



## Views &amp; Comments

# Evolution of Satellite Communication Systems Toward 5G/6G for 2030 and Beyond



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## 1. Introduction

From the first-generation (1G) through the second-generation (2G) Global System for Mobile Communications (GSM), the third-generation (3G) wideband code division multiple access (WCDMA) to the fourth-generation (4G) long-term evolution (LTE) wireless networks, terrestrial networks (TNs) have demonstrated significant success in increasing communication speeds and improving quality of service (QoS) for users. These advancements have been instrumental in meeting the growing demand for mobile data and have laid the foundation for the evolution of subsequent wireless technologies, including the current development of the fifth-generation (5G) new radio (NR) network and the future sixth-generation (6G) network.

5G wireless networks are designed to address service needs with distinct requirements: enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (uRLLC), and massive machine-type communication (mMTC) [1]. Looking ahead, future 6G wireless networks aim to go beyond these capabilities by providing uninterrupted global connectivity, ensuring mobile service coverage anytime and anywhere, including land, sea, and sky. Although 6G is still in the early stages of research and development, several promising use cases and applications have already emerged, such as ubiquitous mobile ultra-broadband (uMUB), ultra-high data density (uHDD), and ultra-high-speed ultra-reliable low-latency communications (uHURLLC) [2,3]. These use cases require global coverage to address diverse needs: uMUB ensures consistent high-speed Internet access for users in urban, rural, and remote areas; uHDD supports the industrial Internet of Things (IIoT) and massive device connectivity in remote or difficult-to-reach locations, such as oceans or deserts, where specialized devices and sensors may be deployed; and uHURLLC enables real-time communication for critical applications such as autonomous vehicles, remote healthcare, and emergency response in remote regions. However, current 5G systems encounter significant

challenges in remote or sparsely populated regions due to the limited reach of TNs, high deployment costs, and geographical constraints. These challenges include insufficient bandwidth, high latency, and unreliable connectivity, which hinder support for advanced use cases such as uMUB, uHDD, and uHURLLC. These limitations are rooted in the inherent bottlenecks of TNs, which include limited geographical coverage, scalability issues, and vulnerability to disasters. For instance, deploying and maintaining ground-based infrastructure in remote areas is economically unfeasible, while traditional satellite solutions often fail to meet the low-latency and high-throughput requirements of modern applications. Additionally, operational and maintenance costs, as well as economic viability, further complicate the deployment of TNs in under-served regions. To address these challenges, advanced satellite constellations—as a key component of non-terrestrial networks (NTNs), which include satellite constellations, high-altitude platforms (HAPs), and unmanned aerial vehicles (UAVs) within mobile communication networks—offer a promising solution by providing global coverage, low latency, and high throughput. In this paper, we focus on satellite networks in NTNs.

In their early stages, NTNs primarily relied on traditional satellite communication (SatCom) systems, such as geostationary-Earth-orbit (GEO) satellites, which are independent systems for specialized applications, including broadcast television (TV), navigation, and military communications. Early SatCom systems mainly focused on providing point-to-point links or broadcasting services, with limited interaction with TNs. These systems were designed for high-latency and low-throughput services, making them unsuitable for the dynamic, high-speed, and interactive applications supported by TNs today. The integration of early SatCom with TNs was constrained by several technical and operational factors:

- Traditional satellite systems, particularly those in GEO, suffered from high latency (typically 250–500 ms round-trip) and limited data rates, making them incompatible with real-time or high-bandwidth TNs services;
- The protocols, modulation techniques, and network architectures used in early SatCom systems were not interoperable with terrestrial standards such as GSM, WCDMA, or LTE;

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- Early satellite systems were costly to deploy and maintain, with limited scalability compared with TNs;
- The static and centralized nature of SatCom systems hindered their ability to integrate into the dynamic, user-centric architecture of TNs.

Several advancements have bridged the gap between SatCom and TNs, enabling seamless integration. The development of high-throughput satellites, mega-constellations in low-Earth orbit (LEO), and improved payloads with beamforming and onboard processing have significantly reduced latency and increased capacity. Efforts by organizations such as the 3rd Generation Partnership Project (3GPP) have standardized NTN protocols to ensure compatibility with TN technologies, such as 5G NR. Additionally, software-defined networking (SDN) and network function virtualization (NFV) have introduced dynamic control mechanisms, making NTNs more adaptive and interoperable with TNs. The miniaturization of satellite components and the use of commercial off-the-shelf technologies have lowered costs, enabling NTNs to be scaled economically. Furthermore, artificial intelligence (AI)-driven network management and automated scheduling have improved NTN performance, ensuring efficient resource utilization and seamless integration with TNs. Notably, the emergence of direct satellite-to-cellphone connectivity has further revolutionized NTNs, allowing standard mobile devices to communicate directly with satellites, thus eliminating the need for specialized ground equipment and extending coverage to previously inaccessible regions. By leveraging these advancements, NTNs have evolved from isolated systems into integral components of global communication networks, addressing critical challenges in coverage, scalability, and reliability for 5G/6G networks.

This paper provides a systematical overview and analysis of the evolution of SatCom to empower 5G/6G networks for 2030 and beyond, with a focus on SatCom technologies, international standardization activities, technical challenges, and future directions. The organization of this article is as follows: We first introduce the architecture of integrated satellites with 5G/6G networks. Then, we review the current development and forecast the future development of integrating satellite telecommunication networks with TNs in 5G/6G systems from the perspective of international standards. Finally, we identify key challenges and technologies for further research in SatCom networks.

## 2. Integrating satellites with 5G/6G networks

The structure of SatCom networks is becoming an integral part of future 5G/6G networks, which combine terrestrial and satellite networks (Fig. 1). TNs encompass sea areas, rural regions, traffic systems, base stations, and other ground-based infrastructure, while satellite networks include satellites at various orbital altitudes, categorized into GEO satellites, medium-Earth-orbit (MEO) satellites, and LEO satellites. Satellite networks provide broad coverage to meet the demands of 5G/6G networks, with different satellites serving as access, forwarding, and relay nodes, as well as supporting network management and control [4]. The key characteristics of satellites at different orbital altitudes are summarized in Table 1 [5,6].

As illustrated in the “payload types” inset of Fig. 1, satellites may carry either non-regenerative (transparent) or regenerative payloads, which represent two fundamental architectural paradigms independent of orbital layer. Transparent payloads handle basic functions such as frequency conversion, filtering, and amplification, relying on ground infrastructure for advanced processing. In these cases, the satellite serves as a simple “bent-pipe” relay. In contrast, regenerative payloads support onboard functions such

as encoding, demodulation, and routing, effectively embedding next-generation Node B (gNB) capabilities within the satellite. By enabling onboard data processing and supporting inter-satellite links (ISLs), regenerative payloads help reduce latency and improve network flexibility—particularly in remote or underserved regions.

In addition to differences in payload types, ISLs are key technologies for efficient SatCom. The concept of ISLs [7] has evolved significantly since its inception. Early satellite systems relied heavily on ground stations, leading to latency and coverage limitations. In the 1970s, National Aeronautics and Space Administration (NASA)’s tracking and data relay satellite system (TDRSS) introduced relay satellites capable of direct communication, reducing ground station dependence and increasing LEO satellite coverage. By the 1990s, constellations such as Iridium and Globalstar had adopted ISLs to support global coverage and dynamic routing. Initially based on radio frequency (RF) technology, ISLs have evolved into optical ISLs (OISLs) [8], which offer significant advantages: OISLs achieve data rates of 400 gigabits per second (Gbps) (versus 300 megabits per second (Mbps) for RF), exhibit superior interference immunity due to a narrow beamwidth, and deliver higher power efficiency [9]. These advancements have made ISLs a cornerstone of NTNs, enabling flexible inter-SatCom, particularly for dense mega-constellations. To meet growing demands for global connectivity and user density, mega-constellations rely heavily on ISLs to ensure seamless communication across hundreds or thousands of satellites. However, significant challenges remain, including the high cost of OISL deployment, the need for precise beam alignment, and the dynamic network management required for large-scale constellations. To address these challenges, future research should explore solutions such as adaptive beamforming for optimized alignment, intelligent scheduling algorithms to reduce interference, and energy-efficient designs to lower deployment and operational costs.

While ISLs significantly improve satellite network capabilities, the growing demand for global coverage and high-capacity connectivity necessitates the deployment of large-scale constellations, such as mega-LEO constellations. Mega-constellations are needed for two key reasons. First, while traditional constellations of hundreds of satellites can address specific regional challenges, they cannot achieve true global coverage. Polar regions, remote islands, and underserved areas often experience connectivity gaps that larger constellations can effectively fill, ensuring continuous and reliable service worldwide. Second, even with global coverage, limited satellite numbers cannot meet the simultaneous access and high-capacity demands of dense user environments. Mega-LEO constellations can also drive down costs and make 5G/6G networks more economically viable by leveraging mass production to reduce satellite manufacturing costs and minimizing the need for expensive terrestrial infrastructure in remote areas. Additionally, dynamic spectrum reuse and seamless integration with TNs further increase cost efficiency. Emerging applications such as real-time augmented reality (AR)/virtual reality (VR), the IoT, and autonomous systems impose stringent requirements on network throughput and latency. With their scalability and flexibility, mega-LEO constellations are essential to address these challenges. However, deploying mega-constellations presents critical challenges, including spectrum resource allocation, orbital debris management, and energy consumption.

SDN-based management plays a critical role in effectively managing the complexity of mega-constellations, as it enables dynamic resource allocation and efficient network control across thousands of satellites. By integrating SDN with regenerative payloads, the network can achieve onboard processing and routing,

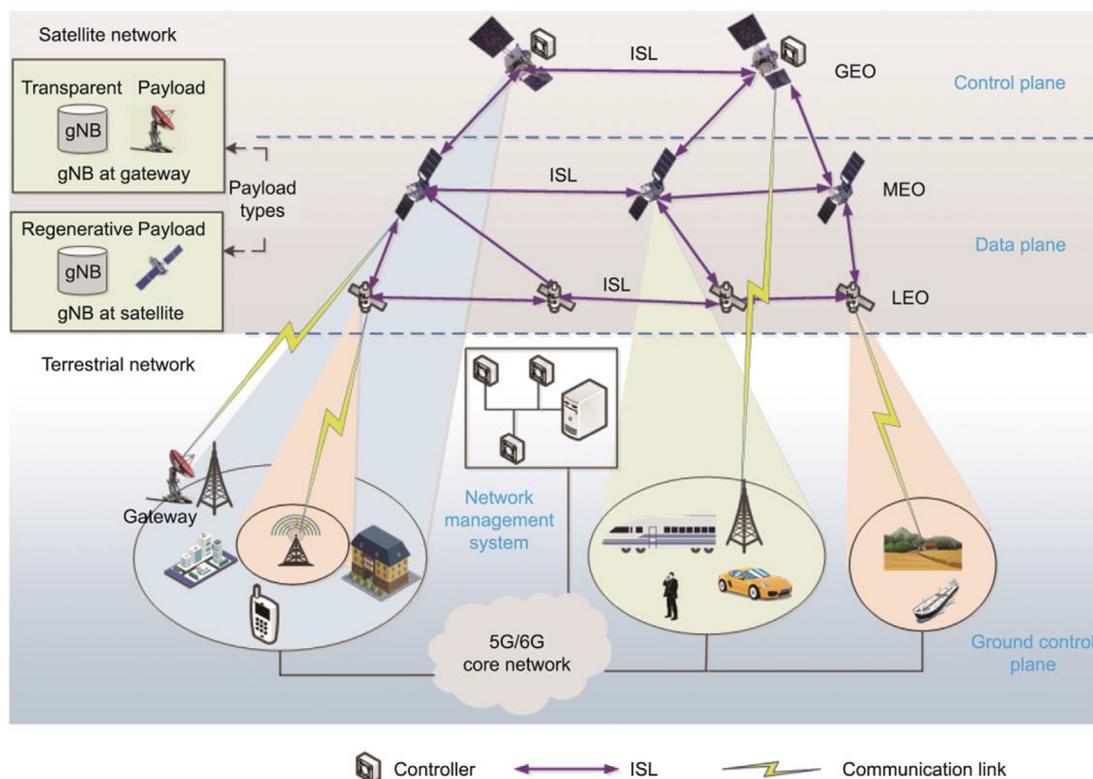


Fig. 1. Integrating satellites with 5G/6G networks. ISL: inter-satellite link; gNB: next-generation Node B.

Table 1  
Key characteristics of satellites at different orbital altitudes.

Category	Orbital altitude (km)	Footprint size [5] (km)	Latency	Primary applications	Orbital period (h)	Examples [6]
GEO	~35 786	200–3500	High (~250 ms)	Fixed satellite services (e.g., television broadcasting); satellite network management	24	Intelsat, SES S.A., and Eutelsat
MEO	2000–20 000	100–1000	Moderate (~100 ms)	Navigation (e.g., Global Positioning System (GPS)); high-speed broadband; network control	2–12	O3b and mPOWER
LEO	500–2000	100–1000	Low (~20–50 ms)	Global broadband access; IoT connectivity; network control	1.5–2.0	Starlink, OneWeb, and Kuiper

further reducing latency and increasing flexibility. As illustrated in Fig. 1, Yang [10] proposed an SDN-based primary-backup controller deployment scheme, in which LEO and MEO satellites function as the data plane, while the ground station and GEO satellites collectively form the control plane. In this setup, the ground controller serves as a backup for the primary GEO controller. Compared with distributed control architectures, centralized SDN control offers several key advantages: It reduces signaling overhead, improves response time, and enables global optimization by maintaining a holistic view of the network. This is particularly important in mega-constellations, where high propagation delay and dynamic topologies make distributed coordination and synchronization extremely challenging. While distributed architectures may provide localized resilience, they often lead to fragmented decision-making and increased complexity. Given the power, computational, and memory constraints on satellites, centralized SDN control aligns more effectively with system requirements, offering improved scalability and flexibility, and consistent performance—especially as the number of connected devices grows in 5G/6G environments. This preference is not only a practical consideration but also reflects a strategic architectural

direction toward more intelligent, adaptable, and globally optimized infrastructures. Therefore, adopting a centralized SDN-based control framework aligns better with the requirements of mega-constellation deployments, especially in support of latency-sensitive and mission-critical services in future 5G/6G systems.

Satellite networks must prioritize seamless integration with TNs in order to achieve truly global connectivity. While current satellite architectures mainly emphasize wide-area coverage, future systems must evolve to address key challenges such as dynamic resource allocation, latency reduction, and support for high user densities in heterogeneous environments. The adoption of regenerative payloads and ISLs plays a critical role in increasing the flexibility and scalability of satellite networks, enabling decentralized data routing and on-orbit processing. Furthermore, centralized SDN-based control mechanisms offer a promising solution for managing these complex systems by optimizing global resource allocation and enabling more responsive and intelligent network orchestration. Such advancements ensure that satellite networks can meet the stringent performance and reliability demands of 5G/6G communications.

### 3. The development of SatCom in 5G/6G

Significant development has been achieved in satellite networks within 5G/6G systems and related technologies, as well as in international standards from the main standardization bodies: 3GPP, the International Telecommunication Union (ITU), the European Telecommunications Standards Institute (ETSI), and the Institute of Electrical and Electronics Engineers (IEEE).

3GPP has released a series of technical reports and specifications about NTN to support future integration with TNs and satellite networks [11,12]. Fig. 2 shows 3GPP's related releases for 5G, 5G-advanced, and 6G systems and their development. Each release passes through three statuses: open, frozen, and closed. It should be noted that, once a release is frozen, systems must be developed, launched, piloted, and then deployed, which takes several years prior to mass deployment.

The 5G releases include Release 15 (Rel-15), Rel-16, and Rel-17. Of these, Rel-15 defined the basic 5G service including NR, and Rel-16 added features including satellite backhaul, satellite access architectural frameworks, and control/user plane protocol mechanisms. Ref. [13] introduces several use cases for satellite access in 5G, and Ref. [14] explains the details of satellite links in 5G. Rel-17 began to incorporate NTNs as a core element within the 5G system architecture for the first time; this led to the addition of more features, including the IoT and direct-to-device satellite links. Rel-17 comprises two distinct projects: One focuses on satellite backhaul communication for customer premises equipment and direct low-data-rate services for handheld devices, while the other enables SatCom to operate enhanced machine-type communication and narrowband IoT (NB-IoT). Notable characteristics of 5G NTNs that are introduced in Rel-17 include the following [15,16]:

(1) **Frequency bands:** Only FR1 bands in the S and Ka bands are considered suitable for NTNs.

(2) **Cell deployment:** Three types of cell deployments are defined for NTNs: Earth-moving cells, quasi-Earth-fixed cells, and Earth-fixed cells. These deployments vary in their complexity and impact on user equipment (UE) mobility. Enhancements such as conditional handover, optimized UE power consumption, and adaptive timing adjustments are also introduced to improve performance in NTN environments.

(3) **Duplexing method:** To address the extended propagation delay and round-trip time associated with NTNs, frequency division duplex is a feasible duplexing method.

(4) **Device compatibility:** NTN-compatible devices include handheld and IoT devices, as well as very small aperture terminals (VSATs) equipped with directive antennas and higher transmission power.

(5) **Positioning and timing:** It is assumed that all UE will be fitted with global navigation satellite systems (GNSSs) for accurate positioning and to correct frequency and time offsets due to satellite motion and extended propagation delay.

(6) **Satellite beam types:** This release supports both Earth-moving and Earth-fixed satellite beams. The freezing of Rel-17 in June 2022 marked the beginning of the integration of NTN technology with 5G development.

Rel-18 specified further improvements of the 5G-advanced system, whose agreed-upon objectives are to provide improved coverage and optimized capacity, multicast and broadcast services (MBSs), regenerative payloads, and support for reduced capability (RedCap) terminals. The improvements in Rel-18 are as follows [15,16]:

(1) **Mobility enhancements:** Improved UE mobility management is introduced to handle transitions between satellites and TNs, as well as to manage Earth-moving and Earth-fixed cells. This is achieved through improved measurement techniques, handover procedures, and cell re-selection. The tracking of Earth surface area remains fixed, consistent with Rel-17.

(2) **Frequency allocation:** Frequencies above 10 GHz have been allocated for VSAT devices—that is, airborne, land-based, and maritime terminals, which feature higher antenna gain and transmission power, enabling broadband communication. However, handheld UEs and IoT devices are unable to access these bands because of their constraints and the significant path loss.

(3) **Coverage expansion:** Coverage for low-data-rate applications has been extended across all satellite types. Additionally, voice-over internet protocol services (VoIPs) are specifically supported by LEO satellites to reduce the impact of propagation delays associated with distance.

(4) **Regulatory compliance:** UE location reporting has been refined to meet the requirements of regulations, including emergency situations, public warnings, and billing accuracy, ensuring compliance and improved service reliability.

(5) **AI and machine learning (ML):** The possibility of leveraging AI/ML algorithms to improve the NR air interface is being explored.

In June 2024, 3GPP's Rel-18 was officially frozen, marking the completion of the first version of 5G-advanced, which lasted more than three years. Rel-19 and Rel-20 are currently underway, and Rel-19 can serve as a bridge to 6G. Possible topics include the following:

(1) **Downlink coverage improvements [17]:** Building on the uplink improvements from Rel-17, further improvements will be proposed for the downlink, particularly for control and data channels in 5G NR, to improve coverage under challenging conditions.

(2) **AI/ML [18]:** There will be a focus on addressing mobility between NTNs and TNs in connected mode, particularly considering the different latencies associated with NTN and TN links. AI/ML will be used to predict the future best-serving cells.

(3) **Support for discontinuous coverage [15]:** For non-geostationary orbit (NGSO) scenarios in which continuous coverage is not feasible, Rel-19 will explore ways to support communication.

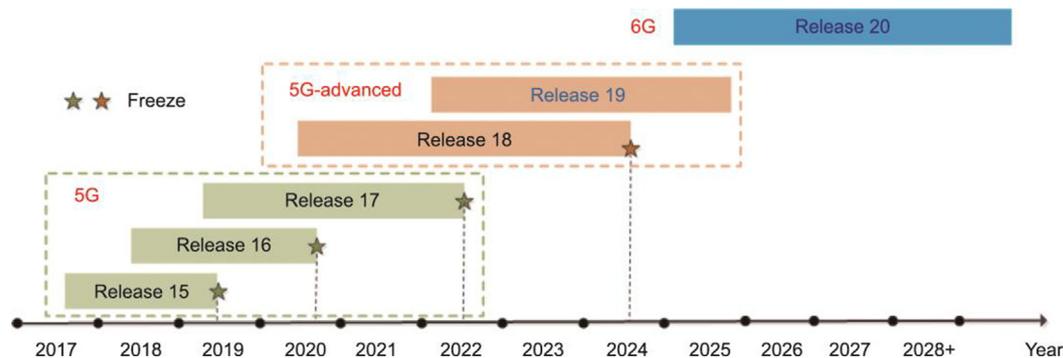


Fig. 2. Timetable of 3GPP's related releases.

(4) **Regenerative payloads [19]:** The satellite payloads in Rel-17 and Rel-18 are transparent; regenerative payloads in satellites will be explored to provide greater flexibility in NTN deployments, allowing parts of the network to be implemented in space.

(5) **MBSs [20]:** The continuation of MBS support—already defined for TNs in Rel-18—will be extended to NTNs to enable efficient broadcasting in SatCom.

(6) **Asynchronous multi-connectivity [15]:** Support for asynchronous multi-connectivity across different orbits (GEO, MEO, and LEO) and multiple frequency bands will be a focus, facilitating the development of three-dimensional (3D) networks.

In summary, the role of NTNs has evolved significantly across the 3GPP releases, reflecting their increasing integration and technical sophistication. In Rel-15, NTNs were primarily considered a complementary solution for extending coverage in underserved areas. By Rel-16, their role had expanded with the introduction of satellite backhaul, architectural frameworks, and IoT support, enabling basic integration with TNs. In Rel-17, NTNs became a core component of the 5G architecture, incorporating advanced features such as IoT support, direct-to-device communication, and increased mobility for satellite links. With Rel-18, NTNs were further developed as part of 5G-advanced networks, with a focus on improving mobility, coverage, and spectrum efficiency while exploring AI/ML integration. Looking ahead to Rel-19 and Rel-20, NTNs are transitioning to support more complex scenarios such as asynchronous multi-connectivity, regenerative payloads, and bridging the gap between 5G and 6G, making them essential in enabling ubiquitous global connectivity.

The integration of NTNs into the existing 5G system significantly enhances uMUB, uHDD, and uHURLLC performance:

(1) **uMUB:** By leveraging global coverage and high-throughput technologies such as LEO satellites and beamforming, NTNs extend broadband connectivity to remote areas and support data-intensive applications.

(2) **uHDD:** Through dynamic spectrum sharing, network slicing, and hybrid architectures, NTNs optimize spectrum utilization and network capacity, addressing high-density scenarios such as urban environments and IoT deployments.

(3) **uHURLLC:** NTNs improve reliability and latency performance for critical applications, such as autonomous driving and industrial automation, by integrating LEO satellites with onboard edge computing, multi-orbit redundancy, and alternative routing.

These capabilities reduce end-to-end delay and provide robust communication paths in failure-prone or infrastructure-scarce environments. For instance, LEO-based NTN scenarios show round-trip latency as low as 30–50 ms and reliability levels exceeding 99.999% [21], meeting the stringent demands of uHURLLC in 5G and beyond.

ITU is the world's leading authority in telecommunications standardization, responsible for the allocation and management of global radio spectrum and satellite orbit resources, the development of international telecommunications standards, the promotion of global connectivity, and the advancement of the telecommunications industry. ITU-Radiocommunication Sector (ITU-R) released “Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-2020 (IMT-2020)” (5G) [22] and “Future technology trends of terrestrial International Mobile Telecommunications systems towards 2030 and beyond” (IMT-2030, 6G) [23], in which interconnection with NTNs was identified as a key technology for improving the radio network. The IMT-2030 vision outlines eight key capabilities for 6G development, setting higher standards for latency, user-experienced data rate, peak data rate, connection density, mobility, energy efficiency, area traffic capacity, and spectrum efficiency.

The vision also emphasizes increased system security, reliability, and resilience. Moreover, 6G systems are expected to integrate with various access technologies, improving system functions and aiming for seamless global broadband mobile communication, including interoperability with NTNs such as LEO, MEO, and GEO SatCom, HAPs, and UAVs. Table 2 provides a technology comparison of IMT-2020 and IMT-2030 listing their specific performance indicators, including SDNs, self-organizing networks (SONs), and NFVs in 5G; and hologram applications, the integration of satellites with NTNs, and teleporting in 6G.

From 5G to 6G, NTNs have evolved from a complementary system primarily focused on extending coverage in remote and underserved areas to an integral component of a unified, global 3D communication network. In 6G, NTNs are expected to provide seamless integration with TNs, enabling advanced use cases such as autonomous mobility, immersive applications, and real-time sensing. To achieve this, NTNs must meet stringent performance metrics, including peak data rates increasing from 10 Gbps in 5G to 1 terabits per second (Tbps), latency improving from 1.0 ms to 0.1–1.0 ms, reliability advancing from  $10^{-5}$  to  $10^{-7}$ – $10^{-5}$ , and connection density growing from  $10^6$  to  $10^6$ – $10^8$  devices per square kilometer. In addition, 6G-NTNs introduce capabilities such as joint communication and sensing, AI-driven resource optimization, increased mobility support of up to  $1000 \text{ km}\cdot\text{h}^{-1}$ , and spectrum sharing, aligning with ITU's IMT-2030 vision for a sustainable, resilient, and ubiquitous connectivity infrastructure. This transition highlights NTNs' pivotal role in bridging the gap between terrestrial and non-terrestrial systems, supporting the demands of next-generation communication networks.

In addition to the extensive efforts by 3GPP and ITU, both ETSI and IEEE have made notable contributions to the standardization of SatComs and NTNs in the context of 5G/6G. Through its satellite Earth stations and systems (SES) technical committee, ETSI has published several key documents. Ref. [24] outlines technical challenges and architectural proposals for integrating satellite and TNs within 5G systems. It addresses the interoperability of GEO, MEO, LEO, and HAPs systems with terrestrial infrastructure and highlights enabling technologies such as network slicing and edge computing. In addition, Ref. [25] provides a technical comparison of digital video broadcasting second-generation satellite extensions/return channel via satellite, second-generation (DVB-S2X/RCS2), and 3GPP NR protocols for broadband satellite systems operating across different frequency bands. It identifies protocol-level challenges, such as peak-to-average power ratio and link adaptation, and evaluates the implications of adapting NR to satellite-specific environments. These efforts complement 3GPP standards by addressing cross-system compatibility and performance optimization from an independent system-level perspective. Furthermore, ETSI has launched the Industry Specification Group (ISG) on NTNs to explore NTN use cases and support early pre-standardization activities for 6G.

IEEE has also contributed through the publication of IEEE 1932.1–2024 [26], which specifies a standardized framework for interoperability between licensed and unlicensed spectra in wireless mobile networks. This standard defines a media access control (MAC) and physical layer coordination mechanism for interoperation among distributed radio interfaces, particularly focusing on supplementary downlinks via unlicensed bands such as wireless fidelity (WiFi). It introduces a virtual controller architecture deployed at the mobile edge that dynamically coordinates multi-connectivity modes based on the real-time availability of unlicensed channels. The traffic-steering mechanism enables improved throughput and reduced delay, supporting uHURLLC requirements in heterogeneous network environments, including satellite and terrestrial system integration for NTN use cases.

**Table 2**  
Comparison of IMT-2020 and IMT-2030.

Category	Latency (ms)	Peak data rate	User experience data rate	Reliability	Mobility support	Connection density	Key technologies
IMT-2020 (5G)	1.0	10 Gb·s <sup>-1</sup>	100 Mbps	10 <sup>-5</sup>	Up to 500 km·h <sup>-1</sup>	10 <sup>6</sup> devices·km <sup>-2</sup>	Slicing, SDN/NFV, SON, QoS, network security and privacy, media with vision, audio, and 3D
IMT-2030 (6G)	0.1–1.0	1 Tb·s <sup>-1</sup>	1 Gbps	10 <sup>-7</sup> –10 <sup>-5</sup>	500–1000 km·h <sup>-1</sup>	10 <sup>6</sup> –10 <sup>8</sup> devices·km <sup>-2</sup>	New switching/routing, QoS, network security, enhancement of new IP protocols, hologram, integration of satellite-NTN, and teleporting

SON: self-organizing network; IP: Internet protocol.

#### 4. Key challenges and technologies for future research

The integration of satellites with TNs in 5G/6G holds great promise, offering the potential for global, ubiquitous coverage and seamless connectivity for everyone and everything across the world. However, achieving this integration presents several challenges that must be addressed. These challenges include handling the long propagation delays inherent in SatCom, managing satellite mobility and handovers, and optimizing routing and path selection. Moreover, efficient resource management is critical for ensuring QoS for users, as these factors can have a significant impact on network performance. To fully realize the potential of satellite–TN integration, overcoming the following challenges is crucial [27–29]:

(1) **Long propagation delay of satellites:** SatCom experiences significant propagation delays due to the high orbits of satellites, especially in GEO systems. These delays can severely affect the overall communication latency. Strategies such as optimized gateway placement, multi-hop transmission adjustments, and mobile edge computing are required to mitigate latency and improve QoS.

(2) **High Doppler shifts:** High Doppler shifts in satellite links, particularly for LEO and MEO satellites, lead to signal degradation and unreliable connections. Effective Doppler-compensation techniques and real-time tracking systems are necessary to maintain link stability, ensuring uninterrupted communication in high-speed satellite networks.

(3) **Resource management:** Efficient resource management is essential in satellite–TN integration to ensure optimal utilization of spectrum, bandwidth, and computational resources. Techniques such as spectrum sharing, network slicing, and AI-driven management systems are necessary to balance the demand across satellite networks and TNs while maintaining QoS.

(4) **Dynamic beam coverage and network adaptation:** As satellites move, their coverage areas can change, which affects the stability of connections and data rates. To address this challenge, advanced adaptive beamforming techniques and real-time coverage-adjustment mechanisms are needed to ensure stable and efficient coverage, especially in mobile and high-speed environments.

(5) **Mobility and handover management:** Satellite networks, especially in those LEO or MEO, require effective mobility and handover management, as satellites move rapidly across the sky. Dynamic beamforming and advanced handover algorithms must be employed to maintain stable connections as users switch between satellite coverage areas.

(6) **Routing and path selection:** In satellite–TN networks, selecting optimal routing paths becomes complex due to varying satellite positions and link qualities. Adaptive routing algorithms that dynamically adjust to changing network conditions are key to ensure efficient data flow and minimize latency, particularly in large-scale constellations.

To further explore SatCom technologies in the context of 5G/6G, potential research directions can be categorized based on the open system interconnect (OSI) model layers, as follows:

##### (1) Application layer—direct smart phone access to satellites

**[30]:** Traditional satellite phones typically require bulky antennas, but recent advancements have enabled direct satellite connectivity on standard 5G smartphones. This technology is rapidly evolving, becoming a cornerstone of the “space–ground” integrated communication infrastructure. Industry leaders such as SpaceX (Starlink), AST SpaceMobile, and Lynk Global have already demonstrated successful implementations of direct satellite-to-phone communication, enabling smartphones to connect to satellites without specialized hardware. Current approaches include dual-mode terminals, legacy phone access via software updates, and 3GPP NTN standards, which are being adopted globally [31]. In the future, satellite systems must support a large number of users simultaneously through advanced spectrum-sharing techniques, interference mitigation, and network slicing to ensure efficient resource allocation and QoS.

(2) **Network layer—mega-LEO constellations [32]:** Mega-LEO constellations will play a critical role in expanding connectivity to remote areas and supporting 5G/6G systems, and are expected to drive down costs and make 5G/6G networks more economically viable. Moreover, mega-LEO constellations with AI and network management will enable more efficient and reliable global communication.

(3) **MAC/physical layer—spectrum sharing [33]:** Spectrum scarcity is becoming increasingly critical due to growing global communication demands and the proliferation of IoT devices, leading to competition between TNs and satellite networks. Spectrum sharing in integrated satellite–TNs is a possible solution that reuses the same spectrum across both networks, thereby improving spectrum efficiency. Techniques such as spatial and temporal spectrum sharing, cognitive architectures, and non-orthogonal multiple-access (NOMA)-based cooperative transmission can improve resource utilization. Future networks may integrate operations under a single operator, enabling full-spectrum sharing and more efficient management through cloud-based architectures, thereby expanding coverage with limited spectrum resources.

(4) **Data-link layer—satellite beam footprint adaptation [34]:** As the satellite moves, the beam’s footprint on the ground decreases in size due to varying elevation angles, which in turn affects coverage. A crucial technology for achieving high data rates in 6G NTNs involves phased-array beamforming. By dynamically adjusting the phase of each antenna element, the satellite can direct the beam toward specific areas on Earth’s surface, concentrating power and extending service time without handover interruptions, as compared with non-steerable beams.

(5) **Physical layer—optical wireless communication:** Optical wireless communication (OWC) is a transformative future technology for NTNs in 6G that offers the potential for terabits-per-second data rates [35]. In ISLs, OWC will enable ultra-fast and precise data exchange through advanced laser communication systems, leveraging beam steering and adaptive optics to maintain alignment. For satellite-to-UE links, OWC will address atmospheric propagation

challenges with robust modulation schemes and hybrid RF-optical solutions. With superior energy efficiency and reduced interference compared with RF, OWC will play a pivotal role in increasing data throughput and enabling sustainable NTN development.

(6) **Physical layer—reconfigurable intelligent surfaces** [36]: Reconfigurable intelligent surfaces (RISs) are a key direction for advancing 6G satellite networks, particularly in IoT applications. By integrating RISs with backscatter communication, significant improvements in network capacity and efficiency can be achieved. The potential of RISs to address the growing demands of IoT in 6G NTNs is significant, and we suggest that future research on integrated satellite networks with RISs should focus on optimizing RIS deployment, channel estimation, and resource management to fully realize its benefits.

## 5. Conclusions

The convergence of satellite networks and TNs is widely recognized as a significant trend from 5G to 6G. This article provided an overview of SatCom empowering 5G/6G for seamless communication across different environments. First, we briefly introduced the architecture of SatCom within 5G/6G systems; then, we over-viewed the development of SatCom from international standards—that is, 3GPP and ITU; finally, we provided an insight into the challenges and possible technologies for future research on SatCom within 5G/6G systems.

### CRedit authorship contribution statement

**Afang Yuan:** Writing – review & editing, Writing – original draft. **Zhihua Yang:** Writing – review & editing. **Zhili Sun:** Writing – review & editing, Writing – original draft, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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