

The Development of Key Technologies for Satellite Broadband Communication

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Abstract: Satellite communication technology has achieved significant advancements across three key domains: broadband communication, mobile communication, and the Internet of Things, offering innovative solutions for the development of global communication networks. This paper, grounded in the core technologies of satellite broadband communication, examines two primary development directions: high-throughput satellites and low-orbit Internet constellations. It provides an in-depth discussion on critical technologies, including ultra-large-scale multi-beam antennas, microwave photonic payloads, and digital beamforming techniques. Furthermore, the paper highlights the advantages of low-orbit constellations in terms of low latency and global coverage, while also addressing the networking challenges they encounter. The trajectory of satellite broadband communication is clearly moving toward higher capacity, reduced latency, and intelligent system integration.

Introduction

In 2023, 85 communication satellite launches were carried out abroad, successfully sending 2,221 communication satellites into space, including 22 military communication satellites and 2,199 civilian and commercial communication satellites. Since the successful launch of the first communication satellite on December 18, 1958, 8,913 communication satellites have been successfully launched abroad^[1]. As of the end of 2023, there were 6,887 communication satellites in orbit abroad, and communication satellites remain the largest type of spacecraft in orbit globally^[2]. In 2023, the number of foreign communication satellites successfully deployed increased by 292

compared to 2022, and large-scale low-orbit constellation deployments such as Starlink remained the primary reason for the increase in the number of satellites. The United States holds the top spot by order of magnitude, with over 90 percent of its total launches, maintaining its absolute lead, while Europe remains in second place. In terms of the number of launches in orbit, the United States, Europe and Russia are the top three, accounting for more than 97% of the total number in orbit.

Satellite communication phased array antennas, as core components of satellite communication systems, have advanced functions such as beamforming, multi-beam switching and multi-target tracking, and are widely used in military communications, civil aviation communications, maritime communications and communications in remote areas. With the continuous growth of global communication demand and the continuous innovation of satellite communication technology, the market demand for satellite communication phased array antennas will continue to expand^[3].

There are numerous manufacturers of satellite communication phased array antennas worldwide^[4], Among them are SpaceX, Boeing, Kymeta, Lockheed Martin, Raytheon Technologies, Intellian Technologies, Cobham Aerospace Communications, Chengdu T-ray, Chengdu RDW, Micro-Ant and others hold significant positions in the market. In 2022, the top ten global vendors accounted for approximately 87.0% of the market share, indicating the intensity of competition.

Among domestic companies and research institutions are CETC 54th Research Institute, Mengsheng Electronics, Hytera, Huali Chuangtong, Shengben Intelligent, DBS Measurement & Control, Kairuidi, Nanjing 711, Tianrui Xingtong, Lezhong Information, Datang Yongsheng, Huachen Beidou, etc. In 2021, the top five Chinese manufacturers accounted for approximately 42.0% of the market share.

The major cities in China have developed the aerospace information industry as a pillar industry, based on the aerospace information-related manufacturing industry and information service industry that integrates the research and development, production and manufacturing of communication equipment and communication technology. Beijing has clearly defined the "South Arrow, North satellite" industrial layout, positioning satellite Internet as a new economic growth pole; Hainan, relying on carriers such as Wenchang International Space City and Sanya Remote Sensing Information Industrial Park, has formed a commercial aerospace industry chain integrating satellite remote sensing, Beidou navigation, satellite communication, launch vehicles, tracking and control, etc. Hefei, Anhui Province, has continuously enhanced its innovation capabilities in the design, manufacture, integration and testing of key payloads in the aerospace field, promoting the development of the aerospace information industry from nothing to something and from small to large, and has gathered more than 100 upstream and downstream enterprises and research institutions in the aerospace information industry cluster.

Satellite broadband communication technology, an important component of modern communication networks, has seen rapid development in recent years in terms of technological breakthroughs, application expansion and market competition^[5]. The new generation of systems represented by low Earth orbit (LEO) satellite constellations is gradually reshaping the industrial landscape, while technological innovations such as high-frequency band applications and satellite-ground coordination are constantly driving its evolution towards high speed and ubiquity.

The realization of high-performance satellite broadband communication depends on the coordinated breakthroughs of multiple core technologies. This paper analyzes the development of related systems and key technologies at home and abroad from two major aspects: high-throughput

satellite communications and low-orbit Internet satellite communications.

1. High-throughput satellites and their technological development

High Throughput satellites (HTS) represent a revolutionary breakthrough in Satellite communications in recent years^[6-8], as shown in Figure 1. They increase the communication capacity of traditional satellites by tens to hundreds of times through multi-point beam coverage, frequency multiplexing, and dynamic resource allocation technologies. Since the launch of the first HTS in 2010, technological iterations have expanded from the C/Ku band to the Ka/V band, and single-satellite throughput has jumped from tens of Gbps in the early days to the current Tbps level. The application of inter-satellite laser links and flexible payload technology has further promoted space-ground integrated networking capabilities. For example, the Viasat-3 series has achieved a capacity of 1Tbps per satellite, covering more than 90 percent of the world's densely populated areas; Low-orbit constellations such as SpaceX Starlink have significantly reduced communication latency to less than 20ms through massive beam coordination and dynamic frequency multiplexing. The technological advancements are also reflected in intelligent management, where AI-driven adaptive beamforming and interference suppression algorithms optimize spectral efficiency in real time, and software-defined satellite platforms (such as ESA's Neo-Sat) support in-orbit reconfiguration capabilities to meet the diverse needs of scenarios such as 5G backhaul and ocean Internet of Things. In the future, with the convergence of quantum key distribution and satellite communications, high-throughput satellites will play a core role in global broadband coverage, emergency communications, and space-ground-sea integrated networks, but their development still faces challenges such as competition for orbital resources, space-ground spectrum coordination, and terminal cost control.



Figure 1. High-throughput satellites

1.1 Ultra-large scale high performance multi-beam antenna technology

To meet the multi-beam coverage requirements of high-throughput satellites, multiple high-gain point beams need to be generated. Given the limitations of phased array antennas in terms of beam quantity and payload cost, such as limited beam quantity and high cost, the current mainstream

approach is to use large-aperture reflector antennas in combination with multi-feed arrays. This combination of reflector and feed array takes full advantage of the high gain characteristics of the reflector, reduces the strict requirements for the scale and performance of the feed array, and thus enables high-gain, low-side-lobe multi-beam coverage in a relatively simple system. Its advantages lie in its light weight, compact structure and mature design process, and thus it has been widely used on many launched high-throughput satellites^[9].

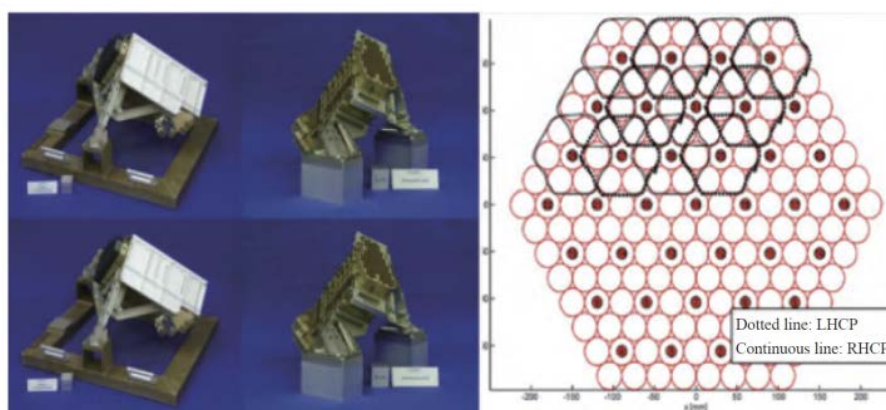


Figure 2. Diagram of the multi-beam antenna feed array and beam formation for a high-throughput satellite

In the field of spaceborne Ka-band multi-beam antennas, reflector + feed array technology is an effective way to optimize payload costs. For the development of super-large capacity satellites, multi-aperture multi-feed multi-beam antennas have become a key technical direction, as shown in Figure 2. The core feature of the technology is that multiple feeders work together to form a beam. This design can effectively balance and optimize the overall beam coverage characteristics and significantly improve key performance metrics such as isolation between adjacent beams. In addition, for the narrow beams generated by such systems, high-precision calibration technology is also an indispensable core element in the development of ultra-large-scale high-performance multi-beam antennas.^[10]

The antenna system of the Viasat-1 satellite adopts an innovative multi-reflector architecture. The diameter of its main reflector is uniformly 2.6m, and the secondary reflector is designed in a rectangular shape of approximately 0.7m×1.2m. The system uses dual circularly polarized feed arrays for shared transmission and reception. 92 feed sources are divided into 4 groups, each corresponding to an independent secondary reflector antenna, forming a separate illumination structure. Based on this design, the four reflectors work in coordination with the 92 feed array to generate 72 0.5° beams facing the user terminal and 20 0.15° narrow beams dedicated to the connection of the gateway station, resulting in high-precision beams.

The core path to scaling up the high-throughput satellite (HTS) system lies in the increase of beam density. The new generation of HTS systems significantly enhances spectral multiplexing efficiency by greatly increasing the number of beams and compressing the beam width. The typical configuration of the Viasat-3 satellite in Figure 3, further validates this trend with its very large in-orbit deployment antenna combined with high-frequency band technology, it achieves higher density beam coverage, providing the hardware foundation for the system capacity leap.

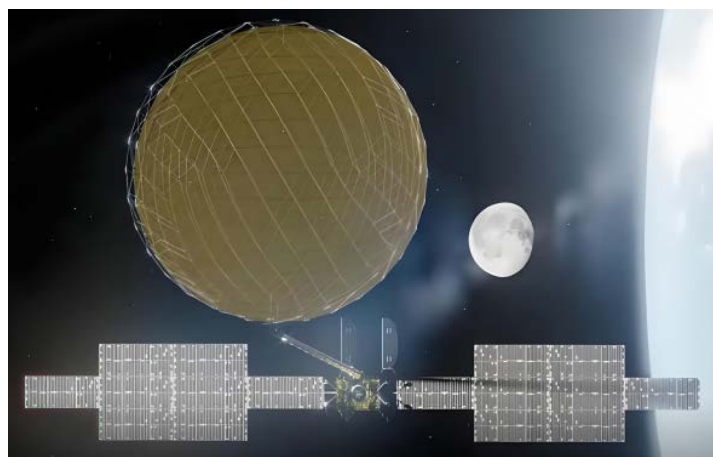


Figure 3 Schematic diagram of high-performance satellite antenna and global beam coverage

1.1 Communication payload technology based on microwave photonics

The on-board forwarding processing of traditional high-throughput satellites has long relied on microwave technology, but its payload design faces inherent bottlenecks: due to the physical properties of microwave devices, it is difficult to effectively optimize volume, weight and power consumption while meeting the functional requirements of the system, which limits engineering implementation. Microwave photonics technology, through the fusion of optical and microwave systems, takes advantage of the low transmission loss and high bandwidth characteristics of the optical domain to achieve efficient transmission and processing of microwave signals, bringing breakthrough advantages to high-throughput satellite payloads in dimensions such as miniaturization, lightweighting, and resistance to electromagnetic interference. Satellite payloads based on this technology can break through the performance boundaries of traditional electronic technology through optical means and reconstruct the transponder architecture. Compared with pure microwave solutions, it significantly reduces payload mass and enhances system connectivity while maintaining the same functionality and scale, opening up a new path for the next generation design of high-throughput satellites.^[11]

In recent years, microwave photonics technology has made breakthroughs in the field of spaceborne communication payloads, with its core advantages in optical domain signal processing and photon-assisted frequency conversion capabilities. By modulating microwave signals to optical carriers, low-loss transmission and flexible scheduling of ultra-wideband signals can be achieved, significantly reducing payload volume weight, while enhancing anti-electromagnetic interference performance. Current research focuses on photonic integrated chip development (such as silicon-based optoelectronic devices), optimization of multi-band optical switching architectures, and enhanced stability of photogenerated millimeter waves. In 2024, the European Space Agency completed the world's first in-orbit verification of an all-optical transponder on a low-orbit satellite, supporting Ka/Q dual-band multiplexing and reducing system power consumption by 40%. Future directions include standardizing photonic interface protocols, advancing integration with terahertz technology, and achieving the engineering deployment of on-board photon-microwave hybrid processing systems.

1.2 Flexible processing payload technology for communications

With the development of long-life communication satellites, the accelerated generational iteration of communication technology, and the innovation of satellite communication business models, traditional fixed-function payloads have become difficult to adapt to the dynamic market and technological environment. A high-throughput satellite flexible payload demand model proposed by the industry, typical key technologies in satellite flexible communication include digital beamforming technology, digital transparent forwarding technology, and satellite jumping beam communication technology.

1.2.1 Digital beamforming technology

digital beamforming (DBF) technology achieves analog-to-digital and digital-to-analog conversion through analog-to-digital/digital-to-analog converters, weighting array signals in the digital domain to form beamforming. DBF has many advantages, such as simple multi-beam implementation, flexible beamforming at bandwidth, rapid response to changes in coverage area for beam reconstruction, support for flexible hopping over a wide range of scanning angles, power distribution between beams, and ease of channel amplitude-phase error correction and adaptive interference suppression.

The issues that digital beamforming technology needs to focus on and solve include the integrated design technology of beamforming and channelization processing, efficient and precise fast calibration technology, and wideband beamforming processing, etc.

1.2.2 Digital transparent forwarding processing technology

Digital transparent forwarding essentially digitizes the traditional microwave analog domain transparent forwarding payload, leveraging the powerful processing capabilities of digital signals to achieve flexible and refined decomposition and combination processing of microwave signals, with interaction between arbitrary subband signals within the communication bandwidth and flexible hinges within and between beams, which can greatly enhance the application flexibility of the system. The core is to achieve flexible control of transponder resources through digital channelization processing, supporting subband switching and dynamic link management. Digital transparent forwarding has become the infrastructure of the trillion-dollar space economy, with a projected global market size of \$4.7 billion by 2028, and its "software-defined sky" paradigm will completely reshape the value chain of the satellite communications industry.

1.2.3 Satellite-hopping beam communications technology

Unlike the fixed beam communication mode of traditional high-throughput systems, the jumping beam communication uses a time-division communication system, adjusts the beam direction according to the rules within the satellite coverage area, and can flexibly allocate beam resources according to the business requirements of different service areas. It is considered a key technology for the evolution of high-throughput satellites to the future and even high-throughput satellites. The composition of a high-throughput satellite system based on hop beam communication is shown in Figure 4.

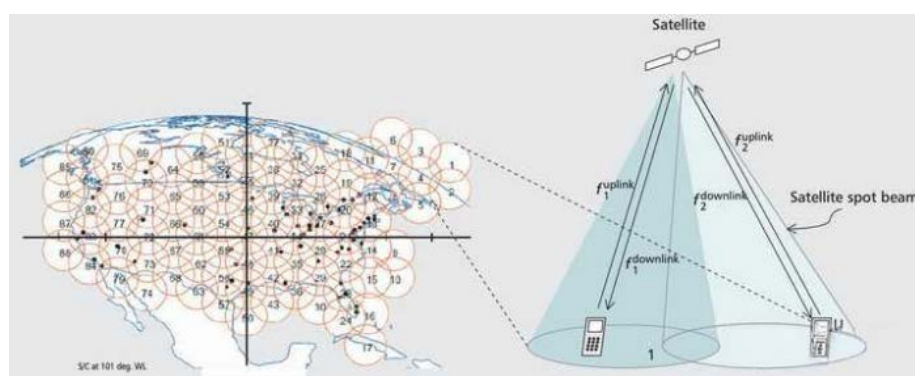


Figure 4 Schematic diagram of forward beam-hopping communication for HTS

Satellite Beam Hopping (Beam Hopping, BH) technology, as a core means to enhance the utilization rate of high-throughput satellite resources, activates some beams on demand through time fragmentation, achieving dynamic allocation of power and frequency resources, and effectively solving the problems of resource fragmentation and uneven beam "work and rest" in traditional multi-beam systems.^[12, 13] The basic principle is to schedule beam coverage using discontinuous time Windows, allowing satellite payloads to flexibly adjust coverage areas and resource inputs according to service requirements.^[14] It is considered a key technology for the evolution of high-throughput satellites to very high-throughput satellites.

Although hopping beam technology has shown significant advantages, its application in space-ground integrated networks still faces challenges: the demand for multi-service convergence transmission demands higher real-time requirements for dynamic resource scheduling, and the combination of cognitive hopping beams and intelligent algorithms needs to further break through engineering bottlenecks. In the future, with the development of very high-throughput satellites, hopping beam technology will be deeply integrated with software-defined satellites and AI-driven resource scheduling, becoming the core support for building flexible and efficient space-based information networks.

2. Low-orbit Internet constellation communication technology

Despite the significant advantages shown by low-orbit satellite constellations in terms of global coverage, low latency and consumer-grade applications, the industry still faces multiple challenges: On the one hand, the global low-orbit satellite constellation is highly competitive, with international giants like Starlink and OneWeb accelerating their layout, while the lagging standardization process may lead to spectrum resource competition and technical compatibility issues (Figure 5).^[15] Counterpoint predicts that standard unification and cost reduction will be key variables for achieving 41 million connections by 2030. On the other hand, the scale of consumer applications still needs to break through terminal costs and chip technology bottlenecks. Although companies like ASR have launched dedicated chips for low-orbit constellations, how to further reduce terminal power consumption and increase chip integration to support direct connection in multiple scenarios such as mobile phones and automobiles remains a core issue that needs to be addressed in the industrial chain synergy. In addition, low-orbit satellite networking involves the deployment and operation and maintenance of hundreds or even thousands of satellites, and the limited orbital resources and the

pressure of space junk management have become increasingly prominent as the scale of the constellation expands, posing potential constraints on the sustainable development of the industry.^[16]

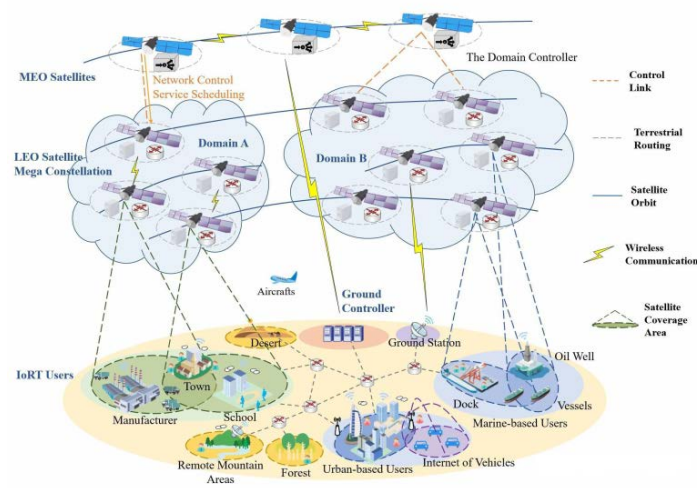


Figure 5 Schematic diagram of the composition for LEO constellation system

2.1 High-speed laser inter-satellite link technology

The inter-satellite laser communication technology, with its high transmission rate, miniaturized terminal and strong anti-interference characteristics, effectively addresses the challenges faced by traditional microwave communication such as rate limitation, heavy payload weight and high energy consumption, and becomes the core solution for low-orbit large-scale constellation networking. The technology not only significantly improves the efficiency of data transmission between satellites, such as Starlink's deployment of laser links for inter-satellite interconnection since 2021, but also enhances communication security through beam directivity and reduces reliance on ground relay stations.^[17] The "Space-based Adaptive Communication Node" program recently advanced by DARPA in the United States further confirms its engineering potential. The goal is to develop 100Gbps-class laser terminals compatible with multi-constellation architectures, and to drive inter-satellite networking technology towards higher integration through miniaturization and cost optimization, thereby building an autonomous and controllable global space-based communication network system.^[18]

2.2 High Reliability and large-scale constellation networking technology

Low-orbit satellite constellations, due to their multi-orbit layout and periodic motion characteristics, show significant dynamic changes in their network topology. At the same time, constrained by the power and computing resources of a single satellite payload, traditional ground-based network architectures and routing strategies are difficult to apply directly. Therefore, research on reliable networking technologies in large-scale constellation dynamic topological environments has become a core issue in satellite system construction. The current constellation deployment scale has expanded from dozens in the early days to tens of thousands. This exponential growth of space nodes, while significantly enhancing network service capabilities, also poses higher requirements for networking technology.^[19]



Figure 6 Schematic diagram of high-speed laser communication in LEO

In response to these challenges, the academic community has proposed a networking architecture that separates management, control, and forwarding functions, dividing the network into three logically independent functional domains: the management plane, the control plane, and the forwarding plane. The forwarding plane is deployed in the spaceborne networking routing module and builds a unified bearer platform through inter-satellite links to achieve the exchange and forwarding of various service data, and its routing table entries are dynamically generated by the control plane. The control plane adopts a space-ground collaborative architecture, where the on-board management control unit and the ground network control center jointly implement the networking control function, as is shown in Figure 6. The management plane performs core functions such as network topology management, configuration management, fault management, performance monitoring and security protection through the collaboration of the ground network management center and on-board modules.

It is notable that the introduction of artificial intelligence technology in recent years has opened up new paths for constellation networking. Researchers have carried out innovative applications such as network traffic prediction, beam resource optimization, and intelligent spectrum situation monitoring through machine learning algorithms, effectively enhancing the dynamic adaptability of constellation systems. This intelligent networking approach not only alleviates the computational bottlenecks of traditional algorithms in large-scale constellation scenarios, but also provides technical support for the autonomous evolution of future space information networks.

3. Conclusions

In summary, satellite broadband communication technology is evolving rapidly towards high capacity, low latency, and intelligence. Multi-beam high-throughput systems based on LEO constellations, combined with cutting-edge technologies such as laser inter-satellite link communications, have built the rudimentary form of space-based communication networks with global wide-area access capabilities. In the future, with the gradual deployment of a new generation of high-throughput and low-orbit Internet systems, the deep integration of AI and edge computing technologies, and the continuous enhancement of inter-satellite collaborative scheduling capabilities, satellite broadband communications will play an irreplaceable role in supporting key tasks such as global interconnection, edge intelligence, and ubiquitous computing. It will provide solid support for the construction of information infrastructure for 6G and beyond.

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