LEO Satellite Access Network (LEO-SAN)
Toward 6G: Challenges and Approaches
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Abstract

With the rapid development of satellite communication technologies, the space-based access network has been envisioned as a promising complementary part of the future 6G network. Aside from terrestrial base stations, satellite nodes, especially the low-earth-orbit (LEO) satellites, can also serve as base stations for Internet access, and constitute the LEO-satellite access network (LEO-SAN). LEO-SAN is expected to provide seamless massive access and extended coverage with high signal quality. However, its practical implementation still faces significant technical challenges, such as high mobility and limited budget for communication payloads of LEO satellite nodes. This article aims at revealing the main technical issues that have not been fully addressed by the existing LEO-SAN designs, from three aspects namely random access, beam management and Doppler-resistant transmission technologies. More specifically, the critical issues of random access in LEO-SAN are discussed regarding low flexibility, long transmission delay, and inefficient handshakes. Then the beam management for LEO-SAN is investigated in complex propagation environments under the constraint of high mobility and limited payload budget. Furthermore, the influence of Doppler shifts on LEO-SAN is explored. Correspondingly, promising technologies to address these challenges are also discussed, respectively. Finally, the future research directions are envisioned.

Introduction

With the commercialization and technology promotion of the fifth-generation (5G) cellular networks, various advanced applications or concepts have been proposed successively, including the industrial Internet of Things (IIoT), holographic communication, digital twins and the meta-universe [1, 2]. These demands are motivating further technical developments of both industry and academic research, to enter the forthcoming sixth-generation (6G) era [1, 2]. Compared to the mobile communication technologies up to 5G, the 6G prospects aim to provide ubiquitous coverage and massive user access with higher levels of communication capacity and reliability, which are quite challenging to achieve with the terrestrial cellular networks only. Fortunately, with the rapid development of satellite communication technologies [2], the aforementioned requirements for 6G can be satisfied by the incorporation of space-based and ground-based cellular networks [1–5].

In the multi-tier structure of satellite communication networks, low earth orbit (LEO) satellite constellations play a particularly important role for space-ground interconnection [3–5], and enable the LEO-satellite access network (LEO-SAN) to provide full-coverage broadband services for ground users. Therefore, great attention has been drawn from telecommunication researchers to this paradigm globally. The concept of communicating via LEO satellite constellation can be traced back to the early 1990s. However, due to various issues such as limited technical capability, high cost and insufficient demand, most of LEO constellation programs ended up with bankruptcy. In recent years, the increasing demand for global coverage of broadband Internet access anytime and anywhere has set off a new wave of research and development on the LEO satellite constellations [3–5]. On one hand, in the industry field, there are currently many projects of new-generation large-scale LEO constellations, represented by Iridium II, Starlink, OneWeb, Telesat, and Kuiper, which have made significant progresses, and are beginning for commercial testing [6]. On the other hand, in the academia, [3] proposed an enabling network architecture of space-ground integration, under which some key technologies and typical application scenarios were introduced. [4, 5] took the development trajectory of LEO satellites as the main line, and expounded the research on integration of the LEO-based and terrestrial networks. Furthermore, the 3rd Generation Partnership Project (3GPP) non-terrestrial Network (NTN) Project is stepping up the standardization of the satellite-ground integrated network. In particular, 5G New Radio (NR) NTN adaptations in Release 17 have been concluded and endorsed in June 2022 (RAN #96 meeting) [7].

Figure 1 illustrates the typical scenarios and technical composition of LEO-SAN. The LEO satellites serve as the space base stations (BSs) to complement the terrestrial communication networks, which are capable of attaining full-coverage transmission as well as supporting massive user access with high data rates. Specifically, the user terminals can perform seamless handover between the space and ground BSs in a flexible manner to optimize its quality-of-service (QoS) level, enjoying both the
This access architecture has low flexibility and large round-trip latency, which makes it inefficient to support massive users access. To this end, the network architecture of LEO-SAN can be re-designed to address the aforementioned issues.

Random access in this article refers to the process from the time when a user sends a random access preamble to the time when a basic signaling connection is established between the user and the BS through information exchange.

Advantages of terrestrial and space-ground data links. Additionally, the inter-satellite links are considered to play a pivotal role in LEO-SAN, since they can support flexible multi-hop data forwarding functions. More specifically, at certain regions (e.g., mountains or oceans) where ground base stations can be hardly deployed, the feeder link is likely to be unavailable for the satellites within these regions. Under such cases, the data can be forwarded via multi-hop inter-satellite links to find available feeder links for space-to-ground transmission. Despite its outstanding merits, LEO-SAN still faces several unsolved problems due to its peculiar characteristics of the large space-time scale, high mobility, complex structure and diversified service types. In the aspect of the random access, the access architecture is also less flexible. Moreover, the high-speed moving satellite leads to the deterioration of the timeliness of the user’s access selection, which may severely affect the access of all kinds of service users. In terms of beam management, there is an inherent trade-off between the range of beam coverage and the access bandwidth. Not only that, limited resources can hardly serve massive users under the existing beam allocation mechanism. As for transmission technology, the high-speed mobility of LEO satellite causes severe Doppler frequency effects, which brings practical challenges to modulation and demodulation.

In this work, different from the existing overview papers [3–5] that addressed the overall development and application scenarios of LEO-SAN, we will focus on the largely open issues pertaining to random access, beam management and Doppler-resistant transmission technologies for LEO-SAN. More specifically, the main problems of random access in LEO-SAN are discussed in terms of coverage requirements, beam scheduling, handover management as well as beam resource management. Additionally, we explore the impacts of Doppler shifts on LEO-SAN, where Doppler-resilient signal processing schemes for classical modulation schemes together with novel waveforms against Doppler shifts, are investigated. Finally, some future research directions are discussed.

**Random Access for LEO-SAN**

In this section, the technical issues in the existing network architecture and random access schemes for LEO-SAN are revealed. To tackle these issues, we provide some design guidelines for the network architecture with random access in LEO-SAN. Moreover, we discuss optimized design of random access algorithms for mobile broadband users and burst short packet users, respectively.

**Enhanced Network Architecture for LEO-SAN**

In the existing access network architecture enabled by 3GPP NTN technology, the core network (CN) is located on the ground, while the BSs of the access network are all or partially located on the satellite-based platform [3]. This access architecture has low flexibility and large round-trip latency, which makes it inefficient to support massive users access. To this end, the network architecture of LEO-SAN can be re-designed to address the aforementioned issues. Figure 2 shows an enhanced service-oriented network architecture in which service-based network elements in the CN are deployed from the ground to the satellite, and the access network is sliced according to different services to satisfy new application scenarios, such as two-step random access. On this basis, several guidelines are provided as follows. Firstly, the network connection is affected by the dynamic changes of LEO network topology, which thus requires flexible and effective architectural design according to the network environment and users’ requirements. The design concept of servitization can be considered in both satellite assess network (SAN) and CN, such that the conventional SAN and CN in 5G can be merged together to facilitate easier network deployment and management. Moreover,
network functions or services need to be flexible, distributed, and can be dynamically deployed in multiple nodes of different satellites to achieve efficient coordination of LEO networks. Finally, unified and efficient interface protocols can be designed to connect different network functions under the servitization framework [1].

**Random Access for Mobile Broadband Services**

The four-step access method is typically applied for mobile broadband service. Most of the current random access algorithms only focus on the current access moment. However, high-speed mobile satellites and flexible access users result in rapid topological changes. Most of the current access algorithms cannot adapt to the highly dynamic change of the LEO network because these algorithms make decisions only from the current handover moment. To address this issue, one possible strategy is to utilize the historical state information for future state prediction via efficient learning methods, which can improve the long-term benefits of mobile broadband access. However, user/satellite state information is not only large in scale, but also changes very quickly, leading to lower computational efficiency and worse time prediction timeliness. Therefore, how to efficiently process the massive amount of data (with rapid change) is also essential for performance enhancement of random access.

**Random Access for Burst Short Packet Services**

In LEO-SAN, burst short packet access is one of the most important services of the satellite IoT. Generally, users only send a few bytes of information at a time. The most typical scheme currently studied is random access without authorization, namely the two-step access method [8]. Compared with the four-step access method, the two-step access method combines the first step and third step to reduce the number of information exchanges and simplify the access process. The preamble and user data have been transmitted together, in the current two-step access method, which helps reduce the signaling complexity and transmission delay. However, the characteristics of channel sparsity and sporadic traffic of massive user devices are ignored. Consequently, a sparse recovery mathematical model can be used to model the problem of joint channel estimation and user detection. Unfortunately, the problem is usually NP-hard. By introducing certain constraints to the objective function, the problem can be solved by some greedy algorithms and message passing algorithms [9]. After saying so, for some emergency communication and condition monitoring scenarios, thousands of devices will initiate the access attempting simultaneously. In this case, it is not enough to rely on grant-free random access alone due to its limited overload rate and high computational complexity. If the throughput of system reaches its peak while the payload continues to increase, the throughput will deteriorate rapidly. The efficient Media Access Control (MAC) access protocol can coordinate multiuser data transmission, avoid data package collision, expand preamble resources and enable interference cancellation technology in access processes to solve this problem in the high payload situation.

**Beam Management in LEO-SAN**

Beam management mainly includes scheduling, handover management and resource allocation of signaling beams, service beams and feeder-link beams, as shown in Fig. 3. In LEO-SAN, the high mobility, complex propagation environment as well as limited budget for communication payloads of the satellite platforms pose great challenges to the beam management operations.

**Coverage Requirement and Beam Scheduling**

**Coverage Requirement:** In LEO-SAN, there are three important steps for user access: signaling synchronization, service transmission and backhaul. Firstly, low bandwidth but full coverage are required for signaling synchronization, where the width of signaling beams need to be sufficiently large to cover the whole ground area. Secondly, the data services require higher bandwidth, and are usually sparsely distributed. Therefore, the service beams only need to point at certain areas of ground users, with reduced beamwidth for higher beamforming gain. Finally, backhaul from LEO satellites to the fixed ground station can be realized by a point-to-point feeder-link beam with even narrower beamwidth and larger communication bandwidth than the counterparts above.

**Signaling Beam Scheduling:** In LEO-SAN, despite the low bandwidth of signaling beams, the link budget is likely to be insufficient due to the limited payload and the high-altitude of LEO satellites. Therefore, the signaling beam may need to cover the ground area in a scanning mode. Each LEO satellite performs a time-division scan of the target area to provide equivalent full coverage. Since each beam scans quickly, the downlink and uplink beams need to be designed independently and spaced at certain intervals to ensure synchronous responses.
The high mobility of satellites and uncertainty of massive user movement bring new difficulties and challenges to handover management. It results in frequent beam recasting and handover, which greatly increases signal delay and handover cost, and severely affects user service experience.

**Service Beam Scheduling:** Service beams are mainly utilized to support bandwidth-consuming fixed/mobile services. Since LEO satellites move generally much faster than ground users, the beam scheduling strategies for fixed and mobile services can be somewhat similar. Due to payload constraints of the LEO satellites, the key challenge for service beam scheduling is how to utilize a limited number of spot beams to serve a massive amount of users worldwide. The possible solutions include beam hopping, effective matching between service beam and signaling beam, and joint scheduling of space, time and frequency resources. In particular, Fig. 4 compares the throughput of service link in a multi-beam LEO-satellite system, using two resource scheduling schemes, namely the adaptive mode and fixed mode, under different settings of communication bandwidth. The satellite in the fixed mode periodically changes beam illumination direction and adopts uniform power allocation strategy. However, the fixed mode does not consider time-varying traffic demand, and fails to fully utilize the space freedom of the beam. In the adaptive mode, we jointly design beam hopping pattern and flexible power allocation according to the distribution of the traffic demand of the ground users, based on matching theory and the successive convex approximation technique [10]. In addition, some simulation parameters are given in the following: beam number is 37 per satellite, single-user requirement bit rate range is from 1 Mb/s to 15 Mb/s, transmit and receive antenna gains are, respectively, 52 dBi and 41.7 dBi, system bit rate is 500 Mb/s, single-feeder power constraint is 100 W and total power constraint is 1000 W. In the simulation, users are randomly distributed under one single satellite and the average throughput is calculated after aggregation. It can be observed that the adaptive beam scheduling mode significantly outperforms the fixed mode under different values of communication bandwidth. This is because the adaptive mode can effectively mitigate the co-channel interference between users, and make full use of the freedom degrees of time, space and transmit power.

**Feeder-Link Beam Scheduling:** Feeder link is the import and export pipeline of the network, which determines the throughput of the whole network. The satellites forward data to the ground through the feeder link for flow evacuation and direction. However, in LEO-SAN, there are two vital problems. Firstly, the ground stations cannot be placed at some remote or extreme region (oceans, mountains, etc.). Therefore, some LEO satellites cannot forward data to ground stations through feeder links directly. To this end, using inter-satellite links is a promising solution. Through inter-satellite links, satellites can forward data by multi-hop transmission to the satellite with a feeder link, and then to the ground stations. However, the possible disruptions and episodic disconnections of inter-satellite links cannot be overlooked, where disruption tolerant networking algorithms such as flow control, congestion control and so on, are necessary to ensure the connectivity robustness. Secondly, the GEO satellites allocate a set of antennas specially for the feeder-link beams. However, for LEO satellites, the feeder-link beam may share one set of phase-array antenna with the service beam, due to limited budget for communication payload. In the future, in order to achieve the lightweight and miniaturization of LEO satellites, the integration of service and feeder-link beams is also an important development trend, which also raises the issue of interference between these two types of beams. To reduce their mutual interference, we can optimize the allocation strategy of communication resources for service and feeder-link beams, such as bandwidth, power and center frequency.

**Handover Management**

In LEO-SAN, handover can be classified into intra-satellite beam handover, inter-satellite beam handover and satellite-ground beam handover, as shown in Fig. 5. The high mobility of satellites and uncertainty of massive user movement bring new difficulties and challenges to handover management. It results in frequent beam recasting and handover, which greatly increases signal delay and handover cost, and severely affects user service experience. To address these problems, the handover management strategy can be enhanced from two aspects of single-user handover and group handover.

**Single-User Handover:** The handover decision is a critical phase in handover management to determine the user’s selection of the next beam. In the literature, the multi-metric handover decision method is widely adopted, by mainly considering receiving signal strength (RSS), service time, the shortest distance, channel resources, available bit rate (ABR), delay, relative speed, network overhead and so on. However, since the traditional method only considers the current state, it is difficult to solve the optimization problem of handover decision that is high-dimensional and highly dynamic, resulting in frequent but unnecessary handovers by users and reduction of the handover success rate. To solve this issue, it is possible to apply more advanced and accurate deep reinforcement learning methods to handover decision. In a deep reinforcement learning framework, the learning agent needs to establish a Markov decision process and maximize the long-term benefits by collecting and training experiences and rewards without knowing the environment in advance [11]. Specifically, the Markov decision process, as an important part of reinforcement learning algorithms, is usually established firstly by building the action set, state set and reward function. The action set contains all candidate base stations and satellites, and its dimension...
equals the number (N) of candidates. The state set is not only related to the candidate base stations and satellites, but also relevant to the metrics which influence the handover decision. Each metric indicator of every candidate represents one type of state, and thus the dimension of state set equals $K = N \times M$, assuming the number of metrics is M. The reward function provides the guidelines for the training of deep reinforcement learning neural network. The input of the neural network is a $K \times 1$ dimensional state set vector, and the output is an $N \times 1$ dimensional normalized action set evaluation (commonly referred to as the Q-value). The candidate with the largest Q-value is the best choice for that time slot. Furthermore, due to the limitation of computing resources on state-of-the-art satellites, the training centers are preferred to be placed in ground base stations or terminals to perform learning tasks with more computing power. For 6G networks, the LEO satellites are envisioned to possess more powerful computing ability to meet the future communication requirement, which can enable the deployment of training centers on the satellites. This, however, necessitates technical breakthroughs on both the payload carrying capability and power supply of LEO satellites in the near future.

**Handover:** The handover decision algorithm and handover process discussed above are mainly designed for the single-user scenario. Group handover is referred to that a group of users carry out handover together. As one LEO satellite moves out of its original coverage area at high speed, handover will be triggered by numerous users at the same time, which leads to severe handover request signaling storms and a significant increase in the probability of handover process collisions. Therefore, group handover has become a new research focus in LEO-SAN handover management. To avoid the handover request signaling storm on satellites, users can be clustered by location or business, and one representative can be selected as handover-triggering user carrying the information of other users in each group. Besides, in the process of numerous group handover, a high probability of collisions leads to a high handover failure rate. Therefore, the correlations between users, such as their handover sequence and so on, need to be fully exploited, while reinforcement learning method can be used to provide more efficient handover strategies.

**Beam Resource Management**

LEO-SAN usually relies on multi-beam coverage schemes to serve numerous users that may be distant from each other. It requires advanced beam resource management strategies to enhance the network performance. The beam resource management mainly concerns allocation strategies of available beam resources to massive users, which should aim at serving as many users as possible with limited beam resources on LEO satellites. Classical beam resource management schemes employ uniform resource allocation strategy for ground users. However, the uniform allocation method is inefficient under payload constraints and uneven distribution of requirements. Therefore, due to the conflict between efficient multi-dimensional resource scheduling and limited space-borne computing resources, how to coordinate beam resource scheduling in space, time, frequency, power and other domains will be a great challenge for future research.

In LEO-SAN, power and frequency resources are limited, while the number of beams is much smaller than the number of users. With the continuous and rapid growth of LEO satellite constellation scale, the variable dimension of multi-domain resource optimization becomes large rapidly, which increases the complexity of constellation resource scheduling. (Beam hopping involves joint optimization of beam pattern design method, power allocation and carrier allocation. We can jointly utilize the convex optimization method, matching theory, machine learning and Lagrange relaxation method for solving beam hopping problems. Compared with the traditional fixed beam resource allocation strategy, it can effectively improve network efficiency and achieve on-demand resource allocation by scheduling multi-dimensional resources such as beam, frequency band, time slot and power.

**Doppler-Resilient Transmission Technology**

In LEO-SAN, the high mobility of LEO satellites causes severe Doppler shift effects on the signal. For instance, the transmitted signals of LEO-SAN at the s-band experiences Doppler shift up to ±48 kHz, which is much higher than the typical initial UE oscillator inaccuracy (about 20 kHz) [4]. The strong Doppler shift can cause undesirable time-selective fast fading, results in performance degradation of channel estimation and signal detection. To this end, the current literature has focused on the estimation and compensation of Doppler shift, mainly based on classical modulation schemes like single-carrier modulation and orthogonal frequency division multiplexing (OFDM) technologies. However, there are still important problems remaining unsolved for effectively dealing with the substantial Doppler frequency shift, such as poor bit-error-rate performance, high inter-carrier interference and low pilot spectrum efficiency. Therefore, some novel Doppler-resilient communication waveforms, including orthogonal time-frequency space (OTFS) modulation [12] and vector OFDM (VOFDM) [13], have been proposed.

**Doppler-Resilient Transmission Technique for Single-Carrier and OFDM Modulation**

For a single-carrier modulation system, Doppler shift will increase the difficulty of receiver demodulation, and cause performance degradation. For OFDM and other multi-carrier transmission systems, Doppler shift can cause high inter-carrier interference and deteriorate signal detection performance. To solve the above problems, the...
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subcarrier interval can be increased to reduce the interference between subcarriers, or the pilot sequence length can be improved to improve the accuracy of Doppler estimation and compensation. However, the above methods will inevitably lead to the decrease of spectrum efficiency, which is difficult to meet the requirement of massive users for high-rate communication. Moreover, existing Doppler shift estimation and compensation algorithms depend on a high signal-to-noise ratio (SNR) threshold and slow variability of physical channel. Therefore, their performances can be degraded under high-maneuvering and long-distance scenarios of LEO satellite communications.

Emerging Modulation Scheme for Doppler Mitigation

In order to circumvent the challenges to mitigate Doppler effects using existing modulation methods as illustrated above, a new two-dimensional modulation scheme, namely OTFS, has been proposed [12]. Unlike classical time-frequency modulation formats, OTFS carries out modulation in the delay-Doppler domain. Consequently, OTFS is particularly more suitable for transmission over time-varying wireless propagation channels. This is because, by taking a series of two-dimensional transforms, the time-frequency doubly-dispersive channel is converted to the delay-Doppler domain with almost no channel fading. Figure 6 shows the bit-error-rate (BER) performance comparison between OTFS and classical OFDM under various levels of Doppler shifts. Different relative speeds between the space and ground transceivers (i.e., 0 km/h, 350 km/h, 500 km/h and 1000 km/h) are considered, and the LEO satellite at an altitude of 780 km moves at a speed of 25,560 km/h. In simulations, quadrature phase-shift keying (QPSK) is employed for modulation. Besides, the Fast Fourier Transform (FFT) size of OFDM is set as 256, while the size of transmitted symbol matrix in the delay-Doppler domain is set as 256 × 14 for OTFS. Moreover, the subcarrier spacing is 15 kHz and coding rate is 0.75. It is observed that, on one hand, OFDM suffers from poor communication performance due to strong Doppler shifts. On the other hand, OTFS is capable of achieving significant performance gain over classical OFDM, which validates its superiority in terms of Doppler-shift resistance. Furthermore, almost the same BER performance can be attained by OTFS at different speeds. This further demonstrates its robustness to various levels of Doppler shift effects. However, since the received signals equal the two-dimensional circular convolution between the modulated symbols and the channel coefficients in the delay-Doppler domain, it will be challenging for efficient design of the channel estimators and equalizers. These tasks can be even harder for OTFS systems equipped with large-scale antenna arrays, which is usually practical for LEO-SAN to compensate for the severe path loss.

In contrast, VOFDM [13] has been proposed as a general format of classical OFDM and single-carrier systems with single transmit antenna, with good robustness to the time-varying channels. Corresponding to the above example in Fig. 6, the OTFS transmitted sequence is equivalent to the VOFDM counterpart with the vector size of 14. Interestingly, the signals in either discrete or continuous format of VOFDM coincide with that in OTFS at the transmitter side [14]. Furthermore, when VOFDM utilizes the same receive algorithm with that of OTFS, the signals of VOFDM coincide with that in OTFS at the receiver side. Therefore, the BER performances of VOFDM and OTFS under different levels of Doppler shift are equivalent in our simulation. Next, we provide discussions explaining why OTFS (or VOFDM) is desirable to deal with the Doppler effects, from the VOFDM point of view. Explicitly, it has been shown in the literature that VOFDM can achieve multithread diversity and/or signal space diversity, even with the minimum mean square error (MMSE) linear receiver in a vectorized subchannel. This is because in VOFDM, at the transmitter side, a vector of information symbols is Discrete Fourier Transform (DFT) or inverse DFT (IDFT) transformed implicitly and then, at the receiver side, the information symbols in this vector are demodulated together. More specifically, since in VOFDM, a vectorized channel matrix is pseudo-circular, it can be diagonalized by DFT/IDFT matrix with a phase shift diagonal matrix (see formula (4.1) in [13]). Thus, this DFT (or IDFT) diagonalizing of a vector of information symbols is similar to the precoding in single antenna systems to attain signal space diversity to combat wireless fading or diagonal space-time block coding in multiple-input multiple-output (MIMO) systems to attain spatial diversity. The resultant diversity gain can effectively mitigate the time-selective channel fading caused by Doppler shifts.

Future Research Direction Toward 6G

With the continuous commercialization of 5G, 6G research is also in full swing. The LEO-SAN is expected to play an important role for the realization of future 6G wireless networks, which requires extensive further exploration. Therefore, we summarize some possible research directions to provide potential inspirations for the industry and academia.

Flexible Network Architecture and Virtualized Network Function (VNF) Deployment

For future development of LEO-SAN, the flexibility of network architecture is required to be further enhanced. In addition to lightweight ZN and virtualization of access networks, technologies such as software-defined network (SDN), network function virtualization (NFV) can also be used to flexibly deploy on-board RAN and CN VNFs, which can support effective load balancing, seamless handover and dynamic resource allocation in LEO-SAN.
EFFICIENT MASSIVE ACCESS

The LEO-SAN is expected to realize massive access for billions of global users in the future 6G networks, which faces a plethora of challenges including the contention for resources request, preamble collision, high signaling overhead and so on. These necessitate advanced technical solutions, such as the grant-free random access based on compressive sensing, which are envisioned to break through the user capacity limits of the classical random access counterparts.

ON-DEMAND BEAM MANAGEMENT

6G aims to achieve seamless global coverage and provide high QoS level for requesting users anytime and anywhere. Therefore, the signaling beams, service beams and feeder-link beams require highly efficient, real-time and dynamic management methods based on specific demands of the user terminals. To this end, the cutting-edge technologies such as artificial intelligence (AI), intelligent optimization and so on, can be introduced to the design of on-demand beam management strategies for LEO-SAN.

GROUP HANDOVER

In the future, as more LEO satellites move across each other at high speed, the user handover signaling storm and congestion will become more severe. To tackle this problem, the combination of group handover and machine learning is regarded as a promising solution to make the handover strategy more adaptable to dynamic scenarios and have more robustness.

INTELLIGENT REFLECTING SURFACE (IRS)

IRS is a large electromagnetic supersurface composed of a large number of low-cost passive reflection elements [15], which can reduce the hardware cost of the LEO-satellite-mounted transceiver by replacing the classical phased array antenna. However, the hardware constraints of IRS including the discrete phase shifts and the phase-dependent amplitude coefficient, causes performance degradation of analog beamforming, and poses great difficulties to the usage of quadrature amplitude modulation (QAM), which require detailed investigation.

SPACE-AERIAL-GROUND INTEGRATED NETWORK

LEO-SAN can be incorporated with both the aerial access network and ground-based access network, constituting the promising space-air-ground integrated network (SAGIN), which are expected to reach a new milestone of achieving ubiquitous coverage and superior data throughput. To facilitate its practical implementation, it is necessary to develop advanced strategies of seamless handover among networks, on-demand access, load balancing, connection management and so on.

CONCLUSION

LEO-SAN is expected to become a promising complementary technique to terrestrial cellular networks for future 6G wireless networks, due to its significant enhancement of capacity and signal coverage. This article provides an overview of the research development of LEO-SAN. Specifically, the existing problems of LEO-SAN are discussed from the aspects of random access, beam management and Doppler-resilient transmission technologies. These issues are mainly caused by the high mobility of LEO satellites and the long distance of satellite-ground links. This article also outlines some possible solutions to tackle these problems and motivate future research. It is hoped that this article will provide useful inspirations for the development of LEO-SAN technologies.

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REFERENCES

[1] H. Cui et al., “Space-Air-Ground Integrated Network (SAGIN) for 6G: Requirements, Architecture and Challenges,” China Commun., vol. 19, no. 2, Feb. 2022, pp. 90–109.
[2] O. Kodhe et al., “Satellite Communications in the New Space Era: A Survey and Future Challenges,” IEEE Commun. Survey Tuts., vol. 23, no. 1, 1st Qtr. 2021, pp. 70–109.
[3] B. Di et al., “Ultra-Dense LEI: Integration of Satellite Access Networks Into 5G and Beyond,” IEEE Wireless Commun., vol. 26, no. 2, Apr. 2019, pp. 62–69.
[4] X. Lin et al., “On the Path to 6G: Embracing the Next Wave of Low Earth Orbit Satellite Access,” IEEE Commun. Mag., vol. 59, no. 12, Dec. 2021, pp. 36–42.
[5] S. Liu et al., “LEO Satellite Constellations for 5G and Beyond: How Will They Reshape Vertical Domains?” IEEE Commun. Mag., vol. 59, no. 7, July 2021, pp. 30–36.
[6] A. Lallakshish et al., “Darkening Low Earth Orbit Satellite Constellations: A Review,” IEEE Access, vol. 10, Feb. 2022, pp. 24,383–94.
[7] G. RP-221745, “NTN Status Report,” Release 17, 3GPP TSG RAN Meeting, June 2022.
[8] Z. Gao et al., “Grant-Free Random Access in Massive MIMO-Based LEO Satellite Internet of Things,” Proc. IEEE/CIC Int’l Conf. Commun. China, Xiamen, China, July 2021, pp. 700–05.
[9] Z. Zhang et al., “User Activity Detection and Channel Estimation for Grant-free Random Access in LEO Satellite Enabled Internet of Things,” IEEE Internet Things J., vol. 7, no. 9, Sept. 2020, pp. 8811–25.
[10] A. Wang et al., “Joint Optimization of Beam-Hopping Design and NOMA-assisted Transmission for Flexible Satellite Systems,” IEEE Trans. Wireless Commun., May 2022.
[11] Z. Li, Z. Xie, and X. Liang, “Dynamic Channel Reservation Strategy Based on DQN Algorithm for Multi-Service LEO Satellite Communication System,” IEEE Wireless Commun. Lett., vol. 10, no. 4, Apr. 2021, pp. 770–74.
[12] R. Hadani et al., “Orthogonal Time Frequency Space Modulation,” IEEE Wireless Commun. Networking Conf., San Francisco, CA, Mar. 2017.
[13] X.-G. Xia, “Precoded and Vector OFDM Robust to Channel Spectral Nulls and With Reduced Cyclic Prefix Length in Single Transmit Antenna Systems,” IEEE Trans. Commun., vol. 49, no. 8, Aug. 2001, pp. 1361–74.
[14] Y. Ge et al., “OTFS Signaling for Uplink NOMA of Heterogeneous Mobility Users,” IEEE Trans. Commun., vol. 69, no. 5, May 2021, pp. 3147–61.
[15] B. Zheng et al., “Intelligent Reflecting Surface-Aided LEO Satellite Communication: Cooperative Passive Beamforming and Distributed Channel Estimation,” IEEE JSAC, vol. 40, no. 10, Oct. 2022, pp. 3057–70.

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