Joint Investigation on Routing and Transmission Performance for Dynamic Low-Earth-Orbit (LEO) Optical Networks

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Abstract: We set up the joint simulation system for the mega-constellation, performing comprehensive investigations on dynamic routing and transmission performance. The best delay result and received quality were simultaneously observed through the Dijkstra strategy.

1. Introduction

The giant low-earth-orbit (LEO) constellation as a promising candidate to offer the capability of the network accessing all over the earth has attracted extensive attentions in recent years, especially after the commercial success by SpaceX [1,2]. The LEO system has also been considered as an effective approach to implement the next-generation 6G network, supporting the high-bandwidth wireless accessing and information delivering [3]. Therefore, the networking performance in LEO system, both over the radio-frequency (RF) and the optical laser (OL) was intensively investigated [4]. With the increase of the LEO constellation scale, the ultra-high bandwidth is necessary to the satellite systems. The free-space laser communication between satellites becomes the only solution to such high performance, although the much higher transmission loss suffered in the laser carrier [5]. The investigations on the giant LEO have focused on the routing strategy, networking form or satellite-end upgrading [6]. The few works are on the transmission performance, which could be used to quantify the signal quality when passing through the selected routing path. In this paper, we carry out the joint optimization by connecting the routing strategy and the signal quality, to reveal the dynamic transmission performance for the real LEO optical networks. The results show that the optimized delay of 48.75ms and the signal quality of EVM=9.21% could be simultaneously achieved by the routing strategy of the shortest path algorithm. The severe degradations would be further observed when the sun outages and the doppler frequency shift happened in the LEO transmission system.

2. Simulation platform

The joint simulation on routing and transmission performance for the giant LEO system includes three parts: constellation construction, delay performance and channel quality metrics, depicted in Fig. 1. We perform such comprehensive simulation by combining the satellite simulation platform system (SSPS), MATLAB, Python and VPI. The former two platforms were used to extract the constellation information from the dynamic LEO system, and assist the other two platforms to complete the functional verification, e.g., dynamic routing and quality measurement. Firstly, we customized the parameters of the satellite constellation with over 1000 satellite nodes as our previous work [7]. Then, we extracted the topology structure of the mega-constellation through the co-simulation of SSPS and MATLAB, and obtained the constellation information. The position information could be used to form the visualization of the topology structure, and the delay information was set as the path weight on the network topology. Subsequently, we input these data into Python to analysis the network delay performance

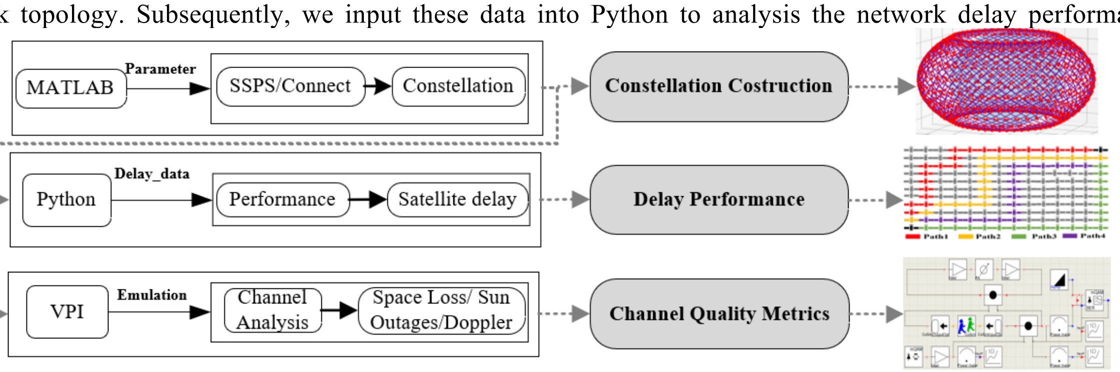

Fig. 1. The architecture of the joint simulation on routing and transmission performance for the giant LEO system

between nodes. Channel simulation was carried out according to the different routing strategy, and the signal quality of the QPSK through the free space channel was measured. Furthermore, three typical distortions, i.e., the free space loss, the sun outages and the doppler frequency shift were investigated in the home-made VPI system "dynamic satellite laser transmission" based on the collected data from other three platforms.

To measure the signal quality under different routing strategy, especially for the dynamic space topology, we established the satellite laser transmission system based on the collected connection information and the free-space channel model. In the simulation, we considered the free space loss, the sun outages, the doppler frequency shift and the amplifier spontaneous emission (ASE) noise as the major distortion sources [8]. The first three factors come from the propagating channel, and the last one is induced by the optical amplifier used in the satellite node. Equations (1-3) represent the three channel factors to impact the signal quality [9,10]:

$$P_r = -92.44 - 20\lg(d) - 20\lg(f_c) \tag{1}$$

$$P = \frac{E \cdot A \cdot \{\cos[\theta_s(t)] + \cos[\theta_s(t)]\}}{2} \tag{2}$$

$$E_{out}(t) = E_{in}(t) \cdot e^{j2\pi\{f_c \frac{v(t)\cos[\theta_d(t)]}{c}\}t} \tag{3}$$

where d represents the transmission distance (km), and f_c is the carrier frequency (GHz). Besides, θ_s indicates the elevation angle and A characterizes the size of the antenna aperture area. The radiation power of the sun shining on the satellite surface can be obtained by Eq. (2). $v(t)$ and θ_d(t) are the relative velocity and relative angle of inter-satellite motion in Eq. (3). It can be seen from Eq. (1) that the space loss is sensitive to the transmission distance and the carrier frequency. Therefore, the power budget for the satellite laser communication should be higher than the RF case. For a typical relay-distance of 500km, the power loss is up to 250dB when the carrier frequency is 1550nm.

Figure 2(a) depicts the communication scenario from Beijing to New York, which contains the major propagating path through the inter-satellite link (ISL). The discussion focuses on the ISL part, including the routing selection and the signal quality measurement. We used the Dijkstra scheme to select the shortest path between the source satellite (receiving the data from Beijing) and the destination satellite (sending the data to New York). The path information, including the dynamic connection and the delay results was compressed into the path tool in Python platform and the link information to the VPI system-dynamic satellite laser transmission, to calculate the transmission results. Due to the time-varying topology of LEO system, the results would also be the function of the delivering time. Figure 2(b) shows the frame structure of the satellite laser communication system. In the system, the power loss would be compensated through the gains from both the optical amplifier and the antenna [11]. Figure 2(c) depicts the loss results through different carriers, further confirmed the 250dB loss expected for the laser transmission.

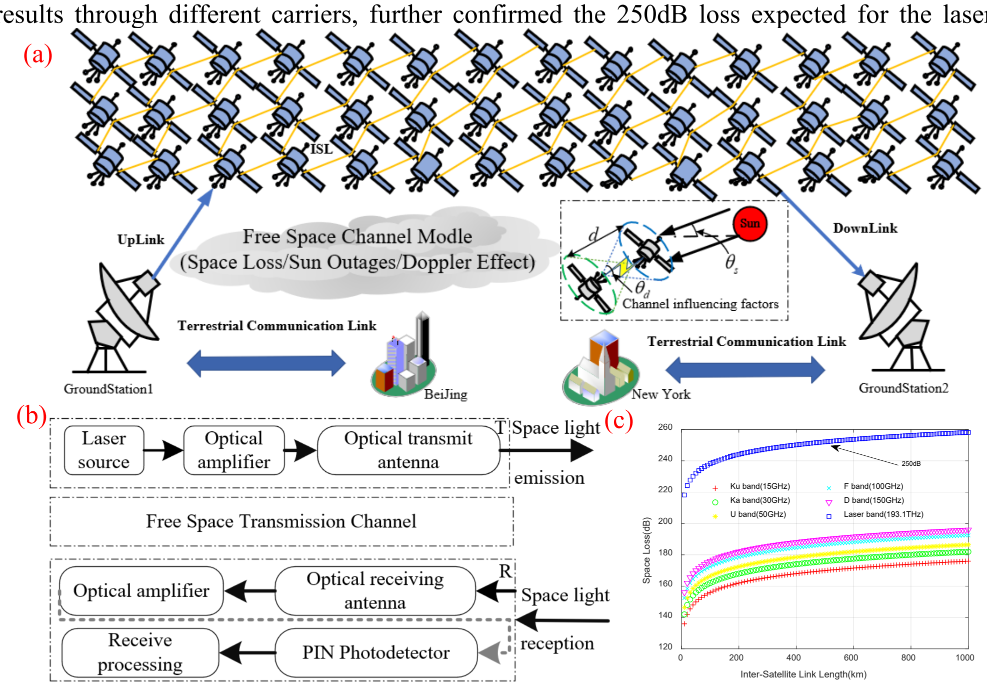

Fig. 2. (a) Satellite Internet communication scenario;(b) Laser communication system structure;(c) Friis free space loss results

3. Results and discussion

Both the routing selection and the transmission quality are investigated by our system for the laser-communication scenario between Beijing and New York (B-NY). We used the Dijkstra routing strategy to select the path in the time-varying satellite topology networks. Based on the giant LEO constellation, the minimum delay was 48.75ms and the number of the relay satellites/jumps was 16, depicted in Fig. 3(a). We also selected four other paths to give a compassion, see the delay results and the jumps in the same figure. The best delay performance was expected by the shortest path selection, consequently the less jumps observed. The time-varying topology nature leads to the dynamic routing behavior. In Fig. 3(b), we collected the whole delay results across the entire communication windows of 5731s, and obtained the variation on the delay results despite the Dijkstra strategy applied. To each slice of the propagating time, the LEO topology is quite different, leading to the routing switching and the delay variation. Therefore, the simulation results given in Fig. 3(b) are the best delay achieved in B-NY, ranging from 47.8ms to 50.7ms. To reduce the switching frequency, the proper threshold could be defined as [12]. Then, we input the routing information into the VPI platform, measuring the signal quality. In Fig. 3(c), the error-vector-magnitude (EVM) results are depicted for the dynamic communication process. In this case, the transmission loss of 250dB was only considered, and the optical amplifier with the noise figure (NF=5dB) was used in the satellite node to restore the power level. According to the simulation results, the EVM of $9.21 \pm 1\%$ is obtained when the transparent transferring behavior happened in the satellite. Fig. 3(d) depicts the comparison between the optimized path and the other four paths. The best EVM is observed at the shortest-path case, lower 2.17% than path 4. Therefore, the best delay result and the transmission performance are achieved at the optimized routing selection. When the sun outages and the doppler shift are considered into the channel model, the worse signal quality is calculated in Fig. 3(e) and (f). To further mitigate the impact from these factors, the all-optical or digital processing measures are required.

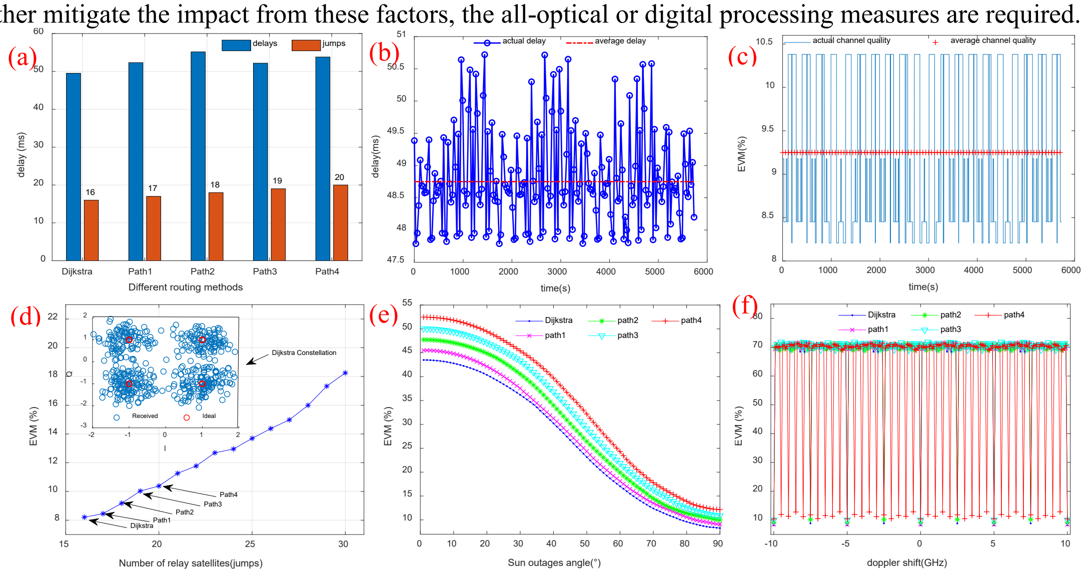

Fig. 3. (a) Delay and jump results in different paths; time-dependent (b) delay and (c) EVM results under Dijkstra; (d) EVM comparison for different routings; (e) sun outages and (f) doppler frequency shift comparisons for different routings.

4. Conclusion

We carry out a comprehensive study on the transmission delay and the transmission performance of the giant LEO system. The simulation results show that under Dijkstra algorithm the best delay result and the received quality are simultaneously achieved.

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