC specifications

5.11.2. Challenges

Table 70 provides the challenges for achieving the needs in the near-term, mid-term, and long-term.

Table 70. 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 71 provides potential solutions for the challenges described in Table 70.

Table 71. 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 to be developed.
Challenge 4 Multilayer 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 network 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, LEOs.

6. STANDARDIZATION LANDSCAPE AND VISION

6.1. Interaction with Standardization WG

The Satellite WG had a successful interaction with Standards WG, and the following results have been identified. These topics need to be followed up to help the satellite industry in providing the guidance in developing the new 5G and B5G satellite systems.

1. **Reference Architectures:**

   As identified in Section 5.10, the challenges for reference architecture include virtualized satellite network, separately virtualized and integrated 5G and satellite network architectures have to be further developed.

2. **Multi-Layer Network Protocols:**

   Multi-layer network consists of GSO, non-GSO, UAV, HAP networks to accomplish earth observation, navigation, mobile broadband, backhauling and ad hoc networking. New integrated protocols have to be developed for meeting the specific goals.

3. **Spectrum Sharing:**

   Interference and Coordination between GSO and non-GSO as well as between different non-GSO systems sharing the same frequency bands have to be developed. Interference mitigation techniques and evaluation of the impact on systems throughput and coverage need to be performed.

4. **QoS/QoE:**

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

5. **Edge Intelligence:**

   There is the need for a study leading to a MEC standardization in this sector by 2025. Important aspects to be addressed will be scenario to be considered, reference services, proposal for an integrated MEC-NTN architecture, overall impact of NTN peculiarities on MEC functionalities.

6.2. Landscape

Several mega-constellations, i.e., thousands of LEO satellites are planned and are being designed. O3b/MEO system has already been providing the services for COVID-19 health services in Peru and e-learning in Colombia. SpaceX has already started to provide (beta) services in some parts of the word while it is still deploying its constellation. 3GPP has already issued Release 17 and is working on Release 18, specifically for Non-Terrestrial Networks 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 WG standardization vision includes the following:

- Spectrum sharing - interference & regulation
- World-Radio Conference (WRC-19) decisions implementation
- World Radio Conference (WRC-23) preparation
- 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.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Summary of Conclusions

5G is a new system concept 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 Report, this document has raised some different challenges and possible approaches to achieve 5G and 6G via satellite.

Recent studies estimate that about 37% of the world's population still lacks high-speed Internet access. Moreover, terrestrial networks cannot guarantee access to the Internet to passengers on aircrafts or high-speed trains, highways, and to remote areas besides urban areas. There is a definite need for satellite systems complementing 5G and 6G terrestrial wireless networks.

First of all, we have shown different architectures and use cases where the satellite (mainly based on LEO and MEO systems), together with HAPs and UAVs, can provide 5G/6G services. Moreover, different types of applications suitable for 5G have been presented, mainly dealing with the eMBB and mMTC cases.

PHY layer has the crucial task of achieving high performance and efficiency to maximize the air interface capacity. This outcome will be made possible by 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 the gain in the desired direction. In addition to this, free-space optical communications will be adopted not only for satellite-to-satellite links but also for satellite-to-ground links; this solution will allow a tremendous increase in the link capacity.

This report has also highlighted the importance of AI/ML schemes that will provide a powerful tool to have real-time optimizations for 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.

MEC approaches have been presented as an efficient approach to deal with 5G/6G services. The adoption of MEC for satellite systems will make possible new services and open new markets based on IoT via satellite. MEC will reduce the need for 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.

We have shown that the QoS/QoE levels provided by the satellite will be comparable with those of terrestrial 6G systems. Expected QoS requirements have been investigated, referring to the 3GPP standardization. MEC, caching, and network slicing can help to support QoS/QoE for the satellite systems reducing latency.

A significant emphasis in this report has been given to network management, encompassing mobility management, radio resource management, support of IoT applications, routing, and softwarization and

virtualization of the satellite network, an essential step for integrating the aerial component with 5G terrestrial systems.

5G 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 infrastructure, and 3GPP standardization work is in progress on this subject in Release 17 and 18. NTN will include not only satellites of GEO and mega-constellations of LEOs, but also HAPs, and UAVs. However, the current standardization does not seem to cover adequately mega-LEO systems, HAPs, and UAVs. An appendix has been provided surveying the current 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. It is important that security-by-design concepts are adopted for 5G/6G development, including NTN systems. Secure communication is needed across all modes of the satellite communication whether user-driven, telemetry, satellite-to-satellite, etc. Moreover, future satellite systems must be able to have mechanisms to manage security quickly to deal attacks before they can cause damage.

All these interesting outcomes identify a clear path for satellites towards 6G systems.

7.2. Working Group Recommendations

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

- Identification of architectures with multiple connectivity (UAVs/HAPs/MEO/LEO). GEO satellites cannot be easily part of the data plane but can be considered for the control plane and feeding caches.
- Efforts have to be pursued to achieve system interoperability not only with the terrestrial 5G but also with the aerial components of other operators. The adoption of the network virtualization and softwarization and orchestrators standard (like ETSI MANO) will be essential.
- MIMO communications will increase the capacity as well as 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.
- The antenna design for the satellite will be based on multi-feed antennas with electronic beam-steering.
- Mega-LEO constellations entail a significant complexity to be managed. AI/ML can provide new methods to solve complex problems such as routing, resource allocation, cross-layer optimization, and handover decision.
- Satellite 5G standards have made significant progress and the last period, but additional work is needed to address multi-layers systems, the role of UAVs and HAPs.
- Security-by-design is an important target for satellite systems.

7.2.1. Future Work

Future work on mobile satellite systems will be needed to address 6G [109], following and adapting the solutions considered for terrestrial systems. In future satellite networks, there will be thousands of satellites around the earth, where each one can play the role of a terminal, a router, or a base station. Traditional network management approaches are not suitable for such a complicated and dynamic environment. In this regard, scalable and distributed mobility management is essential for the efficient operation of the network. 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. Further work will be needed to study space IoT scenarios and their implications in terms of system multi-layer architecture, cooperation of the different layers, and KPIs. The impact of edge intelligence (including both MEC and AI/ML) on future satellite 6G systems need to be further investigated to highlight the implications on system architecture, protocols, and services.

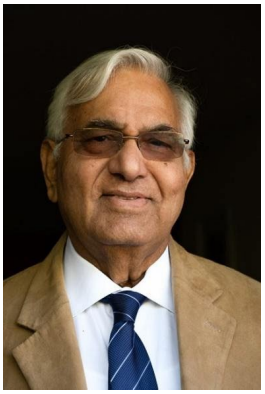
Future work will be needed to address space communications as a possible evolution and extension of the work made on satellite communications. Space communications will become more and more important with the progress with the space exploration. Some of the most recent projects, namely LCE, GeoLITE, SILEX, ALEX, LUCE, LOLA, LCTSX have demonstrated the feasibility of high data rate for near earth communications of the order of 5 – 6 Gbps involving LEO, MEO, and GEOs [110]. 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. Future optical service on deep-space missions will include access links for the Moon and Mars and other planetary missions, for example. 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. Future space missions should perform studies to realistically evaluate their telecommunication needs while taking into account the fact that missions will not rely solely on optical communication but some combination of optical and RF communication. Protocols and standardization are other aspects of any new telecommunications band. The lasercom physical layer can in principle accommodate most telecommunication protocols. Implementation details, such as transmit/receive wavelengths, direct or coherent reception, modulation, and coding, will be carried out by the international committees such as the Consultative Committee for Space Data Systems (CCSDS).

While the basic building blocks for many of the communications link are available to support deep space communications, there are various networking challenges that need to be looked into [112]. One of the challenges is the traffic flow across the physical set of links in the network. FSO communications' extremely narrow beamwidths introduce a new challenge called topology control. A second challenge that relates to the networking of FSO communications nodes is traffic routing. In many cases, routing protocols run over fixed infrastructures, but FSO communications will have a dynamic physical infrastructure. Many routing approaches developed for mobile ad hoc networks could be employed for FSO communications. IETF has developed a class of routing based on a Delay/Disruption-Tolerant Networking (DTN) approach where the routing of network traffic is coupled to the topology control problem in an attempt to mitigate disruptions. All communication systems suffer from some environmental degradation, with the type based on the system's operating frequency, but by using a diverse set of modalities we can mitigate these issues. Hence, FSO communications will be incorporated with other RF communication networks as hybrid solutions. Applications running over these networks need to adapt as the communications data rate may change by orders of magnitude. This adaptation could be via coding to exploit diverse paths or quality-of-service approaches that orchestrate flow onto

each network. While applications have some dynamic ability to adapt over changing networks today, they cannot adapt to the extent that future optical/RF hybrids will require. In addition to traffic routing, and bandwidth, Deep Space communication will also include research into various other factors such as quantum communications, quantum sensing, multi-node communications, optical phased array, battery power, security, topology control, point-to-point vs. multi-directional, non-mechanical beam steering, optical buffer, tunable laser over a large range, optical packet switching,

8. CONTRIBUTOR BIOS

Sastri Kota (Chair)



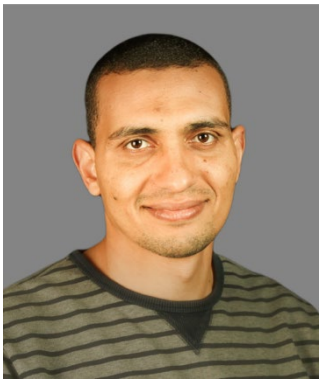
Dr. Kota is President of SoHum Consultants and Adjunct Professor in University of Oulu, Finland. He held technical and management positions at Harris, Loral Space, Lockheed Martin, SRI International, the MITRE Corp, Xerox Corp. and Computer Science Corp. He contributed to satellite and wireless communication network systems, digital video broadcasting, mobile communications, broadband internet and hybrid networks to commercial and defense programs. He provided leadership in international standardization of broadband satellite networks as head of the U.S. delegation and the U.S. chair of the ITU-R Working group onr FSS, MSS and BSS. Currently, Dr. Kota, as a Working Group Co-Chair leads 5G Satellite, an IEEE Future Network Initiative. 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, digital video broadcasting at MILCOM, IEEE, AIAA conferences, 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 IEEE Communications Society, Satellite and Space Communications Technical Committee Distinguished Service Award. He was selected as a Fulbright Specialist by the U.S. Department of State and received the Golden Quill Awards from Harris Corporation for Project Leadership in the field of Broadband Satellite Communications for Internet and Assured Communications. Dr. Kota holds a Ph.D. from University of Oulu, Finland, an Engineer's Degree from Northeastern University, Boston, Massachusetts, and an MSEE from IIT, Roorkee, India. He is a Life Senior Member of IEEE and an Associate Fellow of AIAA.

Giovanni Giambene (co-Chair)

Giovanni Giambene received the Dr. Ing. degree in Electronics in 1993 and the Ph.D. degree 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 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 was with OTE (Marconi Group) in Florence, Italy, working on a GSM development program. In 1999, he joined the Department of Information Engineering and Mathematical Sciences of the University of Siena, Italy. At present, he is 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 coordination action (see the video). At present he is involved in the ESA IIT ROMANTICA project and the ESA SatNEX V project. Giambene is IEEE senior member and has been nominated IEEE Comsoc distinguished lecturers 2021-2022. Since 2015, he is editor of IEEE Transactions on Vehicular Technology. Since 2019, he is 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 the 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 then in the Texas A&M University at 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.

Sarath Babu

Sarath Babu (Member, IEEE) received his Ph.D. degree from Indian Institute of Space Science and Technology, Thiruvananthapuram, India in 2021. He completed his masters degree in Computer Science and Engineering (Information Security) from National Institute of Technology, Calicut, India, and bachelors 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 to 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 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.

Joan Bas

Dr. Joan Bas received the M.Sc and PhD (cum laude) in Electrical Engineering from the Universitat Politècnica de Catalunya (UPC) in 1998 and 2004 respectively. During the pursuit of his PhD, he was recipient of a 1998-2000 fellowship of the UPC's Communication Signal Processing Group, and a 2000-2004 PhD scholarship granted by the Spanish Ministry of Science and Technology. In March 2005 he joined to the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) as a postdoctoral researcher. In 2008 he was granted with 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, a book chapter, supervised Msc. and post-doc students, 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 its 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 and third satellite roadmap of the IEEE International Network Generations Roadmap (INGR) from IEE Future Networks Society.

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Sachin Chaudhari received his B.E.(Electronics) from Visvesvaraya National Institute of Technology, Nagpur, India in 2002 and M.E. Telecommunication from Indian Institute of Science, Bangalore, India in 2004. At IISc, he worked with Prof. KVS Hari. During 2004-2007, he worked at Esqube Communications, Bangalore which was a start-up by IISc Professors, as a Senior Wireless Communications Engineer. At Esqube, he worked on development and implementation of wireless systems such as WLAN, WiMAX, and TDD-SCDMA. During 2007-2012, he obtained a PhD degree from the Department of Signal Processing and Acoustics, Aalto University. Between 2013-2014, he was a post-doctoral researcher at Aalto University. In December 2014, he joined IIITH as an Assistant Professor and was promoted to Associate Professor in July 2021. He is currently the coordinator of the Center of Excellence (CoE) on IoT for Smart Cities at IIITH. He is also a senior IEEE member and the representative of IIITH to the Telecommunication Standards Development Society of India (TSDSI). He is also actively involved in India's First Living Lab for Smart City Research at IIITH.

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Debabrata Dalai (Graduate Student Member, IEEE) received the bachelor's degree in electronics and telecommunication engineering from Biju Patnaik University of Technology (BPUT), Rourkela, India, and the master's degree in computer science and engineering (Advanced Networks) from the Indian Institute of Information Technology and Management, Gwalior, India. He is currently a Senior Research Fellow with the Department of Avionics, Indian Institute of Space Science and Technology, Thiruvananthapuram, India. He serves as the current chair of IEEE IIST Student Branch. His research interests include advanced wireless networks, satellite-IoT networks, satellite edge computing, and 5G satellite integration.

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Tasneem Darwish is currently a postdoctoral fellow at the Department of Systems and Computer Engineering, Carleton University, Canada. She received the MSc. degree with merit in Electronics and Electrical Engineering from the University of Glasgow, UK, in 2007 and her Ph.D. degree in Computer Science from Universiti Teknologi Malaysia (UTM), Malaysia, in 2017. From 2017 to 2019, Tasneem was a postdoctoral fellow at UTM. From 2019 to 2020, she was a research associate at Carleton University, Canada. In 2020, Tasneem started working as a postdoctoral fellow at Carleton University on a collaborative project with MDA Space to investigate mobility management in future LEO satellite networks. Her current research interests include mobility management in future LEO satellite networks, edge/fog computing and data offloading in HAPS, vehicular ad hoc networks, and intelligent transportation

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Tomaso de Cola was 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 Professional Engineer in 2002 and the Ph. D. degree in Electronic and Computer Engineering, Robotics and Telecommunications in 2010 from the University of Genoa, Italy. From 2002 until 2007, he has worked with the Italian Consortium of Telecommunications (CNIT), University of Genoa Research Unit, as 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 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 member of the IEEE Communications Society.

Thomas Delamotte

Thomas Delamotte (Member, IEEE) received the master's degree in communications and network engineering from the National Polytechnic Institute of Toulouse, Toulouse, France, in 2009, and the 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 with the same university. He is currently engaged in several national and international research projects focusing on the application of 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 Cybersecurity 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 author of more than 100 technical papers and 31 issued patents. Ashutosh is co-author of the book, titled, "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 serving as the founding Co-Chair for the IEEE Future Networks Initiative that focuses on 5G standardization, education, publications, testbed, and roadmap activities. Ashutosh is IEEE Communications Society's Distinguished Lecturer for 2017-2020 and as an ACM Distinguished Speaker (2020-2022). Ashutosh currently serves as the founding co-chair for IEEE Future Networks Initiative and Member-At-Large for 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 recipient of 2009 IEEE MGA Leadership award and 2010 IEEE-USA professional leadership award. Ashutosh currently serves as Member-At-Large for 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 Ph.D. in Electrical Engineering from Columbia University under the supervision of Prof. Henning Schulzrinne. Ashutosh is a Fellow of IEEE and Distinguished member ACM.

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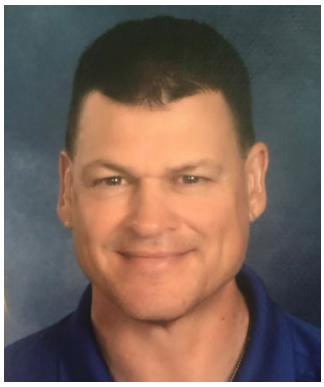
Ayush Kumar Dwivedi received a B.Tech. degree in Electronics and Communication Engineering from Jawaharlal Nehru Technological University Hyderabad, India, in 2017. He is currently pursuing his doctoral research under Dr. Sachin Chaudhari at International Institute of Information Technology Hyderabad, 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 is also contributing to discussions at Telecommunication Standards Development Society of India (TSDSI) for a study item on rural broadband services and architectures. He is also active in operationalizing the research at Center of Excellence (CoE) 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 Quantum Dimension, he has led a team of engineers in the company's technology developments, which includes AI/ML, RF communication, software-defined radio (SDR) and navigation using advanced embedded technologies that include digital signal processor (DSP), graphics processor unit (GPU) and field-programmable gate array (FPGA). Prior to 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. Prior to 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 is also serving as Guest Editor for several Special Issues of the Sensors Journal

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Alberto Gotta

Alberto Gotta is a staff member of the Information Science and Technologies Institute (ISTI) of the Italian National Research Council, from 2005. He is the research leader of the "Communication Protocols and Architectures" section of the Wireless Network Laboratory at ISTI, from 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, from 2013. He is member of the ISTI-IIT CNIT Research Unit. He is member of the Italian Group of Telecommunications and Information Technologies (GTTI). He is also member of the ComSoc Satellite & Space Communications Technical Committee, and of the Machine Learning for Communications and Aerial Communication Emerging Technologies Initiatives. He has been participating at 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 cybersecurity professional & interdisciplinary professional focusing on trustworthy & resilient complex systems and emerging technologies. She obtained her PhD 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 in 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.

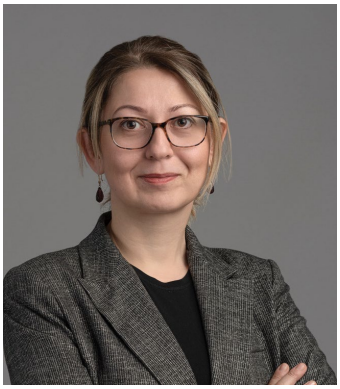
Tamer Khattab

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 the Ph.D. degree 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 with 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 serves as an editor of the IEEE Communications Letters and an editor of the IEEE Open Journal of the Communications Society. In addition to more than 150 high profile academic journal and conference publications, Dr. Khattab has several published and pending patents.

Andreas Knopp

Andreas Knopp is the Chair and Professor of the Information Technology Institute as well as the Chairperson of the Munich SPACE Research Center at the Bundeswehr University in Munich. He is also a board member of the German Aerospace Center (DLR), an advisor to the German Ministry of Defence, and a visiting Professor at the Naval Postgraduate School Monterey (CA), USA. Prof. Knopp is a member of the expert committee on radio systems in the German society of information technologies (VDE/ITG), and an IEEE Senior Member. He has authored and co-authored about 130 publications on radio systems and space communications technologies, including 30 journal publications and 6 patents. In addition, he is an enthusiastic entrepreneur and co-founder of several startups. Prof. Knopp holds a master's degree in information technology (2002) and a Ph.D. in wireless communications (2008), both from the Bundeswehr University Munich. In 2010, he received an Executive MBA degree from the Gutenberg School of Business, Mainz, Germany.

Gunes Karabulut Kurt



Gunes Karabulut Kurt received the B.S. degree with high honors in electronics and electrical engineering from the Bogazici University, Istanbul, Turkey, in 2000 and the M.A.Sc. and the Ph.D. degrees in electrical engineering from the University of Ottawa, ON, Canada, in 2002 and 2006, respectively. From 2000 to 2005, she was a Research Assistant with the CASP Group, University of Ottawa. Between 2005 and 2006, she was with TenXc Wireless, Canada. From 2006 to 2008, Dr. Karabulut Kurt was with Edgewater Computer Systems Inc., Canada. From 2008 to 2010, she was with Turkcell Research and Development Applied Research and Technology, Istanbul. Between 2010 and 2021, she was with Istanbul Technical University. She is currently an Associate Professor of Electrical Engineering at Polytechnique Montréal, Montreal, QC, Canada. She is a Marie Curie Fellow and has received the Turkish Academy of Sciences Outstanding Young Scientist (TÜBA-GEBIP) Award in 2019. In addition, she is an adjunct research professor at Carleton University. She is also currently serving as an Associate Technical Editor (ATE) of the IEEE Communications Magazine and a member of the IEEE WCNC Steering Board. She is the chair of the IEEE special interest group entitled “Satellite Mega-constellations: Communications and Networking”. Her current research interests include space information networks, satellite networking, wireless network coding, wireless security, space security, and wireless testbeds.

B. S. Manoj

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10. ACRONYMS/ABBREVIATIONS

We provide two tables. First of all, Table 72 contains all acronyms and abbreviations. Please refer to the following link for a detailed glossary of satellite-related terms. Moreover, Table 73 lists all the frequency bands used by the satellite community.

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Table 72. 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
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	evolved Node B (base station)
EPC	Evolved Packet Core
EPFD	Effective Power Flux Density
ESA	European Space Agency
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
IMS	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
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
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
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
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
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
WGS	Wideband Gapfiller Satellite
WR12	Waveguide Rectangular 12 waveguides
WRC	World Radiocommunication Conferences
WEP	Wired Equivalent Privacy
WG	Working Group
WPA	Wi-Fi Protected Access

Table 73. 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 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, trans-national crime, transportation of asylum seekers across national borders for profit. This is a vast set of activities in which multiple government agencies are involved (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 and 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 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, paths followed by aircraft and boats for drug smuggling lie in areas that are not covered by terrestrial communication systems. Then it makes sense to adopt UAVs, HAPs, and LEO satellites providing 5G connectivity in these areas to support the activities of agencies.

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 able to support low latency applications at the frontline and condense information generated by sensors before it is sent to the core, conserving bandwidth and maintaining security
- Backhaul 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 anywhere in the world for monitoring events of interest. Information sources include international agencies like Interpol. See Figure 65.

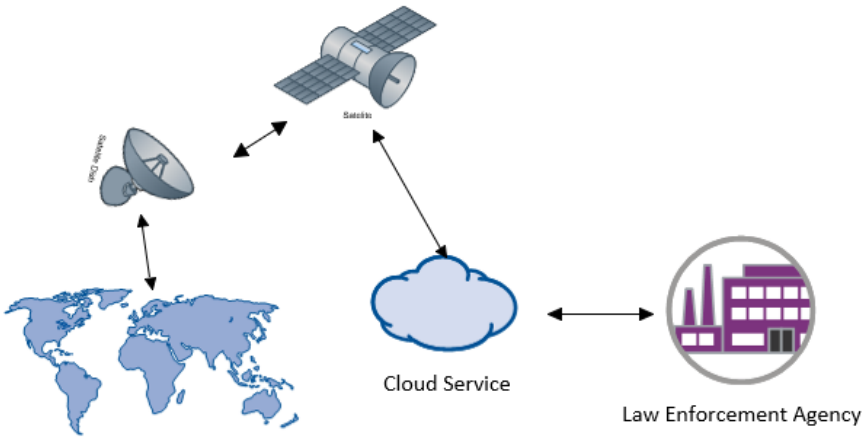

Figure 65. Use of 5G LEO satellites and Cloud Service

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 provides a brief summary of 5G and B5G standards activities, with specific reference to Non-Terrestrial Networks (NTN) by organizations 3GPP, IEEE, ITU, 5GPP and ETSI.

B-1 3GPP Activities

Figure 66 shows 3GPP time plan of standards development. Release 16 is frozen; instead, Release 17 is open, and its expected deadline is in December 2021. Release 17 is working on NTN for 5G systems, which adopt, satellites to support under-served areas (e.g., isolated/remote areas, onboard aircraft or vessels). The status of the 5G standardization of 3GPP can be monitored at the following reference [B1].

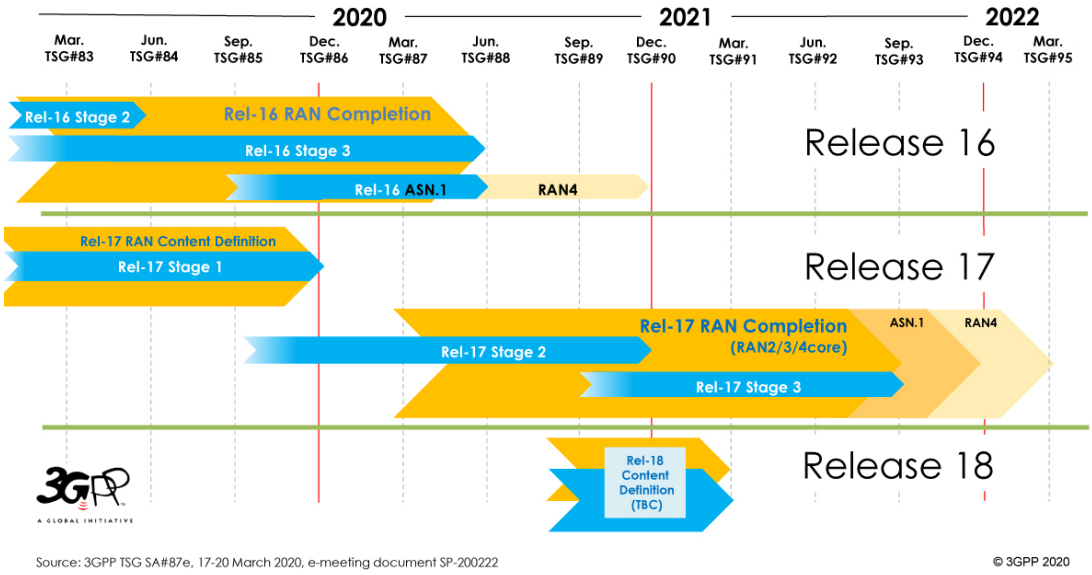

Figure 66. Evolution of 3GPP standardization in Releases [B2]

The most important 3GPP WGs that are dealing 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 74.

Table 74. 3GPP TR documents on SATCOM [B3]

Technical report ID	Impacted specification	Title	WG, Release #
TR 23.737	N/A	Study on architecture aspects for using satellite	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	SA1

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.

3GPP is progressing in the standardization of 5G and beyond [B4]. The satellite component is part of this effort. Satellite systems will be part of the 5G/B5G system. 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, that mobile network 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, 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 is the result of a joint effort between stakeholders of both mobile and satellite industry who both find benefits Satellite helps mobile to provide global service continuity and resiliency Mobile enables satellite to access a unified and large eco system and drive down the cost through economy of scale.

The 3GPP standardization aims to support of all 5G features (slicing, energy saving, mobility, 3rd party network management, application & service platforms) across the access technologies.

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).

The most interesting highlights from the five technical reports mentioned in Table 67 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 cases, 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 the satellite. It is a very comprehensive document that addresses many 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 + gNB
  - Direct access / regenerative satellite + gNB / GW
  - Direct access / regenerative satellite + gNB-DU / GW + gNB-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, satellite backhaul scenario. Challenges and solutions are investigated on 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 backhaul (multihoming)
  - Regulatory services with super-national satellite ground station.
- **TR 22.819:** It considers maritime communication services as one of 3GPP vertical applications and proposes use case on satellite access to support maritime communication services over 5G system.

B-1.1 Releases 17 and 18

The detailed time plan for Release 17 is shown in Figure 67.

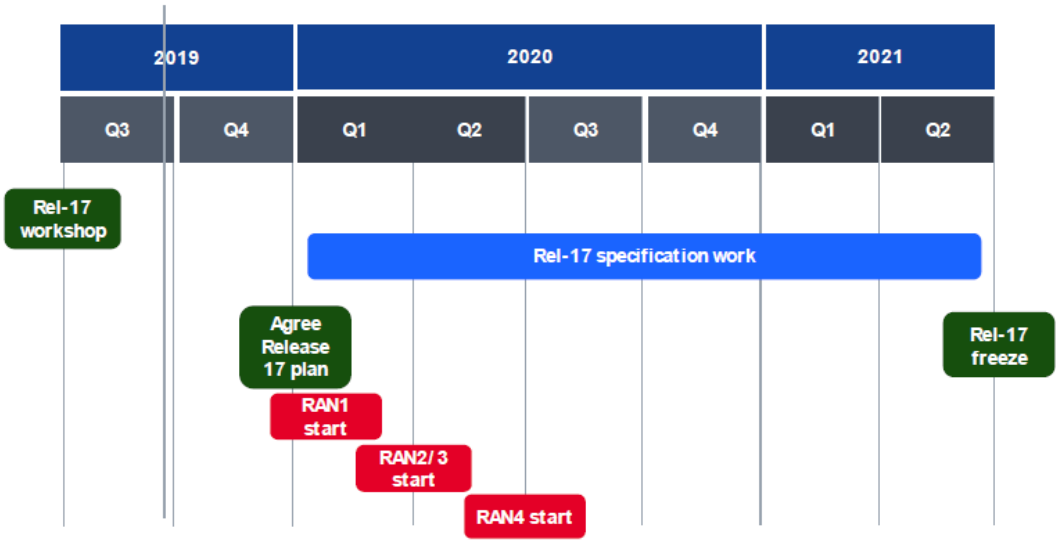

Figure 67. Release 17 schedule

In Release 17, the focus will be on transparent (non-regenerative) payload satellite systems for both LEO and GEO scenarios,. Moreover, the interesting aspects of these new activities are that the satellite industry is actually interested in starting their business cases with IoT devices and moving to NR eMBB next. Release 17 is addressing identified issues due to long propagation delays, large doppler effects, and moving cells in NTN. It also covers NG-RAN architecture enhancements and related procedures and service continuity from TN to NTN and from NTN to TN systems. It is envisaged that UEs will have GNSS capabilities. NR NTN based on LEO and GEO with implicit compatibility to support HAPS and ATG (Air To Ground) scenarios.

GNSS positioning will help for synchronization, estimation of Timing Advance, mobility, etc., but may not always be available, e.g., for IoT-oriented lower-cost devices.

Release 18 work has started with discussion in progress on the main topics to address. Some possible aspects will be [B4]:

- SA2 WG: eMBB New Radio (network-based UE location determination, TN/NTN service continuity), IoT (discontinuous coverage, store and forward)
- RAN WGs: eMBB (coverage enhancements, NR-NTNT in above 10 GHz), IoT (mobility enhancements).

Beyond Release 18, new RAN features will include regenerative payload (including edge computing) and new standard features will include performance enhancement proxy and opportunistic connectivity between network nodes of satellite constellation.

The NTN roadmap with the next study items is provided in Table 75.

Table 75. 3GPP NTN Roadmap

	Study	Specification
Rel-16	NR-based: • LEO/GEO with transparent & regenerative payload (gNB based)	
Rel-17	NR-based: • HAPs with transparent payload • NB-IOT/LTE-M support NTN • NR-NTN-network based UE location • OFDM PAPR perf. assessment for single carrier HPA payload	NR-based • LEO/GEO with transparent payload • LEO with Earth fixed/moving cells
Rel-18 (tentative)	NR-based • MIMO in NTN context • Dual connectivity	NR-based: • NTN-specific positioning • LEO/GEO/HAPs with regenerative payload • OFDM PAPR enhancement for single carrier HPA payload • Dual connectivity
Rel-19 (tentative)	TBD	NR-based: • MIMO in NTN context

The ESA Alix project [B5] project has established a Satellite Standardization Interest Group (SSIG) working with 3GPP and ETSI towards future satellite systems. The aim of SSIG is to allow stakeholders to exchange information about satellite-related standards activities for the integration of satellites into the 5G ecosystem, with the aim of improving mutual understanding and collective effectiveness. Currently, 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 reach, 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 satellite in 5G and beyond 5G setting out relevant groups and their key objectives and milestones, regularly share status of those groups and, as and where appropriate. 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. No draft is available. The expected completion date is by May 2022.

- **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 interface, Electrical interface, and Data interface. 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. A draft was expected for internal review in September 2020.

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, as well as 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 meeting the key technical criteria underpinning the IMT-2020 Vision and global 5G. In July 2020, 3GPP 5G has been 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 to IMT have been already 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 stations 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 ETSI Activities

ETSI is interested in 5G even if not directly related to the satellite components [B7]. ETSI is investigating a number of 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 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-6 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 there are many cross-project working groups identifying shared issues and developing supported program-level position on technical and strategic items. Among the currently active working groups, there is one "Pre-Standardization" with the aim 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 backhaul 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 backhaul”
- Use Case 3: "5G to premises"
- Use Case 4: "5G moving platform backhaul".

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

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