

# 1

## Introduction

As an exceptional amalgamation of scientific principles and technological advancements, satellite communication represents a complex system that facilitates interactions between the terrestrial and celestial spheres. This system is meticulously engineered to traverse extensive distances, thereby allowing for seamless real-time communication across nations, seas, and isolated regions. The basic principle is the transmission of data through electromagnetic waves, which are dispatched from a ground station, transmitted via a satellite positioned in orbit, and subsequently received by another terrestrial station. The synchronized interaction between ground-based infrastructure and space-based technology forms the essential paradigm of worldwide communication [1].

The fundamental tenet of satellite communication encompasses the propagation of electromagnetic waves, thereby enabling extensive geographical connectivity. A ground station transmits signals toward orbiting satellites utilizing high-frequency carriers, wherein the uplink procedure necessitates precise calibration of signal intensity and directional alignment to effectively reach the satellite’s communication payload [2]. Upon receipt, the satellite’s transponder amplifies and reconfigures the received signal via modulation, frequently employing frequency conversion techniques to mitigate interference from concurrent transmissions. The processed signal is subsequently prepared for downlink transmission to guarantee an undistorted return of information to the terrestrial domain. Following this procedure, the satellite dispatches the modified signal toward specified terrestrial receivers. These signals are subsequently decoded by ground stations or terminal devices into their original informational formats, which may include voice communications, video transmissions, or Internet data packets. The downlink mechanism underscores the importance of transmission reliability, notwithstanding the inherent challenges posed by planetary-scale propagation phenomena.

Typically, satellite communications have revolutionized television broadcasting by facilitating the global distribution of signals, particularly benefiting regions that lack robust terrestrial communication infrastructures. This technological advancement guarantees that remote locales receive high-quality programming and additionally functions as an essential component of infrastructure during natural disasters and humanitarian emergencies. In scenarios where terrestrial systems become nonoperational, the utilization of satellites ensures the persistence of dependable communication channels, thereby enabling a multitude of critical operations. These operations encompass emergency response coordination, the swift deployment of relief services, and the dissemination of essential information crucial for survival [3].

### 1.1 A Brief History of Satellite Communications

In the era characterized by an unprecedented proliferation of information, the radio waves traveling over the satellites silently announce the story of human wisdom. Communication satellites function as “messengers” in the sky, facilitating the transmission of information across vast distances on the terrestrial globe. The inception of satellite communication stands as one of the extraordinary accomplishments of contemporary science and technology. From the nascent idea to the advanced technological iterations, satellite communication has not only transformed the modalities of human interaction but has also exerted a substantial influence on socioeconomic progress. Figure 1.1 delineates a chronological depiction of the evolution of satellite communication, highlighting the motivations for its inception, the contextual background, and significant milestones [4].

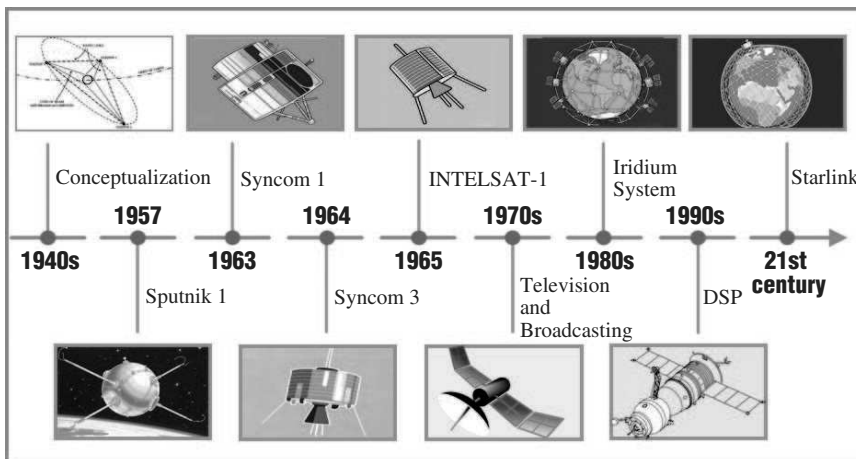


Figure 1.1 History of satellite communications. Source: Author created.

The Conceptualization: Arthur C. Clarke and the idea of Geostationary Satellites in 1945. During World War II, advancements in global communication technologies encountered formidable obstacles. Conventional radio wave communication was constrained by the Earth’s curvature, thereby limiting the transmission range of signals. Long-distance communication, particularly over oceanic expanses, necessitated intricate relay stations or the deployment of under-sea cables. The exigencies of military operations during the conflict motivated scientists to investigate innovative solutions aimed at surmounting the limitations associated with long-distance communication. The British scientist and author Arthur C. Clarke articulated a groundbreaking concept in his 1945 paper published in *Wireless World*, titled “Extra-Terrestrial Relays,” wherein he proposed the implementation of geostationary satellites to facilitate global telecommunications. His transformative proposition delineated an orbital altitude of 35,786 km, at which satellites would exhibit synchronous rotation with Earth, thereby enabling continuous signal coverage over specified terrestrial areas through fixed orbital trajectories. Clarke’s foresight established the theoretical groundwork for the development of contemporary communication satellites. Despite the visionary nature of Clarke’s proposal, the technological infrastructure of the era was inadequate to actualize the concept of geostationary satellites. The domain of rocket technology was nascent, and the precise electronic apparatus requisite for satellite operations had yet to be developed. Consequently, Clarke’s concept remained within the realm of theory, as the necessary technological capabilities to actualize it were unavailable.

The inaugural artificial satellite, Soviet Sputnik 1, was successfully launched in 1957. During the Cold War, the domain of space exploration emerged as a pivotal battleground for the United States and the Soviet Union to assert their supremacy on a global scale. The Soviet Union sought to exhibit its scientific prowess through the launch of the inaugural artificial satellite, which concurrently served to evaluate the reliability of rocket technology crucial for subsequent advancements. On 4 October 1957, the Soviet Union ushered in the space age by achieving a significant historical milestone: the deployment of Sputnik 1, recognized as humanity’s first artificial satellite orbiting Earth. With a mass of 83.6 kg, it functioned within low Earth orbit (LEO) and transmitted fundamental radio signals. Although it was not specifically engineered for communication purposes, it validated the concept that terrestrial objects could be successfully placed in space, thereby igniting a worldwide fascination with space exploration. Notwithstanding its achievements, Sputnik 1 exhibited several significant limitations. It facilitated only rudimentary scientific experiments, experienced constrained coverage attributable to its low orbital altitude, and endured for merely a few weeks before disintegrating upon reentry. These constraints underscored the imperative for subsequent technological advancements.

Geostationary satellites, heralding the advent of the Communication Era, commenced their deployment in 1963. Following the Soviet Union’s successful launch of Sputnik 1, the United States expedited its space exploration initiatives to attain technological supremacy. Geostationary satellites, which are proficient in providing fixed coverage over designated regions, emerged as the optimal solution for facilitating global communication. The United States successfully launched Syncom 1, marking the inception of geostationary satellites. Despite its experimental nature, this satellite demonstrated the viability of geostationary orbits, establishing a foundation for subsequent communication satellites. The ensuing launches facilitated the transition of satellite communication from abstract theory to tangible application. Initial geostationary satellites encountered several challenges, including limited signal capacity, significant latency attributable to orbital distance, and elevated costs. These constraints underscored the imperative for continued technological advancement.

Syncom 3 and the live transmission of the Tokyo Olympics in 1964. The 1964 Tokyo Olympics offered Japan a platform to exhibit its economic resurgence and technological sophistication to a global audience. In order to facilitate a worldwide live transmission of the event, Japan opted to employ satellite communication technology, thereby surmounting the constraints associated with conventional television signal transmission. Japan adeptly launched the Syncom 3 communication satellite. For the inaugural instance, a worldwide live transmission of the Tokyo Olympics was accomplished via satellite technology. This event signified the initial application of satellite communication within the context of a significant international occasion. It not only illustrated the operational utility of satellite communication but also expedited the commercialization of satellite technology. Nonetheless, Syncom 3 possessed certain deficiencies. Its coverage area was limited, and the quality of the broadcast was constrained by the technological capabilities prevalent at the time. Furthermore, the transmission of live content still depended on terrestrial infrastructure, and the overall expenditure remained substantial.

The inaugural commercial communication satellite, known as the International Telecommunications Satellite Organization (INTELSAT), was successfully launched in the year 1965. The escalating necessity for international communication, particularly in terms of transoceanic linkages, underscored the inadequacies of conventional submarine cables, which were incapable of facilitating real-time voice and video interactions. In response to this predicament, the INTELSAT organization was founded in 1964. The primary objective of this initiative was to orchestrate global resources for the advancement of communication satellites. INTELSAT achieved a significant milestone by launching the world’s first commercial communication satellite, INTELSAT-1, colloquially referred to as “Early Bird.” This pioneering satellite enabled the transmission of telephone,

telegraph, and television signals, thereby signifying the initial achievement of real-time intercontinental communication. INTELSAT-1 established the groundwork for the commercialization of satellite communication and considerably enhanced global information dissemination. Notwithstanding its revolutionary contributions, INTELSAT-1 exhibited significant limitations. Its capacity was confined to approximately 240 telephone circuits or a singular television channel. Furthermore, the quality of communication was susceptible to atmospheric disruptions and contingent upon the efficacy of ground stations. These constraints emphasized the necessity for continued advancements in satellite technology.

**The Proliferation of Satellite Communication:** The pinnacle era of television and broadcasting in the 1970s. The extensive integration of television and radio on a global scale engendered an escalating demand for large-scale signal transmission. Due to its expansive coverage and instantaneous capabilities, satellite communication emerged as the fundamental technology for disseminating television and radio signals. Numerous nations have initiated the deployment of communication satellites explicitly designated for broadcasting and television relay functions. Satellites during this epoch were predominantly employed to convey international news, sporting events, and entertainment programs, thus signifying a golden age for satellite communication within the media landscape. Furthermore, the exorbitant costs associated with satellite construction and launch constituted considerable financial impediments, thereby limiting the involvement of smaller nations and developing countries. This situation underscored the inequitable accessibility of satellite technology during this time.

**Motorola’s Iridium System:** An endeavor in global mobile communication initiated in the 1980s [5]. The elevated latency and restricted coverage associated with geostationary satellites were inadequate to satisfy the escalating requirements of mobile communication. To mitigate these obstacles, Motorola proposed the development of an LEO satellite constellation to enable comprehensive global coverage. The Motorola Iridium system comprised 66 LEO satellites, specifically engineered to deliver global voice and data communication services. Its low-orbit architecture substantially diminished communication latency while guaranteeing worldwide coverage, encompassing both remote regions and maritime areas. This pioneering methodology rendered it one of the most ambitious satellite communication initiatives of its era. However, the Iridium system encountered exorbitantly high construction and maintenance expenditures, coupled with market demand that fell short of projections, ultimately culminating in its commercial demise. This case underscored the critical necessity of aligning technological advancements with pragmatic market requisites.

**Technological Advancements:** Innovations in the digital era, during the 1990s. The escalating demand for enhanced bandwidth and improved efficiency in communication illuminated the constraints inherent in traditional satellite systems. Progress in digital signal processing (DSP) presents new opportunities for addressing these obstacles. In that era, satellite communication integrated technologies such as digital modulation, data compression, and multi-beam antennas. These advancements significantly improved both efficiency and capacity. For example, multi-beam antennas enabled satellites to serve multiple regions, thereby meeting varied market demands simultaneously. Although these developments represented considerable advancements, satellite communication continued to fall short of terrestrial fiber-optic systems in terms of cost-effectiveness and overall efficiency. This disparity underscored the ongoing necessity for innovation to maintain a competitive edge.

**The Internet Epoch:** High-throughput satellites (HTS) in the 21st century. The unprecedented expansion of the Internet has substantially elevated the global demand for broadband services. This necessity was particularly pronounced in remote locales, aboard maritime vessels, and within aerial frameworks, where conventional satellites encountered significant challenges in providing the requisite data transmission speeds. The HTS emerged as a viable solution, utilizing multi-beam technologies and frequency reuse methodologies to enhance capacity markedly. For instance, ViaSat's HTS systems accomplished data transmission velocities reaching hundreds of gigabits per second, thereby facilitating applications such as in-flight broadband connectivity and distance learning initiatives. Despite the considerable advancements offered by HTS, the exorbitant costs associated with deployment and protracted implementation timelines persist as formidable obstacles. Moreover, the advent of LEO constellations, exemplified by Starlink, has introduced formidable competition, thereby undermining the preeminence of traditional HTS systems.

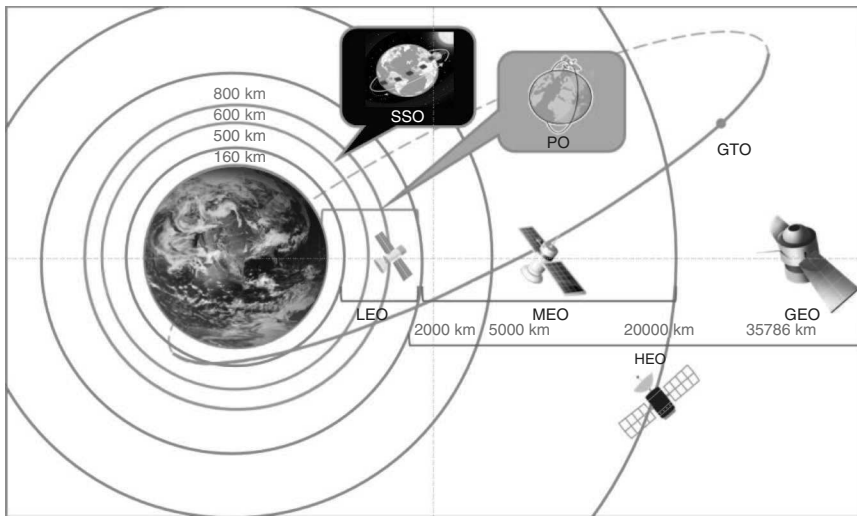
## 1.2 Development of Satellite Communications

### 1.2.1 Classification of Satellite Orbits

In the majority of instances, satellites are deployed into a predefined orbital path surrounding Earth subsequent to their launch. Nonetheless, in certain exceptional scenarios, a satellite may undergo a process of orbital realignment, resulting in its traversal along a modified orbital trajectory. Satellites are typically categorized based on their orbital altitude (i.e., the distance from the Earth's surface), which significantly influences their coverage area and velocity as they orbit Earth. When selecting the appropriate type of orbit, developers must take into account their

intended purposes, the data to be collected, the services to be rendered, as well as the associated costs, coverage regions, and the practicality of various orbital configurations. According to their respective orbits, satellites are classified into five principal types: LEO, medium Earth orbit (MEO), geostationary orbit (GEO), sun-synchronous orbit (SSO), and geostationary transfer orbit (GTO), as illustrated in Figure 1.2.

As illustrated in Table 1.1, LEO satellites operate at altitudes ranging from approximately 500–2,000 km above the terrestrial surface. These satellites exhibit brief orbital periods, typically between 90 and 120 minutes, enabling them to complete up to 16 orbits of Earth within a single day. LEO satellites are particularly advantageous for a diverse array of applications, including remote sensing, high-resolution Earth observation, and scientific inquiry, attributable to their capability for rapid data acquisition and transmission. All classifications of LEO satellites possess the ability to adjust their orientation in relation to the plane of the Earth’s surface. Due to the relatively proximate distance of LEO satellites to Earth,



**Figure 1.2** Classification of satellite orbits. *Source:* Author created.

**Table 1.1** Satellite altitude and operational period.

Satellite type	LEO	SSO	MEO	GTO	GEO
Altitude (km)	500–2,000	600–800	2,000–20,000	up to 35,786	35,786
Period (minutes)	up to 129	96–100	720	630	1,436

their coverage area is comparatively smaller when juxtaposed with other satellite classifications. Typically, a collective of LEO satellites, referred to as a constellation, is deployed concurrently. Collectively, LEO satellites possess the capacity to cover extensive geographical regions simultaneously [6].

MEO satellites are situated between LEO and GEO, generally at altitudes ranging from approximately 2,000 to 20,000 km. Positioning and navigation systems, such as the global positioning system (GPS), significantly rely on MEO satellites for their operational functionality. Recently, the HTS MEO constellation has been implemented to facilitate low-latency data communication services. MEO satellites exhibit an extended orbital period, varying between 2 and 12 hours, which establishes a balance between the coverage area and the data transmission rate. MEO satellites necessitate a reduced amount of infrastructure to achieve global coverage compared to LEO satellites; however, they experience longer latency and exhibit weaker signal strength.

When viewed from terrestrial vantage points, objects situated in GEO manifest an apparent state of permanence. The orbital period of GEO aligns precisely with the rotational period of Earth—specifically, 23 hours, 56 minutes, and 4 seconds—thereby enabling ground-based antennas to maintain continuous alignment with the same spaceborne apparatus. Furthermore, GEO satellites serve critical functions in the realm of meteorology, facilitating the continuous surveillance of atmospheric conditions within specific geographic locales and the meticulous observation of the evolution of localized meteorological phenomena. Nevertheless, a significant drawback of utilizing GEO satellites for instantaneous communication arises from their considerable distance from Earth, which results in substantial latency in signal transmission.

SSO satellites operate at altitudes ranging from approximately 600 to 800 km above the Earth's surface as they navigate the polar regions from north to south; the orbital inclination and altitude of these satellites are meticulously calibrated to guarantee that they consistently pass over any specific location at precisely the same local solar time. Consequently, the illumination conditions during imaging remain uniform, rendering this category of satellite exceptionally well-suited for missions related to Earth observation and environmental monitoring. Both contemporary and historical satellite imagery obtained from SSO are particularly effective for change detection. Researchers utilize these sequences of images to comprehend the progression of meteorological phenomena, forecast cyclones, oversee and mitigate wildfires and flooding events, as well as to collect data on persistent issues such as deforestation and alterations in shorelines. Nevertheless, due to their relatively low orbital altitude, SSO satellites are capable of covering only a limited geographic area at any given moment, thus necessitating the deployment of additional equipment to accomplish continuous coverage.

The most prevalent transfer orbit utilized for satellite deployment is the GTO, which facilitates the transition of satellites from a transitional orbit to GEO. When

a launch vehicle propels a spacecraft into the cosmos, the spacecraft does not invariably proceed directly to its ultimate orbital position. Initially, the rocket will position the spacecraft into a transfer orbit, serving as an intermediary station on its trajectory toward the final destination. Subsequently, the satellite's propulsion system is activated to enable the satellite to attain its designated orbital position and modify its orbital inclination. This expedited approach permits the satellite to attain a geostationary orbit while expending minimal resources.

Moreover, there exist a variety of specialized satellites in orbit, which are delineated as follows.

The GEO satellite is situated within a highly elliptical orbit (HEO) characterized by significant orbital eccentricity, resulting in a pronounced disparity in distance between the segment of the orbit nearest to Earth and that which is more distally located. The operational altitude of an HEO satellite generally spans from approximately 2,000 to several hundred thousand kilometers. The inclination of HEO satellites is predominantly substantial, catering to specific mission exigencies. Due to their capacity to encompass the polar regions of Earth and higher latitudinal zones, HEO satellites are frequently utilized for military reconnaissance and surveillance purposes, particularly in operations that complement other orbital frameworks.

Polar orbit (PO) satellites are defined as satellites that traverse the atmospheric region above the polar extremities of Earth. Satellites positioned within such orbits intersect the Earth's northern and southern poles at a specific angular inclination. With each passage over the terrestrial surface, the satellite's trajectory establishes a particular angle relative to the Earth's rotational vector, thereby enabling a progressive coverage of diverse geographical areas. Owing to the Earth's axial rotation, the satellite experiences a minor deviation during each successive transit over the identical location, ultimately facilitating comprehensive surveillance of the entire polar region. Typically, PO satellites operate within an altitude spectrum ranging from approximately 160 to 2,000 km, exhibiting an orbital inclination approaching 90°. These satellites function at relatively elevated velocities, generally between 7.6 and 8 km per second, with an orbital period of approximately 90–100 minutes to complete one revolution around Earth. The operational characteristics of PO satellites render them particularly advantageous for military reconnaissance, surveillance, and espionage activities, attributed to their capacity to survey all global territories. They are generally equipped with advanced high-resolution imaging capabilities and can maintain prolonged observational periods, exemplified by the KH-11 series of reconnaissance satellites deployed by the United States. Furthermore, PO satellites hold substantial significance for scientific inquiry, particularly in the realm of long-term observations pertaining to geology, climate, and ecology on a planetary scale [7].

**Table 1.2** Configuration parameters of the VLEO satellite.

Parameters	VLEO satellite	LEO satellite
Altitude (km)	1,500–450	500–2,000
End-to-end delay (ms)	<5	20–40
Satellite lifetime (year)	1–3	5–10
Transmission costs	< 100 kg, 500,000–1,000,000	500–1,000 kg, 500,000, or more
Atmospheric drag effects	Orbital decay of 0.5–1 km per day	None

Very low Earth orbit (VLEO) satellites utilize high-frequency bands (Ka/V-band, 40–75 GHz) to attain terabit-level data throughput; however, this incurs an additional atmospheric attenuation of 15–20 dB in comparison to LEO, as illustrated in Table 1.2. In order to alleviate this issue, adaptive coding and modulation (ACM) algorithms are employed to dynamically modify transmission parameters, a strategy exemplified within the National Aeronautics and Space Administration’s (NASA’s) Space Communications and Navigation program. Multi-beam phased array (PA) antennas, such as those integrated into Airbus’s VLEO-COM prototype, facilitate precise beamforming (BF) with a pointing accuracy of less than 0.1, thereby compensating for signal degradation while achieving a capacity of 1 Tbps per satellite [8].

Ultra-low latency represents a crucial advantage, characterized by round-trip delays falling below 5 ms at an altitude of 300 km—imperative for financial trading activities and autonomous systems. In order to mitigate spectrum congestion, cognitive radio systems, propelled by artificial intelligence (AI) and exemplified by DARPA’s prototypes from the Spectrum Collaboration Challenge, facilitate real-time interference mitigation within shared frequency bands [9]. Dual-circular polarization antennas, utilized in China’s Galaxy space VLEO test satellites, enhance spectral efficiency threefold through the polarization multiplexing technique. The implementation of onboard AI autonomy is poised to transform operational methodologies. Machine learning (ML) algorithms, such as the European Space Agency’s (ESA’s) CyberSeed, empower autonomous collision avoidance mechanisms and network self-healing capabilities, allowing for the reconfiguration of routing paths within a mere 10 seconds following the occurrence of satellite failure.

Quantum key distribution (QKD) can support a speed of 10 kbps over a distance of 1,000 km. Moreover, as reported by *Nature* on 19 March 2025, researchers have made a groundbreaking advancement in quantum communication by achieving QKD over an impressive distance of 13,000 km, from China to South Africa, using

the lightweight, cost-effective microsatellite, Jinan-1 [10]. This satellite transmitted laser pulses in quantum states, generating a secure quantum key that ensures confidentiality even in the presence of future quantum computing threats. Compared to its predecessor, Micius, Jinan-1 is significantly smaller, more affordable, and more efficient, with a greatly reduced ground-station receiver. This breakthrough represents a major step toward establishing a global QKD network, making transmissions virtually impervious to quantum computing threats. Although Jinan-1 does not yet support advanced features such as entangled photon generation, future miniaturization developments could enable these capabilities, further advancing the creation of a global quantum Internet. In-orbit manufacturing technologies, exemplified by Airbus’s CIMON 3D-printing initiative, are designed to fabricate satellite structures directly in the extraterrestrial environment, circumventing launch mass limitations and extending operational lifespans to a duration of 5 years.

Numerous pioneering projects demonstrate the commercial feasibility of VLEO:

- SpaceX’s VLEO Starlink Layer: Functioning at an altitude of 340 km and utilizing laser inter-satellite links (ISL), it achieves a latency of less than 4 ms, thereby facilitating high-frequency trading as well as autonomous vehicle networks.
- Lockheed Martin’s Pony Express: A constellation positioned at 450 km that incorporates QKD-enabled military communications, which exhibit a high degree of resistance to eavesdropping attempts.
- NorthStar’s Skylark: A network composed of 60 satellites operating at 320 km, delivering 20 Mbps broadband services to Arctic shipping routes at a cost of 50 dollars/GB, utilizing ice-resistant 28 GHz antenna technology.

### 1.2.2 Developments and Future Evolution of Satellite Communication

Satellite communication is currently experiencing a significant transformation, propelled by advancements in technology, evolving market requirements, and the imperative for worldwide connectivity. Prospective advancements will prioritize enhanced throughput, diminished latency, comprehensive global coverage, sustainability, and seamless integration with terrestrial communication networks. The swift implementation of LEO mega-constellations, as illustrated by initiatives such as SpaceX’s Starlink, OneWeb, and China’s GuoWang, signifies a fundamental shift in the domain of global satellite communication. These constellations employ cutting-edge technologies—including PA antennas for agile beam steering, optical ISLs (OISLs) for expedited data transmission, and non-terrestrial network (NTN) integration compliant with the 3rd generation partnership project (3GPP)—to provide unparalleled low-latency (sub-50 ms) and high-throughput connectivity. SpaceX’s Starlink stands as the preeminent satellite Internet provider

globally, having launched over 6,000 satellites by July 2024, with aspirations to increase this number to 42,000 in its Generation 2 constellation. Its services encompass the majority of the globe, although polar regions remain under regulatory constraints. OneWeb is set to finalize its constellation deployment of 648 satellites in 2024 and has merged with Eutelsat in 2023, thereby integrating GEO and LEO capabilities. This initiative is predominantly targeted toward enterprise and government sectors (for instance, maritime, aerospace, and defense), with collaborators that include Airbus, Hughes, and Airtel. The technology employed is Ku-band, and the terminals are specifically engineered for high-mobility applications. Amazon’s Project Kuiper is poised to launch 3,236 satellites by 2029 and has already initiated its first test satellites in 2023. Its innovations encompass cost-effective terminals (with an anticipated 400–500 consumer terminals utilizing PA antennas). Telesat envisions the deployment of 298 satellites, primarily focusing on the enterprise and government sectors, placing particular emphasis on low latency (30–50 ms), which is especially advantageous for financial transactions and telecommunications backhaul. The technology utilized incorporates advanced PA antennas and optical interplanetary links. China’s GuoWang Constellation intends to deploy over 13,000 satellites to compete with Starlink. This initiative is supported by state-owned enterprises, such as the China Satellite Network Group, and aims to facilitate domestic and Belt and Road Initiative connectivity, with a pronounced focus on military-civil fusion applications [11].

The HTS systems utilizing elevated frequency bands such as Q/V (40–50 GHz) and Ka/Ku facilitate terabit-level data throughput [12], thereby substantially augmenting data capacity. Software-defined satellites equipped with reconfigurable payloads proficiently allocate bandwidth and power in real-time, thereby optimizing operational performance in accordance with demand fluctuations. OISLs further mitigate latency by facilitating laser-based communication between satellites, thus circumventing the necessity for ground station involvement. These technological advancements yield significant advantages for both enterprise and governmental sectors by delivering ultra-secure, high-capacity communication links for industries including mining, energy, and defense, while concurrently addressing the digital divide in underserved and rural locales.

The amalgamation of satellites with 5th generation mobile networks (5G) and 6th generation mobile networks (6G) alongside terrestrial networks is facilitating a seamless integration of connectivity. Through 3GPP NTN, satellite technology is poised to become an intrinsic element of 6G, thereby enabling uninterrupted roaming capabilities between cellular and satellite infrastructures. The implementation of edge computing on satellites will permit on-orbit data processing, thereby diminishing latency for Internet of Things (IoT) applications, which encompass autonomous vehicles and disaster management operations. Hybrid frameworks that integrate GEO, MEO, and LEO satellites with terrestrial 5G small cells will

establish a cohesive “network of networks,” thereby augmenting global connectivity [13]. Practical applications such as emergency communication systems for disaster-stricken areas and smart agricultural initiatives utilizing IoT sensor connectivity in remote farming locales underscore the transformative potential of these integrated systems.

Emerging technologies in the realm of quantum communication are poised to fundamentally transform secure data transmission methodologies. QKD, as exemplified by China’s Micius satellite, facilitates ultra-secure encryption through the application of quantum mechanical principles [14], rendering it virtually infeasible to intercept or compromise communication without being detected. Concurrently, experimental endeavors in satellite-based quantum entanglement are laying the groundwork for the establishment of global quantum networks, which have the potential to substantially improve both the security and efficacy of communication systems. These advancements hold the promise of delivering unbreakable encryption, thereby guaranteeing the utmost levels of security for sensitive data and communications on a global scale.

Innovations in AI are revolutionizing satellite operations, thereby enhancing both operational efficiency and autonomy [15]. Resource allocation driven by AI employs ML algorithms to optimize essential satellite functions, including bandwidth, power, and routing, in real time, thereby ensuring optimal performance and dynamic adaptability to varying network conditions. Autonomous collision avoidance systems, which are fueled by AI, enable satellites to anticipate potential collisions with space debris and execute real-time adjustments, effectively mitigating the risk of catastrophic incidents without necessitating human intervention. Furthermore, predictive maintenance algorithms persistently monitor the operational health of satellites, utilizing data to anticipate potential failures and initiate preemptive measures, consequently minimizing downtime and prolonging the operational lifespan of the satellite fleet. These advancements in AI are crucial for attaining more efficient, secure, and sustainable satellite operations in the foreseeable future.

The commercial satellite industry is currently experiencing a significant transformation influenced by advancements in technology and the dynamics of the market. The increasing prevalence of small satellites, encompassing CubeSats and nanosatellites, has facilitated broader access to space, allowing for the economically viable deployment of extensive mega-constellations such as SpaceX’s Starlink and OneWeb [16]. These satellite constellations provide low-latency broadband services to remote and underserved areas, thereby diminishing the digital divide while simultaneously lowering per-unit expenses through the principles of economies of scale. Concurrently, advancements in additive manufacturing (3D printing) and the design of modular satellites are optimizing production processes, leading to cost reductions of up to 40%, and fostering the rapid

prototyping of reusable components—elements that are essential for the expansion of next-generation networks.

As the phenomenon of orbital congestion intensifies, the mitigation of space debris has emerged as a paramount strategic concern. Current assessments suggest that there are in excess of 130 million debris fragments within LEO, thereby necessitating the implementation of sophisticated deorbiting mechanisms such as drag sails, electrodynamic tethers, and active removal systems, exemplified by the ESA’s ClearSpace-1 initiative. The objective of these technologies is to ensure adherence to the 25-year deorbiting guideline and to mitigate the potential for Kessler Syndrome—a catastrophic scenario characterized by a chain reaction of collisions that could jeopardize the usability of essential orbital paths. Regulatory frameworks are undergoing evolution to enforce end-of-life disposal protocols, while AI-driven collision avoidance systems are being assimilated into satellite operations to augment real-time decision-making capabilities.

The commercial exploration of space is experiencing a marked intensification, characterized by competition among nation-states and corporate entities to capitalize on lunar resource extraction and establish advantageous positions within LEO. Private sector organizations are at the forefront of developing in-situ resource utilization technologies aimed at lunar ice extraction, whereas governmental agencies are utilizing satellite constellations for dual-purpose applications, encompassing Earth observation alongside secure military communications. This competitive landscape reflects dynamics reminiscent of the Cold War era; however, it is now significantly propelled by private financial investments, which have surpassed \$10 billion annually [17]. As regulatory agencies contend with the complexities of spectrum allocation and the management of orbital slots, the industry’s emphasis on sustainability, cost-effectiveness, and technological adaptability will be critical in determining its ability to reconcile growth with the safeguarding of the extraterrestrial environment.

### 1.2.3 Basic Patterns of Satellite Communications

With the persistent escalation of demand and advancements in technology, satellite communication has transcended its conventional confines of terrestrial space communication and has progressively evolved into a multifaceted communication system encompassing interstellar communication, collaborative multi-satellite communication, inter-orbit satellite communication, and deep-space communication across a diverse array of modalities.

Satellite-ground communication represents the quintessential and foundational modality of satellite communication, encompassing the bidirectional transfer of data between satellites and terrestrial ground stations. The primary operation of satellite-ground communication entails the transmission of signals from the ground station to the satellite (uplink) and the subsequent return of these

signals to the terrestrial domain (downlink) [18]. The hardware and apparatus associated with satellite-to-ground communication systems have been subject to continuous enhancements aimed at augmenting efficiency, reliability, and coverage capabilities. The satellite payload constitutes the principal component of the satellite tasked with the reception, processing, and retransmission of signals, wherein the radio frequency (RF) link serves as the medium for signal transmission and reception. Concurrently, the modem facilitates the modulation and demodulation of signals, thereby accommodating diverse communication modes and data rates. Through the application of modulation methodologies such as quadrature phase shift keying (QPSK) and 16-quadrature amplitude modulation (16QAM), in conjunction with coding strategies like low-density parity-check (LDPC) code and turbo code, the modem enhances the data transmission rate and resilience against interference. It is the satellite's antenna that is charged with the reception of signals from terrestrial ground stations in the orbital environment, transmitting these signals to the satellite payload and relaying the processed information back to the ground. Satellite antennas typically employ PA antennas or beam steering antennas, which possess the capability for precise beam alignment and multi-beam operational functionality. Furthermore, the ground station serves as both the initiation and conclusion point for star-earth communication, equipped with a high-gain parabolic antenna [19]. The ground station's antenna can be accurately oriented toward the satellite, thereby ensuring optimal signal transmission quality. The diameter of these antennas is typically substantial, often spanning several meters or even tens of meters.

Inter-satellite communication pertains to the direct transmission of data between satellites via wireless communication channels. In contrast to conventional satellite-to-ground communications, inter-satellite communications eliminate the necessity for terrestrial ground stations by facilitating the forwarding and transmission of signals through direct interlinks among multiple satellites. Data is exchanged among satellites through ISLs, typically employing microwave or laser communication methods. The function of inter-satellite communication is to augment the flexibility, scalability, and reliability of satellite networks, particularly within LEO and MEO satellite constellations. A quintessential application scenario for inter-satellite communication can be observed in LEO constellations, such as SpaceX's Starlink and OneWeb, among others. By utilizing inter-satellite communication, LEO satellites can directly exchange information with one another without reliance on ground relay, thereby establishing a vast, interconnected satellite network.

In conventional single-satellite communications, the integrity of the signal is predominantly influenced by the spatial separation between the satellite and the terrestrial station, the design specifications of the antenna, ambient environmental noise, and the phenomenon of signal attenuation. The implementation of

multi-satellite collaborative communication significantly enhances both the quality of the signal and the capacity for coverage across multiple dimensions through the synergistic efforts of multiple satellites. The interference arising from various satellites presents a considerable challenge within multi-satellite collaborative networks. Through the utilization of adaptive signal processing techniques and spectrum multiplexing technology, multiple satellites are proficiently able to circumvent interference amongst themselves, thereby facilitating the dynamic allocation of spectral resources. The malfunction of a solitary satellite has the potential to precipitate a cessation of communication. Conversely, in the multi-satellite cooperative communication framework, the presence of multiple satellites functions as a redundancy mechanism for one another, allowing for swift transition and management by alternative satellites in the event of a satellite's failure or operational dysfunction. Even in scenarios where the communication link of a single satellite is subjected to interference or damage, the remaining satellites can sustain the continuity of communication through rapid link switching, thus mitigating the risk associated with a singular point of failure within the system. An ensemble of satellites outfitted with multi-beam antennas collaborates to augment signal coverage by leveraging the angular disparities present in the spatial domain. The concurrent coverage of distinct regions by multiple beams emanating from each satellite not only enhances signal strength but also effectively diminishes the adverse effects of environmental factors, such as atmospheric attenuation and interference.

Inter-orbit satellite communications refer to the interactions among satellites positioned in distinct orbital paths, particularly the exchanges occurring between LEO satellites and GEO satellites. Given that LEO satellites are characterized by reduced signal transmission latency and augmented data throughput capabilities, while GEO satellites offer extensive coverage areas, the integration of inter-orbit satellite communications can effectively amalgamate the respective advantages of both categories to facilitate efficient global communications. GEO satellites are capable of functioning as pivotal relay stations to support LEO satellites in extending their coverage across broader global regions [20].

Deep-space communications encompass the transmission of signals throughout the solar system and into interstellar space, specifically concerning celestial bodies or spacecraft and their corresponding ground control centers. The principal attributes of this communication framework include exceedingly extensive transmission ranges, significant signal degradation, as well as the complexities posed by exceptionally high latency and diminished signal strength. The technology utilized for deep-space communication is extensively applied in missions aimed at planetary exploration (e.g., NASA's Mars rovers), remote sensing in deep space, and communications associated with space station operations.

### 1.2.4 Development of Satellite Bands

The frequency bands designated for satellite communication are typically categorized into various segments based on the frequencies of electromagnetic radiation, with each segment exhibiting distinct characteristics and applications as delineated in Table 1.3. In accordance with the definition posited by the International Telecommunication Union (ITU), the frequency bands employed by satellite communication systems (SCSs) principally encompass the L-band through the Ka-band and extend to higher frequency bands. These frequency bands are optimized for a variety of application contexts, including but not limited to communications between terrestrial ground stations and satellites, inter-satellite connectivity, and backhaul links originating from satellites to terrestrial infrastructures [21]. The subsequent sections delineate the frequency bands that are prevalently utilized in satellite communication, along with their associated nomenclature.

In recent years, the evolution of technological capabilities has led to an increased scholarly focus on the terahertz (THz) band, particularly within the domains of satellite communications and air-to-air communications, wherein it facilitates electromagnetic wave bands characterized by frequencies ranging from 0.1 to 10 THz. A principal advantage associated with the THz band lies in its exceptionally large bandwidth, which is adept at accommodating extremely high data transmission rates; however, it concurrently contends with the impediments posed by atmospheric absorption and attenuation.

Laser communication systems, employing visible and near-infrared light wavelengths, represent a significant advancement for prospective satellite communication architectures. Through the utilization of laser links, data transmission rates

**Table 1.3** Applications of different frequency bands of satellites.

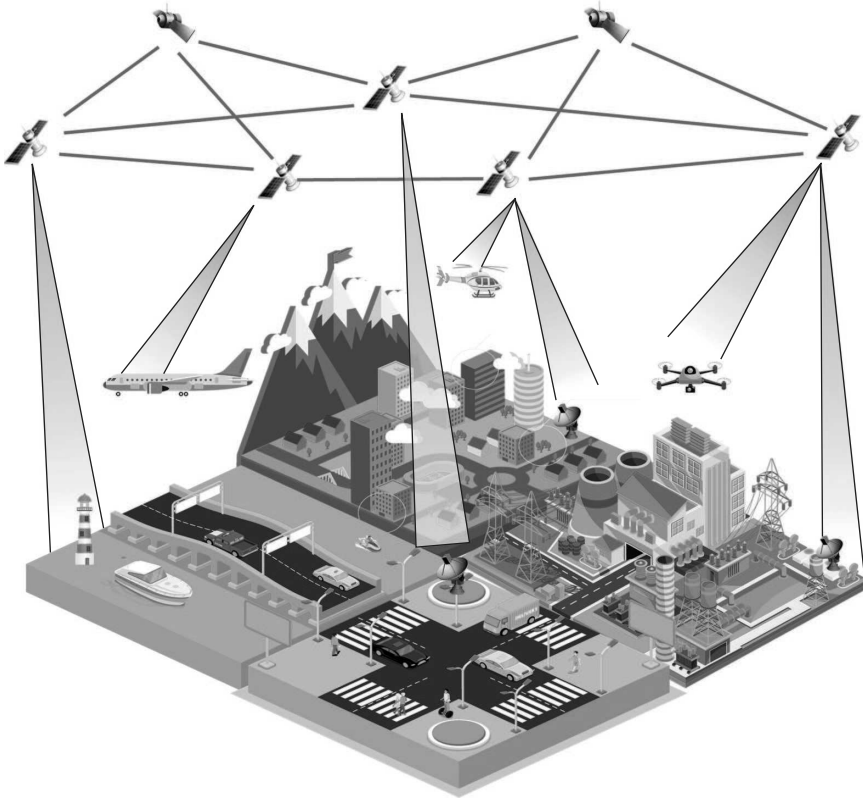
Frequency band	Frequency range	Applications
L-band	1.53–1.72 GHz	Low-speed data, navigation
S-band	2.0–4.0 GHz	Weather radar, aviation
C-band	4.0–8.0 GHz	Satellite TV, military
X-band	8.0–12.0 GHz	Military, government
Ku-band	12.0–18.0 GHz	Satellite Internet, TV
Ka-band	26.5–40.0 GHz	High-speed Internet, broadband
V-band	40–75 GHz	High bandwidth, point-to-point
W-band	75–110 GHz	High bandwidth, military

can reach 1 Gbps, exceed 10 Gbps, and potentially achieve Tbps. This system is comprised of a laser transmitter, a receiver, an optical targeting mechanism, and a data processing unit, which collectively facilitate effective communication within an exceptionally compact framework [22].

### 1.3 Applications of Satellite Communications

In contemporary satellite communication frameworks, the deployment of the integrated sensing, communication, and computation (SCC) network has emerged as a pivotal factor in enhancing the performance, efficiency, and dependability of the system. By leveraging AI and edge computing technologies, the integrated terminal dismantles the technical barriers that exist among SCC through effective data fusion and collaborative computation, thereby optimizing the efficacy of the SCS. Through its network architecture, the terminal device not only executes data sensing but also facilitates instantaneous communication and local computation, thereby diminishing the latency of data transmission and alleviating bandwidth constraints, while enhancing the stability and responsiveness of the network.

As illustrated in Figure 1.3, in the context of satellite communication scenarios, the terminal acquires data across diverse domains, including aerial, terrestrial, and maritime environments, employing an array of sensing devices. These data encompass satellite signal strength, meteorological parameters, user geographic coordinates, and equipment operational status. The pay-per-click (PPC) network engages in the expeditious analysis and processing of extensive sensory data utilizing edge computing and AI technologies. On this premise, the PPC network is proficient in eliminating superfluous data and extracting pertinent information, thereby furnishing more precise inputs for subsequent communication and computational processes. By intricately integrating perception data with information derived from the communication system, the satellite terminal is capable of executing target identification and localization with high accuracy in more intricate environments. In adverse climatic or dynamic conditions, the synergistic interplay of perception and communication endows satellite communication with the capacity to adjust communication parameters while ensuring the reliable transmission of signals. Edge computing represents a fundamental technology within the integrated SCC network, facilitating computations on the terminal side and diminishing the duration required for data transmission to distant central servers. Consequently, edge computing enhances the speed and efficiency of data processing, particularly in scenarios characterized by high real-time demands, such as autonomous driving and the industrial Internet. In the realm of autonomous driving, the satellite communication terminal employs edge computing to analyze surrounding environmental data, including road conditions, traffic signage,



**Figure 1.3** Satellite communication application scenarios.

and obstacle information, while concurrently communicating with the satellite in real-time regarding navigation and control. Furthermore, through the implementation of edge computing, the driving system is enabled to make rapid decisions, thereby safeguarding the safety and efficacy of the self-driving vehicle.

The utilization of AI technology within satellite communications is primarily manifested in the enhancement of communication protocols and the determination of signal transmission pathways. AI possesses the capability for pattern recognition of acquired data via deep learning (DL) algorithms, thereby enabling the forecasting of network traffic, the modification of channel resources, and even the preemptive identification of potential interference factors. By integrating sensing and computational abilities, AI markedly augments the adaptability and robustness of satellite communication networks. In the context of channel estimation within SCSs, AI can dynamically modulate spectrum resources and transmission

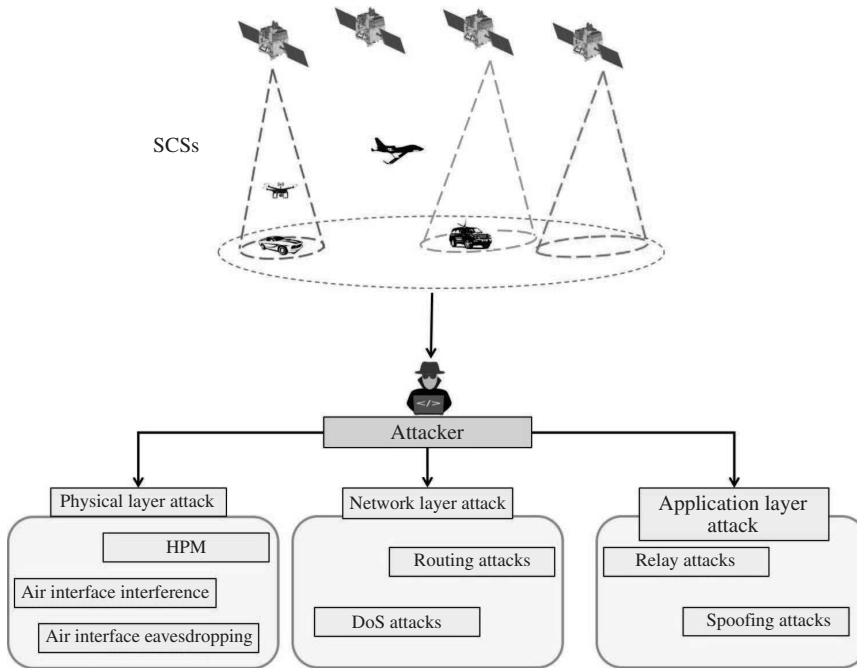
power by assimilating historical communication data and environmental information to guarantee the quality and stability of communication. Furthermore, AI adeptly optimizes the communication link by autonomously adjusting the channel in response to real-time environmental fluctuations, thereby enhancing the overall performance of the entire communication link.

It is essential to acknowledge that the integrated SCC network necessitates not only the amalgamation of terminal and edge computing paradigms but also engages in a profound interaction with the central cloud server. By leveraging resource synergy, the central cloud server is capable of executing dynamic resource scheduling and allocation in accordance with the real-time requirements emanating from terminals and edge nodes. The central cloud server employs mechanisms such as channel estimation and resource allocation to adaptively modify the resource allocation strategy of the network, contingent upon the demand scenarios presented by the satellite terminals (e.g., requirements for bandwidth, computational power, etc.). Consequently, this approach mitigates the risk of resource wastage within the satellite network; for instance, during periods of elevated load, the system can dynamically re-calibrate the signal coverage area or enhance the transmission path to minimize communication latency and alleviate bandwidth constraints. The merits of the integrated communications and computing network of satellites are manifested not only in their data fusion and computational capabilities but also in their potential to foster the iterative enhancement of system performance via continuous self-optimization processes. Satellite communications facilitate a plethora of applications, encompassing cognitive radio for dynamic spectrum sharing, stratospheric platforms aimed at IoT integration, smart city infrastructures, and space-based energy transmission systems.

## **1.4 A Brief Description of Security Issues in Satellite Communications**

### **1.4.1 Security Risks of Satellite Communications**

The satellite communication infrastructure encounters a multitude of security vulnerabilities, which include those emanating from weaknesses inherent in satellite communication protocols as well as the potential misuse of emerging technologies. In addition to the security challenges analogous to those encountered by conventional terrestrial mobile networks, the distinctive security threats illustrated in Figure 1.4 relevant to SCSs predominantly comprise interference, unauthorized eavesdropping, and assaults targeting radio links, payloads, and the satellite platforms associated with SCSs.



**Figure 1.4** Satellite security communications model. *Source:* Author created.

The vulnerability of legitimate user signals to malicious jamming is exacerbated by the inadequate wireless signals received by all devices within the satellite communication framework. The disruption of user links, feeder links, and interstellar links may precipitate the cessation of communication services within specific geographic locales. Concurrently, interference affecting measurement and control links results in the temporary incapacitation of telemetry, remote control, and various operational functions, thereby undermining the regular functioning of the satellite. The interference encountered by SCSs can be systematically classified into suppression interference and deception interference. The inherent openness and extensive coverage of satellite communications render them particularly susceptible to air-interface eavesdropping. Given the broad spectrum of downlink beams, adversaries frequently possess the capability to intercept signals from considerable distances, facilitating the eavesdropping or interception of communication content, especially in the absence of robust encryption protocols. Adversaries not only have the capacity to capture signals via antennas but may also exploit advanced signal processing methodologies to decode the transmitted communication content. In the future, satellite communications are anticipated to encounter increasingly intricate environments, wherein not only the challenges associated

with physical eavesdropping but also the dynamic interaction between satellite and terminal apparatus, along with signal interference, must be effectively mitigated.

The peril associated with a high-power microwave assault lies in its capacity to obliterate satellite apparatus and generate extensive electromagnetic interference phenomena. Through the transmission of high-power pulses aimed at the designated satellite, the assailant effectively annihilates the electronic components within the satellite’s reception system and may even incapacitate its measurement and control infrastructure. In contrast to conventional cyberattacks, this form of assault results in the physical destruction of the satellite system, thereby inducing irreversible harm. It is imperative to acknowledge that, given the escalating complexity of satellite functionalities, the implementation of protective strategies against high-power microwave assaults must increasingly emphasize electronic anti-jamming technologies, redundant satellite architecture, and comprehensive electromagnetic compatibility.

The pathways for data transmission within satellite networks exhibit considerable diversity and complexity. Malicious actors fabricate spurious routes within spatial links by either falsifying or manipulating routing data. The repercussions of routing attacks in satellite networks are significantly more pronounced than in conventional networks, attributable to the prolonged propagation times and limited fault tolerance inherent in satellite links, which exacerbate routing inaccuracies. Nevertheless, in the context of multi-constellation or multi-link satellite networks, adversaries are capable of not only manipulating the data flow through the falsification of routing information but also executing aggressive distributed denial-of-service (DDoS) assaults. To mitigate such threats effectively, SCSs must implement robust routing authentication protocols and integrate dynamic monitoring alongside intelligent response mechanisms. Within the dynamic architecture of satellite Internet, the authentication challenges between nodes represent a notable vulnerability in terms of security. Intruders infiltrate the satellite network by masquerading as legitimate nodes, thereby causing disruptions in network data transmission or complete operational paralysis. In contrast to conventional computer network intrusions, the highly distributed nature and low latency prerequisites of satellite communications amplify the potential severity of these attacks. By impersonating an earth station or satellite node and engaging in network activities, the integrity of communication is compromised, and data flow is redirected toward illicit pathways. Consequently, in addition to authentication measures, there is a pressing need to enhance the dynamic security management of nodes through the integration of multi-factor authentication (MFA) and behavioral monitoring methodologies.

The satellite communication platform is characterized by constrained resources, and adversaries emulate legitimate terminals to initiate a substantial volume of

random access requests, thereby monopolizing the channel resources at the physical layer. Nevertheless, this phenomenon represents merely the preliminary aspect of “denial of service (DoS).” As adversaries persist in augmenting their jamming capabilities, the repercussions on satellite communications are becoming progressively pervasive. Furthermore, attackers possess the ability to compel satellites to function within the nonlinear domain by deploying high-power interference, which consequently engenders a power-skimming effect. This can inhibit normal signals and potentially incapacitate the entire satellite communication network. In contrast to conventional network environments, the extensive link spans, stringent low-latency requirements, and issues associated with single points of failure present in satellite systems exacerbate the lethality of these attacks on satellite communications. The peril associated with replay attacks is frequently undervalued, particularly in scenarios where satellite platforms are constrained by limited resources. Numerous satellite measurement and control links are inadequately equipped to address the threat posed by replay attacks. By intercepting and archiving commands transmitted between satellites and ground stations, adversaries can repetitively issue these commands. Indeed, not only is the command level vulnerable, but also orbit control, antenna positioning, and even the allocation of satellite resources may be jeopardized by replay attacks. In instances where commands are not safeguarded by robust authentication or time-stamping mechanisms, satellites risk executing redundant operations. This threat is especially acute in military or strategic communication contexts and necessitates the implementation of more rigorous security protocols, along with real-time monitoring and defensive strategies to alleviate its potential impact.

#### **1.4.2 Security Protocols and Mechanisms of Satellite Communication**

Owing to the complexities inherent in historical evolution and the diverse requirements of various industries, it proves to be a formidable task to pinpoint a singular SCS that completely conforms to universally recognized standards. Nevertheless, the majority of modern SCSs are constructed upon international standards established by entities such as the Consultative Committee for Space Data Systems (CCSDS), the European Telecommunications Standards Institute (ETSI), and 3GPP. These standards present an array of alternatives that are specifically designed to accommodate distinct user requirements and operational contexts.

The Space Communication Protocol Specifications (SCPS), introduced by the CCSDS during the 1990s, primarily concentrated on the communication protocols pertaining to the link and network layers. Subsequently, the TCP/IP was incorporated to facilitate the interconnection of various layers within the SCPS architecture, thereby enabling a more holistic approach to communication. The principal

design objective of SCPS was to address the resource-constrained demands inherent in satellite communication by minimizing communication overhead while optimizing bit rates. The security protocol associated with SCPS is dedicated to ensuring the security of communications between the network and transport layers, employing data encapsulation methodologies to achieve authentication and access control. The provision of services such as data integrity verification, mechanisms for confidentiality, and identity authentication is contingent upon the specific requirements of the users. Notwithstanding its provision of minimal communication overhead and enhanced transmission efficiency, the defensive measures of the SCPS protocol against replay attacks are still markedly inadequate.

Digital Video Broadcasting-Return Channel via Satellite (DVB-RCS), which was established by the ETSI in 2000, represented the inaugural standard for interactive satellite communication applications. In 2012, DVB-RCS2 was introduced, incorporating substantial enhancements in the foundational protocols, higher-layer functionalities, and security frameworks. Since its inception, DVB-RCS2 has achieved widespread implementation in Ku-band and Ka-band broadband SCSSs.

In the 5G communication framework, 3GPP delineates an extensive security architecture that caters to the requirements of satellite communications, encompassing user-plane confidentiality, control-plane integrity, anti-replay protocols, access authentication, and key negotiation processes. These security provisions collectively ensure the confidentiality and integrity of data transmissions while mitigating potential threats such as replay attacks and identity impersonation.

## 1.5 Organization of This Book

The framework of this book is carefully orchestrated to facilitate a comprehensive examination of satellite communication frameworks, emphasizing their security, architectural design, and prospective innovations. The composition is segmented into five sections, each addressing unique yet interrelated subjects essential for grasping the field.

Part 1: Fundamentals commences with an examination of the historical context surrounding satellite communications, presenting a succinct yet thorough analysis of their progression, utilization, and the emerging security dilemmas associated with them. Chapter 1 familiarizes the reader with the historical framework, advancements, and extensive applications of satellite communications while simultaneously offering an initial comprehension of the intrinsic security issues pertinent to these systems. Subsequently, Chapter 2 shifts focus to the architectural framework of satellite communications, delineating the functions of space, terrestrial, and user segments, in addition to elucidating the notion of terrestrial coverage areas.

Part 2: Security issues and requirements provides an in-depth examination of the particular security threats that confront SCSs. Chapter 3 delineates the diverse categories of security risks, encompassing both active and passive attacks, and scrutinizes the vulnerabilities inherent within satellite systems. It further confronts reliability challenges, including interference and single-event upsets (SEUs). Expanding upon this foundation, Chapter 4 analyzes the critical security requirements pertinent to satellite communication, emphasizing essential performance metrics such as confidentiality, integrity, accountability, and system reliability with respect to latency, capacity, and throughput.

Part 3: Security enhancement solutions concentrates on prospective methodologies aimed at augmenting the security framework of satellite communications. In Chapter 5, active security enhancement methodologies are examined, encompassing pioneering technologies such as quantum communication, blockchain systems, THz communication, spaceborne laser systems, and AI applications. Conversely, Chapter 6 emphasizes passive security methodologies, including sophisticated antenna designs, reconfigurable intelligent surfaces (RISs), and techniques for interference coordination. The collaboration of satellites and the application of AI are also evaluated to bolster reliability and security measures. Chapter 7 redirects focus toward enhancements related to security-driven reliability, addressing critical elements such as outage mitigation, bit error rate (BER) management, and forward error correction (FEC), with AI playing a pivotal role in system optimization.

Part 4: Design criteria for security SCSs offers a comprehensive technical analysis regarding the development of secure and dependable SCSs. Chapter 8 delineates essential design parameters, including the selection of orbital positions and the management of frequency allocations. In Chapter 9, the functionalities of spaceborne payloads, encompassing on-board processing (OBP) and transparent forwarding, are meticulously scrutinized. Chapter 10 investigates the amalgamation of security and reliability within system design, underscoring the necessity of concurrently addressing both dimensions throughout the design process.

Part 5: Future directions examines the prospective advancements in satellite communication technologies alongside their dynamic security requirements. Chapter 11 evaluates next-generation secure transmission methodologies, including integrated sensing and communication (ISAC) assisted and computer vision (CV) assisted approaches, which bear significant implications for the forthcoming communication systems. Chapter 12 investigates the architecture and security frameworks of mega-constellations, addressing both single-layer and multilayer constellations and their secure inter-orbit communication protocols. Lastly, Chapter 13 scrutinizes the critical role of physical layer security (PLS), encompassing key generation, authentication, and encryption methodologies, all of which are essential for the protection of satellite communications within an increasingly intricate environment.

Through a methodical examination of the fundamental elements inherent in satellite communication, including the associated security challenges, strategies for enhancement, and design considerations, this scholarly work provides an extensive resource that integrates theoretical principles with practical implementations while concurrently delineating the prospective trajectory for secure and dependable SCSs.

## References

- 1 T Teichmann. Some elementary considerations of satellite-earth communication systems. *IRE Trans. Space Electron. Telem.*, SET-7(2):51–54, Jun. 1961.
- 2 Walid Saad, Mehdi Bennis, and Mingzhe Chen. A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE Netw.*, 34(3):134–142, May 2020.
- 3 Oltjon Kodheli, Eva Lagunas, Nicola Maturo, et al. Satellite communications in the new space era: A survey and future challenges. *IEEE Commun. Surv. Tutor.*, 23(1):70–109, Oct. 2021.
- 4 Mauro De Sanctis, Ernestina Cianca, Giuseppe Araniti, Igor Bisio, and Ramjee Prasad. Satellite communications supporting internet of remote things. *IEEE Internet Things J.*, 3(1):113–123, Feb. 2016.
- 5 Raymond J Leopold. Motorola’s IRIDIUM system: Low-earth orbit global cellular communications network. In *IEEE Antennas and Propagation Society International Symposium 1992 Digest*, volume 3, pages 1270, Chicago, IL, USA, 1992.
- 6 Alessandro Vanelli-Coralli, Alessandro Guidotti, Tommaso Foggi, Giulio Colavolpe, and Guido Montorsi. 5G and beyond 5G non-terrestrial networks: Trends and research challenges. In *2020 IEEE 3rd 5G World Forum (SGWF)*, pages 163–169. IEEE, 2020.
- 7 Athanasios D Panagopoulos, Pantelis-Daniel M Arapoglou, and Panayotis G Cottis. Satellite communications at KU, KA, and V bands: Propagation impairments and mitigation techniques. *IEEE Commun. Surv. Tutor.*, 6(3):2–14, Dec. 2004.
- 8 Xuwen Luo, Hsiao-Hwa Chen, and Qing Guo. LEO/VLEO satellite communications in 6G and beyond networks—technologies, applications, and challenges. *IEEE Netw.*, 38(5):273–285, Sep. 2024.
- 9 Zhe Niu, Hui Yang, Qiuyan Yao, et al. Reliable low-latency routing for VLEO satellite optical network: A multiagent reinforcement learning approach. *IEEE Internet Things J.*, 12(3):2309–2321, Feb. 2025.
- 10 Li Yang, Cai Wen-Qi, Ren Ji-Gang, et al. Microsatellite-based real-time quantum key distribution. *Nature*, 640:47–54, Mar. 2025.

- 11 Xingfa Gu and Xudong Tong. Overview of China earth observation satellite programs [space agencies]. *IEEE Geosci. Remote Sens. Mag.*, 3(3):113–129, Sep. 2015.
- 12 Ramy Samy, Hong-Chuan Yang, Tamer Rakia, and Mohamed-Slim Alouini. Space-air-ground FSO networks for high-throughput satellite communications. *IEEE Commun. Mag.*, 61(3):82–87, Mar. 2023.
- 13 John Lodge. Mobile satellite communications systems: Toward global personal communications. *IEEE Commun. Mag.*, 29(11):24–30, Nov. 1991.
- 14 Andrea Conti, Robert Malaney, and Moe Z Win. Satellite-terrestrial quantum networks and the global quantum internet. *IEEE Commun. Mag.*, 62(10):34–39, Oct. 2024.
- 15 Shadab Mahboob and Lingjia Liu. Revolutionizing future connectivity: A contemporary survey on AI-empowered satellite-based non-terrestrial networks in 6G. *IEEE Commun. Surv. Tutor.*, 26(2):1279–1321, Jan. 2024.
- 16 Gianluca Furano, Gabriele Meoni, Aubrey Dunne, et al. Towards the use of artificial intelligence on the edge in space systems: Challenges and opportunities. *IEEE Aerosp. Electron. Syst. Mag.*, 35(12):44–56, Dec. 2020.
- 17 Gary K Noreen. Regulatory flexibility in commercial satellite communications. *IEEE Commun. Mag.*, 29(2):58–60, Feb. 1991.
- 18 Chenbo Hu, Hongjuan Yang, Zhiquan Zhou, et al. Outage analysis of RSMA enabled integrated satellite-terrestrial networks. *IEEE Trans. Veh. Technol.*, 74:10023–10028, Feb. 2025.
- 19 Yunyang Zhang, Yulun Wu, Aijun Liu, Xiaochen Xia, Ting Pan, and Xian Liu. Deep learning-based channel prediction for LEO satellite massive MIMO communication system. *IEEE Wirel. Commun. Lett.*, 10(8):1835–1839, 2021.
- 20 Wenqing Li, Bo Ai, Yong Niu, Zhu Han, Ning Wang, and Lei Xiong. End-to-end scheduling of space-air-ground integrated networks for high-speed railways. *IEEE Trans. Veh. Technol.*, 74:9591–9603, Feb. 2025.
- 21 Louis J Ippolito. Characterization of the CTS 12 and 14 GHz communications links-preliminary measurements and evaluation. In *International Conference on Communications*, volume 1, pages 12\_26–12\_29, 1976.
- 22 Rui Sen Hao, Jin Fan Zhang, Shi Chao Jin, Dun Ge Liu, Ting Jun Li, and Yu Jian Cheng. K-/Ka-band shared-aperture phased array with wide bandwidth and wide beam coverage for LEO satellite communication. *IEEE Trans. Antennas Propag.*, 71(1):672–680, 2022.

