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Comparison Between Low Earth Orbit Satellite and Geostationary Earth Orbit Satellite in Direct-to-Phone Satellite Communication Technology

Jiazhen Li

School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, China
lijiazhen@bupt.edu.cn

Abstract. Direct-to-phone satellite communication technology is primarily applied in remote areas, emergency rescue and other scenarios where communication network coverage is significantly insufficient or a coverage dead zone. This paper mainly compares the differences between GEO and LEO satellites achieving direct-to-phone connectivity through literature analysis and comparative analysis methods. The differences include hardware technology comparisons and non-terrestrial network technology comparisons. The aim is to elucidate the differences and key technologies between GEO and LEO satellites at different orbital altitudes in achieving satellite direct-to-phone Communication, and to point out the possibilities for future integration and development of these technologies. Through the research and comparison in this paper, it is found that the GEO scheme needs a special terminal with particular chips, suitable for emergency communication but limited capacity; LEO scheme is compatible with existing mobile phones and is implemented by spaceborne base stations and large-scale antennas, which have low latency but requires dense networking. The NTN technologies effectively solve the problems of time delay and frequency shift and so on in satellite-ground fusion. In the future, the coordinated development of terminal-satellite-NTN network should be combined to realize a more efficient satellite-ground integrated communication system.

Keywords: Direct-to-Phone Satellite Technology, Satellite Mobile Communication, Low Earth Orbit Satellite Communication, Non-Terrestrial Network

1. Introduction

As communication demands continue to grow and diversify, higher requirements are being placed on the coverage, reliability, and emergency communication capabilities of communications. With the rapid development of terrestrial mobile communication networks, their limitations have gradually emerged, particularly in remote districts, oceans and other areas where communication coverage remains significantly inadequate. Direct-to-phone satellite communication technology is one way to solve these problems. It avoids the reliance of ground communication on fixed base stations through direct communication between orbital satellites and smart phones. Geostationary earth orbit (GEO)

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satellites, combined with existing satellite communication systems, have achieved direct-to-phone satellite communication through technological breakthroughs in mobile terminals. Low earth orbit (LEO) satellites whose orbit is lower than GEO satellites, with their advantages of global coverage and low transmission latency, have become one of the key solutions to this issue. This paper compares the different technologies used by GEO and LEO satellites for direct-to-phone satellite communication through literature analysis and technical comparison, aiming to clarify the application fields of these technologies and the possibilities for future technological integration. This paper provides a systematic comparative analysis of the hardware technology of GEO and LEO satellites achieving direct-to-phone communication for subsequent researchers, and focuses on revealing the decisive role of Non-Terrestrial Network (NTN) technology on satellite-ground fusion, indicating the research direction of terminal - satellite -NTN collaborative innovation for the evolution of 6G satellite-ground integrated communication technology, which has important theoretical guiding value.

2. Comparison of hardware technology in direct-to-phone satellite communication

2.1. Multi-mode terminal technology

Using existing GEO satellites for communication can achieve direct-to-phone connectivity through multi-mode terminal technology. For example, HUAWEI Mate 60 phones contain a radio frequency (RF) and baseband integrated chip for Beidou short message communication and a RX6003 highly integrated RF transceiver chip for Tiantong-1 satellite. These chips enable functions such as satellite phone calls and direct emergency communication between mobile phones. Since these two types of satellites experience much greater path loss in geostationary orbit compared to terrestrial mobile communication systems, higher reception sensitivity and greater transmission power are required for the satellite-to-mobile phone function.

The RX600 transceiver channel isolation design of the Tiantong-1 satellite integrates a low-power fractional-N phase-locked loop (PLL) with a built-in loop filter, enabling the simultaneous provision of high-performance local oscillator (LO) signals for both the receiving and transmitting circuits. Additionally, the receive and transmit channels use independent phase-locked loops, supporting both frequency division duplexing (FDD) and time division duplexing (TDD) mode [1]. Furthermore, the chip supports conventional mobile mode, interference resistance mode and emergency life-saving mode.

2.2. Direct-to-phone satellite technology for existing mobile phones

LEO satellite networks offer technical merits such as low latency and wide broadband, making direct-to-phone satellite technology for existing mobile phones a priority development area in the direct-to-phone technology. This technology targets the unmodified existing phones, therefore, the satellite equipment needs to have the capability to properly process the original mobile phone signals. Traditional satellites employ a transparent forwarding mode, where the satellite only acts as a relay and amplifies the signal; whereas Starlink satellites employ the regenerative forwarding mode, where they function as base stations with modulation and demodulation capabilities, further enhancing the efficiency of communication. Starlink employs standardized long-term evolution or the 4th generation mobile communication technology (LTE or 4G) protocols by deploying LTE modem units on each Starlink V2-mini-DTC satellite, thereby enabling the satellite platform to function as a terrestrial cellular base station [2]. All satellites within the Starlink V2-mini system are

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actively controlled to maintain their transmit and receive antenna beam patterns within predefined minimum and maximum gain boundaries [3]. This operational flexibility enables dynamic adaptation to varying user densities and service altitudes [3].

2.3. Comparison of GEO and LEO satellites in hardware technology of direct-to-phone

Multi-mode terminal technology makes use of existing GEO satellite communication systems, and its core lies in the hardware modification on the terminal side, requiring users to change their user equipment (UE). Due to the approximately 36,000 kilometers orbital altitude of GEO satellites, the path loss exceeds 200 decibels. Consequently, mobile phones need to incorporate high-performance satellite communication chips and optimize antenna design to enhance reception sensitivity and transmission power. Traditional satellite communication functions can be added to mobile phones through miniaturized chips and optimized RF antenna designs, making them Multi-mode terminals for both terrestrial and satellite mobile communications [4]. This approach enables seamless interworking between satellite core networks and terrestrial mobile core networks through protocol conversion of signaling messages [4]. This technology is currently mainly used for emergency communication, but it is difficult to support large-capacity communication, because the high latency and limited spectrum resources of GEO satellites constrain their communication capacity.

Direct-to-phone satellite technology for existing mobile phones is commonly used in large-scale deployment of LEO satellites, typically employing onboard base station technology combined with inter-satellite links to achieve seamless global coverage without the need for overseas gateway earth stations, while preserving users exchanging their existing UE. Satellite communication operators that adopt direct-to-phone satellite technology for existing mobile phones generally collaborate commercially with terrestrial mobile network operators (MNOs) to reuse existing 4G or 5G frequency bands, moving base stations hundreds of kilometers into space to enable direct-to-phone satellite communication. The key of this technology primarily involves installing higher-power and higher-gain antennas on satellites to enable direct-to-phone satellite communication. The core of satellite-mounted large antenna technology lies in equipping satellites with large antenna arrays to increase overall array gain and address the loss issues in the satellite-to-ground link [5]. This technology currently also focuses on emergency communication and has the potential to evolve into high-capacity communications such as video streaming in the future.

From the perspective of system architecture, the GEO satellites adopt a "terminal enhancement" technical approach. The core challenge is achieving sufficient RF performance within the limited space of the terminal. In contrast, the LEO satellites employ an innovative onboard base station technology, shifting complexity and cost to the satellite end. It achieves compatibility with ordinary mobile phones by enhancing the performance of satellite-borne equipment. In terms of signal processing, GEO satellites mostly utilize a transparent forwarding mode, where signals are merely amplified and frequency-converted. Consequently, terminals need to support dedicated satellite communication protocols. On the other hand, LEO satellites adopt a regenerative forwarding mode, completing full baseband processing onboard the satellite, which enables direct compatibility with terrestrial mobile communication standards. Regarding development potential, the GEO satellites are constrained by their inherent high-latency characteristics and limited spectrum resources, making them more suitable as a supplementary means for emergency communications. In contrast, the LEO satellites, with their low-latency, high-bandwidth features, and deep integration with terrestrial networks, hold greater development prospects in the future integrated space-air-ground communication networks.

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3. Application of 3GPP-standardized NTN technologies in GEO and LEO satellites

3.1. NTN technology

While focusing on 5G terrestrial mobile technologies, the 3GPP standards also consider integrating 5G terrestrial systems and satellite communication networks, carrying out NTN standardization research work and incorporating satellite communication into 5G network to solve the key problem of 5G air interface support for NTN [6]. Specifically, NTN technology involves satellites transmitting 5G signals for direct connectivity with user equipment (UE), with ground-based gateway stations (GSs) serving as network entry points that ultimately interface with the 5G core network (5GC).

NTN technology comprises two common payload architectures:

Transparent Payload, also known as Transparent Forwarding: This configuration treats the satellite as a mere signal-relaying link, performing only frequency conversion and amplification without onboard signal processing [7].

Regenerative Payload, also known as Onboard Base Station: This architecture effectively deploys a 5G base station (gNB) on the satellite, enabling onboard signal processing, decoding, and retransmission [7].

3.2. Comparison of NTN technology between GEO and LEO satellites

In 2023, MediaTek released the MT6825 IoT-NTN standalone chipset, which supports 3GPP Release 17 NTN standard while adding less than 10 dollars to the cost of devices or smartphones [8]. This chipset can be integrated into any 4G or 5G device and can connect to GEO satellites such as Inmarsat and EchoStar. Moreover, MediaTek collaborated with NTN service provider Skylo to use 6 L-band GEO satellites of Inmarsat, enabling smartphone and IoT manufacturers to develop new devices, sensors, and wearables with embedded satellite connectivity [8].

For LEO satellite systems, the high-speed movement of LEO satellites relative to ground users introduces Doppler frequency shifts and time-varying delays, significantly exceeding those in terrestrial communication systems. Existing frequency offset compensation schemes cannot be adapted to satellite communication scenarios. Therefore, during frequency-domain synchronization, NTN technology delegates the compensation of the uplink and downlink Doppler frequency offsets in the feeder link to the base station, which autonomously performs adjustments based on ephemeris data while remaining transparent to the terminal [9]. Additionally, pre-correction techniques are employed to pre-adjust the carrier frequency of the transmitted signal before transmission, utilizing satellite orbital parameters and velocity information, thereby minimizing frequency deviations at the receiver end [9].

3.3. Comparison of NTN technical performance between GEO and LEO satellites

The key technologies of NTN include the design of network architecture, frequency planning (L, S, Ka bands), high transmission delay compensation, Doppler frequency shift mitigation, synchronization optimization for ultra-large cell radii, mobility management (conditional handover) and enhanced Hybrid Automatic Repeat reQuest (HARQ) mechanisms. These technologies address issues such as latency, frequency shifts and wide-coverage in LEO satellite communication, ensuring the integration of NTN with terrestrial 5G network, enabling direct connections between existing terminals and satellites and enhancing the global communication coverage.

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Within the 3GPP-standardized NTN technical framework, GEO and LEO satellite systems exhibit distinct technical characteristics and suitable application scenarios. The GEO satellite communication system has the advantages of relatively fixed satellites and good channel conditions, with three satellites covering all regions except the North and South Poles. Since GEO satellites remain stationary relative to the Earth's surface, they avoid issues like handovers and exhibit minimal Doppler frequency shifts [10]. However, GEO satellites orbit at an altitude of approximately 36,000 kilometers, resulting in significant path loss. So, they need high-power satellite transmitters and high-sensitivity receivers in user terminals to achieve direct-to-phone satellite communication technology.

In comparison, LEO satellite systems face more complex technical challenges in the implementation of NTN, yet they also demonstrate greater performance potential. Due to their low orbital altitude, the high-speed motion of LEO satellites introduces significant doppler frequency shifts that far exceed the compensation capabilities of terrestrial systems. To address this issue, the 3GPP NTN standard proposes innovative solution by utilizing ephemeris information for pre-compensation, the primary task of frequency offset correction is shifted to the network side, remaining transparent to the terminals. Meanwhile, a dynamic delay compensation mechanism is employed to ensure the accuracy of timing synchronization. Additionally, the large-scale constellation characteristic of LEO systems enables them to achieve true global coverage, including high-latitude regions that are difficult to cover with traditional GEO systems.

Compared to LEO satellites, GEO satellites also have longer life, limited collision risks, and fewer handovers are needed. On the flip side, LEO satellites offer better propagation conditions, smaller delays, and larger throughput, even more so with decreasing altitude and increasing constellation sizes (number of satellites in the constellation) [11]. LEO satellites are also capable of providing better coverage compared to GEO satellites (no polar regions) [10]. From the perspective of application prospects, the GEO system is better suited as a supplement to existing terrestrial networks, providing basic connectivity services for specialized fields such as maritime and aviation, as well as for emergency communication scenarios. On the other hand, the LEO system, with its low-latency and high-bandwidth characteristics, is poised to become a core component of future integrated space-air-ground networks, supporting a wider range of application scenarios from the Internet of Things (IoT) to broadband multimedia. As the 3GPP NTN standard continues to evolve and onboard processing capabilities improve, the technical and economic viability of the LEO solution will further enhance, driving the rapid development of direct-to-phone satellite technology towards mass adoption and commercialization.

4. Conclusion

This paper compares the differences between LEO Satellite and GEO Satellite in Direct-to-Phone Satellite Communication Technology from two aspects, the hardware technology and the NTN technology. The study finds that GEO satellites, currently in orbit, achieve direct-to-phone satellite communication primarily through Multi-mode terminal technology and NTN technology, with a focus on researching technologies such as miniaturized chips and optimized RF antenna designs. This satellite demonstrates unique advantages in specific scenarios such as emergency communications, thanks to its mature satellite infrastructure and stable communication links. The deployment of LEO satellite groups is the key plan of the current satellite-ground fusion. This technology is mainly realized by direct-to-phone satellite technology for existing mobile phones and NTN technology, mainly exploring the onboard base station technology, large-scale antenna array, NTN network and other technologies. In particular, the formulation of the 3GPP NTN standard has

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effectively addressed critical technical bottlenecks in satellite-terrestrial integration, proposing innovative solutions specifically for the unique challenges of Doppler frequency shifts and frequent handovers in LEO systems.

The following areas of this study require improvement. Firstly, the economic analysis is relatively weak, lacking a systematic assessment of the full lifecycle costs for the two technological approaches. Secondly, the research methodology primarily relies on literature analysis, lacking practical link budget calculations and system-level simulation validations. Future research could employ tools such as MATLAB to establish accurate communication models and quantitatively analyze the performance boundaries under different scenarios.

The future direct-to-phone satellite technology can be combined with terminal-satellite-NTN to achieve faster and wider satellite-ground fusion communication technology. On the terminal side, it is necessary to develop intelligent and reconfigurable RF chips that support multi-mode and multi-frequency operations, facilitating adaptive switching between GEO and LEO systems. On the satellite side, a hybrid constellation design can be employed, utilizing GEO satellites for wide-area coverage and basic services, while LEO satellite clusters handle high-bandwidth and low-latency applications. At the network level, an intelligent core network based on the 3GPP NTN standard will enable dynamic scheduling and collaborative management of terrestrial and space resources. This integrated architecture leverages the advantages of GEO systems, such as stable coverage and low operational and maintenance costs, while also harnessing the high capacity and low latency characteristics of LEO systems. Through intelligent network slicing technology, differentiated services can be provided for various application scenarios. As onboard processing capabilities improve and artificial intelligence (AI) technologies are introduced, future satellite-ground integrated communication systems will achieve faster response times, broader coverage, and superior service quality, ultimately establishing a truly global and seamless communication network.

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