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**APT REPORT ON**

**EMERGING SATELLITE TECHNOLOGIES AND LEO SYSTEMS**

**IN ASIA-PACIFIC**

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**EMERGING Satellite technologies and LEO Systems**

**in Asia-Pacific**

# Introduction

The satellite communications industry is experiencing unprecedented innovation and growth. As new technologies emerge and existing ones evolve, there is a pressing need for a comprehensive and accessible resource that captures these advancements. Satellite communications are increasingly critical in bridging the digital divide and enabling connectivity across all regions, including remote and underserved areas. Understanding the full potential of these emerging technologies is essential for informed strategic planning and effective decision-making.

This report aims to highlight the transformative potential of emerging satellite technologies in enhancing global connectivity. It provides a timely and comprehensive overview of the latest innovations in satellite communications, along with clear insights into complex technological advancements. Through this resource, APT Members will be empowered to effectively harness these technologies to support national development goals, improve service delivery, and expand access to reliable connectivity across their respective jurisdictions.

# Scope

This report is divided into two complementary parts, each addressing critical aspects of the evolving satellite communications landscape.

* **Part I**  provides a comprehensive overview of emerging satellite technologies, highlighting their role in enhancing global connectivity, expanding network capacity, and meeting the diverse needs of users. It underscores the satellite industry's vital contribution to bridging the digital divide and promoting global inclusivity through continuous innovation.
* **Part II** focuses on the deployment of Low Earth Orbit (LEO) satellite systems in the Asia-Pacific region, which presents both opportunities and challenges, and outlines its features for the provision of connectivity across the region.

**PART I**

**EMERGING Satellite Technologies**

*This part of the report is structured to provide a detailed exploration of emerging satellite technologies and their enabling components.*

* ***Section 1*** *focuses on Space-based Technologies, including Non-Terrestrial Networks such as Direct-to-Device communications, IoT via satellite, Mobile VSAT, and satellite backhaul for 5G. It further examines multi-orbit satellite systems, software-defined satellites, inter-satellite links (ISL), life extension and in-orbit servicing, High Throughput Satellites (HTS/VHTS), and onboard processing with edge computing.*
* ***Section 2****shifts to Ground-based Technologies, highlighting innovations in ground segments.*
* ***Section 3****covers Enabling Technologies, including Artificial Intelligence and Machine Learning, Quantum Technologies, and Adaptive Coding and Modulation (ACM), with detailed sub-sections on implementation and performance factors.*

# Space-based Technologies

## Non-terrestrial Networks

Non-terrestrial networks (NTN) represent a transformative approach to global connectivity by integrating satellite systems with terrestrial 5G infrastructure. The 3GPP has made significant progress in standardizing 5G NTN, with Release 17 establishing foundational support for transparent satellite operations, introducing basic support for both transparent and regenerative satellite payloads and defining the necessary adaptations for large delay and Doppler shift, primarily targeting broadband services. Release 18 built upon this foundation by enhancing mobility, power efficiency, and positioning capabilities, focusing on improved performance and integration with terrestrial networks. Release 19 further advances NTN, focusing on new use cases like the Internet of Things (IoT) and Reduced Capability (RedCap) devices, support for advanced architectures like store-and-forward, driving NTN towards widespread commercial deployment as a fully integrated component of 5G-Advanced.

This technological evolution enables satellite operators to deliver IMT-2020 compliant services, extending 5G's reach to regions beyond traditional terrestrial coverage. The satellite component of IMT-2020 allows satellites to meet stringent performance requirements for high-speed data, low latency, and massive IoT connectivity, creating a truly global 5G ecosystem. Major industry players are actively conducting trials, demonstrating the technology's potential to provide seamless connectivity between terrestrial and satellite networks, though challenges remain in optimizing latency, handover protocols, and spectrum management for widespread commercial deployment.

* + 1. Direct-to-Device

A noteworthy aspect of NTNs is Direct-to-Device (D2D) connectivity, which allows satellites to connect directly to devices like off the shelf smartphones and IoT terminals, facilitating seamless communication without the need for traditional terrestrial infrastructure. D2D connectivity leverages existing satellite technologies to enhance mobile communication capabilities, especially in areas where terrestrial networks are sparse or non-existent.

There are two different variants for D2D connectivity.

The first utilize spectrum already allocated to the Mobile Satellite Service (MSS) and generally leverages 3GPP NTN standard specifications enabling features to be implemented in both the Radio Access Network (RAN) and User Equipment (UE), ensuring compatibility and multi-vendor interoperability, and eventually integration across terrestrial and non-terrestrial radio interface. It utilizes existing allocations and standardized protocols and frameworks, capitalizing on 3GPP NTN specifications for seamless terrestrial and satellite connectivity networks across various applications, with no additional changes to ITU Radio Regulations. This approach needs increased collaboration with mobile chipset vendors to develop and support relevant MSS frequencies in their user equipment.

The second approach aims at addressing already commercialized mobile handsets (i.e., UE pre 3GPP Release–17 specifications) by utilizing spectrum allocated to the Mobile Service (MS) and identified for IMT. This approach requires careful consideration to ensure that the D2D service is compatible with the terrestrial mobile service. It provides a solution to complement mobile coverage, addressing gaps in connectivity where traditional networks fall short, potentially using off-the-shelf mobile handsets. However, the technical requirements and regulatory frameworks of these approaches are under development.

Overall, the evolution of D2D paves the way for a more interconnected world, enhancing access to reliable communication services across diverse environments. By integrating satellite capabilities into mobile ecosystems, D2D connectivity promises to bridge the coverage gap of 80% of landmass currently uncovered by terrestrial networks[[1]](#footnote-1), improve user experience, and expand market opportunities in telecommunications.

* + 1. Internet of Things (IoT)

The Internet of Things (IoT) is significantly enhanced by the capabilities provided by Non-Terrestrial Networks (NTNs), which encompass satellite communications integrated with terrestrial networks. As the number of connected devices is projected to skyrocket, with estimates reaching over 20 billion, NTNs are critical for addressing the limitations of terrestrial networks, particularly in remote or underserved areas.

One of the key advantages of NTNs is their ability to provide seamless and reliable connectivity to IoT devices, regardless of their location. This is particularly valuable for industries like agriculture, logistics, and disaster management, where operational efficiency relies on seamless and robust connectivity. The integration of satellite-based IoT solutions facilitates applications such as precision agriculture, which requires monitoring of crop conditions and resource usage on a regular basis, thereby enabling farmers to make informed decisions that increase yield. Moreover, logistics and transportation sectors are transforming through seamless tracking of assets and vehicles, enhancing supply chain management and operational efficiencies.

Since Release 17, 3GPP has progressively standardized IoT-NTN (Non-Terrestrial Networks) to enable satellite-based global connectivity for IoT devices. Release 17 established the foundation by adapting NB-IoT (Narrowband IoT) and eMTC (LTE-M) to support satellite communication, introducing essential features to handle challenges like high latency and Doppler shift in transparent payload architectures. Release 18 built on this by enhancing power efficiency, mobility management, and integration with terrestrial networks. Looking ahead, Release 19 aims to advance IoT-NTN further with studies on regenerative satellite payloads, and seamless terrestrial-NTN service continuity, ensuring scalable and efficient IoT connectivity across diverse environments. Satellite NB-IoT solutions employ small, low power and low-cost IoT modules designed for efficient operation with satellite networks, making applications more affordable and sustainable. As NTNs and terrestrial networks converge, they enable devices to transition smoothly between different types of connectivity, ensuring uninterrupted service. This integration will reshape the way we connect and interact with the world, allowing for innovative solutions that bridge the digital divide and foster a more inclusive and connected future.

Additionally, CEPT has introduced satellite usage in the Short-Range Devices (SRD) bands (also referred to as license-exempt or class license bands, depending on national regulations), specifically the 862-870 MHz band, to enable communication with terrestrial SRDs. This approach, considered as IoT-NTN in SRD bands, ensures interoperability with terrestrial networks and supports new use cases through seamless and robust satellite network coverage. The solution facilitates efficient operation of satellite systems using low-power, low-cost IoT modules while enhancing spectrum efficiency by complementing terrestrial spectrum usage. It is based on existing terrestrial standards and technologies, employing the same technical conditions as terrestrial SRDs in the uplink direction, along with in-band and out-of-band power-flux density limits in the downlink direction to prevent any unacceptable interference with existing applications and services.

* + 1. Mobile VSAT

The growing demand for seamless connectivity is leading to a significant increase in the number of connected vehicles, vessels and aircraft in the mobility market. This expansion presents huge opportunities, however, to date the satellite industry has relied on proprietary technologies for its connectivity solution, with the growing interest and success of 5G-NR and NTN Technologies and the 3GPP Open Standards, the natural trend is to migrate services to a more a cost effective and a more widely accessible industry[[2]](#footnote-2).

Currently, mobile VSATs are being introduced in the 3GPP for Release 19 to understand the large assortment of performances, antenna form-factors, and radiation patterns. The large variations of mobile VSATs builds make the standardization process difficult due to large number of antenna characteristics.

To provide a baseline model of the mobile VSAT terminals, and to streamline the standardization activities, 3GPP is evaluating four antennas models that reflect the performance and characteristics of combined Land, Maritime, Aeronautical and Vehicular mobile VSATs.

The first two i.e. 60cm x 60cm and 40cm x 40cm antenna models are based on empirical values gathered from a variety of Mobile VSAT terminals already deployed in the Ku Band. Furthermore, the antenna models presented for the 20cm x 20cm reflect a new conceptual approach which is being considered within 3GPP Release 19 specification.

Mobile VSATs constitute a large category of terminals which are the workhorse of the satellite communication industry and provide connectivity to GSO and to NGSO Satellite constellations. These mobile VSATs are being standardized in Ku band for NTN within 3GPP. These Mobile VSATs are in four main categories:

1. Portable and Land Mobile VSAT**s**
2. Maritime Mobile VSATs and
3. Aeronautical Mobile VSATs
4. Vehicular VSAT

These advanced VSAT terminals will consist of Electronically Steered Flat Panel Antennas (FPAs) that provide connectivity to stationary GSO and NGSO Satellites such as those in MEOs and LEOs. Furthermore, multiple connectivity guarantees that customers and partners aren't confined to single satellite technology. This flexibility allows for the customization of services to fit a wide range of market segments, use cases and applications.

* + 1. Satellite Backhaul for 5G Networks

Satellite systems/networks can provide 5G backhaul in areas where deploying terrestrial backhaul (e.g., fiber or microwave links) is not feasible or commercially viable.

Satellites act as fiber in space, enabling 5G service providers to deliver mobile broadband even in hard-to-reach areas. Satellites thus serve as a critical component for extending 5G coverage, especially in remote locations, and also in maritime and airborne environments.

## Multi-orbit Satellite Systems

Multi-orbit satellite systems represent an advanced approach to space infrastructure, integrating satellites operating in different orbital regimes such as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Earth Orbit (GEO), and Highly Elliptical Orbits (HEO). These systems leverage the unique advantages of each orbital category to create more comprehensive and resilient communication networks. LEO satellites provide low-latency, high-bandwidth connectivity but require large constellations due to their short orbital periods and limited coverage per satellite. MEO satellites strike a balance between coverage and latency, while GEO satellites offer persistent coverage over specific regions. HEO satellites can provide enhanced coverage at high latitudes where GEO satellites have limitations. By combining these orbital assets, operators can create systems that optimize coverage, capacity, and latency across diverse geographical regions, supporting applications ranging from global broadband internet to precision navigation and Earth observation. The integration of multiple orbits presents technical challenges in terms of coordination, data relay, and orbital mechanics, but also offers significant opportunities for creating more robust and versatile space-based services.

The goal of multi-orbit solutions is to meet various service level requirements set by customers across a diverse range of applications and geographic locations. By employing a multi-orbit strategy, satellite operators can effectively route traffic based on real-time conditions and user demands. The combination of these orbits allows for more flexible and efficient data transmission, enabling seamless connectivity across different environments — be it urban, rural, or isolated locations. This capability is particularly beneficial for enterprises, governments, and individual users who require reliable and high-capacity communication services in real-time.

Moreover, multi-orbit networks facilitate advanced applications such as earth observation and remote sensing. By connecting satellites across different altitudes and orbits, operators can relay large volumes of data more efficiently, thereby providing timely information critical for various sectors including agriculture, disaster response, and environmental monitoring. This integration not only enhances connectivity but also plays a pivotal role in addressing the rising demands for improved data services and global inclusivity in the digital landscape. Overall, multi-orbit solutions are reshaping the satellite communication industry, ensuring that diverse communication needs are met while advancing the sustainability and efficiency of satellite networks.

To summarize, Multi-Orbit Connectivity allows:

* Fully benefit from the attributes and characteristics of each constellation in GSO and NGSO, such as MEO and LEO – and seamlessly switch between them or blend networks together based on the capacity needs of individual applications.
* Continue to leverage the coverage breadth, bandwidth capacity, stability, security, and location-surging capabilities of GSO networks.
* Access connectivity from NGSO networks for applications that require lower latency and as overflow to deliver high quality of experience (QoE) even at peak times.
* Ultimately leverage the power of satellite communication with greater applicability, ease, and affordability.

## Software Defined Satellite

Software-defined satellites represent a transformative approach to satellite technology, where the primary functionality and operations of the satellite are controlled through software rather than being fixed in hardware. Unlike traditional satellites that have fixed capabilities determined at manufacturing, software-defined satellites can be reprogrammed and updated while in orbit, allowing their mission parameters, communication protocols, and operational capabilities to be modified according to changing needs. This flexibility enables operators to adapt to new requirements, fix issues remotely, and implement upgrades without launching new hardware, significantly reducing costs and extending the useful life of satellite systems. Technology finds applications in various domains including telecommunications, Earth observation, and scientific research, where the ability to rapidly adapt to new challenges or opportunities provides substantial advantages. As the space industry continues to evolve, software-defined satellites are expected to play an increasingly important role in creating more dynamic, responsive, and efficient space-based systems.

This innovation significantly simplifies management, enhances the efficiency of resource utilization, and reduces operational costs. By moving towards a global network ecosystem that incorporates software-defined satellites, modems, antennas, and the necessary interoperability, the satellite industry is poised to realize the full potential of future applications and connectivity demands.

These software-based satellites have notable features, such as superior connectivity where beam shapes and power allocation can be dynamically adapted to optimize coverage and link performance. They also offer flexible capacity availability with dynamic bandwidth allocation that adjusts based on demand, allowing satellites to modify their capacity to align with user traffic needs. Furthermore, SDS enables seamless end-to-end networking through dynamic software-based interactions with user terminals and central networks, which facilitates comprehensive service orchestration.

Thus, software-defined satellites are setting the stage for a new era of scalable, cost-effective, and reliable satellite communication systems that promise to enhance global connectivity.

## Inter-satellite links

Inter-satellite links (ISLs) are innovative technologies that enable direct communication between satellites in orbit. These links facilitate the real-time transfer of data, which is particularly valuable for LEO satellite constellations. Traditionally, LEO satellites could only communicate with ground stations within a limited view of the Earth. However, with the implementation of ISLs, data can be relayed between LEO satellites and those satellites at higher altitudes, allowing for enhanced connectivity and a more efficient communication network.

The capabilities provided by ISLs are critical for the growing demands of various sectors, ranging from telecommunications to disaster response and emergency services. They enable a broader array of services, such as real-time bandwidth allocation for IoT traffic and improved weather forecasting data transmission. Overall, ISLs represent a significant leap forward in satellite communication technologies, allowing for more interconnected and resilient networks that can meet the increasing global demand for high-capacity communications.

* + 1. ISL for Earth observation and space science missions

This capability is also crucial for applications such as Earth observation, where satellites can transmit high-quality images and data back to the ground in real time through satellites in other orbits, even when they are not in direct line of sight to a ground station.

All these ISL systems need to downlink data generated on-board down to Earth in an efficient, fast and cost-effective manner. In many cases, the downlink capacity is a bottleneck as well as a strong design driver. The payload data generation is normally limited by the downlink capacity. Both Small and Large satellite missions would benefit from ISL transmission services. Even Nanosatellites (1-25 kg) may carry a satellite-to-satellite transmission payload.

The anticipated downlink performances build on the assumption that future earth-exploration satellite service (EESS) will benefit from Ka downlink spectrum, which is not heavily used today by these missions. On-board storage capacity is limited. As a result, ISL transmissions to access collected data is a viable solution to enhance data downlink capabilities and payload data collection.

* + 1. Optical Inter-Satellite Links (OISL) for enhanced data transfer

The advancement of optical communication technology plays a significant role in transforming ISLs by providing high-speed connections that enhance the efficiency and security of data transmissions. Optical inter-satellite links offer greater resiliency compared to traditional radio frequency communications, resulting in less interference and improved data integrity. As these optical technologies become more widely adopted and their costs continue to decrease, they are expected to drive further innovations in satellite communications, expanding the number of potential applications and increasing overall capacity.

## Life Extension and In-Orbit Servicing

In-Orbit Life Extension and Servicing are vital components of modern satellite operations, aimed at enhancing the longevity and functionality of satellites beyond their originally intended lifespan. Life extension services allow satellite operators to reuse existing assets rather than replace them, which is particularly important given the high costs associated with deploying new satellites. By focusing on in-orbit servicing—repairing, upgrading, or refueling satellites—operators can maximize their investments and ensure continued service delivery without incurring the significant costs of replacement.

The benefits of in-orbit servicing extend beyond mere cost savings. These services can enhance satellite reliability, ensuring that satellites continue to function even after they exhaust their fuel or experience subsystem failures. For example, through life extension initiatives, satellites can remain operational longer, with projections suggesting that in-orbit servicing could generate over US$4 billion in revenues by 2028[[3]](#footnote-3) GSO satellites often cost well over $200 million to deploy, underscoring the value of servicing, repairing or upgrading such satellites rather than just replacing them.

This capacity to maintain and extend operational life spans helps prevent potential service disruptions in critical sectors such as telecommunications, defense, and disaster response.

Furthermore, as the satellite industry continues to evolve, various new in-orbit services are being developed, from refurbishment to debris removal, indicating a shift towards ensuring safer and more sustainable use of the orbital environment. This proactive approach to satellite management aims to keep orbital highways safe and secure for economic development, ultimately supporting a robust and resilient satellite ecosystem

## High Throughput Satellites (HTS) and Very High Throughput Satellites (VHTS)

High Throughput Satellites (HTS) and Very High Throughput Satellites (VHTS) represent a significant evolution in satellite communications technology, offering data throughput capacities that are orders of magnitude greater than traditional satellites. These advanced systems achieve their remarkable performance through the use of multiple spot beams, frequency reuse techniques, and higher-order modulation schemes, which dramatically increase spectral efficiency. HTS typically deliver throughput in the range of 10 Gbps to 100 Gbps per satellite, while VHTS push this further to exceed 100 Gbps, making them capable of supporting modern broadband applications such as streaming, cloud services, and IoT connectivity. The technology has transformed connectivity options for rural and remote areas, maritime and aviation communications, and emergency response operations where terrestrial infrastructure is unavailable or insufficient. Major satellite operators have invested heavily in HTS/VHTS constellations, with some systems now offering consumer broadband services competitive with terrestrial options in certain regions. As the technology continues to advance, HTS/VHTS are becoming increasingly integrated with terrestrial 5G networks through 3GPP standards, creating a more seamless global communication ecosystem and driving innovation in hybrid connectivity

# Ground-based Technologies

## Innovation in the ground segment

The satellite system ground segment is evolving with the changing nature of both GSO and NGSO satellite constellations. With the proliferation of NGSO constellations and satellites in inclined orbits, the need for antennas that track the satellites has become essential. This can be served by traditional parabolic antennas, often operating in pairs to ensure a “make before break” connection, or by flat panel antennas (FPA).

This shift is fueled by advancements like Ground Segment as a Service (GSaaS), Digital Intermediate Frequency (DIF) interoperability, and the strategic integration of artificial intelligence (AI) and cloud computing.

Key technologies driving this evolution include:

1. **Ground Segment as a Service (GSaaS):** GSaaS provides satellite operators with on-demand access to a network of ground stations and associated services. This pay-per-use model offers significant scalability and flexibility. Core advantages include reduced upfront investment by eliminating the need for extensive ground infrastructure development and maintenance. Furthermore, operators can dynamically adjust ground station usage to match operational demands, while cloud-based solutions accelerate deployment and customization.
2. **Digital Intermediate Frequency (DIF) Interoperability:** DIF interoperability standardizes the digitization of satellite signals at the intermediate frequency (IF) level, fostering seamless communication between diverse ground segment systems. This standardization enables interoperability between different ground stations and terminals and facilitates the use of standard IP networks for data transport. Additionally, it simplifies infrastructure upgrades and maintenance. Its initiative utilizes an existing ANSI standard as a means to achieve this by presenting the signal for onward processing in a generic form. This is being used in hub architecture and there are moves to have it more widely implemented in terminals.
3. **Cloud Computing and Virtualization:** Migrating ground segment functions to the cloud enhances flexibility, scalability, and resource management. Cloud-based solutions enable remote control and management of operations and allow for dynamic scaling of resources. This transition also leads to significant reductions in capital expenditure and operational costs.
4. **Artificial Intelligence (AI):** AI is revolutionizing ground segment operations by automating tasks, optimizing performance, and bolstering system resilience. AI automates complex tasks such as payload reconfiguration and data processing, while also optimizing resource utilization and network performance.
5. **User Terminals:** Satellite user terminals have been reduced in size, weight, power consumption and cost, and provide a wide array of solutions for the end user. For instance, significant improvements in small form factor antennas have created terminals that are more portable, while providing a better performance than earlier generation models. These improvements are facilitating the wider deployment of user terminals that facilitate greater connectivity to the global network.

# Enabling technologies

## Artificial Intelligence and Machine Learning

Artificial Intelligence and Machine Learning play a transformative role in the field of satellite communications, significantly enhancing the efficiency, reliability, and security of satellite operations. By optimizing various operational aspects, AI can improve network performance and enable predictive maintenance, which is crucial for preventing system failures. For example, employing AI algorithms for data analysis allows operators to identify patterns and anomalies in performance data, facilitating timely interventions before potential issues escalate.

Moreover, AI’s capabilities extend to dynamic resource allocation, particularly concerning radio spectrum management. Through ML techniques, satellite systems can better detect and mitigate interference, ensuring clearer communication channels. This not only enhances user experience but also maximizes the bandwidth utilization across satellite networks. As the demand for higher capacity and more reliable communication services grows, integrating AI and ML into satellite operations is becoming essential for maintaining competitive advantages in the evolving telecommunications landscape.

The advent of AI and ML technologies also paves the way for innovative applications in satellite-based services, such as intelligent routing for data transmission and enhanced security measures to protect against cyber threats These advancements are particularly vital as satellites become increasingly integral in supporting emerging technologies, including the Internet of Things (IoT) and the next generation of mobile networks like 5G and 6G. The convergence of AI and satellite technology is poised to not only optimize current operations but also to define new paradigms in global connectivity and communication capabilities

## Quantum Technologies

Quantum technologies are revolutionizing satellite systems through applications in secure communication, precision sensing, and advanced computing. Quantum key distribution (QKD) enables satellites to transmit encryption keys with virtually unbreakable security, leveraging the principles of quantum mechanics to detect eavesdropping attempts. Quantum sensors aboard satellites can achieve unprecedented measurement precision for applications including navigation, Earth observation, and climate monitoring, with atomic clocks providing timing accuracy critical for GPS and telecommunications. Quantum technologies also enable novel approaches to satellite-based experiments, such as testing fundamental physics principles in space or developing entanglement-based communication systems. While quantum computing remains largely terrestrial, its potential for processing the vast amounts of data generated by satellite constellations suggests future integration opportunities, both onboard satellites and in ground-based systems.

Satellite operators are now investing in next generation end-to-end system testbeds that include a spacecraft, a ground station and an operational segment of ground network infrastructure to demonstrate that quantum technology can actually be used to protect existing networks, by adding a layer of security that is unbreakable with quantum computers.

## Adaptive Coding and Modulation (ACM)

* + 1. Definition and Basic Principle

ACM is a link adaptation technology at the physical layer. Its fundamental principle is to adjust the modulation mode and coding rate of wireless link transmission while keeping the transmission power constant to ensure the transmission quality of the link. When the channel condition is poor, a smaller modulation mode and coding rate are selected; when the channel condition is good, a larger modulation mode is chosen to maximize the transmission rate. In other words, the system always aims to make the data transmission rate consistent with the trend of channel changes, thus maximizing the utilization of the wireless channel's transmission capacity.

* + 1. Implementation in Different Systems

In non-geostationary satellite orbit, fixed-satellite service (NGSO FSS) systems, ACM plays a vital role. These systems operate in complex environments where factors such as path distance, elevation angle, antenna scanning angle, and atmospheric conditions (like rain fade) can cause signal attenuation and performance degradation. ACM enables the system to adapt to these changing conditions. For example, when the signal is degraded due to rain fade or other interference, the system can adjust the modulation and coding rate through ACM to ensure continuous data service, although the throughput may be lower. It is an important technology for NGSO FSS systems to cope with signal attenuation caused by path loss changes and interference from other systems.

The implementation methods of AMC for uplink and downlink are different.

* **Downlink AMC control process:** The terminal measures the downlink channel quality by detecting the downlink common reference signal and then feeds back the channel quality information to the base station through the feedback channel. The base station adjusts the corresponding downlink transmission MCS (Modulation and Coding Scheme) format according to the feedback received.
* **Uplink AMC control process:** The base station measures the uplink channel quality by detecting the uplink reference signal sent by the terminal. Based on the measured channel quality information, the base station adjusts the MCS format of the uplink transmission data and notifies the UE (User Equipment) through control signaling.
	+ 1. Influence Factors in ACM Performance

**Granularity of MCS:** When defining the MCS granularity of the system, it is necessary to comprehensively consider the utilization of the wireless channel capacity, the feedback error of the channel quality, and the signaling overhead, and strive for a trade - off among them. If the MCS granularity is too large, the system cannot fully utilize the current wireless channel capacity; if the MCS granularity is too small, although it can fully reflect the wireless channel capacity, it will increase the signaling overhead, and the feedback error of the channel quality will further weaken the gain brought by the smaller MCS granularity.

**Accuracy and Real - time of Channel Quality Information:** The accuracy of channel quality information is directly related to the channel estimation algorithm and the quantization error of the channel quality. The real-time channel quality is affected by the time delay between the channel quality measurement time and the transmission time, which is caused by the system's own processing delay and scheduling delay. Generally, when the moving speed is low, the channel changes slowly, and a limited delay will not cause a significant loss of performance. However, if the moving speed is high and the channel changes rapidly, the same delay will have a serious impact on the system performance.

* + 1. ITU-R Recommendation

ITU-R Recommendation S.2131 “*Method for the determination of performance objectives for satellite hypothetical reference digital paths using adaptive coding and modulation”* recommends that satellite systems using ACM should be designed to meet the performance objectives given by either the packet error ratio (PER) or the spectral efficiency (bit/s/Hz) as a function of C/N. Further, the annex of this recommendation provides example method for the determination of performance objectives for satellite hypothetical reference digital paths using adaptive coding and modulation, including PER, Spectral efficiency as a function of C/N and throughput degradation.

**PART II**

**LEO Systems in Asia-Pacific**

*This part of the report provides a focused analysis of the deployment and impact of Low Earth Orbit (LEO) in the Asia-Pacific region.*

* ***Section 1****explores the role of LEO in enhancing connectivity, including growth trends, current operational deployments, and planned initiatives.*
* ***Section 2****addresses regulatory and licensing frameworks, detailing the current landscape and challenges in spectrum allocation and licensing. This section also highlights concern around unauthorized earth station operations and relevant ITU regulations.*
* ***Section 3****discusses communication security aspects, including preventive measures.*
* ***Section 4****evaluates the economic and social impact of enhanced connectivity, covering potential economic benefits, social outcomes for underserved communities, and support for digital transformation.*
* ***Section 5****looks ahead to future prospects and challenges, including technological innovations, such as mass production, advanced antenna systems, ISLs, spectrum reuse, and integration with 4G/5G and beyond. It also touches on international regulatory developments, potential applications beyond telecommunications, and remaining challenges.*

# The Role of LEO Satellites in Enhancing Connectivity

* 1. **LEO networks and growth trends**

At present, NGSO satellites represent the vast majority of all orbiting satellites. ITU-R Resolution 35 defines a milestone-based approach for the implementation of frequency assignments to space stations in a NGSO satellite system in specific frequency bands and services. The ITU-R maintains the list of all NGSO satellite systems under Resolution 35 frequency bands notified to the Bureau at <https://www.itu.int/net/ITU-R/space/res35/index.html>.

Ensuring safe and sustainable use of space is fundamental. LEO satellite operators are cooperating to ensure safe and sustainable use of outer space, as per ITU Resolutions and the UN Treaty on the Peaceful Uses of Outer Space.

LEO satellites can offer:

* **Low Latency:** Operating at low Earth orbits, LEO satellites can offer low latency broadband services.
* **Global Coverage:** The use of an appropriate constellation design of LEO satellites can ensure global coverage, including remote and underserved regions.
* **Scalability:** LEO satellite networks can be scaled incrementally, allowing for gradual deployment and expansion based on demand. This approach reduces upfront costs for operators and allows for quicker adaptation to technological advancements or market shift.

FIGURE 1

**Latency of Different Orbital Types [[4]](#footnote-4)**



* 1. **Operational LEO Satellite Deployments in Asia Pacific**

**SpaceX's Starlink:** Starlink operates a direct-to-consumer model, offering satellite broadband services directly to end users through individual user terminals. Starlink's deployment in the Asia-Pacific region has demonstrated the feasibility of using LEO satellites to provide high-speed low-latency internet where needed.

In January 2022 Tonga was hit by a devastating volcanic eruption and tsunami. LEO user terminals from Starlink were distributed to the outlying islands worst hit by the tsunami. The service remained in place and free until a submarine cable connecting the outlying islands with Tonga's main island Tongatapu was repaired, which took around 18 months. The same LEO satellite system helped isolated villages in desparate need of connectivity. The terminals connected government offices and local businesses while also providing free public Wi-Fi.

Other operators / Kacific GEO broadband satellite solution provided connectivity to the isolated villages government offices and local businesses during Tonga recovering of submarine cable.

**Eutelsat Group’s OneWeb LEO constellation:** OneWeb partners with local internet service providers in countries to enhance connectivity using its LEO satellite constellation. OneWeb focuses on a B2B model, partnering with telecommunications providers, enterprises, and governments to deliver high-speed connectivity. Rather than providing direct-to-consumer services, OneWeb enables local operators to integrate its satellite broadband solutions into their existing networks, extending coverage to remote and underserved regions. This model allows for seamless interoperability with terrestrial infrastructure, working with local distributors, reducing costs and enhancing service reliability.

These different approaches illustrate the flexibility of LEO satellite constellations in meeting diverse market demands. Both strategies contribute significantly to bridging the digital divide in Asia-Pacific.

* 1. **Planned LEO Satellite Deployments**

**Telesat Lightspeed:** Telesat’s LEO 3 demonstration satellite was launched to provide continuity of customer and ecosystem vendor testing campaigns worldwide. Telesat is collaborating with several domestic telecommunication service providers to provide satellite capacity. Global commercial service is expected to be in 2027.

**Amazon:** Project Kuiper is Amazon's low Earth orbit satellite broadband network designed to provide reliable, affordable internet access to unserved and underserved communities worldwide. Project Kuiper aims to address the digital divide with a LEO satellite network of 3232 satellites, bringing connectivity to consumers, enterprises, mobility and government services.

1. **Regulatory and Licensing Frameworks**
	1. **Current Regulatory Landscape in Asia-Pacific**

The regulatory landscape in the Asia-Pacific region is characterized by a diversity of regulatory frameworks. Each country has its own set of regulations governing satellite communications, spectrum allocation, and licensing processes.

National spectrum management policies in the region are evolving to accommodate new technologies and increasing demand for satellite connectivity taking into account national priorities.

Some administrations have already established policies or frameworks to authorize NGSO systems within their jurisdictions, while others are in the process of developing regulatory approaches following spectrum management due diligence in line with national framework. Some administrations undertaking spectrum management due diligence are doing so based on ITU Plenipotentiary Resolutions 18 (Kyoto, 1994), ITU Plenipotentiary Conference 2022 (PP-22) Resolution 219, ITU Radiocommunications Assembly 2023 (RA-23) Resolution 74, WRC-23 Resolutions 49 and 76, and ITU Radio Regulation Article 22, Section II, paragraph 22.2.

As the demand for satellite connectivity, particularly through LEO satellites, grows, new regulations and policies are emerging. These include updates to existing frameworks to accommodate new technologies and operational requirements. Keeping abreast of these developments is crucial for stakeholders to navigate the regulatory landscape effectively and ensure compliance with both national and international standards.

* 1. **Challenges in Licensing and Spectrum Allocation**

The deployment of LEO satellite networks providing broadband services has introduced new challenges.

The efficient national allocation of spectrum is crucial for the successful deployment and operation of LEO satellites. With the limited availability of spectrum, regulatory bodies are developing strategies to optimize spectrum usage. This involves balancing the needs of satellite operators and terrestrial networks while ensuring that spectrum is used effectively to support high-speed, low-latency communication.

Different countries and regions have varying regulations and policies regarding satellite communications and spectrum allocation. Achieving regulatory harmonization could be useful for the seamless operation of global satellite networks. In particular, a transparent and streamlined satellite regulatory framework with timely publication and updates of authorization procedures is desirable.

Regulatory frameworks would need to evolve to keep pace with developments, accommodating new technologies while ensuring the best possible service.

Coordination / Constructive dialogues between Administrations, including stakeholders, such as satellite operators and other industry players, can be useful for the successful implementation of LEO satellite networks.

One of the regulatory challenges faced by some LEO operators is the requirement for in-country gateway earth stations in some jurisdictions resulting in high costs and increase operational complexity. Advancements in satellite technology may help in this aspect.

Regardless of these technology aspects, each country can always exercise its sovereign right to request in-country gateway earth stations.

Another major challenge for LEO operators is the high fees imposed by some countries for spectrum access both for gateway stations and user satellite terminals. Excessive licensing costs can hinder the deployment of LEO networks, especially in developing regions where satellite connectivity could bridge the digital divide. Establishing a more balanced and cost-effective approach to spectrum pricing would enable wider adoption of satellite services while ensuring fair competition between all satellite operators and service providers.

* 1. **Unauthorized Earth Station Operations**
		1. ITU Regulations on Unauthorized Earth Station Operations

In addition to technical cybersecurity measures, regulatory frameworks play a crucial role in maintaining the integrity of satellite networks. The International Telecommunication Union (ITU) has already established specific guidelines to address the issue of unauthorized earth station operations, which may pose potential risks to both satellite networks and national security.

ITU Resolution **22** (Rev.WRC-23) outlines measures to limit unauthorized operations by earth stations. Relevant aspects include:

* ***resolves 1* on National Authorization:** Earth station operations within a country’s territory are only permitted if authorized by the relevant national regulatory authority. This ensures that all transmitting stations comply with local regulations and operate within designated frequency bands.
* ***resolves 2* on Role of Notifying Administrations:** Notifying Administrations are required, to the extent practicable, to limit the operation of transmitting earth stations on the territory of an administration on which they are located and operated to only those licensed or authorized by that administration.
* ***resolves 3* on Enforcement Actions:** When a country detects unauthorized earth station operations within its territory, the national regulatory authority must take appropriate measures to cease these operations. If the issue persists, the authority may notify the notifying administrations of these satellite networks or systems, which shall cooperate with the reporting administration, to the maximum extent possible, in order to resolve the matter in a satisfactory and timely manner.

Recognizing the growing importance of addressing unauthorized earth station operations in the Earth-to-space direction, the ITU has set an agenda item 1.5 for the World Radiocommunication Conference 2027 (WRC-27).

Current regulations provide a foundation for managing unauthorized operations:

* **ITU Radio Regulations**, particularly **Article 18**, require that transmitting earth stations be licensed by the administration of the territory in which they operate.
* **Resolution 22 (Rev.WRC-23)** outlines enforcement actions and cooperation mechanisms between administrations.
* National licensing frameworks typically include provisions for authorization, monitoring, and enforcement.

These existing tools are expected to strengthen global efforts to ensure responsible and authorized use of satellite communications infrastructure.

1. **Security of Communication Aspects**

The deployment of any telecommunication network introduces several cybersecurity threats that must be addressed to ensure the safety and reliability of these systems. Accordingly, satellites are vulnerable to a variety of cyberattacks, including hacking, jamming, and spoofing. These threats can compromise the integrity, confidentiality, and availability of communication networks, potentially leading to significant service disruptions.

A LEO constellation comprises a multitude of satellites which leads to redundancy without a single point of failure. This is further facilitated by the availability, in some constellations, of optical intersatellite links creating a mesh in the sky with multiple paths for data to be delivered.

1. **Economic and Social Impact**
	1. **Potential Economic Benefits of Enhanced Connectivity**

The deployment of LEO satellite networks has the potential to generate significant economic benefits, particularly in remote and underserved areas. This section will explore the economic impact of improved connectivity, including increased access to education, healthcare, and economic opportunities.

There will be significant economic benefits of LEO satellite networks to different types of user segments. Though connectivity to remote and underserved areas appears to be primary economic benefit, there are multiple other user segments which will be benefitted by the LEO satellite networks. Enterprises in remote and barren locations like mineral exploration, oil drilling etc. require connectivity for automation and also to facilitate different services to personnel working in such locations. Similarly, government agencies require connectivity in remote, isolated as well as difficult to reach topographic areas. It is also expected that commercial maritime and aviation segments will also utilize such LEO satellite networks.

* 1. **Social Impact on Remote and Underserved Communities**

Improved connectivity can have profound social impacts, particularly in rural and remote communities. This section will discuss the potential benefits of LEO satellite networks in areas such as education, healthcare, and social inclusion, using case studies from countries. There is rapid deployment of Digital Public Infrastructure (DPI) across various social sectors like health, education and various financial incentives for different purposes. In the absence of reliable connectivity, utilization of DPI has become a bottle neck for rural and remote communities. Improved connectivity through LEO satellite network may aid the utilization of DPI for the benefit of rural and remote communities.

* 1. **Supporting Digital Transformation in Asia-Pacific**

The Asia-Pacific region is undergoing digital transformation, with increasing adoption of digital technologies across all sectors. This section will explore how LEO satellites can support this transformation, particularly in areas such as e-governance, smart cities, and digital finance.

1. **Future Prospects and Challenges**
	1. **Technological Innovations and Future Trends**

The development and deployment of Low Earth Orbit (LEO) satellite constellations for global internet coverage represent one of the most transformative technological trends in telecommunications. These constellations, composed of hundreds or thousands of small satellites, are designed to deliver high-speed, low-latency internet access across the globe, including in remote and underserved areas. This section delves into the key technological innovations and future trends shaping the evolution of LEO constellations for worldwide internet, highlighting their potential for the Asia Pacific region.

* + 1. Mass Production and Cost Reduction

Advances in satellite manufacturing have made it possible to produce satellites on a scale, significantly reducing the cost per unit. This mass production approach is crucial especially when deploying large constellations. The economies of scale achieved through mass production also enable more frequent launches and faster deployment of the full constellation.

* + 1. Advanced Antenna and Ground Station Technologies

To effectively manage the high data throughput and connectivity demands of LEO constellations, significant advancements have been made in antenna and ground station technologies.

* **Phased Array Antennas:** Phased array antennas are a critical component of LEO satellite systems, enabling satellites to steer their beams electronically without moving parts. This allows for rapid and precise targeting of user terminals on the ground, ensuring consistent and reliable connections. Phased array technology is particularly important for maintaining connectivity with fast-moving LEO satellites, as it can quickly switch between satellites as they pass overhead.
* **User Terminals:** The development of compact, cost-effective user terminals is essential for the widespread adoption of LEO satellite internet. These terminals, often equipped with electronically steerable antennas, can automatically track LEO satellites as they move across the sky, providing continuous internet access without requiring manual adjustment. Innovations in user terminal design are focused on making these devices more affordable and easier to deploy in both urban and remote environments.
* **Global Ground Station Networks:** Ground stations play a vital role in LEO satellite constellations, acting as the bridge between the satellites and the global internet backbone. The deployment of a global network of ground stations, strategically located to ensure continuous communication with the satellites, is crucial for minimizing latency and maximizing data throughput. Advancements in ground station technology, including the use of optical communication links and automated operation, are enhancing the efficiency and capacity of these networks.

* + 1. Inter-Satellite Links (ISLs) and Mesh Networking

One of the most significant innovations in LEO satellite constellations is the implementation of inter-satellite links (ISLs). This feature enables direct communication between satellites without relying solely on ground stations, thereby increasing network resiliency and reducing the number of required ground stations.

* **Laser-Based ISLs:** Laser communication systems are being integrated into LEO satellites to establish high-speed links between satellites in the constellation. These laser-based ISLs allow data to be transmitted across the network at the speed of light, significantly reducing latency and increasing the overall efficiency of the system. By creating a mesh network in space, where data can be routed through multiple satellites to reach its destination, ISLs enhance the resilience and scalability of LEO constellations.
* **Global Mesh Networks:** The use of ISLs enables the formation of a global mesh network, where data can be dynamically routed through the most efficient path, even if ground stations are not within the line of sight. This capability is particularly beneficial for maintaining continuous global coverage, ensuring that users in remote or polar regions can access the internet without relying on nearby ground stations.
	+ 1. Spectrum Management and Frequency Reuse

The deployment of large LEO constellations requires careful management of radio frequency spectrum to manage interference and ensure reliable communication.

* **Frequency Reuse:** LEO satellites can utilize the same frequency bands multiple times across different geographical areas through a technique known as frequency reuse. By dividing the Earth's surface into multiple cells, each served by different satellites, the same frequencies can be reused in non-adjacent cells,
* **Dynamic Spectrum Allocation:** Advances in dynamic spectrum management allow LEO satellites to adjust their frequency usage in real-time based on demand and interference. This dynamic allocation ensures that the available spectrum is used most efficiently, reducing the risk of congestion and improving the quality of service for end-users.
	+ 1. Integration with Terrestrial networks

LEO satellite constellations are increasingly being integrated with terrestrial networks to provide seamless global connectivity.

* **Terrestrial networks:** The convergence of terrestrial networks and satellite technologies is enabling the creation of hybrid networks that leverage the strengths of both systems. LEO satellites can extend the reach of terrestrial networks to underserved areas, providing connectivity where terrestrial infrastructure is lacking. This integration also supports, amongst other applications, the deployment of IoT (Internet of Things) devices and services on a global scale, enabling applications such as smart agriculture, remote healthcare, and autonomous transportation.
* **Future-Ready Architecture:** As the telecommunications industry moves beyond 5G, LEO satellite networks are being designed with future compatibility in mind. This includes support for advanced network slicing, edge computing, and AI-driven network management, which will be critical for supporting the next generation of internet services and applications.

The technological innovations in LEO satellite constellations are driving the transformation of global internet connectivity, making high-speed, low-latency internet access available to everyone, regardless of their location.

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3. Astroscale U.S. Enters the GEO Satellite Life Extension Market – Astroscale (<https://astroscale.com/astroscale-u-s-enters-the-geo-satellite-life-extension-market/>) [↑](#footnote-ref-3)
4. LEO satellite Broadband: Satellite-based internet connectivity. Available at https://www.fujitsu.com/global/vision/insights/22-leo-satellite-broadband/ [↑](#footnote-ref-4)