5G Integrated Radio Transmission Scheme for Low Earth Orbit Satellite Access Network

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2022 IEEE 22nd International Conference on Communication Technology (ICCT) | 978-1-6654-7067-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICCT56141.2022.10073001

***Abstract*—This paper comprehensively analyzes the channel transmission characteristics of the low earth orbit satellite. On this basis, the problems when each physical layer process of terrestrial 5G new radio is directly applied to the LEO satellite access network is further analyzed, then the feasible implementation schemes for each 5G integrated physical layer process of the LEO satellite access network are carefully designed. Furthermore, the core technologies of each key step of each 5G integrated physical layer process are briefly discussed.**

Keywords—LEO satellite Internet, 5G, NR, Initial cell search, Random access, Beam management, Adaptive transmission

I. Introduction

Low earth orbit (LEO) satellite Internet refers to a new type of network that uses LEO constellations to provide Internet access services anytime and anywhere for users around the world [1]. Compared with high earth orbit satellite networks, the LEO satellite Internet has lower transmission delay, lower link loss, higher transmission rate, and can achieve super-large system capacity through the giant constellation [2], [3]; Compared with the terrestrial networks, the LEO satellite Internet has the ability to provide global coverage and lower coverage costs than terrestrial networks for sparsely populated areas, and it also has transmission performance comparable to fiber-optic networks.

The combination of 5G cellular mobile networks and fiber-optic networks could provide high-speed and reliable Internet access to more than 60 percent of the world's population. There is no doubt that the terrestrial communication network has absolute dominant advantage in the densely populated cities and other areas. However, in the sparsely populated and unevenly distributed ocean, forest, desert and other remote areas where terrestrial communication networks cannot provide coverage or the coverage cost is too high, the LEO satellite Internet can provide low-cost and efficient Internet access services to these areas. Therefore, the integration of the LEO satellite Internet and 5G mobile cellular networks have become one of the important trends in the development of the satellite network, and also one of the important links of the 6G space-air-ground-sea integrated communication network [4]-[7].

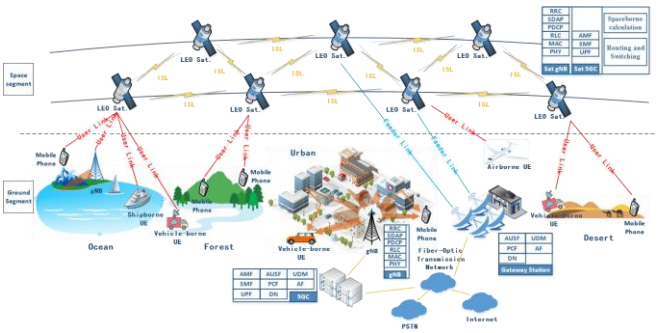

Fig. 1. Integrated architecture of the LEO satellite Internet and 5G cellular mobile networks

Since the unified integration of the terrestrial radio interface and the satellite radio interface is the core to enabling the users to seamlessly switch between the terrestrial network and the satellite network, this paper mainly focuses on analyzing and summarizing the key radio transmission technologies of the integrated 5G LEO satellite access network. The rest of this paper is organized as follows: Firstly, the channel transmission characteristics of the LEO satellite are

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comprehensively analyzed to provide boundary conditions for the adaptability analysis in Section II. Secondly, based on the analysis of channel characteristics of the LEO satellite, the problems faced by each physical layer process of 5G NR when applied to the LEO satellite access network are analyzed one by one, and the transmission scheme or improvement suggestion for the integrated 5G LEO satellite access network is also given in Section III. Finally, Section IV gives the conclusion.

II. Channel Characteristics of the LEO Satellite

The channel characteristics of the LEO satellite can be divided into large-scale fading, small-scale fading and propagation delay characteristics, as shown in figure 2.

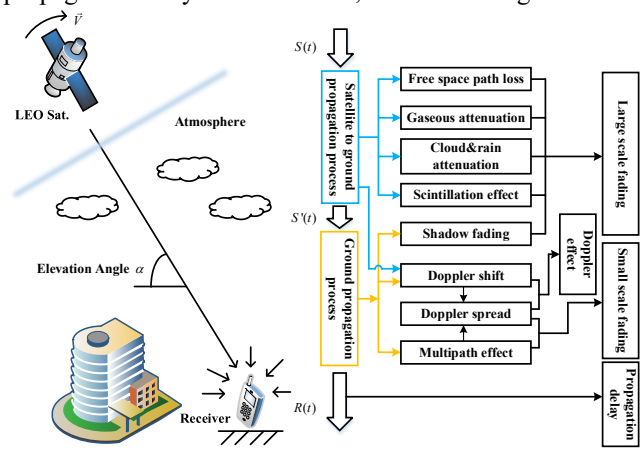

Fig. 2. Channel transmission characteristics of the LEO satellite

The weights of the above channel characteristics are different in different communication frequency operating bands, different communication elevation angles and different antenna types. This paper only considers the Ka frequency band for the broadband satellite access network. Consider the communication elevation angles ranging from 10 to 170 degrees and the antenna type is the phased array antenna, which can enhance the single beam transmission capacity based on beamforming and can also achieve the full coverage within the field of view of a single satellite through beam sweeping [8]. Figure 3 shows the large-scale fading characteristics of the LEO satellite under the above conditions.

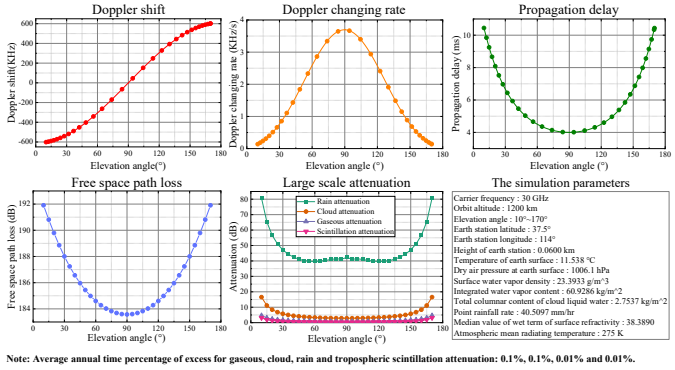

Fig. 3. Large-scale fading characteristics of the LEO satellite

Based on the simulation results in figure 3, the following conclusions can be drawn. Firstly, the 600KHz ultra large Doppler frequency offset exceeds the capability of traditional time-frequency initial acquisition algorithms, which will bring some challenges to the design of the time-frequency initial acquisition scheme, especially in the beam sweeping scenario. Secondly, the large change rate of Doppler frequency offset and the large propagation delay will also bring some challenges to the design of time-frequency tracking and random access schemes. Thirdly, the large and dynamic link loss will also bring some challenges to the design of the link adaptive transmission scheme.

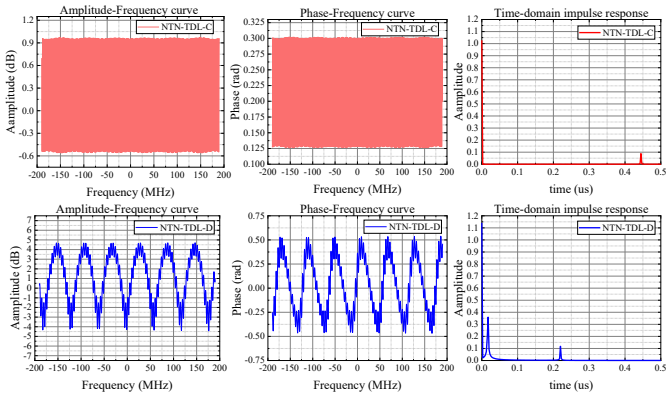

Fig. 4. Small-scale channel fading characteristics of the LEO satellite

The small-scale fading characteristics are mainly caused by the superposition of the signals received from different paths. For the Ka frequency band, the energy of the beam is more concentrated, which includes a direct path that obeys the Rice distribution and few indirect paths that obeys the Rayleigh distribution. Therefore, this paper only considers the NTN-TDL-C/D channels suggested by the 3GPP TR 38.811 [4].

It can be seen in figure 4 that the amplitude and phase change with the frequency, both NTN-TDL-C and D channels exhibit frequency selection characteristics under the condition of 400MHz bandwidth. It is necessary to insert more pilots on the frequency-domain for a more accurate channel estimation. Moreover, if the UE is moving at high speed, the channel will further exhibit fast fading characteristics in the time domain. The time-frequency dual selection characteristics of the above LEO satellite channel will bring challenges to the design of the channel measurement scheme.

III. 5G Integrated Radio Transmission Scheme Fro LEO Satellite

A. 5G based initial cell search scheme for LEO satellite

1) Cell configuration: LEO satellites have far greater coverage than the 5G base stations (gNBs), and the number of beam footprints in the field of view of a single satellite far exceeds the support capacity of 5G's maximum 64 beam footprints. Obviously, it is not feasible to use a single satellite as a cell, but it is possible to configure a satellite beam footprint as a cell.

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2) SSB burst configuration: The number of synchronization signal block (SSB) in the 5ms SSB burst must be configured based on the link budget for the applied downlink time-frequency synchronization scheme. In addition, the Type-0 PDCCH and SIB1-PDSCH corresponding to each SSB should also be included in the SSB burst to ensure that the user equipment (UE) can obtain the minimum system information by sweeping that beam footprint only once.

3) Efficient initial downlink synchronization scheme: The initial downlink synchronization can be achieved by GSCN search to find the carrier center frequency of SSB, frequency offset preset to overcome the Doppler frequency offset caused by the high speed movement of the LEO satellite, PSS based cross-correlation and CP based frequency offset estimation to achieve the time-frequency synchronization. However, the synchronization efficiency of the above scheme is low in beam sweeping scenario of the LEO satellite. In particular, the GSCN search process is extremely time consuming, in order to eliminate the GSCN search process and reduce the frequency offset search range, it is a simple and feasible implementation scheme to provide the prior information, such as orbit position and velocity, of the LEO satellite for UE with the help of satellite TT&C system and GNSS system.

B. 5G based random access scheme for LEO satellite

1) Beam management: The initial random access of 5G consists of four steps, and at least two rounds of interaction between the 5G gNB and the UE are needed to complete the access. The number of beam footprints of the LEO satellite is huge, and the round-trip propagation delay is much longer than that of the 5G. Using only the signalling beam to complete the 4-step random access requires waiting at least three beam sweeping periods under the condition that the phased array antenna can simultaneously transmit signal to and receive signal from different beam footprints, otherwise, at least five beam sweeping periods is required.

In order to reduce the number of beam sweeping periods and improve the utilization efficiency of service beams, it is an efficient method to combine signaling beam and service beam to complete the 4-step random access process. The signaling beam is used to transmit the MIB, SIB1, Msg1 and Msg2, after that, the idle service beam is scheduled to gaze at the service beam footprint where the UE is located to complete the subsequent transmission of Msg3 and Msg4. Note that SIB1 should include the service beam footprint information related to the UE location information and the preamble sequence sets information bound to the service beam footprints.

2) Uplink frequency offset compensation: It is impossible to complete the PRACH detection when the Doppler frequency offset is far more than the value of 1/2 Sub-carrier spacing (SCS) of the PRACH.

$$\Delta f_{DL} = \frac{v_{gNB2UE}}{c} \cdot f_{DL}, \quad \Delta f_{UL} = \frac{v_{UE2gNB}}{c} \cdot f_{UL} = \frac{f_{UL}}{f_{DL}} \Delta f_{DL} \tag{1}$$

The uplink Doppler frequency offset Δf_{UL} is equal to that of the downlink Δf_{DL} when the velocity v_{gNB2UE} of the gNB pointing to the UE is equal to the velocity v_{UE2gNB} of the UE pointing to the gNB, as shown in equation (1). In fact, due to the dynamic large propagation delay and the long period for beam sweeping, there is a certain range of deviation between Δf_{UL} and Δf_{DL}. Therefore, the SCS and detection algorithm of the PRACH should be designed to meet the anti-frequency offset requirement.

3) TA estimation: The maximum round-trip delay difference ΔRTD_{max} of the LEO satellite cell is far beyond the tolerance range of the 5G preamble format, where the length T_{CP} of cyclic prefix (CP), cyclic shift step N_{CS} and the length T_{GT} of guard time should meet the requirements of equation (2).

$$\begin{aligned} &T_{CP} > \Delta RTD_{\max} + T_{DS} + T_{DL_TE} \\ &N_{CS} / L_{RA} > (\Delta RTD_{\max} + T_{DS} + T_{DL_TE}) / T_{SEQ} \\ &T_{GT} > \Delta RTD_{\max} \end{aligned} \tag{2}$$

Where T_{DS} is the multipath delay spread, T_{DL_TE} is the downlink timing error, and T_{SEQ} is the length of a single data field of a certain preamble format.

The most direct way to solve the above problem caused by the large ΔRTD_{max} is to provide timing advance (TA) prior information for the UE with the help of the satellite TT&C system and GNSS system. Thus, the spaceborne gNB can directly adopt the preamble format and the frequency domain based detection algorithm of 5G under the condition that the deviation between the TA prior information and the round-trip delay of a specific UE is smaller than T_{CP} of the adopted preamble format.

Other methods include redesigning the preamble format [9] that meet the constrains of equation (2), and the time domain-based preamble detection [10].

4) Dynamic TA update: There are two types of TA update strategies [11]. The first type is the open-loop TA update strategy, where the TA is calculated by the ephemeris information and UE's location information, this strategy requires real-time updated precise ephemeris information and real-time updated precise location information of the UE to ensure that the calculated TA error can meet the performance requirements of OFDM demodulation; The second type is the closed-loop TA update strategy, the TA is measured by the periodically transmitted uplink signals and will be sent to UE through the spaceborne gNB, then the UE adjusts the sending time of the signal based on the feedback information of TA value.

C. 5G Based Service Data Adaptive Transmission Scheme for LEO Satellite

1) Service data adaptive transmission flow: The large propagation delay will bring very high implementation cost when applying HARQ to the LEO satellite. the root cause of this problem is the data retransmission, during the process of waiting for the retransmission feedback, a large number of

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caches are needed to store the newly arrived data, and more threads are needed to ensure the priority transmission of high-QoS service data.

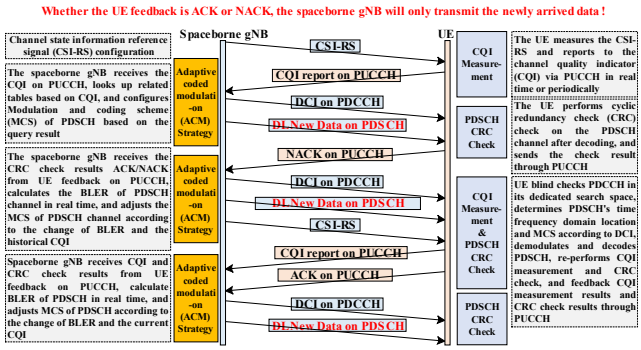

Fig. 5. 5G based service data adaptive transmission flow for LEO satellite

Based on the above analysis, the downlink service data adaptive transmission flow as shown in the figure 5 is designed, where the data retransmission function of HARQ is deleted, but the CRC check feedback function is retained. The advantages of this design are not only greatly reducing the implementation cost, but also reducing the loss of BER/BLER performance caused by the cancellation of data retransmission.

2) Channel estimation: Under static or quasi-static channel conditions, after completing a series of simple and classic operations of the least square (LS) based frequency domain response estimation for polit symbols, linear interpolation for data symbols, channel impulse response (CIR) denoising, and averaging and interpolation in frequency and/or time direction, very accurate channel estimation can be achieved with less pilot overhead. However, in the case of fast time-varying channels, such as the signal is sent to a high-speed UE via the NTN-TDL channels, the performance of the above classical channel estimation method will decrease sharply. Although the performance loss can be compensated by inserting a large number of pilots, the spectrum efficiency will be seriously degraded. Therefore, it is necessary to design a channel estimation method suitable for fast time-varying channels to ensure efficient communication in high-speed moving scenarios under the coverage of LEO satellites.

3) Adaptive MCS switching strategy: The fixed threshold based MCS switching strategy is optimal only when the CSI is accurately measured and timely feedback. The large-scale and small-scale channel fading characteristics of LEO satellites change dynamically all the time, so it is difficult to ensure the accurate measurement of CSI, Especially in the low SNR range. When the error of the measured CSI is large, the performance of the ACM scheme based on the fixed threshold switching strategy will be greatly reduced, therefore, It is necessary to design an accurate SNR estimation algorithm in the large range of SNR. The scenario covered by the LEO satellite is ever-changing, and the ACM scheme based on the fixed threshold switching strategy has poor robustness performance, which is difficult to adapt to dynamic changing scenarios. Therefore, it is necessary to use AI to design the robust adaptive switching strategy for multiple scenarios.

IV. Conclusions

This paper comprehensively analyzes the large-scale, small-scale and propagation delay channel transmission characteristics of the LEO satellite. Based on the above analysis and the beam configuration characteristics of LEO satellites, the problems when each physical layer process of the terrestrial 5G NR is directly applied to LEO satellite access network is further analyzed, then the feasible implementation schemes for each physical layer process are carefully designed. Furthermore, the core technologies of each key step of each physical layer process are briefly discussed. This research work provides a feasible 5G integrated radio transmission scheme for the LEO satellite access network, we believe that it will promote the realization of the future 6G space-air-ground-sea integrated communication network.

Acknowledgment

This study is supported by the Hebei Province High-level Talent Funding Project (B2021003032) and the Science and Technology on Communication Networks Laboratory Foundation project (FFX22641X010, HHX22641X003 and SCX21641X1009).

References

[1] C. E. Fossa, R. A. Raines, G. H. Gunsch and M. A. Temple, "An overview of the IRIDIUM (R) low Earth orbit (LEO) satellite system," Proceedings of the IEEE 1998 National Aerospace and Electronics Conference. NAECON 1998. Celebrating 50 Years (Cat. No.98CH36185), 1998, pp. 152-159.

[2] Y. Su, Y. Liu, Y. Zhou, J. Yuan, H. Cao and J. Shi, "Broadband LEO Satellite Communications: Architectures and Key Technologies," in IEEE Wireless Communications, vol. 26, no. 2, pp. 55-61, April 2019.

[3] I. Leyva-Mayorga et al., "LEO Small-Satellite Constellations for 5G and Beyond-5G Communications," in IEEE Access, vol. 8, pp. 184955-184964, 2020.

[4] 3GPP TR 38.811. "Study on new radio (NR) to support non-terrestrial networks." 3rd Generation Partnership Project; Technical Specification Group Radio Access Network.

[5] 3GPP TR 38.821. " Solutions for NR to support non-terrestrial networks (NTN)" 3rd Generation Partnership Project; Technical Specification Group Radio Access Network.

[6] W. Saad, M. Bennis and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," in IEEE Network, vol. 34, no. 3, pp. 134-142, May/June 2020, doi: 10.1109/MNET.001.1900287.

[7] T. Darwish, G. K. Kurt, H. Yanikomeroglu, M. Bellemare and G. Lamontagne, "LEO Satellites in 5G and Beyond Networks: A Review From a Standardization Perspective," in *IEEE Access*, vol. 10, pp. 35040-35060, 2022.

[8] S. C. Jin, S. H. Zhang, F. Gao, B. Wu and Z. Cui, "High Integration Ka-band Multi-beam Antenna for LEO Communication Satellite," *2021 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, 2021, pp. 1-3.

[9] L. Zhen, et al., "Preamble Design and Detection for 5G Enabled Satellite Random Access," IEEE Access, vol. 8, pp. 49873-49884, March, 2020.

[10] Z. Zheng, D. Wang, L. Liu, et al., "Robust Random Access Preamble Detection Scheme for 5G Integrated LEO Satellites Communication Systems", IEEE ICCT, November, 2022.

[11] Technical Specification Group Radio Access Network; Physical layer procedures for control; NR; Physical layer procedures for control (Release 17), document 3GPP TS 38.213, 2022.

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