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Overview of Low Earth Orbit Satellite Communication Systems

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Abstract: Low Earth Orbit (LEO) satellite communication systems have emerged as a critical solution to address the growing demand for global, seamless, and low-latency connectivity. Compared with Geosynchronous Earth Orbit (GEO) satellites, LEO satellites enable reduced signal delays and broad coverage. Therefore, they are particularly suitable for remote and underserved regions. This paper provides a comprehensive review of LEO satellite communication systems, focusing on three major aspects: frequency band division, system architecture, and case analysis. The study explores the utilization of various frequency bands, including L, S, C, X, Ku, Ka, Q, and V bands, highlighting their characteristics and applications. The system architecture, including the space, user, and ground segments, is analyzed in detail. Additionally, the paper examines the Starlink constellation as a typical example and discusses its architecture, performance, and coverage capabilities. However, LEO satellite communication systems face significant challenges, such as limited resources, high costs, and problems due to the high speed of satellites. Therefore, advancements in artificial intelligence, ultra-narrow beamforming, and 5G and 6G networks present promising opportunities for future development.

Keywords: Low Earth Orbit, Satellite Communication, Radio Frequency, System Architecture

1. Introduction

With the rapid development of global communication technologies, the demand for seamless, high-speed, and low-latency connectivity has grown significantly. Conventional terrestrial communication networks are constrained in their capacity to offer coverage in remote areas. LEO satellite communication systems have emerged as a viable solution, providing improved communication capacity [1], diminished latency, global coverage, and reduced size of the user terminals [2]. With these characteristics, LEO satellite communication systems are considered a complement to traditional terrestrial networks. Moreover, in the future, LEO satellite communication systems will constitute an integrated space-terrestrial communication network [3].

The development of LEO satellite communication has witnessed significant progress in recent years. Systems like Starlink, OneWeb, and other large-scale satellite constellations have successfully deployed thousands of satellites. They demonstrate the feasibility and effectiveness of LEO satellite communication systems. Compared with GEO satellites, which are about 35,000 km above the earth's surface, LEO satellites operate at much lower altitudes [4]. Thus, they have fewer signal propagation

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delays and improved communication efficiency. However, despite these advancements, the field still faces critical challenges that limit the application and development of LEO satellite communication systems.

This paper aims to provide a comprehensive review of LEO satellite communication systems, focusing on three key aspects: frequency band division, system architecture, and case analysis. By systematically analyzing the technological factors and practical applications of LEO satellite communication systems, this paper highlights their growing significance in global communication networks and explores the critical factors driving their future development.

2. Frequency Bands and Architecture of LEO Satellite Communication Systems

2.1. Frequency Bands in LEO Satellite Communication

From a radio frequency perspective, satellite communication mainly uses frequency bands above 1 GHz, as shown in Table 1. In general, lower-frequency bands have stronger signal penetration but provide relatively limited bandwidth. Nevertheless, higher-frequency bands experience increased propagation loss, yet they provide substantially wider bandwidth and enhanced data transmission rates. In practical applications, as various communication demands continue to grow, satellite communication requires even broader bandwidth and higher data rates. Therefore, in LEO satellite communication, the Ku, Ka, Q, and V bands are most commonly used. Moreover, in the future, the low THz band will be increasingly used in specific scenarios in order to pursue higher communication performance.

Table 1: Frequency Bands

Frequency Band	Frequency (GHz)	Characteristics	Applications
L band	1 – 2	Strong signal penetration Wide coverage	Mobile communication Satellite phone Navigation satellite
S band	2 – 4	Good signal penetration	Mobile communication Meteorological satellite Radio direction finding
C band	4 – 8	Strong anti-jamming capability Strong stability	Mobile communication Satellite TV broadcasting
X band	8 - 12	Strong anti-jamming capability High-resolution	Military communication Radar Detection satellite
Ku band	12 – 18	Broad bandwidth High atmospheric attenuation	Digital satellite broadcasting Satellite internet
Ka band	26.5 - 40	Broad bandwidth High data rate High atmospheric attenuation	High-capacity satellite communication High-rate communication net
Q/V band	40 – 50 (Q band) 50 – 75 (V band)	Very high data rate Very high atmospheric attenuation	Very high throughput satellite communication Spacecraft communication and aeronautical terminal communication [5]
Low THz band	100 - 1000	Extremely wide spectrum Ultra-high data rate Limited propagation distance	Communication between earth stations and satellites and inter-satellite links [6] Indoor wireless communication and vehicular communication [7]

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2.2. Architecture of LEO Satellite Communication System

In general, as shown in Figure 1, the architecture of the LEO satellite communication system can be divided into three major segments: space segment, user segment, and ground segment.

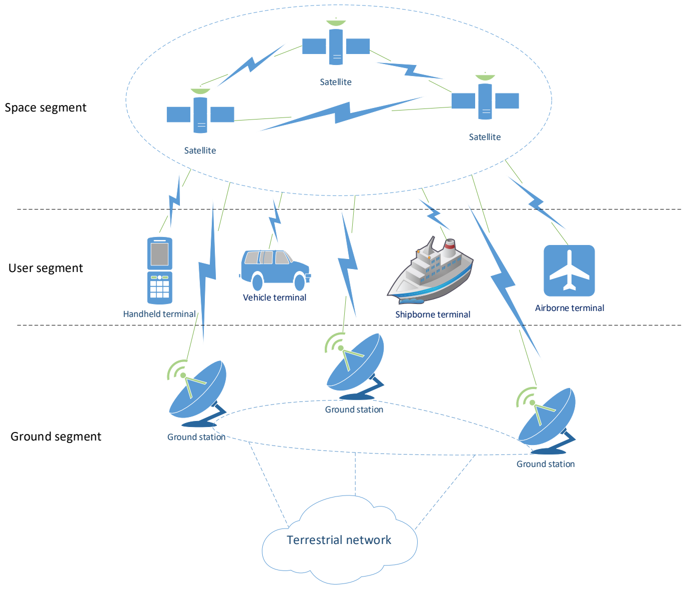

Figure 1: Architecture of an LEO Satellite Communication System

2.2.1. Space Segment

The space segment is the core part of an LEO satellite communication system, and its primary function is to provide global communication coverage and data relay services. It comprises a constellation of LEO satellites orbiting at altitudes ranging from approximately 500 to 1,200 km. Each constellation generally consists of tens to thousands of satellites distributed across multiple orbital planes with various altitudes and inclinations to ensure comprehensive coverage and low communication latency [8]. These satellites serve as access nodes within the space-based network, and they function as mobile base stations in orbit. Inter-satellite links, established through microwave, laser, or other transmission methods [9], enable connectivity among satellites and facilitate data transmission and routing. The design of the space segment guarantees that LEO satellite communication systems provide extensive coverage, substantial capacity, reliable transmission, and significant flexibility [3]. Therefore, the space segment enables the provision of high-quality communication services.

2.2.2. User Segment

The user segment is the interactive terminal part of an LEO satellite communication system. In general, the user segment has three main characteristics: various terminal types, broad geographic distribution, and diverse applications.

Firstly, user terminals comprise a wide array of devices, including handheld terminals, vehicle terminals, shipborne terminals, and IoT (Internet of Things) devices. On one hand, based on the operational characteristics, these user terminals can be divided into two categories. The first category includes sensor devices deployed in remote, wild environments. These devices are immobile, and they are capable of collecting and transmitting short messages, such as forest fire warning systems. The second category consists of handheld terminals, portable terminals, and airborne terminals. These terminals are primarily designed for bidirectional data transmission and interactive communication

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in mobile scenarios, such as aircraft and high-speed vehicles in the sky, handheld terminals and vehicles on land, as well as maritime vessels [1]. On the other hand, based on the connection mode with satellites, user terminals can also be classified into two categories: direct interaction devices, like traditional satellite phones, and indirect interaction devices, such as mobile phones. Future advancements in technology will enable LEO satellite communication to support direct connections with more terminals, reducing dependence on additional equipment and enhancing communication convenience and flexibility. For example, nowadays, research into "direct-to-handset satellite" technology has emerged as a significant focus.

User terminals are widely distributed in urban or rural areas and even extreme environments. The application of these devices can be either general or highly specialized, including daily communication, emergency rescue, remote monitoring, industrial automation, military communication, and the satellite-based Internet of Things [10].

2.2.3. Ground Segment

The ground segment primarily includes ground stations, core networks, control centers, etc. Ground stations are key facilities that connect the space segment and terrestrial networks. They are responsible for receiving satellite signals and transmitting them to the core network through the bearer networks [11]. Core networks are in charge of core tasks such as user access and session connections [12]. Traditional core networks typically feature centralized deployment which simplifies management but simultaneously creates single points of failure. Recent research has focused on distributed core network architectures to address mass user access and global service demands. By utilizing multiple distributed nodes, these architectures enhance traffic load balancing and disaster recovery, thereby improving system reliability and efficiency [11]. Control centers are responsible for the entire system’s operation and maintenance, including satellite monitoring and service routing control [1]. Through efficient design, the ground segment ensures a seamless connection with the space segment and supports large-scale, diverse user communication requirements. In this case, the ground segment provides a robust foundation for overall system operations.

2.3. Analysis of a Typical LEO Satellite Communication System – Starlink

2.3.1. Constellation Architecture Analysis

Starlink, founded by SpaceX, is divided into two generations and will deploy approximately 42,000 satellites. These satellites are generally arranged in orbits at about 340 km, 550 km, and 1,150 km [13]. The first-generation Starlink system consists of LEO and VLEO constellations [14]. In the LEO constellation, user links use the Ku band and feeder links use the Ka band, which helps achieve broader coverage. In the VLEO constellation, the V band is used to provide enhanced transmission signals, thereby delivering targeted information services to specific users [3]. In addition, the second-generation Starlink system involves a significantly larger number of satellites than the first generation.

2.3.2. Performance Analysis

Experimental analyses of shell-4 satellites of the Starlink constellation were conducted, examining the transmission delay, transmission rate, and coverage capability of the constellation [14].

(1) Latency Analysis

There are significant differences in transmission delay between the optimal and worst cases of satellite networks. Due to the high-speed motion of LEO satellites, when providing service, the transmission latency of the Starlink system varies between minimum and maximum values. The variation period is related to the inter-satellite switching strategy and the number of serving satellites.

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Therefore, Starlink allows users to select the best-access satellite node, thereby reducing transmission latency by launching more satellites.

(2) Rate Analysis

Currently, Starlink generally provides two types of services: broadband and mobile. For broadband users, SpaceX's self-developed phased array antennas are mainly used. Under ideal transmission conditions, the uplink transmission rate can reach 500 Mbit/s, and the downlink transmission rate can reach 1.2 Gbit/s. Besides, mobile users use LTE phones. Under ideal transmission conditions, the uplink transmission rate can reach 12 Mbit/s, and the downlink transmission rate can reach 21 Mbit/s.

(3) Coverage Analysis

For shell-4, the Starlink system's global coverage rate ranges from approximately 83% to 83.7%. Shell-4 primarily covers regions between 60° north and 60° south and can provide service for major population areas worldwide. As shell-4 cannot achieve continuous full-time coverage at low latitudes, the Starlink system includes multiple shells distributed at different orbital inclinations and altitudes. In this way, the Starlink system achieves seamless global coverage in both time and space.

The Starlink constellation offers users a maximum of 28 visible satellites and a minimum of 11, typically over 20. This redundancy enhances network robustness and communication capacity. Due to the swift revolve of LEO satellites, the maximum connection time is approximately 6.7 minutes, with a 50% chance of being under 6 minutes. Users must evaluate the trade-off between service duration and communication quality when selecting a satellite access point, which consequently leads to more frequent satellite handovers and heightened signaling overhead.

3. Conclusion

This paper comprehensively reviews LEO satellite communication systems. They typically utilize Ku, Ka, Q, and V bands which offer high data rates despite atmospheric attenuation. The system architecture includes space segment (LEO constellations), user segment (various terminals), and ground segment (ground stations, core networks, etc.), ensuring global coverage and terrestrial connectivity.

Nowadays, LEO satellite communication faces various challenges. Firstly, with several large-scale constellations competing in the world, bandwidth and orbital resources are becoming increasingly scarce [13]. Besides, the cost of LEO satellite communication systems is substantial. The manufacturing, launch, and maintenance of satellites as well as the updating and expansion of constellations require enormous financial investment. Thus, the sustainability of business models is faced with uncertainty. Moreover, as satellites revolve at high speeds, inevitably, there are problems such as Doppler shift and frequent connection switches between satellites and user terminals, which causes increased communication delays and instability [15]. In addition, due to current technology, it is difficult to largely reduce the size of antennas, and therefore, terminal hardware remains large.

In conclusion, LEO satellite communication systems possess significant application and development potential. With continuous technological advancement and the optimization of business models, LEO satellite communication systems will play an increasingly significant role in global communication networks.

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