SLSA: A Link Stability Based Algorithm for the Topology Optimization of IGSO/MEO Double-Layered Satellite Network

Kun Li, Huachun Zhou*, Zhe Tu, and Guanglei Li
School of Electronic and Information Engineering
Beijing Jiaotong University, Beijing, 100044, China
{19111021, hchzhou, $\text{zhe}_t u$, 15111035}@$bjtu.edu.cn$

Abstract

With satellite networks playing an important role in many areas, how to design a satellite network topology and interconnect with terrestrial networks has also attracted widespread attention. However, due to the high mobility of the satellite nodes and the limited number of connected antennas, it is challenging to effectively construct a fixed network topology with stable link quality during the satellite operation period. In this paper, we propose a satellite link stability based algorithm (SLSA) for the topology optimization, which is based on link stability to generate Inclined Geosynchronous Satellite Orbit / Medium Earth Orbit (IGSO/MEO) double-layered satellite network (DLSN) topology. SLSA aims to build a stable topology with uninterrupted link connection and low transmission delay to reduce the extra transmission delay caused by frequent interruptions under the condition of the limited number of satellite links. We compare SLSA with the shortest path based topology generation method, implement the simulation topology and conduct contrast experiments. The experimental results verify that SLSA has longer connection time and lower transmission delay than the traditional method.

Keywords: Double-Layered Satellite Network, SLSA, Link Stability

1 Introduction

Since double-layered satellite network (DLSN) can combine the advantages of both low-orbit satellites and high-orbit satellites, it can achieve better transmission performance by interconnecting with terrestrial networks, which has become a research hotspot for satellite networks [**?**]. However, the network topology changes dramatically in DLSN. Not only are the links between the constellations of low and medium orbit satellites periodically switched, but the inter-satellite links between the inter-orbiting satellites change more frequently with the high-speed relative motion of satellites. In addition, the topology changes will cause routing failures, thereby affecting the energy consumption, latency, and throughput of satellite networks [**?**]. Therefore, constructing a stable topology with long link connection time and less dynamic switching plays an important role in improving the overall performance of the satellite network. However, Many algorithms pay more attention to the dynamic switching of inter-satellite links. It is difficult to construct a fixed network topology with uninterrupted link connection and low transmission delay. In this paper, we first establish a two-layer satellite network link visibility model based on IGSO/MEO. Then, comprehensively considering the mobility of satellite nodes and the limited number of inter-satellite links, we propose a topological optimization algorithm based on satellite link stability and establish a simulation experiment, and its performance is compared with existing methods.

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*Corresponding author: Huachun Zhou, Beijing Jiaotong University, No.3 Shangyuancun, Haidian District, Beijing 100044, China, Tel: +86-137-1816-8186

The rest of the paper is organized as follows. Section 2 reviews the related work. Section 3 describes a DLSN model. Section 4 presents a topology optimization algorithm based on satellite link stability. In section 5,we simulate the topology and analyze the experimental results. Finally, Section 6 sums up the paper and presents our future work.

2 Related work

Recently, many researches have focused on the establishment of models based on architectural design or topology modeling based on space-ground integrated networks. With regard to the former, Shi et al.[?] designed a multi-layer satellite-terrestrial network architecture, and proposed a traffic-aware inter-layer contact selection method. Shi et al.[?] proposed an integrated network architecture for satellite communications to handle cross-layer data transmission problems in a generalized manner. However, they did not consider the scarcity of spatial information resources, and it is difficult to meet the limitation of inter-satellite links. Xiao et al. [?] analyzed a Low Earth Orbit (LEO) satellite network capacity model to achieve optimization and robustness on network capacity. However, nodes in a single-layer LEO satellite network are prone to traffic congestion. Different from the above work, Zhang et al. [?] proposed a topology optimization model suitable for polar orbit satellite network to improve network operation efficiency. Li et al.[?] propose a novel Temporal Netgrid Model (TNM) to portray the time-varying topology of large-scale small satellite networks. All of the above work is based on the dynamic switching of the satellite network topology. It is difficult to ensure a stable topology. The method of this paper solves such a problem and can build a stable topology with uninterrupted link connection and low transmission delay under the premise of ensuring the optimal link condition.

In addition, the inter-satellite link allocation strategy for satellites has also received much attention. Juan et al.[?] proposed a comprehensive weighted for inter-satellite link assignment strategy based on link stability for the dynamic topology change of satellite networks and the limited inter-satellite link problem. However, this method places too much emphasis on minimizing link costs and ignoring the long link delay caused by link switching. Based on the analysis of permanent inter-satellite-links, Wang et al. [?] designed a hierarchical satellite network to solve the problem of continual handoff caused by the relative movements of satellites in different orbits. Different from it only considering the modeling perspective, our method proposes an algorithm to verify the feasibility of the strategy. Yan et al.[?] considered the constraint of the number of inter-layer links between IGSO and MEO and proposed a strategy for establishing inter-layer links centered on high orbits. However, they do not consider the link constraint in the MEO layer, and only considers the longest visible time of the link when building the chain between layers, it is hard to apply in practice. Our method fully considers the inter-layer and intra-layer link constraints to save satellite construction costs.

In this paper, we propose a topology optimization algorithm based on satellite link stability for IGSO/MEO two-layer satellite network topology. It aims to make full use of the low mobility, long-lasting and sufficient margin links, and build a fixed network topology with uninterrupted link connection and low transmission delay when the number of connected antennas is limited, effectively reduces topology reconstruction and routing overhead caused by inter-satellite link switching, simplifies network topology and improves network performance.

3 Research on DLSN Model

This paper researches the topology optimization of IGSO/MEO DLSN. The following analysis is carried out on the design of satellite network architecture, model establishment and optimization target, which is helpful for the research of satellite network topology optimization algorithm.

3.1 Design of Satellite Network Architecture

The satellite-terrestrial network architecture composed of the IGSO/MEO DLSN and the terrestrial core network is shown in Figure 1. The overall structure is divided into three parts, namely the IGSO satellite layer, the MEO satellite layer, and the ground station.

The IGSO satellite has the same orbital height as the GEO satellite, and the IGSO satellite has the same orbital period as the Earth's rotation. Meanwhile, the constellation with several IGSO satellites has better coverage than a single GEO satellite and can cover the polar regions and high latitudes that GEO cannot cover[**?**]. In addition, LEO satellites require extensive deployment to cover the entire surface of the Earth, resulting in complex systems and high costs, while a small number of MEO satellites can achieve global coverage to simplify network topology. Compared with single-layer satellites, the IGSO/MEO DLSN can take advantage of the various layers of satellite nodes to provide more flexible network management and control capabilities.

Considering that actual satellite networks are usually limited by power and other factors, both high-orbit satellites and low-orbit satellites can only be equipped with a limited number of inter-satellite links to save costs. Therefore, it is assumed that each IGSO satellite is configured with three inter-satellite links, two of which are used to establish links with two adjacent IGSO satellites and one for chaining with MEO satellites; it is assumed that each MEO is configured with two inter-satellite links, which can be used to build chains with MEO, IGSO, and ground gateways.

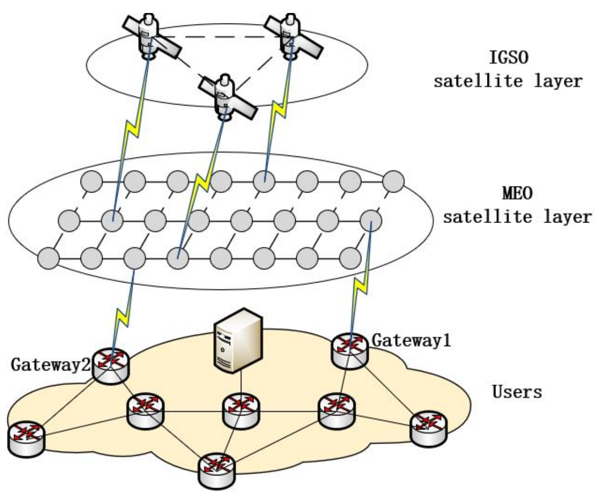


Figure 1: Satellite-terrestrial network architecture

3.2 Modeling Methodology for DLSN

Based on the time-varying characteristics of IGSO/MEO DLSN topology, a satellite network model is established to analyze the impact of topology time-varying on satellite network performance.

Different from terrestrial networks, satellite networks have time-varying characteristics regardless of nodes or topologies. However, the satellite network has the characteristics of predictability and periodicity, and the influence of node motion on the satellite time-varying topology network G in the continuous state is slow and insignificant. Therefore, based on the knowledge of graph theory, the time-varying satellite network topology in a continuous state is static within a period, and the model of defining the satellite network topology is:$G(V,A,W)$.

Where $V = \{v_1, v_2 \dots v_n\}$ represents the set of finite nodes in the satellite network; A represents a finite set of links, $A \subseteq V \times V$; $W = \{w_{ij}\}$ represents a weight matrix, and w_{ij} represents the stability weight between node v_i and v_j, which is defined as:

$$w_{ij} = \begin{cases} \log_2\left(\frac{T}{T_{ij}} \cdot \frac{C_{ij}}{C_{\min}} \cdot \frac{D_{ij}}{D_k}\right), & i = j \\ 0, & i \neq j \end{cases} \tag{1}$$

Where T is the period of the satellite topology network model,T_{ij} is the maximum visible time of satellite nodes v_i and v_j within a period, C_{ij} is the inter-satellite link capacity, and the minimum link capacity $C_m in$ is required to prevent network congestion; The satellite node has its own link weight of 0, that is, it is impossible to establish a link with itself; $k = \{1, 2\}$ represents the intra-layer or inter-layer links of the satellite, and different link distance thresholds D_k should be defined for links at different levels. D_{ij} is the weighted distance between satellite node v_i and v_j within one period T, which is defined as follows:

$$D_{ij} = \frac{T_s}{T} \cdot \sum_{m=1}^{n} D_m^{ij} \tag{2}$$

Where $s = \{t_1, t_2 \ldots t_n\}$ represent time slices for visibility between satellite nodes, T_s is the length of each time slice, and D_m^{ij} is the physical distance between node v_i and v_j within each time slice physical distance. Therefore, a weighted distance is assigned to each inter-satellite link as the basis for measuring link connection quality to evaluate the impact on link stability.

3.3 Target Optimization

According to the modeling and analysis of the IGSO/MEO DLSN, the topology design of satellite network can be summarized as a linear constrained optimization problem. There are M IGSO satellite nodes, N MEO satellite nodes, and L ground gateway access points. The optimization objective is to maximize link weight between satellites to ensure higher link stability. The optimization problem is as follows:

$$Max\ J = \left(\sum_{i=j=1}^{M} w_{ij}x_{ij} + \sum_{j=1}^{M}\sum_{k=1}^{N} w_{jk}y_{jk} + \sum_{k=l=1}^{N} w_{kl}z_{kl} + \sum_{l=1}^{N}\sum_{m=1}^{L} w_{lm}q_{lm}\right) \tag{3}$$

$$s.t. \qquad \sum_{k=l=1}^{N} z_{kl} \leq \mu \qquad k, l = 1, 2 \ldots N \tag{4}$$

$$\sum_{i=j=1}^{M} x_{ij} = \alpha \qquad i, j = 1, 2 \ldots M \tag{5}$$

$$\sum_{j=1}^{M}\sum_{k=1}^{N} y_{jk} = \beta \tag{6}$$

$$\sum_{l=1}^{N}\sum_{m=1}^{L} q_{lm} = \gamma \qquad m = 1, 2 \ldots L \tag{7}$$

$$x_{ij}, y_{jk}, z_{kl}, q_{lm} \geq 0 \tag{8}$$

In formula (3),x_{ij} refers to the connection of satellite links in IGSO layer, y_{jk} refers to the link connection between IGSO and the MEO layer, z_{kl} refers to the link connection in MEO layer, and q_{lm} refers to the link connection between MEO layer and ground gateway, taking the value of 0 or 1. Equations (4-7) indicate link number constraints, ensuring that the number of inter-satellite links in each layer does not exceed the specified number of satellite antennas. $2\alpha + \beta$ is the sum of IGSO satellite antennas, $\beta + 2\mu + \gamma$ is the sum of MEO satellite antennas, and γ is the number of ground gateways. Finally, equation (8) defines the value constraints on variables x_{ij}, y_{jk}, z_{kl} and q_{lm}.

4 Topology Optimization Algorithm

In addition to considering the number of connected antennas in the satellite network and the frequent movement of nodes, establishing a persistent and effective connection with the terrestrial network is also an important factor in determining the network topology. Therefore, the algorithm firstly establishes the stable topology between the IGSO layer and the layer with reference to the link weight, then fully considers the requirements of terrestrial network access, establishes the optimal link between the MEO layer and the ground gateway, and eventually based on breadth-first search method[**?**] to establish a global optimal satellite link stability topology generation algorithm (SLSA). The basic steps are as follows:

Algorithm 1 Satellite Link Stability Based Topology Optimization.

Inputs: The number of satellites in IGSO layer M; the number of satellites in MEO layer N; Inter-satellite link-time T_{ij}; Satellite operating cycle T; Stability weight w_{ij}; MEO node with preferential access to the ground gateway L and null matrix B.

Outputs: Satellite connection matrix J.

Interlayer Topology:
for $i = 1$ to M **do**
    For N MEO layer satellites
    while T_{ij}=T **do**
        Extract w_{ij} of the corresponding node and store the largest w_{ij} and node j on the stack S;
    end while
    Take the node information from S and set the matrix corresponding element to 1;
end for
MEO Layer Topology:
Record the MEO node that has established the inter-layer topology as $\{N_1, N_2 \dots N_M\}$;
for $k = 1$ to N **do**
    while T_{ij}=T **do**
        if $k \in \{N_1, N_2 \dots N_M\}$ **then**
            Set the matrix corresponding element to 1;
        else
            Extract w_{ij} and store the largest w_{ij} and corresponding node j on the stack S;
        end if
    end while
end for
Randomly take one out of $\{N_1, N_2 \dots N_M\}$ remaining nodes and name it $N_M^{'}$;
while J_m=$\{0, 0 \dots 0\}$ **do**
    Traverse the remaining nodes until $\{N_1, N_2 \dots N_M\}$ is empty;
    break;
end while
return J;

5 Simulation Experiments And Analysis

In this section, the classic IGSO/MEO constellation configuration is proposed to simulate the satellite network topology generated by SLSA-based method through satellite toolkit (STK), NS3[**?**] and other simulation tools, and to evaluate the performance of this method by comparing with the network topology generated by traditional methods.

5.1 Simulation Environment

In this paper, the standard Walker24/3/1 constellation is adopted. The IGSO satellite has the same trajectory of subsatellite points and the right longitude of ascending intersection is 120 degrees[**?**]. The simulation time is 1 day, which is the operation cycle of the Walker24/3/1 constellation, and the step size is 1 second. Table 1 shows the specific parameters of the IGSO/MEO constellation.

Table 1: Parameters of IGSO/MEO constellation

Constellation parameter	IGSO	MEO
Inclination($^\circ$)	55	55
Altitude(km)	35768	21500
Number of planes	3	3
Number of satellites per plane	1	8

In addition, we also set up a ground station, Beijing Station (116°E, 40°N), to measure the link performance of the satellite network and the ground network under high-speed mobile state.

We deployed the Walker24/3/1 constellation in STK. The visibility report between satellite nodes based on STK is used as the input of the SLSA method to generate a DLSN topology. We use the traditional Dijkstra algorithm previously stated to generate a satellite network with link stability as the target. The number of links is constrained by the constraints presented in Section 3, that is, each IGSO satellite is equipped with 3 antennas, and each MEO satellite is equipped with 2 antennas. In order to evaluate its performance, we also implemented the double-layer satellite and terrestrial gateway interconnection network based on the Dijkstra algorithm and SLSA algorithm in the NS3 simulation environment.

The traditional shortest path first routing protocol is adopted in the topology, and the intra-layer and inter-layer link capacity is set to 500 Mbps to avoid network congestion. The link delay in the IGSO layer is set to 15ms. The link delay τ_{ij} in the IGSO/MEO layer, MEO layer, and MEO-terrestrial gateway is defined as:

$$\tau_{ij} = w_{ij} \cdot \tilde{\tau} \tag{9}$$

Where $\tilde{\tau}$ is the link delay threshold, corresponding to the values of IGSO/MEO layer, MEO layer and MEO and ground gateway are 10ms, 5ms, 3ms respectively; stability weight w_{ij} is calculated by formula (1).

During the experiment, we set up to send packets, each 1Mb in size, at 4 Mb/s rate from the ground gateway node to all 27 nodes in the satellite network. We use the propagation delay of the packet from terrestrial gateway 1 via each IGSO or MEO as the evaluation parameter. In order to eliminate the test error, we repeat each experiment 10 times and calculate their average value as the average time delay of the topology.

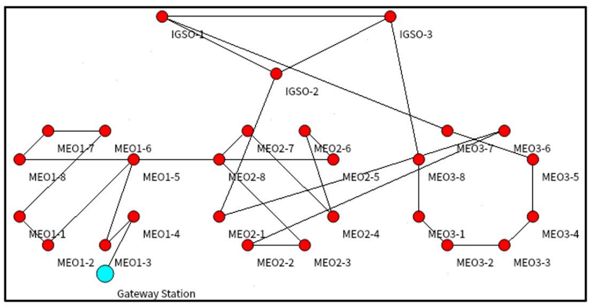
Table 2 shows the values of the main parameters in sections 3 and 4[**?**].

Table 2: Main parameter values of Sec.3 and 4

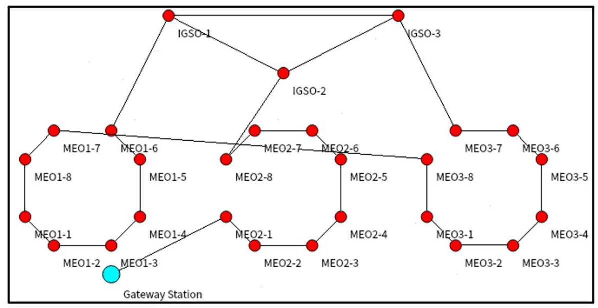
Parameter	Value	Parameter	Value
T(s)	86400	N	3
$C_{\min}$(Mbps)	500	L	1
D_1(km)	66000	α	3
D_2(km)	40000	β	3
T_s(s)	60	γ	1
M	24	μ	19

5.2 Results Analysis

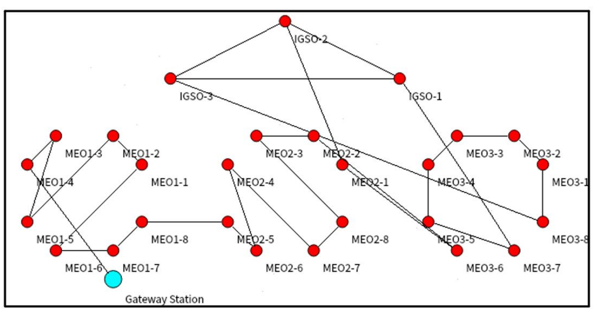
Figure 2 shows the DLSN topology based on the Dijkstra algorithm [**?**] and the SLSA algorithm based on different time slices under the NS3 simulation. The topology generated by the two methods can be stable with the high-speed movement of the satellite nodes in one cycle. At 0 o'clock, the topology generated by the SLSA algorithm in 2(a) refers to the stability weight matrix in the period, while the topology generated based on the Dijkstra algorithm in 2(b) only considers the shortest connection path between satellites at this moment. Therefore, the average delay between each node generated by the Dijkstra algorithm is lower in the initial state; at 12 o'clock, due to the periodic operation of the satellite, the distance between nodes in the topology generated by Dijkstra algorithm in 2(d) is far beyond the requirement of the shortest connection, leading to a rapid increase in the time delay between nodes, while the topology generated by SLSA algorithm in 2(c) can always maintain a relatively stable low transmission delay.



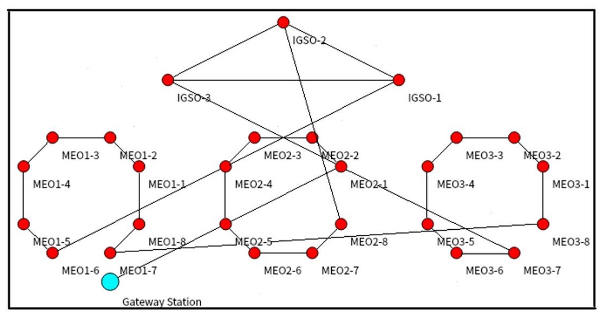
(a) SLSA-based Topology at 0 o'clock



(b) Dijkstra-based Topology at 0 o'clock



(c) SLSA-based Topology at 12 o'clock

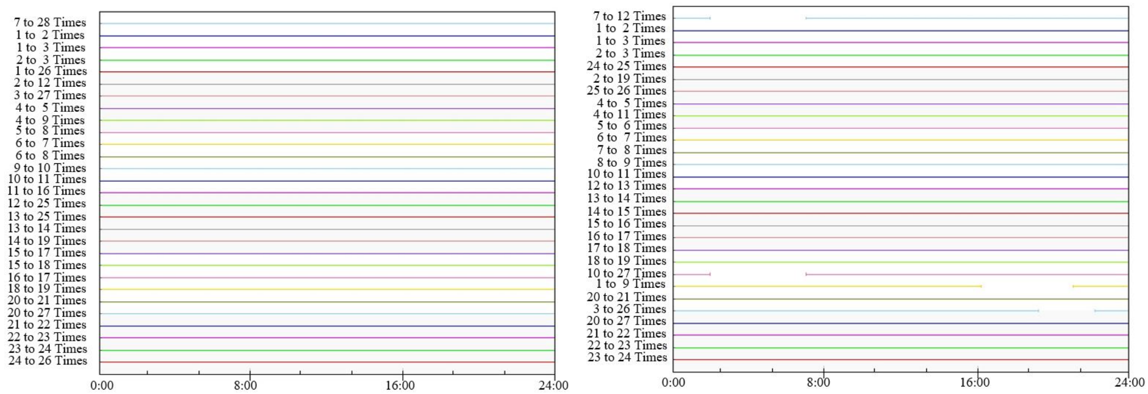


(d) Dijkstra-based Topology at 12 o'clock

Figure 2: Experiment topology

Figure 3 shows the visibility report of each inter-satellite link based on STK simulation, and increases the continuity of each inter-satellite link during a satellite operation period after constraints in section 3.3, node number = $\{1,2\ldots 28\}$. It can be seen that the topology generated based on the SLSA method can maintain link connectivity between any nodes in one cycle, while the topology generated by the traditional Dijkstra algorithm will have link interruption at 02:10-07:00 and 16:30-22:30 during the time period.

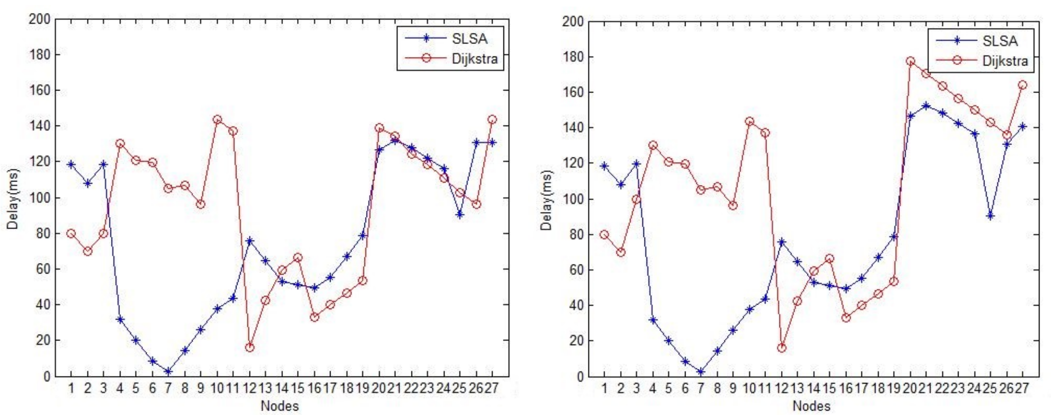
Figure 4(a) shows the average arrival delay of each node in different topologies under normal link conditions. Numbers 1 to 27 represent three IGSO satellites and three orbits of MEO satellite nodes in order. Compared with the topology generated based on the Dijkstra algorithm, the average arrival delay of all nodes receiving data packets is reduced by 20.47% in the SLSA-based topology, and the delay optimization is mainly concentrated in the nodes of the first track of the MEO layer. The other



(a) SLSA-based topological link connectivity (b) Dijkstra-based topological link connectivity

Figure 3: Comparison of numerical results and experimental results

two tracks show similar average delays. The average delay of the data packet arriving at the three IGSO nodes is that the Dijkstra algorithm performs better. The reason is that Dijkstra, as a greedy algorithm, only selects the locally optimal link and pays attention to the lower delay when selecting the IGSO node, so it cannot realize the link quality optimization of global topology. Therefore, we can conclude that under the premise of ensuring the longest link time and the limited connection antenna, the proposed SLSA method can effectively reduce the average arrival delay of packets and improve the link stability of DLSN compared with the satellite network topology generated by traditional Dijkstra algorithm.



(a) Average delay of each node in normal scenario (b) Average delay of each node when the link is interrupted between node 2 and node3

Figure 4: Link connectivity

Figure 4(b) shows the average arrival delay of each node in different topologies when the random link in the IGSO layer is interrupted. The link interruption between node 2 and node 3 is shown in the figure. The Dijkstra algorithm's average delay increased by 12.37%, and the SLSA's corresponding average delay increased by 5.57%. Compared with the topology generated based on the Dijkstra algorithm, the average arrival delay of all nodes receiving data packets is reduced by 25.28% on the SLSA-based topology. Although the average time delay of packets arriving at 3 IGSO nodes using the Dijkstra algorithm is lower, the average delay of packets reaching node 3 significantly increases compared with the normal link scenario, while the topology generated by SLSA method maintains a relatively stable average delay. At the same time, in the third orbit (No.20-27) of the MEO layer, the average arrival delay of the nodes on the topology using the Dijkstra algorithm deteriorates, completely exceeding the SLSA method. Therefore, in the case of the interruption of the high-rise satellite link, our method can prevent the network deterioration to a greater extent than the satellite network topology generated by the Dijkstra algorithm, so as to provide more stable services.

6 Conclusion

This paper proposes an IGSO/MEO DLSN topology optimization algorithm based on link stability, which aims to generate a DLSN topology with uninterrupted link connection and low transmission delay, and to overcome the influence of limited connection antenna on the connectivity between satellite nodes. The simulation results show that the proposed SLSA method is superior to the traditional topology generation algorithm. In future work, we will consider adding neural networks to satellite networks to optimize routing and other issues.

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Author Biography

Kun Li received his B.S. degree from Beijing Jiaotong University in June 2018. He is currently a Ph.D. candidate at the National Engineering Laboratory for Next Generation Internet Interconnection Devices, Beijing Jiaotong University, Beijing, China. His research interests includes next-generation networks and space networks.

Huachun Zhou received the B.S. degree from the People’s Police Officer University of China in 1986. He received the M.S. in telecommunication automation and Ph.D. degrees in telecommunications and information system from Beijing Jiaotong University in 1989 and 2008, respectively. Now, he is a professor in National Engineering Lab for Next Generation Internet Interconnection Devices at BJTU. He has authored more than 40 peer-reviewed papers and he is the holder of 17 patents. His main research interests are in the area of mobility management, mobile and secure computing, routing protocols, network management and satellite network.

Zhe Tu received his B.S. degree from Beijing Jiaotong University in June 2016. He is currently a Ph.D. candidate at the National Engineering Laboratory for Next Generation Internet Interconnection Devices, Beijing Jiaotong University, Beijing, China. His research interests includes next-generation networks and space networks.

Guanglei Li received his B.S. degree from Beijing Jiaotong University in June 2015. He is currently a Ph.D. candidate at the National Engineering Laboratory for Next Generation Internet Interconnection Devices, Beijing Jiaotong University, Beijing, China. His research interests includes next-generation networks and space networks.