Delay-minimized Distributed Sequence Routing for Satellite Optical Networks

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Abstract: A sequence routing algorithm based geographical information is proposed to reduce delay in satellite optical networks. The simulation results show that compared with the static topological routing algorithm, the average delay is reduced by 30%.

1. Introduction

Currently, the scale of low-earth-orbit (LEO) satellites constellation is gradually expanding, with SpaceX planning to launch approximately 42,000 satellites into near-earth orbits at altitudes of 350 to 550 kilometers. Each satellite is equipped with four laser terminals, and they can establish links between satellites based on the Acquisition, Tracking, and Pointing (ATP) process. The detailed procedure includes initial line-of-sight alignment, acquisition, coarse tracking, fine tracking, and precise targeting, forming laser links.

The traditional routing algorithm based on centralized control architecture has the problems of delay in routing update, lack of flexibility in control and high delay cost. The centralized architecture generates a large load at a single point, and the overall control structure is relatively fixed. The amount of computation at a single point also increases, resulting in a delay in routing updates. When establishing links, the point-to-point connection mode is adopted. With the increase of distance, the link establishment delay will gradually increase. One way to do this is to build control planes for different functions, reducing the complexity of single-point processing and improving computational efficiency [1]. When dealing with long-distance routing, regionalized management can bring about higher computational efficiency and improved timeliness in routing [2]. However, for the huge low-orbit satellite optical network, the delay caused by establishing links is also a key part.

This paper introduces a distributed sequence routing method that segments LEO satellite optical networks geographically to diversify the topology structure. Through an SDN controller at the regional center, source and destination domain information received from the ground control center is subjected to distributed precomputation. Simulation results demonstrate reduced path calculation delay and decreased link establishment delay.

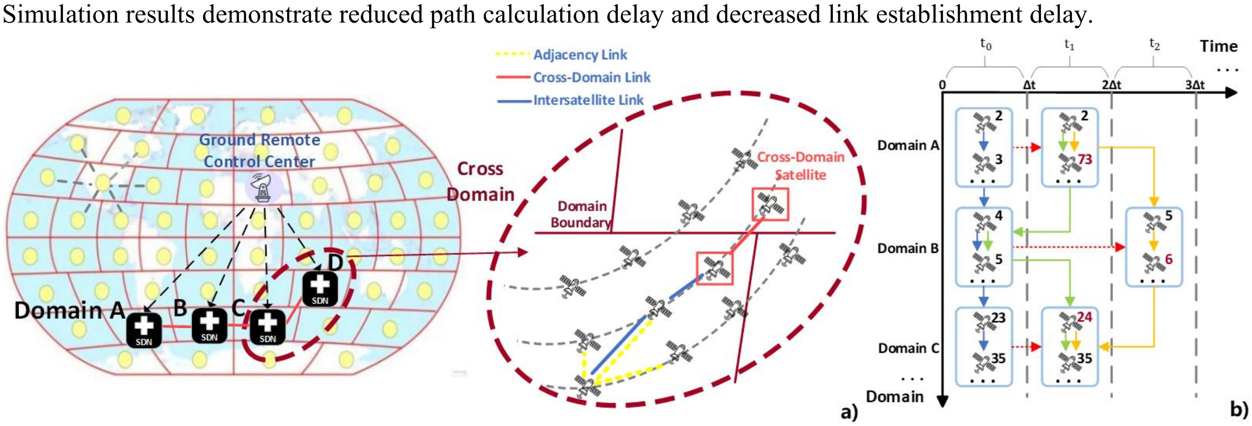

Fig. 1. (a) The link diagram of distributed sequence routing based on geographic location division of control plane is established. (b) Domain-sequential routing sequence switching.

2. Laser Communication Model

The operating period of the satellite is divided into t_{all} time slots, with each slot representing 1 second. We define the path change rate as λ that is expressed as a percentage and is denoted by,

$$\lambda = \frac{1}{t_{all}} \sum_{i=1}^{t_{all}} \alpha_i \times 100\% \quad (1) \qquad \overline{d_{all}} = \overline{d_c} + \frac{\lambda}{100} \times d_s \quad (2)$$

where α indicate whether the path has changed. The value of α equals 1 when the path changes, otherwise is 0. The quantifies the average number of shortest path changes from the source node to the target node.

The laser inter-satellite links (LISL) delay d_{all} split into two components, the communication delay, and the LISL setting delay. If the path changes, the end-to-end delay includes the LISL setting delay. According to the settings related to ATP, in long-distance communications such as satellite communication and ground-to-satellite communication The stability and high-quality transmission of the laser communication link should be ensured when the operation of alignment, acquisition, tracking and aiming is carried out. Real-time monitoring and adjustments may be performed, with the delay d_s allocated for ATP processes typically about 100ms.

The communication delay d_c includes propagation delay and node delay. The node delay encompasses both processing delay and queuing delay. The propagation delay is determined by summing the lengths of all laser links along the shortest path and dividing it by the speed of light in a vacuum. The node delay is considered as 1ms [3].

The LEO segment is comprised of LEO satellites, and the ground segment includes ground stations used for source and destination node calculations. To adapt to the dynamic characteristics of satellite constellations, we need to divide time period into sufficiently fine-grained time slots, ensuring the accuracy of real-time links while considering the visibility range of the links.

In our control architecture, the remote-control center receives service information from the ground station and sends it to the SDN controller within each domain. These controllers are responsible for receiving and fusion control signals from the control center. They then transmit the compiled data flow with identified transmission directions to the satellite using the southbound interface protocol within the respective domain.

3. Distributed Slicing Sequence Routing for LEO Satellite Optical Network

3.1. Domain partition method

Divide the Earth's surface into multiple small grids based on satellite orbit. Each grid is abstracted as a domain, and adjacent grids are different domains. The celestial sphere housing the satellite constellation is divided into multiple grids, and the relative positions between these grids remain constant. In the meshing process, different shapes are selected based on given mesh requirements. Fig. 1(a) shows that a more diverse topology can be achieved using a mixed mesh.

The remote-control center calculates routes for domains and provides a domain-level path. This is done by treating each domain on the map as a vertex, where the distance of the virtual Inter-Satellite-Link (ISL) serves as the edge weight. Additionally, it establishes a space coordinate system with the center of the Earth as the origin.

The center of the domain in the grid represents the spatial coordinate. Since the position of the domain remains constant, only the relative distance between the two domains is calculated as the weight, denoted as,

$$arc\_d_{ij} = 2 \times sin^{-1}\left(\frac{d_{ij}}{2 \times (r+h)}\right) \times r \tag{3}$$

where r is the earth radius, h is the orbit height, and the distance weight between domains is determined using the arc distance formula.

3.2. Based on the geographic location distributed slicing sequences routing

To speed up the calculation of distributed routing, the domain level routes are calculated first, and the shortest path is calculated according to the domain division. Then the star routing calculation is carried out, and temporary cross-domain nodes establish for each domain along the sequence path mentioned earlier. This division method includes both longitude cross-domain and latitude cross-domain divisions. Different baseline standards are defined based on the type of cross-domain to minimize cross-domain consumption.

When dealing with cross-domain operations that involve latitude cross-domain and irregular regional divisions, always seek the correct longitude value for the low-latitude domain to determine if it falls within the longitude span of the next domain in the path. If it falls within this range, use that value as the longitude baseline. Otherwise, use the longitude value on the left as the baseline. In cases of latitude cross-domain operations with regular regional divisions, where the longitude intervals between consecutive domains are equal, the midpoint of these intervals is selected as the longitude baseline. For cross-domain operations involving longitude cross-domain, where the latitude intervals between preceding and succeeding domains are the same, the midpoint of these intervals is chosen as the latitude baseline.

SDN controllers in different domains obtain temporary inter-domain node information from a remote-control center. The controllers simultaneously launch data to establish laser links, reducing the time they consume and aiding in creating a satellite topology for distributed routing within the region. The range of satellite laser communication includes four values, 1500 kilometers, 1700 kilometers, 2500 kilometers, and 5016 kilometers. Based on a visual range of 2500 kilometers, internal topologies of domains can be configured, resulting in shorter propagation delay compared to traditional static topologies.

The storage method, as shown in Fig. 1(b), records only the satellite sequence within the domain and updates only the link of a specific domain during switching. This approach allows for more efficient resource utilization while maintaining switching delays similar to those of storing the global routing table.

4. Simulation Results

We simulated the first-phase version 2 satellite constellation AGI on the System Toolkit (STK) platform for Starlink. This constellation comprises a total of 1584 satellites. The orbital altitude is 550 km, and the inclination angle is 53° [5]. We compared three algorithms: equidistant location-based distributed slicing sequences routing (EDSR), global shortest path routing (GSPR), and geographic location distributed slicing sequences routing (GDSR).

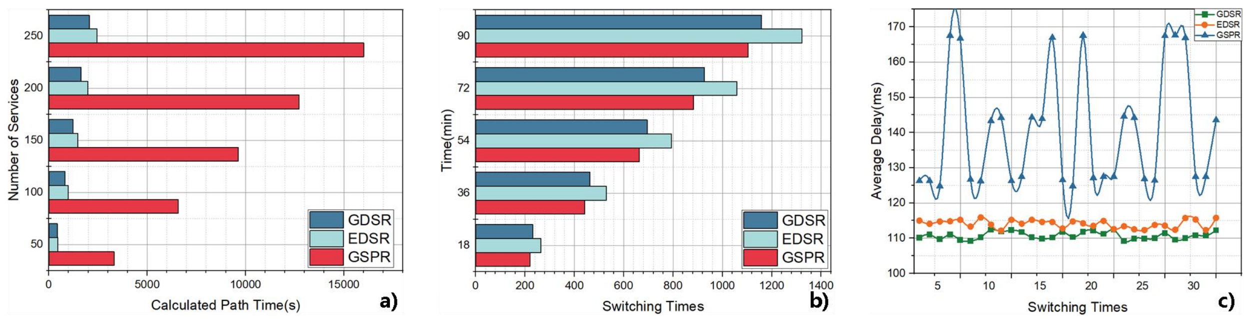

Fig. 2. (a) Calculate the path time required for random service generation. (b) Maintain the number of switches generated by service communication. (c) Generates a comparison of the total average delay when switching.

Service communication traffic, generated with a Poisson distribution, was injected into these algorithms, with session durations following an exponential distribution. The results represent the averages from 10 experiments. In Fig. 2(a), both GDSR and EDSR pruned the satellite topology graph, resulting in a significant reduction in data processing times compared to GSPR. GDSR further enhanced pruning operations, improving data processing efficiency.

In Fig. 2(b), assuming a laser communication range of 2500 kilometers, we studied handovers during continuous 90-minute communication for Terrestrial-Satellite (T-S) and Satellite-Satellite (S-S) connections. It can be observed that the handover frequency between GDSR and GSPR is relatively close. The reason for the discrepancies is due to additional handovers when satellites move out of their domains.

Fig. 2(c) compares the total delay for 30 toggles for the same type of service. The reason for the fluctuations in GSPR is the fixed topology and links. In contrast, GDSR and EDSR only involve pruning results of satellite topological structure map and can calculate real-time optimal solutions. Additionally, each SDN controller can transmit signals to cross-domain nodes, enabling the simultaneous establishment of laser links in different domains and reducing link establishment delay.

5. Conclusion

We propose a distributed sequential routing algorithm for satellite optical networks based on geographical location, which can increase control flexibility, improve the timeliness of updating routes, and reduce delay cost while ensuring fewer switching times.

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