

# **Report ITU-R M.2569-0**

## **(05/2026)**

M Series: Mobile, radiodetermination, amateur  
and related satellite services

# **Development and technology trends for the satellite component of IMT towards 2030 and beyond**



## Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

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SA	Space applications and meteorology
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*Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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## 1 Introduction

International Mobile Telecommunications (IMT) systems are mobile broadband systems encompassing IMT-2000, IMT-Advanced, IMT-2020 and IMT-2030.

IMT-2000 systems are the third generation mobile systems which provide access, by means of one or more radio links, to a wide range of telecommunications services supported by the fixed telecommunication networks (e.g. Public Switched Telephone Network (PSTN)/ Integrated Services Digital Network (ISDN)/Internet protocol (IP)), and to other services which are specific to mobile users. Recommendation ITU-R M.1850 forms the final part of the process of specifying the radio

interfaces of IMT-2000, as defined in Recommendation ITU-R M.1225. It identifies the detailed specifications for the IMT-2000 satellite radio interfaces.

IMT-Advanced systems are mobile systems that include the new capabilities of IMT that go beyond those of IMT-2000. Such systems provide access to a wide range of telecommunication services, including advanced mobile services supported by mobile and fixed networks, which are increasingly packet-based. Recommendation ITU-R M.2047 identifies the satellite radio interface technologies of IMT-Advanced and provides detailed radio interface specifications.

IMT-2020 systems are mobile systems that include novel radio interface(s) which support the new capabilities of systems beyond IMT-2000 and IMT-Advanced. Such systems provide access to a wide range of telecommunication services, including mobile and mobile satellite services. The IMT-2020 satellite component is able to support three service categories i.e. enhanced Mobile Broadband-satellite (eMBB-s), massive Machine Type Communications-satellite (mMTC-s) and High Reliability Communications-satellite (HRC-s). Recommendation ITU-R M.2177 – Detailed specifications of the satellite radio interfaces of International Mobile Telecommunications-2020 (IMT-2020), identifies the satellite radio interface technologies of IMT-2020 and provides the detailed radio interface specifications.

This Report provides development trends and technology trends of the satellite component of IMT-2030.

Notably, the various standardization bodies have been advancing the development of Non-Terrestrial Networks (NTN) technology to ensure the interworking of satellite components with terrestrial communications. For example, 3GPP established a global standard for access technologies applicable to Geostationary Orbit (GSO) and/or non-Geostationary Orbit (non-GSO) based satellite networks supporting communications for smartphones, handheld, Internet of Things (IoT) and vehicle-mounted devices and able to operate in the frequency bands identified for the satellite component of IMT within a range from ~1 GHz up to 30 GHz.

## **2 Scope**

This Report provides a broad view of future development and technical aspects of the Satellite Component of IMT systems considering the timeframe 2030 and beyond. It includes the Satellite Component of IMT development and the application of driving factors for future technology trends, and information on advanced technology features and their impact on network deployment/architecture, terminal, privacy, security, resiliency, and market trends amongst others.

The technology trends described in this Report are a collection of potential technology enablers for discussion purposes. They are not intended to mandate any particular implementation of an IMT-2030 technology, nor do they preclude the adoption of any other potential technologies. Reference to spectrum contained in this Report should in no way be seen as demanding of spectrum needs for the satellite component of IMT-2030.

## **3 Related documents**

### **3.1 ITU-R Recommendations**

Recommendation ITU-R M.1167 – Framework for the satellite component of International Mobile Telecommunications-2000 (IMT-2000)

Recommendation ITU-R M.1225 – Guidelines for evaluation of radio transmission technologies for IMT-2000

Recommendation ITU-R M.1850 – Detailed specifications of the radio interfaces for the satellite component of International Mobile Telecommunications-2000 (IMT-2000)

Recommendation ITU-R M.2047 – Detailed specifications of the satellite radio interfaces of International Mobile Telecommunications-Advanced (IMT-Advanced)

Recommendation ITU-R M.2177 – Detailed specifications of the satellite radio interfaces of International Mobile Telecommunications-2020 (IMT-2020)

### 3.2 ITU-R Reports

Report ITU-R M.2176 – Vision and requirements for the satellite radio interface(s) of IMT-Advanced

Report ITU-R M.2460 – Key elements for integration of satellite systems into Next Generation Access Technologies

Report ITU-R M.2514 – Vision, requirements and evaluation guidelines for satellite radio interface(s) of IMT-2020

Report ITU-R M.2516 – Future technology trends of terrestrial International Mobile Telecommunications systems towards 2030 and beyond

### 3.3 ITU-R Resolutions

Resolution ITU-R 56 – Naming for International Mobile Telecommunications

Resolution ITU-R 65 – Principles for the process of future development of IMT-2020 and IMT-2030

## 4 Developing trends

### 4.1 Future technology drivers

In the context of the IMT-2030 satellite component, some UEs may also operate on the terrestrial component of IMT-2030, hence supporting both the terrestrial and satellite components of IMT-2030.

A diversity of current and upgraded UEs (e.g. handheld terminals, IoT terminals and platform mounted broadband terminals) are expected to be supported.

In the context of IMT-2030, it is expected there is a value to harmonize the design of the satellite component's radio interface with the terrestrial component's radio interface.

Technology trends for the satellite component of IMT are evolving in response to increasing interworking between terrestrial and satellite systems and emerging IMT-2030 requirements. Satellite systems – particularly non-GSO systems – are increasingly designed to complement and interwork with terrestrial IMT systems at the service, terminal, and network-architecture levels while operating in their allocated satellite service spectrum, supporting connectivity, resiliency, and service-continuity objectives. Further, the emergence of satellite-based PNT capabilities also reflects growing recognition that resilient timing and positioning are foundational enablers for future interworking of terrestrial and satellite systems.

**Service coverage and continuity:** The IMT-2030 satellite component is expected to promote enhanced link level and system level techniques to enhance coverage performance also in adverse propagation conditions. The IMT-2030 system is expected to support enhanced mobility between the terrestrial and the satellite component. There is an expectation in reducing the coverage discontinuities where there are gaps in terrestrial component coverage.

**Resiliency** is expected to be improved to ensure maximum service availability. Satellite can also contribute to the resiliency of the overall IMT-2030 system as complementary / a backup component to the terrestrial component, however with differing technical capabilities and capacity prioritized for the most critical services. The satellite component itself can be designed for intrinsic resiliency through multi-layer infrastructure combining multi orbit satellite (e.g. GSO, non-GSO) or for

resiliency towards the service degradation or unavailability of 3<sup>rd</sup> party systems (e.g. Global Navigation Satellite Systems (GNSS)).

**Energy efficiency** considerations should be taken into account in the architecture and network design of the satellite component with the aim, for instance, to:

- minimize its intrinsic energy consumption;
- indirectly contribute to minimize the overall energy consumption of the IMT-2030 system including the UE.

**Security** is expected to be reinforced but also to take into account distributed intelligence across the network infrastructure including onboard satellites possibly interconnected.

Compared to the satellite component of IMT-2020, the satellite component of IMT-2030 is expected to provide enhanced performance as well as new use cases thanks to new capabilities. Requirements to be established may include enhanced location services, enhanced coverage in adverse propagation conditions, integrated communication and sensing amongst others.

The satellite component of IMT-2030 may support specific characteristics (e.g. orbital altitude, user speed) that differ from the ones already supported by the IMT-2020 satellite component. Therefore, different types of satellite systems, and channel access techniques may be taken into account.

Hence the satellite component of IMT-2030, together with the terrestrial component, is envisioned to contribute to IMT objectives, such as improved coverage continuity and resilience, among other capabilities.

Notably, work within standards bodies has made significant progress in supporting satellite communications as part of the IMT-2020 ecosystem, including for enhanced mobile broadband and enterprise-grade connectivity.

## 4.2 New application trends

New applications trends include but are not limited to the following aspects:

The Satellite Component of IMT-2030 is expected to provide connectivity directly to UE (among which consumer handheld or wearable devices) and/or connectivity to a vehicle or building mounted devices with improved performances. In this context “vehicle” may refer to any moving platforms such as land, maritime or air vehicles.

The Quality of Experience (QoE) of the satellite component should be improved in the context of IMT-2030. This includes the device characteristics that should be adapted to the installation/operational constraints of the targeted use cases:

- Connectivity to handheld or wearable devices: enabling global coverage to any user, increased data rate, as well as a certain level of service in light indoor/in vehicle environment<sup>1</sup>.
- Connectivity to vehicle mounted devices: serving devices with ultra-small aperture antenna adapted to the installation constraints on the most demanding moving platforms which are cars and drones.

While connectivity to handheld or wearable devices aims primarily at the consumer market segment, both connectivity scenarios will serve a wide range of enterprise and vertical market segments including public safety, transport (i.e. aeronautic, maritime, railway, automotive) as well as agriculture, utilities, media and entertainment.

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<sup>1</sup> First wall/window penetration.

Updated architectures of satellite networks may take advantage of the respective characteristics of various satellites in terms of orbit type around the Earth, altitude with respect to the Earth, payload type (transparent or regenerative), types of radio beams generated (Earth fixed or Earth moving) on the service link amongst others.

However, hybrid satellite–terrestrial connectivity is not merely a future concept. Current systems interwork satellite links with terrestrial networks and cloud platforms to support robust IoT and mobile broadband applications, providing a preview of the expanded role of Satellite Component of IMT-2030.

Emerging use cases, such as connected vehicles and broadband access for moving platforms, are expected to benefit significantly from the satellite component of IMT framework, enabling Mobile VSAT-type terminals that support broadband services in motion. These developments support a broader ecosystem of terminals capable of operation on both terrestrial and satellite networks.

### 4.3 Service and applications

In recent years, the development of satellite communication technology has shown a rapid development trend, which stimulates more applications in addition to traditional satellite services and also makes breakthroughs toward handheld terminals. The service capabilities of satellite communication have undergone great changes in both service types and quality, which have a profound impact on people's daily lives and industrial manufacture. Generally, from service type, satellite communication applications can be categorized as voice, video, data, IoT, relay services, etc. From terminal type, satellite communication applications can be categorized according to the type of antenna, omnidirectional (e.g. handheld, IoT) or directional. From user type, satellite communication applications can be categorized as consumer, enterprise and government users. The Satellite Component of IMT-2020 can provide satellite specific solutions for massive machine type communications, highly reliable communication, enhanced mobile broadband services. This allows to support a wide range of applications among which real time conversational video and/or speech and others (see examples in Recommendation ITU-T G.1010). In the aspect of data transmission, satellite communication can provide data rates from a few kbit/s to hundreds of Mbit/s. In conclusion, as satellite communication application scenarios become more diversified, the coverage and data transmission capabilities of satellite networks are becoming increasingly diversified, and people's expectations for the capabilities of satellite communication services are also increasing.

In the future, the expected main application categories of satellite services are shown in Table 1.

TABLE 1

**Use cases and application scenarios for satellite communication**

Use cases	Technical capability	Typical application scenario
Connectivity directly to handheld or wearable devices	To provide quasi seamless global coverage of messaging, voice and to some extent data and video services capabilities	Direct connectivity to mobile phones
Connectivity to fixed local area networks	To provide high-speed communication connections to local area networks that are hard to reach by terrestrial network technologies	Remote area communication, remote Internet of Things
Connectivity to moving platforms	To provide smooth and seamless handover for high-speed mobile devices	Shipborne communications, airborne communications, Unmanned Aerial Vehicle (UAV), land vehicles

TABLE 1 (*end*)

Use cases	Technical capability	Typical application scenario
Connectivity to IoT devices	To provide bidirectional non real time transmission	Internet of Things

NOTE 1 – The following capabilities may be transversal to several of these use cases:

- Broadcast/multicast service eventually to edge resources: for efficient delivery of data and video content.
- Emergency communication services including disaster warning, information reporting.

#### 4.4 Spectrum considerations

As in IMT-2020, the bands identified for the satellite component of IMT can be considered for the deployment and operation of the satellite IMT-2030. Other frequency bands may be also considered subject to changes in the Radio Regulations.

It is important to recognize that there are (both terrestrial and satellite) operators today, deploying or intending to deploy in either paired or unpaired spectrum. Therefore, it is important to continue to explore the possibility of supporting FDD, Half-Duplex FDD (HD-FDD) and TDD modes of operation, depending on frequency allocations, intended services/applications and technical considerations, in order to boost deployment growth.

### 5 Technology trends

This section explores the emerging technology trends that are set to define the Satellite Component of IMT-2030. It examines advances across multiple dimensions including radio interface techniques, adaptive modulation and coding, waveform innovations, novel multiple access and synchronization and timing methods to enhance network performance, spectral efficiency, and system resiliency. Although the focus is forward-looking, many of these trends are already being realized in modern systems operating in their respective service allocations, while interworking with terrestrial IMT.

These trends address key challenges, such as reducing latency, improving energy efficiency and interworking with terrestrial networks.

Together, these innovations are poised to transform network deployment, terminal capabilities, and overall system performance within the evolving IMT-2030 landscape. They also reflect the emergence of satellite systems with regenerative payloads, routing within the space segment, and embedded timing capabilities that support resilience and continuity functions.

#### 5.1 Radio interface technology

The definition of a harmonised radio interface for IMT-2030 should be able to support both terrestrial and satellite components to address common goals (e.g. coverage continuity, resilience) for end users.

It is expected that the design of this radio interface may be mostly driven by the requirements of terrestrial component but also address the specifics of the satellite component.

Advanced modulation, coding, waveform and multiple access schemes, the precise time and frequency synchronization technology, as well as semantic communication technology are expected to establish an efficient and adaptable data transmission bridge for satellite communications networks. The combination of beam-hopping, spatial division multiplexing, and Multiple Input Multiple Output (MIMO) technology used across multiple satellite beams may not only markedly enhance the signal's directionality and anti-jamming capabilities but also significantly boost system capacity and spectral efficiency. Further enhancements on coverage and positioning will optimize the overall service of the satellite communication network.

The radio interface is expected to support a wide range of channel bandwidth, service rate, Quality of Service (QoS), link budget and propagation conditions to address the maximum number of deployment scenarios.

### 5.1.1 Modulation technology

Modulation technology is a factor that affects the transmission efficiency of satellite communication. High-order Quadrature Amplitude Modulation (QAM) has been used in terrestrial mobile communications to improve the spectral efficiency with high Signal-to-Noise Ratio (SNR). However, the advantage of high-order QAM diminishes gradually with increasing hardware nonlinearity. Rectangular QAM has multiple amplitudes. When it passes the satellite nonlinear transponder, on one hand there exists the problem of low power efficiency due to some amplitudes lying far away from the saturation point, on the other hand there exists the problem of complex pre-distortion correction due to some amplitudes lying near the saturation point resulting in heavy nonlinear distortion. To accommodate the nonlinearity of hardware, traditional satellite communications prefer constant envelope modulation mode, where Phase Shift Keying (PSK) modulation is an example initially. With the increase in wideband satellite services and the expansion of system capacity, spectrum resources are becoming scarce. Therefore, signal transmission may consider a modulation type with high spectral efficiency.

Recent satellite communication systems have adopted high-order amplitude and phase-shift keying (APSK) modulation schemes, e.g., DVB-S2X specifies modulation orders up to 256-APSK. Although QAM achieves superior error-rate performance compared with APSK of the same modulation order in an additive white Gaussian noise (AWGN) channel, APSK constellations are typically preferred for satellite applications because of their robustness to non-linear distortion inherent in satellite transponders. However, for IMT-2030, compatibility with terrestrial specification will be another critical factor.

The selection of modulation type depends on a series of factors such as Peak-to-Average Power Ratio (PAPR), demodulation complexity and Power Amplifier (PA) efficiency amongst others. In the future, it may be useful to take into account modulations with low PAPR and high Error Vector Magnitude (EVM) performance, and consider the influence of nonlinear factors of satellite channel on modulation. For example, the sensitivity of the modulation signal to the carrier phase noise increases with the modulation order, and the group delay distortion affects the performance of modulation.

Many techniques and schemes have been introduced to cope with the non-linearity of power amplifiers and various linearization techniques; however, they can lead to complicated solutions and not all provide a consistent solution.

### 5.1.2 Channel coding technology

In IMT-2020 era, Low Density Parity Check (LDPC) coding and polar coding are respectively applied to the service channel and control channel. Both coding schemes are rate-compatible and hardware-friendly with high capacity, contributing to increased coding gains. In future IMT-2030 era, since the present schemes are very close to theoretical coding limits, and to retain backwards compatibility, the current coding schemes may be extended in lower SNR regions and possible lower implementation complexity.

The LDPC coding evolution scheme mainly focuses on how to increase the throughput. The parallel decoding method can improve the decoding speed, thereby obtaining higher throughput. The parallel mode is divided into two architectures of block parallel and line parallel, which can be selected according to different channel types.

The polar coding evolution scheme mainly focuses on how to reduce the decoding complexity in large throughput scenarios. At present, polar coding is used to control channels with short coding

length, and high-quality transmission can be guaranteed under the premise of low complexity through pre-generated codebooks. However, with the increase of coding length, achieving Polar coding with both high reliability and low complexity has become a problem to be solved.

A channel codec design with the aid of Artificial Intelligence (AI) is expected to deliver better performances and the support of multi-dimensional optimization tasks in local optimal solutions within a limited range of conditions.

The channel coding scheme used in satellite communication also needs to place greater emphasis on its error-correction capability. Due to the large delay of the service link, it cannot over-rely on retransmission mechanism (e.g. Hybrid Automatic Repeat reQuest (HARQ)), requires adaptations for satellite-specific environment, or the coding scheme must ensure sufficient error correction capability to be able to operate at low SNR.

### 5.1.3 Waveform technology

In the context of systems prior to IMT-2020, satellite communications typically use single-carrier waveform such as Time Division Multiplexing (TDM)/Time Division Multiple Access (TDMA) (e.g. Digital Video Broadcasting for Satellite (DVB-S) or DVB-S2 on the down link and Digital Video Broadcasting – with Return Channel via Satellite system (DVB-RCS) on the uplink). The advantage of this waveform is its low PAPR, resulting in less signal distortion after amplification by the satellite power amplifier.

On the other hand, modern standardized terrestrial communications systems typically use waveforms based on the Orthogonal Frequency Division Multiplexing (OFDM) on both downlink and uplink. Due to the orthogonality of OFDM, it has a high spectral efficiency and flexible resource allocation in Orthogonal Frequency Division Multiple Access (OFDMA). Two possible schemes are Cyclic Prefix Orthogonal Frequency Division Multiplex (CP-OFDM) and Discrete Fourier Transformation-spread-Orthogonal Frequency Division Multiplex (DFT-s-OFDM), where DFT-s-OFDM waveform takes CP-OFDM waveform as a baseline but adds DFT precoding. This later scheme allows to achieve low PAPR which is critical with the limited transmit power of UE.

In the context of IMT-2020, the 5G-NR waveform technology initially designed for the terrestrial component has also been adopted for the satellite component.

For communications to handheld devices, the use of the same waveform allows simplified implementation of the devices and for broadband communication to platform mounted devices.

A comparison of the performance of DVB-S2/RCS2 and 3GPP NR-NTN radio interface is reported in ETSI TR 103 886 “Satellite Earth Stations & Systems (SES); DVB-S2x/RCS2 versus 3GPP New Radio protocol technical comparison for broadband satellite systems”.

In the context of IMT-2030 where the objective is to achieve a harmonised radio interface, the definition of the common waveform is expected to make implementation efficient and cheap while at the same time maintaining backwards compatibility.

It should be noted that among candidate waveforms, some would provide high resilience to delay-Doppler for satellite communications.

For example, Orthogonal Time Frequency Space (OTFS) has the ability to overcome the impact of Doppler effects caused by high-speed satellite motion, allowing each transmission symbol to experience an approximately constant channel gain in delay-Doppler domain. The two-dimensional Inverse Symplectic Finite Fourier Transform (ISFFT) and Symplectic Finite Fourier Transform (SFFT) can be utilized to map each transmission symbol between the delay-Doppler domain and the time-frequency domain each other.

In addition, Affine Frequency Division Multiplexing (AFDM) provides a waveform structure that is inherently resilient to delay-Doppler impairments, exhibits lower PAPR, and supports joint sensing

and communication. AFDM is based on the affine Fourier transform, which introduces chirp-like orthogonal basis functions. Unlike OFDM, where each subcarrier is localized in frequency, AFDM subcarriers sweep linearly in frequency across time, thereby covering the entire time-frequency plane. This fundamental property ensures resilience to delay and Doppler spread. Although AFDM differs structurally from OFDM, it can be designed to align with the existing OFDM waveform frameworks, thereby facilitating smooth migration.

Furthermore, the radio interface should provide high resilience to intentional interferences caused by typical commercial jammers, which can be mobile, such as:

- Regular partial-band jammer that uses random bit sequences of frequency-modulated sinusoidal signal to jam a predefined bandwidth part, e.g. targeting possible locations of the Common broadcasted signalling.
- Responsive jammer that monitors the broadcast channel and uses system information to target the dedicated control channels.
- Synchronization signal jammer that spoofs the network with fake synchronization signals to disrupt the correlation of synchronization signals.

#### **5.1.4 Multiple access technology**

Since the available wireless channel resources in the IMT satellite system are limited, how to meet the requirements of users will be the key point of satellite communication in the future.

Present satellite communications use multiple access techniques such as OFDMA, Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). In some such schemes, orthogonal resources may be assigned in the time, frequency, or code domains to distinguish different users.

Since there is theoretically no interference between users, a low-complexity detector with linear complexity can be used to separate signals from different users. However, the finite number of available resources in conventional multiple-access schemes may limit the number of users that can be simultaneously supported, which may make it difficult to meet requirements involving very large numbers of connected users. Advanced multi-user detection techniques may be investigated while keeping a balance between improvement of capacity, implementation complexity, costs and backwards compatibility.

To support high density user access, including IoT connectivity use cases with limited radio resources, grant free access scheme may be considered. An advanced multi-user detection algorithm may be used to distinguish multi-user signals at the receiver. Multiple access technology should be studied jointly with the selected waveform to address satellite communication requirements.

#### **5.1.5 Time-frequency synchronization technology**

For downlink synchronization, UE needs to search for reference signals at possible time-frequency positions. The IMT-2020 specifications for the satellite component assume that the UE has GNSS capabilities. Users can perform uplink timing and frequency pre-compensation based on UE location information and satellite ephemeris information. In addition, employing new Positioning Navigation and Timing (PNT) technology may augment or replace GNSS capabilities.

In satellite communication systems, the precise time and frequency synchronization is paramount for preserving stable communication quality and ensuring the fidelity of data transmission. Given the dynamic fluctuations and intricate characteristics inherent in satellite links, including the Doppler shift, path loss, and signal attenuation, Two-Way Satellite Time-Frequency Transfer (TWSTFT) technique emerges as a viable solution to achieve sub-nanosecond accuracy in time synchronization. This is accomplished through direct communication between satellites, while the utilization of atomic

clocks serves as an ultra-high-precision reference time source, providing a robust temporal benchmark for the synchronization system.

To enhance synchronization performance further, the adaptive synchronization algorithms are capable of dynamically accommodating varying channel conditions. These algorithms harness machine learning and artificial intelligence methodologies to analyse the channel state in real-time, subsequently fine-tuning synchronization parameters autonomously to ensure precision amidst complex environments. By integrating channel state information, these algorithms are also helpful to improve the robustness of synchronization, enabling it to sustain stable performance even amidst interferences and noise.

The deployment of large-scale satellite constellations has heralded the ascendancy of distributed synchronization architectures. This paradigm fosters synchronization not only among satellites but also between satellites and ground stations, leveraging both network-based synchronization protocols and point-to-point synchronization techniques. By capitalizing on the redundancy inherent in the mixed satellite links, the reliability of synchronization is augmented, ensuring that the synchronization performance of the entire system remains robust in the event of link disruptions.

New PNT technologies are expected to elevate time-frequency synchronization to new levels. The L-band timing signals, roughly 30 dB stronger than MEO GNSS, can mitigate adverse propagation conditions (e.g. light indoor, urban canyon, and subterranean environments), guaranteeing continuous PNT service availability where traditional GNSS cannot. This design may ensure rapid recovery of service (< 1 min outdoors; < 10 mins indoors) after outages or jamming events.

#### **5.1.6 Beam hopping**

The satellite to ground channel exhibits dynamic characteristics stemming from factors including the mobility of non-GSO satellites and users. This dynamic nature poses significant challenges to the performance and resource utilization efficiency of the communication system. Conventionally, the majority of the cell (satellite beam) related functions, such as admittance, load control and mobility, can be managed by conventional Radio Resource Management (RRM) Algorithms. However, in non-GSO type deployment where the cell traffic is more dynamic than in GSOs, adaptive beam hopping technology has emerged as a promising solution, enabling the dynamic adjustment of beam coverage and dwell time to optimize both performance and resource utilization. Furthermore, the implementation of intelligent beam scheduling necessitates the development of sophisticated algorithms capable of effectively managing scarce satellite resources, such as power and bandwidth, in order to cater to the dynamic demands of users. By harnessing the power of machine learning (ML) and optimization techniques, intelligent beam scheduling achieves a high level of autonomy and adaptability. Specifically, in the context of smart beam scheduling, advanced machine learning algorithms, including neural networks and deep learning methodologies, are employed to analyse vast quantities of data and subsequently adjust beam coverage strategies in a precise manner. These algorithms possess the capability to learn from historical data, recognize patterns in the evolution of resource states and user demands, and predict future states with a high degree of accuracy, thereby facilitating more precise and expeditious beam scheduling decisions. Furthermore, the adoption of multi-beam and multi-layer satellite constellations, such as those comprising GSO and non-GSO satellites, facilitated by advanced satellite antenna designs, can further amplify both coverage and capacity gains through coordinated beam-hopping strategies. By leveraging network assisted information regarding beam-hopping information, the UE energy efficiency can be optimized.

In the evolution of IMT-2030, with the expansion of antenna scale, facing the uneven geographical distribution and the time-varying nature of ground traffic demands, higher requirements are put forward for beam management to achieve agile response and adaptive channel environment.

In this context, the integration of AI, especially ML technology, provides an innovative path for beam management. The intelligent beam management analyses signal characteristics through ML

algorithms to achieve rapid and accurate decision-making. Its method based on deep neural networks can effectively utilize multi-dimensional information, such as receiver location, direction, power, and angle-of-arrival (AoA), for efficient training and intelligent selection. Intelligent beam hopping management further utilizes deep reinforcement learning to design full-frequency reuse beam hopping strategies, optimizing through both time and space dimensions to reduce inter-beam interference and enhance spectral efficiency. At the same time, targeting the high mobility of non-GSO satellites and the uneven distribution of on-ground users, the multi-satellite intelligent beam hopping scheme achieves load balancing and interference avoidance through online decision-making, which can optimize resource allocation among satellites and significantly reduce inter-satellite interference, pave an intelligent and efficient path for the future development of IMT-2030 satellite communications.

The development of more advanced antenna technology such as phased arrays benefits in improving the capability to manage the beams as well as to cope with the global coverage and co-frequency interference.

### **5.1.7 Multi-beam cooperation and satellite-specific MIMO techniques**

Multi-beam satellite antenna technology enables precise control over the pointing direction and shape of individual beams, facilitating the simultaneous transmission of multiple independent beams within the same frequency band. This capability realizes effective spatial domain spectrum multiplexing, whereby the spectral efficiency of the system is significantly enhanced. Furthermore, this spatial division multiplexing strategy not only boosts spectral efficiency but also markedly augments the multi-user access capability of the system, enabling a more efficient and inclusive utilization of satellite communication resources.

Upon this foundation, the integration of virtual MIMO technology further pushes the performance boundaries of multi-beam satellite antenna systems. By orchestrating the cooperation among multiple satellite beams or multiple satellites to constitute a distributed MIMO architecture, the virtual MIMO technique realizes the transmission gains inherent in multi-antenna systems, all without necessitating an increase in the number of physical antennas. Through the employment of joint precoding and distributed space-time coding strategies, this technique effectively mitigates adverse factors encountered in satellite-to-ground channels, including long propagation delays, Doppler frequency shifts, and time-varying fading. Consequently, it enhances the robustness and reliability of signal transmission, ensuring a more resilient and dependable communication link.

However, the wide coverage and broadcast nature of satellite downlinks result in strong spatial channel correlation over large geographical areas. Moreover, satellite channels are often dominated by line-of-sight propagation and exhibit limited scattering, which restricts the randomness and limits the divert gains found in the terrestrial systems. This necessitates further amendments of MIMO techniques for satellite communications.

The application of beam spatial division multiplexing technology, encompassing intra-satellite beam spatial division multiplexing and inter-satellite beam spatial division multiplexing, notably augments the system's capacity, coverage, and stability, while concurrently minimizing transmission delays. The technological evolution trend can be divided into following distinct stages: 1) multi-beam cooperative transmission from a single satellite, 2) cooperative transmission orchestrated across disparate satellites. Within these developmental stages, Single-User MIMO (SU-MIMO) and Multi-User MIMO (MU-MIMO), as pivotal transmission paradigms, respectively improve transmission performance and data throughput from the viewpoints of individual terminals and multiple terminals, thereby enhancing the overall user service experience.

However, achieving synchronization among clustered satellite nodes presents a significant challenge due to the dynamic characteristics of the transmission channels between satellite nodes, and the limited accuracy of available time and frequency references on satellites. To ensure proper

synchronization, satellite nodes must establish inter-satellite link transmissions to obtain accurate reference information from external sources. The topic of Inter-Satellite Links (ISL) is currently being studied in various forums for its reliability and robustness against intrusion and hacking.

Inter-satellite links and efficient control mechanisms occupy a pivotal position in enabling effective network-layer coordination amongst satellites. The advancement and deployment of these technologies serve as a robust foundation for synchronized real-time data interchange, beam administration, resource allocation, and signal processing operations. Concurrently, system-level performance optimization necessitates the collaborative refinement of satellite constellation architecture, beam allocation strategies, power control mechanisms, and resource management frameworks. This optimization is to maximize system throughput, enlarge coverage, and improve user quality of service.

#### **5.1.8 Coverage enhancement technology**

For satellite communication, achieving global coverage and providing reliable services for all users has always been a focus of attention. Due to the large coverage of satellites, even though satellites generally use multi-beam mode of operation, it is still difficult to provide services simultaneously for the entire coverage area due to the limitation of satellite transmitting power and number of beams. Furthermore, due to the considerable distance between satellites and users, there is a challenging link budget for the service link. Improving the quality of the service link is important to ensure the reliability of user services. Given these challenges, coverage enhancement can be taken from both system-level and link-level.

The system-level coverage enhancement mainly solves the problem of service coverage, and it can be achieved through techniques such as beam-hopping and dynamic resource allocation to address coverage issues and improve link budget.

The link-level coverage enhancement focuses on resolving insufficient user link budgets especially to mitigate adverse propagation conditions. It mainly uses repeated transmission, multi-slot joint channel estimation, reference signal power enhancement and other technologies to enhance physical channels or physical signals.

#### **5.1.9 Satellite positioning technology**

With the extensive deployment of non-GSO satellite constellations, it not only provides infrastructure support for satellite positioning technology, but also enhances the power of positioning signals due to its low-altitude flight characteristics, effectively overcomes the limitations of traditional positioning systems, and provides a method to achieve high-precision and high-reliability positioning services worldwide.

In the context of IMT-2030, combining mobile communication and satellite positioning methods to design multi-level positioning schemes may be of significance to improve the positioning accuracy, availability and efficiency.

New satellite positioning techniques may be integrated with satellite-based timing distribution and synchronization capabilities within IMT-2030 satellite component, to support resilient PNT functions independently of traditional GNSS.

While GNSS may remain being used for synchronization and mobility management, it faces physical limitations under some conditions, including vulnerability to intentional jamming or spoofing. To enhance system robustness against such threats, additional mechanisms may be introduced by leveraging the IMT internal measurements. For example, round-trip time (RTT) and AoA measurements obtained through terrestrial and satellite infrastructure can be used to cross-validate GNSS-derived positioning and timing information. By comparing UE-reported GNSS information (e.g., satellite IDs and signal strength measurements) with internally measured network observations,

the system can detect potential inconsistencies and mitigate GNSS signal anomalies in real time. Such cross-layer verification mechanisms can therefore improve the reliability and security of synchronization and PNT services in future IMT-2030 satellite network deployments.

For example, one operational global LEO mesh constellation<sup>2</sup> operator states that it delivers global PNT (Positioning Navigation and Timing) with end-to-end timing accuracy of 50–240 ns (Allan deviation  $< 3 \times 10^{-13}$  over one day) and 95 % positioning accuracy of ~25 m horizontally and ~12 m vertically—expected to extend precise timing and location into indoor, urban canyon, and GNSS-denied environments. This service strengthens system resiliency by providing an independent, Stratum-0 primary reference time clock (PRTC-A) per Recommendation ITU-T G.8272, without any new ground-station infrastructure.

### 5.1.10 Semantic communication technology

Semantic communication technology is capable of intelligence and autonomous learning, empowering communication systems with the ability to autonomously comprehend and interpret the semantic content of information. This technology utilizes the semantic space of information, thereby facilitating efficient data transmission and processing, which is inherently well-suited to the constrained bandwidth characteristics of satellite communication. Moreover, it streamlines the processes of information encoding and decoding, leading not only to an enhancement in the efficiency and accuracy of transmission but also ensuring the specific requirements of diverse use cases and applications are met in a precise and tailored manner.

With the enhancement, the progression of semantic communication technology is expected to promote interoperability and compatibility among diverse devices and networks, and establish a highly efficient, low-latency, and semantically interoperable communication architecture. Furthermore, it is anticipated that the realization of intelligent communication and networking will advance satellite networks towards the direction of unmanned operation and maintenance.

By leveraging semantic compression and generative reconstruction, generative semantic communications can significantly enhance the efficiency of limited power and bandwidth resources in satellite systems. To implement this in IMT-2030, improved computational complexity, heterogeneous user capabilities and adaptation to dynamic network topologies would need to be addressed.

### 5.1.11 Spectrum usage efficiency

The integration of gateway stations facilitates the interconnection between GSO and non-GSO satellite systems. This enables the utilization of software-defined networking (SDN) and network function virtualization (NFV) technologies, which are instrumental in achieving flexible cross-network connection management. Furthermore, the development of adaptive channel compensation and resource scheduling algorithms, grounded in machine learning principles, enhances the reliability of connectivity. Additionally, the adoption of multi-frequency band and multi-beam antenna technologies may improve spectrum usage efficiency within the interface between GSO and non-GSO satellite systems.

Software-defined satellites (SDS), which possess on-demand update and reconfiguration capabilities, are enabled by software defined radio (SDR). SDR can play a key role to the future of the satellite component of IMT-2030 which will enable dynamic spectrum management, allowing real-time adjustments to frequency use, beam patterns, and power levels to optimize network performance. SDS are expected to help ensure efficient coexistence between GSO and non-GSO satellites. By

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<sup>2</sup> See <https://www.nist.gov/publications/validating-timing-performance-improvement-ionspheric-corrections-iridium-pnt-receivers>

leveraging SDN and NFV, SDS can dynamically manage interference, optimize spectrum usage, and improve coverage, especially in underserved areas.

In IMT-2030, SDR is expected to support advanced mobility management, ensuring reliable connectivity for high-speed applications like autonomous vehicles and IoT, while facilitating efficient spectrum usage to meet diverse user demands. This adaptability is expected to be crucial for meeting the connectivity goals of IMT-2030 networks, contributing to the efficient utilization of spectrum.

### **5.1.12 Integrated Sensing and Communication (ISAC)**

ISAC capability may be applied to specific use cases with the satellite component of IMT-2030, such as scenarios at lower altitudes (e.g. Very Low Earth Orbit (VLEO)), where satellite-based ISAC may allow for better channel sensing performance due to reduced propagation loss.

## **5.2 Technology of satellite networks**

In IMT-2030, the satellite component is expected to support GSO and non-GSO satellites. Non-GSO includes but may not be limited to MEO, LEO and VLEO. In such orbits, different Size, Weight, Power, and Cost (SWaP-C) constrained satellite classes, including possibly CubeSat, may operate.

Flexible network architecture is expected to be applied to IMT-2030 satellite networks to accommodate key technologies, such as Radio Access Network (RAN) slicing, mobility management, broadcast and multi-cast, Mobile Edge Computing (MEC), etc. The inter-satellite links as well as cooperation between GSO and non-GSO systems are expected to extend the coverage, improve the network resilience, adapt to varying communication needs across environments, and enhance reliability and efficiency. The interworking between terrestrial IMT networks and satellite IMT networks is expected to enhance global service coverage. Regenerative payload may support the features described above.

### **5.2.1 RAN architecture**

Satellite RAN facilitates wireless access and data transmission for terminals, catering to terminals with diverse data rate and mobility requirements while ensuring low-latency switching and service continuity. For transparent payload architecture, the Satellite RAN is split between satellites and gateway stations. While for regenerative payload architecture, the Satellite RAN may be confined to the satellites.

The architecture of the Satellite RAN can be further enhanced based on the Satellite RAN of IMT-2020, considering the on-demand deployment of multi-satellite and satellite-ground network elements. According to satellite capabilities and deployment requirements, the satellite component of IMT-2030 system design is expected to continue to adopt the separation architecture of the satellite component of IMT-2020, flexibly deploying different RAN functions on satellite nodes and ground nodes.

### **5.2.2 RAN slicing**

Satellite communication has the characteristics of high dynamic and layered distribution, which is quite different from terrestrial communication networks. These characteristics present considerable challenges for end-to-end slice management and quality of service assurance in the satellite communication system. To address these challenges, the intelligent end-to-end network slice management architecture need to be adopted. This will enable intelligent slice selection, full-life cycle autonomous slicing management, as well as multi-domain network coordinated orchestration.

Network slice selection should consider the requirements of different users and scenarios. On-demand end-to-end slicing covering the satellite RAN, transmission network, and core network can be selected to achieve intelligent and accurate slice selection.

Network slice management encompasses the intelligent management of network slices throughout full life cycle. This includes intelligent slice deployment, selection, scheduling, deletion, error locating, and real-time monitoring of slice status. These measures ensure the safe and healthy operation of slices. By adopting an intelligent end-to-end network slice management architecture and leveraging AI technology, the satellite system can effectively address the challenges and achieve efficient slice management and QoS assurance.

### **5.2.3 Mobility management**

Due to the high-speed movement of satellites, handover happens frequently for both service and feeder links, which may result in excessive signalling overhead and temporary service disruptions. To address these inherent challenges of satellite networks, location-based mobility management mechanisms may be introduced. By pre-configuring handover conditions through the integration of UE location information and satellite ephemeris data, seamless service continuity can be achieved even under rapid channel variations, and improve the efficiency of network control signalling. The service link handover can be further classified as inter-beam handover and inter-satellite handover, and feeder link handover as intra-station handover and inter-station handover.

For the service link handover, since a satellite beam serves a large number of active users, each handover may result in communication interruptions lasting tens to thousands of milliseconds. So, it is necessary to minimize the service link handover to reduce signalling overhead and consumption of on-board processor resources. The service link handover can be optimized from a series of aspects, such as handover judgment conditions, handover methods, target base station selection strategy, steering beam mode and “Make-Before-Break”.

Similarly, the feeder link handover causes the Space Bearer Network (SBN) topology to change, altering the traffic path. To minimize the impact of feeder link handover on QoS, the “Make-Before-Break” handover mode is generally adopted, and further optimization is made in combination with the routing switching mechanism of the SBN to reduce congestion, packet loss and delay jitter caused by path changes. For the feeder link handover in transparent mode, special consideration is given to the overall handover of connected users, and group handover can be utilized to mitigate the impact of signalling storms.

Furthermore, to better meet user service requirements, the design of network selection and reselection from UE side can consider selecting the appropriate target network (such as GSO, non-GSO) to initiate services based on UE capabilities and service types. The network side can also select the appropriate target network for the UE based on its QoS requirements during handover decision-making to better meet the service requirements of the UE.

### **5.2.4 Inter-satellite collaboration within the same system**

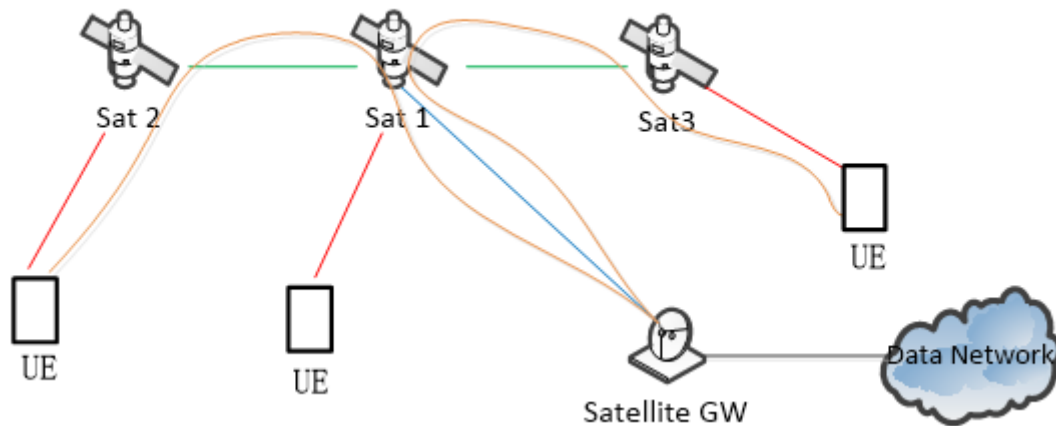
Optimized resource management within a GSO network or non-GSO system may be managed through ISL between satellites from the same orbit to ensure efficient resource utilization.

Optical ISLs may provide higher throughput and improved resistance to interference and congestion between space and ground segments. These characteristics make them especially well-suited for high-capacity data transfer.

Joint processing of user signalling and data can be achieved from different satellites with various service capabilities. UE can select or reselect a satellite and even switch between satellite constellations to better meet service requirements.

The satellite RAN's decoupled architecture allows for flexible processing capabilities of payloads on different satellites, enabling full or partial base station functions.

FIGURE 1  
Example of non-GSO inter-satellite collaboration



As shown in Fig. 1, Sat 1 has robust capabilities, supporting full base station processing. It provides services to UE normally. Adjacent Sat 2 and Sat 3 can be transparent type satellites or satellites with only partial base station. They can connect to Sat 1 via inter-satellite links to jointly process signalling and data, and connect to the satellite gateway (Satellite GW) through Sat 1.

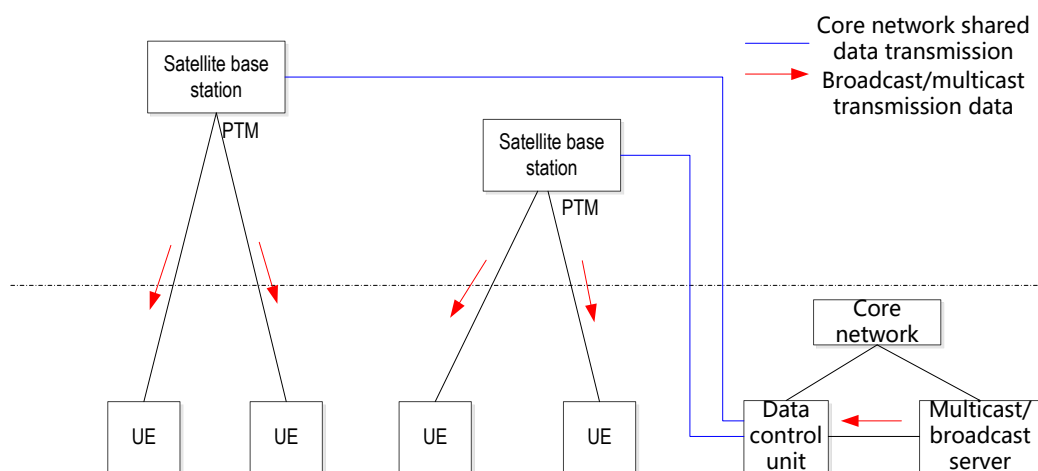
### 5.2.5 Broadcast and multi-cast

The satellite communication with its global coverage has advantages on broadcast and multicast and is capable of providing information content services, public safety and emergency tasks, as well as group communications.

For broadcast service, the continuity of services from different satellites or cells is a key consideration. In an optimal broadcast scheme, a UE initially obtains the broadcast service configuration from the application layer. It then acquires frequency resources and bearer configuration through real-time broadcast information, followed by detecting specific control scheduling information for the broadcast. Finally, the UE completes the reception of the broadcast information. Additionally, the satellite network can transmit broadcasting services through satellites based on the requirements of the broadcast area.

For multicast service, efficient multicast management and multicast routing are the main technical challenges. The satellite network needs to group users and establish group sessions to deliver the same service data to users within the same group. If users in the same multicast group belong to the same beam, only one instance of the multicast information needs to be transmitted within that beam. However, if these users belong to different beams within the same satellite, multicast information must be transmitted through the appropriate beams. Similarly, if the users belong to different satellites, multicast information should be transmitted through the appropriate beams belong to different satellites, and the satellite network must support multicast routing to facilitate this communication. For non-GSO satellite communication networks, users within the same multicast group are typically located under different satellites and frequently make inter-satellite handover. This necessitates an efficient multicast management mechanism and multicast routing protocol.

FIGURE 2  
Illustration of satellite broadcast and multicast network



### 5.2.6 Technology of Mobile Edge Computing (MEC)

Amidst the exponential proliferation of the IoT, the emergence of MEC technology serves as a timely remedy to the limitations confronted by cloud computing in addressing latency-critical applications. By relocating computational capabilities to the network's edge, MEC technology imparts unparalleled flexibility to satellite networks, empowering them to dynamically adjust to evolving network demands and resource availabilities. The application of MEC is extended to non-GSO satellites, thereby constituting a dynamic network that interconnects ground and space domains. This interconnected ground network and space network facilitate agile offloading of computational tasks to either ground-based MEC servers or those on-board processing non-GSO satellites, which promotes computational efficiency and offers necessary performance guarantees for emerging applications that demand low latency and high reliability, such as autonomous driving, tele-surgery, and Extended Reality (XR). Furthermore, the traffic load on the backbone satellite network can be alleviated and the risk of data leakage can be limited by MEC.

In the context of offloading and resource allocation, the MEC servers within both ground and satellite networks can be interconnected to devise an intelligent task allocation strategy. This strategy considers both the average response time of individual tasks and the associated satellite resource overhead, thereby enhancing the overall network performance and ensuring the sustained delivery of high-quality services even under complex operational conditions.

In addition, the system may support MEC on board a constellation of non-GSO satellites interconnected with ISL addressing the transfer of MEC context information between the satellites.

### 5.2.7 Cooperation between GSO and non-GSO systems

GSO satellite communication systems will exist alongside non-GSO satellite systems. GSO satellite systems are able to provide high latency service over a stable regional coverage and can be operated by a single network operator.

Non-GSO satellite systems may be able to provide lower latency service for real time and non-real time services. They could be shared between multiple network operators.

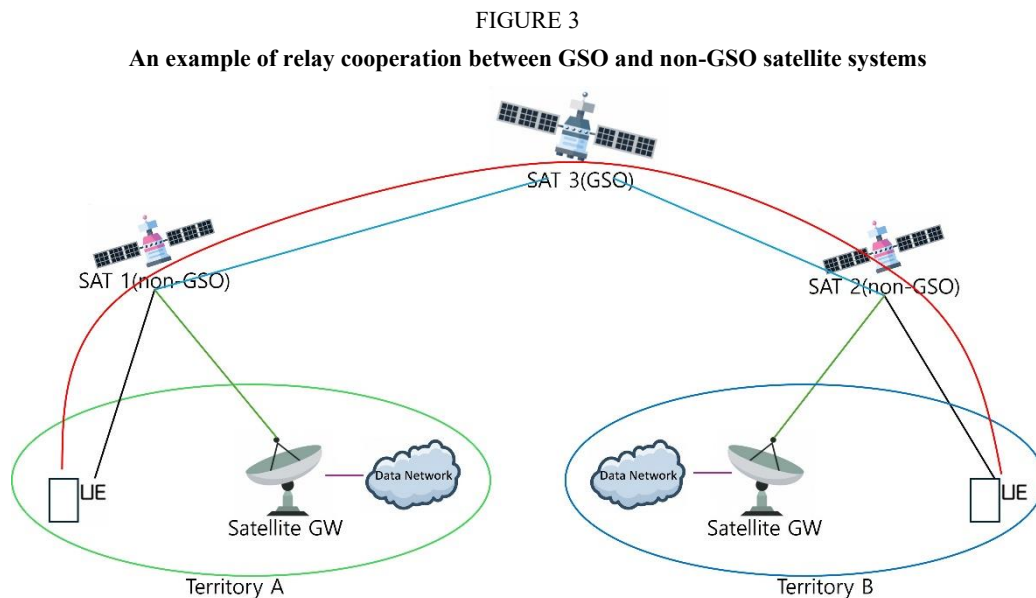
GSO satellite systems are expected to cooperate with non-GSO satellite systems providing:

- Efficient broadcast services over a wide area;
- Efficient support of UE in idle mode;

- Back-up capacity in case of regional traffic congestion;
- Backhaul relay of non-GSO data.

Figure 3 shows an example of relay cooperation between GSO and non-GSO satellite systems.

Development of inter-satellite links between GSO and non-GSO satellites makes it possible to dynamically offload traffic from non-GSO to GSO and vice versa depending on applications.



### 5.2.8 Interworking with terrestrial IMT network

The satellite and terrestrial components can interwork to offer diverse communication access modes. In the context of the satellite component, the employment of regenerative processing mode and inter-satellite links significantly mitigates the complexity and burden associated with gateway station deployment. However, due to constraints posed by technical limitations and transmission capabilities, the system may evolve to incorporate both regenerative processing and transparent forwarding modes in the future.

### 5.2.9 Regenerative payload

Communication satellites are continuously improving the on-board signal processing capabilities of their payloads. Within the Intermediate Frequency (IF) and baseband processing units, the fine-grained bandwidth segmentation is integrated with seamless switching capabilities of the digital channelized operating in the IF and the AI-driven signal processing capability of on-board processor to achieve flexible and efficient data processing. Within the inter-satellite link processing and satellite routing units, high-capacity data processing and exchange capabilities enable multi-terabit/s throughput and resilient satellite networking. These regenerative payloads facilitate support for multiple protocols, enhance communication efficiency, and enable flexible networking across satellites, beams, and users. Moreover, the regenerative payloads are expected to play a critical role in advancing the integration of communication, navigation, sensing, storage, and computing capabilities in space systems. The seamless coordination between the capabilities is expected to enable holistic and efficient resource utilization, flexible data transport, real-time data fusion, intelligent on-board information distribution, sensing communication integration, etc.

Typical regenerative payload mission considered for the Satellite Component of IMT-2030 system may provide:

- store-and-forward capabilities for non-real time services;

- ISL (e.g. ISL in-plane/inter-plane, inter-orbit);
- mesh connectivity via satellite (i.e. UE-satellite-UE communication);
- PNT capability;
- ISAC capability.

### 5.3 Terminal development

Evolved satellite networks will be enabled by next-generation user terminals characterized by diversified architectures, enhanced functionality, and advanced antenna systems. These terminals encompass a broad range of types and application scenarios –including handheld, IoT, and high-capacity platforms– and are supported by key enabling technologies such as adaptive antenna aiming and tracking, low-power operation, and optimized terminal design.

#### 5.3.1 Terminal types and application scenarios

Satellite communication systems are expected to comprehensively support diverse terminals, ensuring their capability to accommodate varying data transmission rates and optimizing performance in accordance with distinct rate requirements. Diverse terminals necessitate optimization across various aspects, including antenna, radio frequency front-end, baseband processing, computing, durability and radiation hardness.

Several categories of terminals may be supported by the IMT-2030 according to the service capability (e.g. maximum data rate), to the antenna type (omnidirectional versus directive), to the RF characteristics or to the targeted use case (e.g. pedestrian/in vehicle, IoT or verticals).

Typically, the following categories could be defined:

- Handheld terminals, such as smartphones.
- Internet of Things (IoT) and machine-type devices.
- Platform mounted broadband terminals including those on land vehicles, aircraft, ships, trains, drones, spacecraft and fixed platform.

##### 5.3.1.1 Handheld terminals

Given the widespread access to mobile handheld terminals, it is a trend to facilitate a technology transition through compatibility designs that enable handheld terminals to support the satellite component of IMT-2030, or some functions of both the terrestrial and satellite components of IMT-2030, as applicable.

##### 5.3.1.2 Internet of Things (IoT) and machine-type devices

Satellite systems offer extensive coverage enabling connectivity for widely distributed IoT terminals and machinery, particularly facilitating the transmission of sensor data and control commands. These IoT terminals and machines can be mounted on various vehicles of varying speeds and altitudes, including but not limited to cars, ships, drones, and satellites.

Satellite IoT systems integrate advanced terminal processing, satellite-edge computing, and intelligent collaboration to enable massive device connectivity. This approach optimizes communication efficiency while minimizing reliance on large communication bandwidth and complex RF chains.

Satellite IoT terminals are anticipated to incorporate Systems-on-Chips (SoCs) that integrate AI computing, general-purpose computing, and communication baseband functions. Embedding deep neural processors into IoT and machine-type devices enables local data processing and AI-driven RRM, effectively addressing the timeliness and communication efficiency challenges posed by large scale IoT networks. Additionally, leveraging satellite-based edge nodes to offload computational

tasks and coordinate numerous machine-type devices can improve the overall system efficiency. This integrated approach may overcome the current limitations and pave the way for more reliable and efficient satellite IoT systems in the future.

### **5.3.1.3 Platform mounted broadband terminals**

Platform mounted broadband terminals with directive antennas emphasize delivering high-performance satellite communications for providing communications while in motion or at fixed locations. This supports a wide range of applications such as provided below.

For ocean-going vessels, access to the Internet is paramount, encompassing the timely updating of electronic nautical charts and weather forecasting, seamless information sharing among vessels, remote video monitoring, and addressing crew communication needs.

For passengers on-board aircraft, the existing on-board connectivity services are currently facilitated by High-Throughput Satellites (HTS) in GSO or by non-GSO systems enabling passengers to connect to their services (e.g. live broadcast, video streaming, online information access, etc.) utilizing low-profile terminals.

For land mobile/automotive terminals, terminals may support applications of interest to passengers, as well as vehicle maintenance-related data.

For human-rated spacecraft, the introduction of high-capacity terminals of the IMT satellite component, characterized by their high performances, provides an additional means of data transmission to/from the crew, and potentially to support spacecraft operations.

## **5.3.2 Terminal technology**

### **5.3.2.1 Antenna aiming and tracking technology**

Directive antennas are used in platform mounted broadband terminals, such as those used in vehicles, ships, and aircraft, providing broadband services.

For vehicular communications with GSO and non-GSO satellites, the terminal continuously calculates its antenna direction based on its own position to ensure its antenna is accurately aligned with the satellite by updating the pointing direction dynamically. More advanced antenna technology may be needed, such as AI-assisted electronical steering antenna, to meet dynamic requirements.

The IMT-2020 radio interface specifications stipulate that the UE can get the location information by GNSS during the network access procedure. Since non-GSO satellites move rapidly relative to the Earth's surface, it poses significant challenges for antenna tracking in non-GSO vehicular mobile communication. The high-speed motion of vehicle-mounted antennas complicates accurate alignment. While traditional mechanical tracking systems struggle with vibration and latency, advanced electronically steered phased array antennas used for satellite applications can offer rapid beam steering, better resistance to motion-induced misalignment, and support for multi-beam tracking and handover, which are essential for seamless broadband service in mobile environments.

In modern non-GSO satellites, to avoid handover signalling the beam is fixed on the earth. And the fixed beam is handed over from outgoing to the incoming satellite.

The satellite component of IMT-2030 is envisaged to support GNSS-independent operations. This independence from the traditional GNSS system is expected to improve performance and resiliency of the networks.

### **5.3.2.2 Low power consumption technology**

Low power consumption technology is important to achieving sustainable system operation.

One direction for the development of low power consumption technology focuses on the research and development of energy-saving communication protocols adapted to the satellite communication environment, such as random access procedures and power control algorithms, aiming to optimize data transmission processes through lightweight and efficient protocol design. A UE should support unified protocol to avoid additional power consumption caused by multiple protocols.

Intelligent sleep mechanisms can utilize machine learning to predict task demands, dynamically adjusting terminal power states to achieve deep sleep during non-operational periods and rapid wake-up. Combined with data transmission optimization algorithms like compression and fusion techniques, further reductions in transmission energy consumption are possible.

In satellite communication, the implementation of low power consumption technology still faces challenges. One issue is how to ensure the system can flexibly switch between different operating modes to meet burst high-speed transmission demands, while reducing power consumption.

#### 5.4 Privacy and security

Security threats may be originated by illegal access, wiretapping, information tampering, replay attacks, traffic analysis, wireless intrusion, virus infection, Trojan infiltration, backdoor infiltration, etc.

In order to avoid the above security threats, the security requirements of the satellite communication network include at least following three aspects.

First is service link security. The service link between the terminal and the satellite is expected to ensure secure communication between the terminal and the node of the satellite. It should also ensure the privacy of protection for user identities and user location information. The confidentiality and integrity protection of control signal and transmission data should be supported. It should support mutual authentication of terminal and the network to prevent illegal terminal access.

Second is inter-satellite security. It needs to support the confidentiality and integrity protection of data. The adoption of laser communication technology is one alternative that may mitigate the threat to the ISL.

Third is the feeder link security. It needs to support the confidentiality and integrity protection of the data. At the same time, mutual authentication between gateway station and satellites is required to prevent the access of fake gateway stations or fake satellites.

Furthermore, IMT-2030 satellite component may use advance security schemes, such as Quantum Key Distribution (QKD) to enhance the security performance. Studies and standardization activities on satellite-based QKD have been undertaken, as summarized in Technical Report ITU-T TR.SQKDN (03/2025), "*Standardization considerations of satellite-based QKDN*".

## 6 Summary

This Report describes development and technology trends of the Satellite Component of IMT systems for the time frame 2030 and beyond. Requirements, services and applications are described to show the Satellite Component of IMT-2030 development driven factors impacting technologies. Considerations on the Technology trends for the Satellite Component of IMT-2030 that may be applicable to radio interfaces, terminals, and network infrastructure levels are discussed.

The technology trends described in this Report indicate that, in the context of IMT-2030 and beyond, radio interface harmonization may be pursued, as appropriate, in support of satellite components.

## 7 Acronyms and abbreviations

3GPP	Third-Generation Partnership Project
AFDM	Affine frequency division multiplexing
AI	Artificial intelligence
AOA	Angle of arrival
APSK	Amplitude and phase shift keying
CDMA	Code division multiple access
CP-CDMA	Cyclic prefix – code division multiple access
DFT-s-OFDM	Discrete Fourier transformation single carrier orthogonal frequency division multiplex
DL	Downlink
DVB-RCS	Digital Video Broadcasting - with Return Channel via Satellite
DVB-S	Digital video broadcasting for satellite
eMBB-s	Enhanced Mobile BroadBand-Satellite
EVM	Error vector magnitude
FDD	Frequency division duplex
FDMA	Frequency division multiple access
GNSS	Global Navigation Satellite System
GSO	Geosynchronous orbit
HARQ	Hybrid Automatic Repeat reQuest
HD-FDD	Half-duplex FDD
HIBS	High altitude platform stations as IMT Base Stations
HRC-s	High reliability communications-satellite
IF	Intermediate frequency
IMT	International Mobile Telecommunications
IoT	Internet of Things
IP	Internet Protocol
ISAC	Integrated sensing and communication
ISFFT	Inverse symplectic finite Fourier transform
ISL	Inter-satellite link
LDPC	Low density parity check
LEO	Low Earth orbit
MEC	Mobile edge computing
MEO	Medium Earth orbit
MIMO	Multiple-input multiple-output
ML	Machine learning

mMTC-s	massive Machine-Type Communications-satellite
MU-MIMO	Multi-user MIMO
NFV	Network function virtualization
non-GSO	non-geostationary satellite orbit
NTN	Non-terrestrial network
OFDM	Orthogonal frequency division multiplexing
OMA	Orthogonal multiple access
OTFS	Orthogonal time frequency space
PA	Power amplifier
PAPR	Peak-to-average power ratio
PNT	Positioning navigation and timing
PSK	Phase shift keying
PSTN	Public switched telephone network
PNT	Positing, navigation and timing
QAM	Quadrature amplitude modulation
QKD	Quantum key distribution
QoE	Quality of experience
QoS	Quality of service
RAN	Radio access network
RF	Radio frequency
RRM	Radio resource management
RTT	Round trip time
SBN	Space bearer network
SDN	Software-defined networking
SFFT	Symplectic finite Fourier transform
SNR	Signal-to-noise ratio
SoC	Systems-on-chip
SU-MIMO	Single-user MIMO
SWaP-C	Size, Weight, Power, and Cost
TDD	Time division duplex
TDMA	Time division multiple access
TWSTFT	Two-way satellite time-frequency transfer
UAV	Unmanned arial vehicle
UE	User equipment
UL	Uplink

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