A Routing Strategy for GEO/LEO Satellite Network Based on Dynamic Delay Prediction and Link Control

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Abstract. As an important part of modern communication, the satellite communication is attracting more and more attention. In recent years, the low earth orbit (LEO) satellite constellations are being developed vigorously. To achieve better performance and flexibility, many researchers have proposed to combine the LEO and geostationary earth orbit (GEO) satellites to construct a double-layer network. However, this double-layer structure brings significant challenges to the design of routing strategy. In this paper, we propose a routing strategy for GEO/LEO satellite network based on dynamic delay prediction and link control. In particular, we craft a link cost function that comprehensively considers the link load, queuing delay, processing delay and transmission delay. The cost function can provide more accurate estimation of the link delay compared with the existing methods roughly using hop counts. Based on it, the proposed double-layer strategy can not only optimize the end-to-end delay but also achieve better traffic balance. Simulations on STK and OPNET verify that the proposed approach can greatly improve the performance of packet loss rate, end-to-end delay and throughput.

Keywords: GEO/LEO double-layer satellite network · Routing strategy · Clustering mechanism · Layered transmission

1 Introduction

LEO satellite mobile communication systems are of great significance in national development and improving people's life. Due to the feature of low orbital altitude, the relative movement of LEO satellites on different planes is relatively fast, which might cause poor communication effect when the LEO satellites carry heavy traffic [1]. In addition, the distribution of users is usually uneven due to terrain, climate and economy, which can result in significant load imbalance between different satellites [2]. In this case, the satellite networks will be prone to link congestion if only single layer routing within LEO

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constellations is considered [3]. Moreover, the LEO single layer routing is usually with high latency and unstable robustness, which prompts more and more systems to adopt multi-layer satellite routing that involves medium earth orbit (MEO) or GEO satellites.

Compared with single-layer satellite networks, multi-layer satellite networks have many advantages, such as good invulnerability, high spectrum utilization, flexible networking and large capacity, which are more potential for the development of satellite networks in the future. However, the multi-layer satellite networks contain numerous nodes and links, which makes the network topology change more frequently and the routing design more challenging. In the literature of multi-layer satellite routing, most strategies adopt the idea of hierarchical grouping to reduce complexity. Among the representative studies, Akyildiz et al. [4] proposes the idea of layering and grouping concurrently for LEO/MEO/GEO three-layer satellite networks. According to the coverage of high-layer satellites, low-layer satellites are divided into several groups, and the high-layer satellites as group managers collect topological information within the group and recalculate routing table when a group switch occurs. This algorithm provides a good management strategy for multi-layer satellite networks. Nonetheless, it fails to take into account the link load and thus is unable to deal with traffic burst well.

In order to balance traffic effectively and improve network congestion response capability, many other strategies have been proposed for multi-layer satellite networks in recent years. For example, the authors in [5] adopt a double-layer satellite routing strategy based on hop number limit and cluster management. Two LEO satellites on the same orbital plane are designated as cluster headers to collect network link information, and then the information is collected to GEO satellites. A certain hop number threshold and queuing delay threshold are used to judge whether the GEO-assisted routing is needed. In [6], a method based on hop limit and link control is proposed, which is based on clustering and grouping of double-layer satellite management mode. LEO satellites are grouped according to the coverage relationship between the upper and lower layers, and the nearest GEO satellite is a group manager in the mode. The strategy reduces the number of inter-satellite links between layers and the complexity of connection relations, and improves the efficiency of network management. Besides, the link load factor is taken into consideration in this work.

Furthermore, in addition to the optimization of the double-layer satellite management strategy, many scholars have made some innovations in routing mode and link weight. In [7], a new double-layer satellite routing strategy calculation is proposed, which sets different routing patterns according to the different coverage relationship between the source address and destination address. This strategy takes the GEO satellites as cluster headers as the cluster header, and makes different processing patterns according to the different number of GEO satellites covering LEO satellites, so as to ensure that there is a manager for each LEO satellite throughout. Besides, the inter-cluster and intra-cluster routes are distinguished by whether the cluster headers of the source and destination LEO are the same. The delivery of the routing table is not period but triggered by the variation of link conditions, which is more efficient. In [8], the authors propose a new link weight calculation method for double-layer routing, which takes not only the propagation and queuing delays but also the residual bandwidth into consideration to improve the response speed to link congestion.

At present, most of the existing double-layer satellite routing algorithms use the number of hops as a crucial metric to determine routes. However, the propagation delay between satellites often changes greatly with their relative motion, and the queuing delay also changes with the alteration of traffic. Consequently, in double-layer routing, it is not reasonable enough to regard the hop counts as the equivalent of delay. In this context, this paper proposes a new double-layer routing strategy. We craft a novel cost function based on dynamic delay estimation and queue load. Using this function as a metric, we further propose a clustered link control method to optimize the routing efficiency and traffic balance.

The rest of the article is organized as follows. Section 2 briefly introduces the architecture of the double-layer satellite network. Section 3 introduces the routing strategy based on dynamic delay estimation and cluster management. Section 4 presents and analyzes the simulation results based on the OPNET simulation platform. Finally, Sect. 5 concludes this paper.

2 GEO/LEO Satellite Network Architecture

2.1 Double-Layer Satellite Network Model

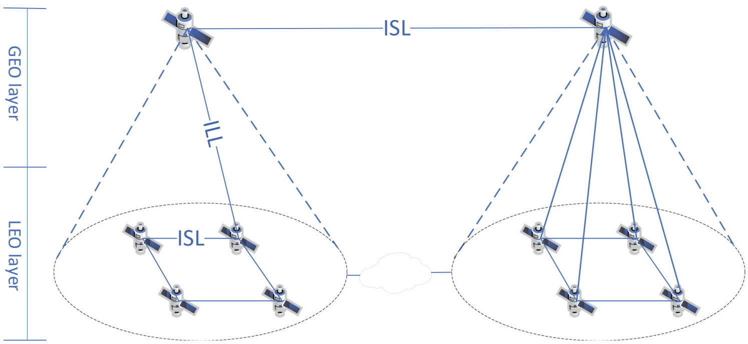

Fig. 1. GEO/LEO double layer satellite network architecture

Compared with single-layer network, multi-layer network can exploit the advantages of different layers, which are the wide coverage of the high-layer satellites and the low transmission delay of the low-layer ones. There are two kinds of links in double-layer satellite networks, namely inter-satellite link (ISL) and inter-layer link (ILL). We consider a Architecture for LEO/GEO satellite networks, and its network structure is shown in Fig. 1.

The LEO satellite constellation in this paper adopts the inclined orbit design, and 216 LEO satellites are built based on OPNET, as shown in Fig. 2. The LEO satellites are evenly distributed on 12 orbital planes, with 18 satellites on each orbital plane. The altitude of the orbit of LEO satellites is 1,150 km. Each satellite has 4 links, which are fixed inter-satellite links (ISL) and used to communicate with its adjacent satellites in four directions.

Considering the coverage characteristics of GEO satellites, this paper uses three GEO satellites to realize the coverage of all LEO satellites. This is because three GEO satellites can cover most of the Earth's surface except the polar region, they can meet the requirements of routing strategy. The altitude of the orbit of GEO satellites is 36,000 km. The longitudes of the three GEO satellites are −80°, 40° and 160° respectively. Regardless of the process of service interaction between satellites and users, all services are generated randomly by the LEO satellites.

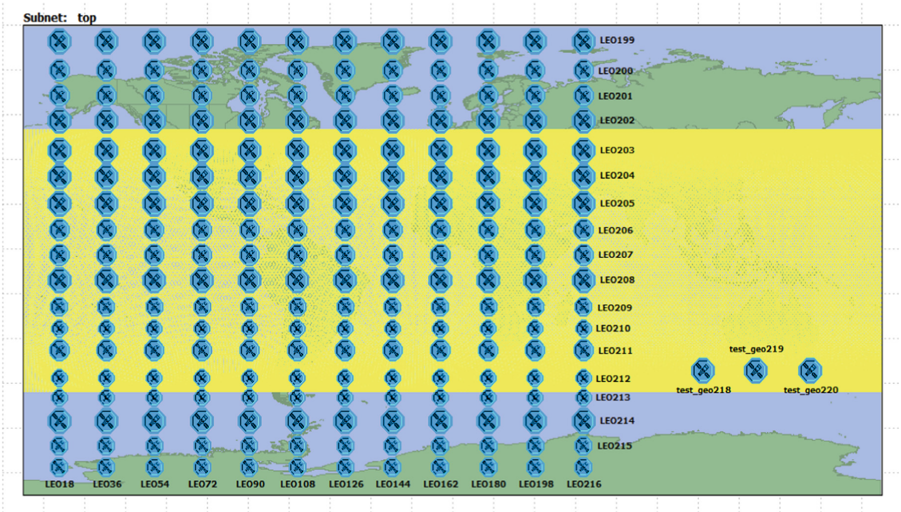

Fig. 2. Network layer model

2.2 Introduction of GEO and LEO Node Models and Process Models

OPNET is a software to simulate the behavior and performance of satellite networks. We use OPNET as a tool to design and verify our strategy in this work. The OPNET satellite node domain is mainly used to simulate the communication function of satellite nodes to realize the resume and data forwarding of the inter-satellite routing table. As shown in Fig. 3, each GEO node consists of the following modules: two sets of inter-satellite link models for communication with other GEO satellites, a set of inter-layer link modules for communication with the LEO satellites, a central processing module named net and a packet destruction module named sink.

Each LEO satellite node consists of the following models: four sets of inter-satellite link models for LEO layer communication, a set of inter-satellite link models for communication with the GEO satellites, a central processing model named net, a packet sending model named app_gen and a packet destroying model named sink, as shown in Fig. 4. The packet generating model is used to simulate traffic from the users while the destroying model is to simulate that the packets have been delivered to the users. Queue is a special component in OPNET, which can be used to buffer packets. In this work, each link is equipped with a queue. When the queue if full, the packet will be automatically discarded. Eight statistical lines are used to feedback the queue length and queue delay of the four inter-satellite links to the central processing model.

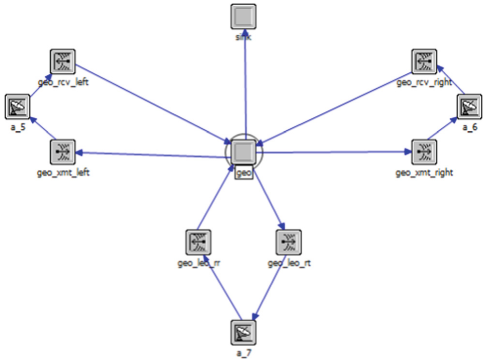

Fig. 3. GEO satellite node model

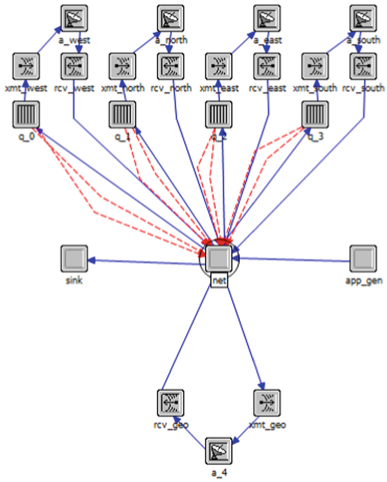

Fig. 4. LEO satellite node model

Process models are the lowest layer of three-layer modeling architecture in OPNET for realizing the jump of code and protocol and thus controlling the action of each node. The GEO process model is a key module to realize centralized routing strategy. In addition to the basic functions of receiving and forwarding data packets, the GEO process model also has several other functions, which include updating the global network topology information. Figure 5 shows the GEO satellite process model, and Table 1 shows the functions of the various states of the GEO process model.

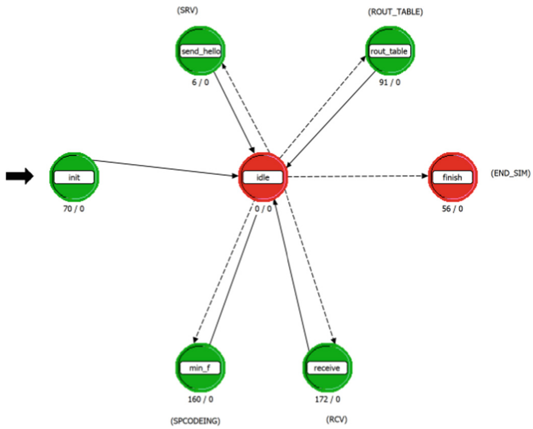

Fig. 5. GEO satellite process model

Table 1. Functions of states in the GEO satellite process model

state	function
init	Initialize GEO satellite node addresses, object id, and global network topology, etc.
rout_table	Periodically send routing tables to the LEO satellites that are registered within the cluster
min_f	Set the communication frequency of all transceivers of the GEO nodes
receive	Receive packets that join and exit the group and link information packets from LEO satellites, and update the coverage table of LEO satellites in the group and the global network topology
idle	Wait for the arrival of the interrupt and determine the status of the next hop
time	Periodically update the propagation delay between LEO satellites
finish	Collect statistics, such as the number of covered LEO satellites and the number of received packets within and between clusters

The main functions of the LEO process model are to update the GEO satellite currently accessed, record the information of adjacent satellites through hello packets, upload the information to the GEO satellite, and update the local routing information with the routing tables received from the GEO manager. Figure 6 shows the process model of the central processing module of the LEO satellite node models, and Table 2 shows the functions of the various states of the LEO process model.

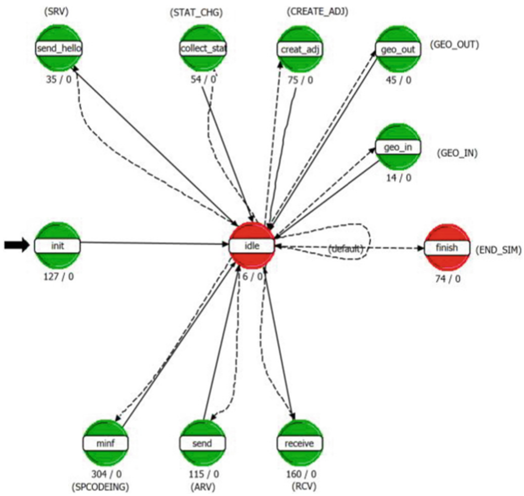

Fig. 6. LEO satellite process model

Table 2. Functions of states in LEO satellite process model

state	function
init	Initialize satellite node addresses, object id and the number of orbital planes and other parameters
send_hello	Sends hello packets to obtain information about the neighboring nodes
creat_adj	Send the link information of this node to the GEO manager
minf	Set the communication frequency of all transceivers of the LEO satellite nodes
send	Forward the data packets generated by the app_gen module according to the routing table
receive	Receive data packets from other satellites, hello packets, and routing tables from the GEO manager
geo_out	Update the GEO manager number and send packages to exit the group of the old GEO manager
geo_in	Send packages to join the group of the new GEO manager
collect_stat	Collect queue delay and queue occupancy length
finish	Calculate throughput, packet loss rate, and average end-to-end delay

3 Double-Layer Satellite Routing Strategy Based on Cluster Management

In order to reduce the cost of signal packets and collect the global network topology information more quickly, this paper adopts a strategy of hierarchical cluster to manage the double-layer satellites. GEO satellites serve as cluster headers to dynamically collect the link information of LEO satellites and update the global network topology.

3.1 Cluster Management Strategy

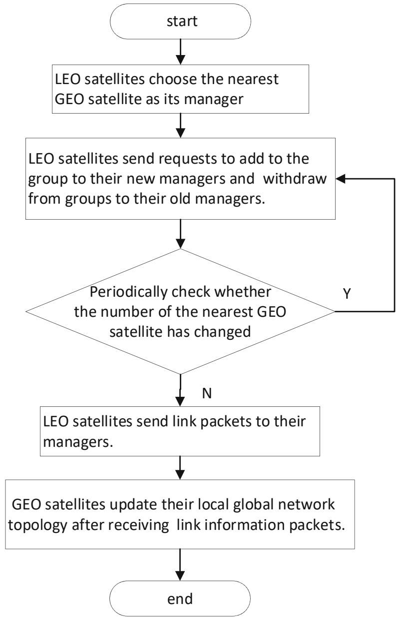

Fig. 7. Cluster management strategy of the double-layer satellite network

In practice, each GEO satellite cannot establish inter-satellite links with all the LEO satellites. Therefore, in this work, the LEO satellites are divided into three groups according to the GEO satellite that they are accessing. Each LEO satellite is only linked to its nearest GEO satellite and all the LEO satellites linked to the same GEO satellite form a group. Figure 7 is the specific flow chart of the clustering management strategy in this paper. More details of the cluster management strategy are as below:

- LEO satellites periodically check whether it is necessary to make handover between the GEO satellites through the "shortest distance" criterion. If necessary, the LEO satellite need to send packets to inform the old GEO manager of exiting and the new one of joining.
- GEO satellites will update the local registration table of LEO satellites after receiving packages of exiting or joining the group from LEO satellites.

- After confirming the unique manager number, LEO satellites send link information packets to the corresponding GEO manager.
- GEO satellites update the local network topology table of LEO layer and deliver routing tables to the LEO satellites after receiving link information packets from the LEO satellites and forwarding link information packets to their neighboring GEO satellites. The link information packet contains information of queuing delay, link cost between the satellite and its neighbors, and the addresses of the satellite and its neighbors.

3.2 Link Cost Design

Delay is an important metric for routing design, which usually consists of the propagation delay related to inter-satellite distance and queuing delay related to the traffic load. However, the existing works either consider the minimization of delay but fail to balance the traffic [5], or only consider part of the factors that infect the total delay [8]. Therefore, in this work, we propose a comprehensive link cost function that takes queuing delay, processing delay, propagation delay and queue load into consideration. This method can not only keep the end-to-end delay relatively low but also balance the network load and improve the response speed to local congestion. The proposed cost function is determined by queue occupancy ratio and delay, which is given by

$$W_0 = \alpha \cdot \frac{Q(i,j)}{Q_{max}} + \beta \cdot \frac{D_p(i,j) + D_q(i,j) + D_d(i,j)}{D_{min}} \tag{1}$$

Here, $Q(i, j)$ is the queue occupation length of the link between the LEO satellite i and j, and Q_{max} is the total length of the queue. D_{min} denotes the minimal total delay, which is the sum of the propagation delay and queuing delay, of all the LEO satellite links. $D_p(i, j)$ means the propagation delay between the LEO satellite nodes i and j link. $D_q(i, j)$ denotes the queuing delay of the link between the LEO satellite nodes i and j, $D_d(i, j)$ means the processing delay of the link between the LEO satellite nodes i and j, which refers to the time from receiving the packet to sending the packet.

In link cost function (1), α and β represent the importance of delay and queue load in the link cost evaluation model. In the routing strategy presented in this paper, the delay and the queue load have almost the same importance, but in order to improve the response speed to the queue load, α and β are set to 0.6, 0.4 relatively.

3.3 Design of the Double-Layer Satellite Routing Strategy

The double-layer satellite routing strategy in this paper is designed based on Dijkstra algorithm, which solves the problem of the shortest path of single source on non-negatively weighted directed graph. The weight of Dijkstra algorithm adopts the link cost defined by (1). Combing the cluster management described in Sect. 3.1 and the link cost function proposed in Sect. 3.2, we design a GEO/LEO double-layer satellite routing strategy as shown in Fig. 8.

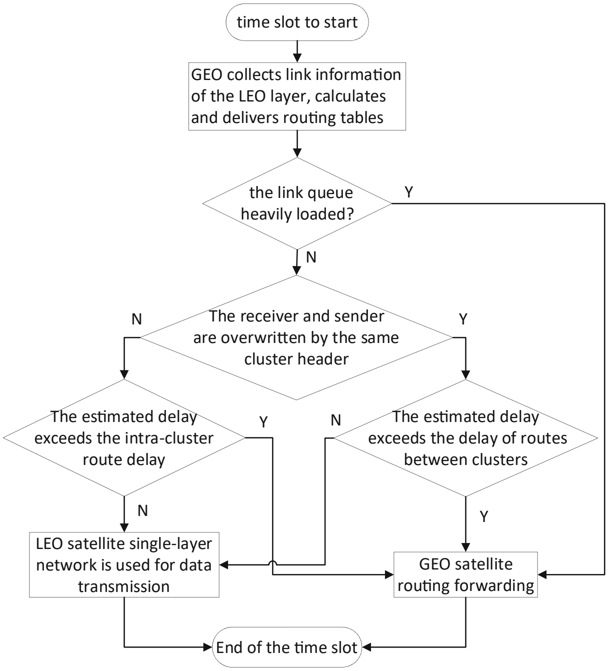

Fig. 8. Double-layer routing strategy

To leverage the low-latency advantage of the LEO satellites, the packets are preferentially routed in the LEO layer. And they are diverted to the GEO satellites only when:

Case 1: The current path is congested. When the queue load of the LEO satellites reaches a certain load threshold, the packets arriving after will be routed via the GEO satellites to reduce packet loss.

Case 2: The source and the destination nodes are covered by the same GEO manager, and the delay of "intra-cluster routing" is lower than the predicted delay of the LEO layer.

Case 3: The source and the destination nodes are covered by different GEO managers, but the delay of "inter-cluster routing" is lower than the predicted delay of the LEO layer.

Among them, intra-cluster routing refers to the forwarding of data packets via only one GEO satellite, while inter-cluster routing refers to the forwarding of data packets via two GEO satellites. The case 2 and 3 usually occur when the LEO constellation is bearing massive amount of traffic.

4 Verification of Simulation Results

4.1 Simulation Environment Setting

In order to evaluate the communication performance of the double-layer satellite network under the actual high-speed motion condition, this paper build a simulation environment of double-layer satellite network based on OPNET and STK. The orbit files generated by STK can be used to approximate real trajectory of satellites. By exporting the orbit files into OPNET, the double-layer satellite constellation scene can be rapidly built. The link parameters of the double-layer satellite network are shown in Table 3. The size of data packets is set to a constant value of 128b, and the size of the other signal packets is specified as 0.25b.

Table 3. Link parameters

Link type	sending rate/(Mbit $\cdot$ s^{-1})	queue length/kb
LEO inter-satellite link	1.5	12.5
GEO inter-satellite link	64	125
The link between the layers	64	12.5

We compare the performance of our strategy with the one based on hop limit proposed by [5] in several aspects, including packet loss rate, throughput and delay. For convenience, in the following, we will refer to the hop-limit method as the traditional strategy. In order to simulate network congestion at different levels, the rate of package generation for 18 satellites were randomly assigned in the LEO network layer. The packet transmission rate is constant. The packet sending time is 5 s, and the total simulation time is 30 s.

4.2 Average End-to-End Delay

Figure 9 shows the end-to-end delay comparison of the two routing strategies with different data traffic. Among them, the hop threshold of the traditional strategy is set to 10 according to the scale of LEO satellites. For our algorithm when the queue occupancy ratio is greater than 0.75, it is perceived as severe congestion. Apparently, with the increase of packet generation rate, the average delay of both strategies increases. However, the proposed method can reduce the delay by 10–50 ms compared with the traditional one. This is because the link load is added into the link cost calculation. Therefore, the GEO satellites can bypass those LEO satellites with high link load. The link cost function is helpful to balance the link load of the LEO layer and reduce the queuing delay and eventually reduces the total end-to-end delay.

In addition, when the link load of LEO layer is high, the routing strategy proposed in this paper can compare the total delay of LEO satellite transmission with the total delay of GEO transmission for data packets, then choose a route mode with lower delay, which also reduces the end-to-end delay of packet transmission to a certain extent.

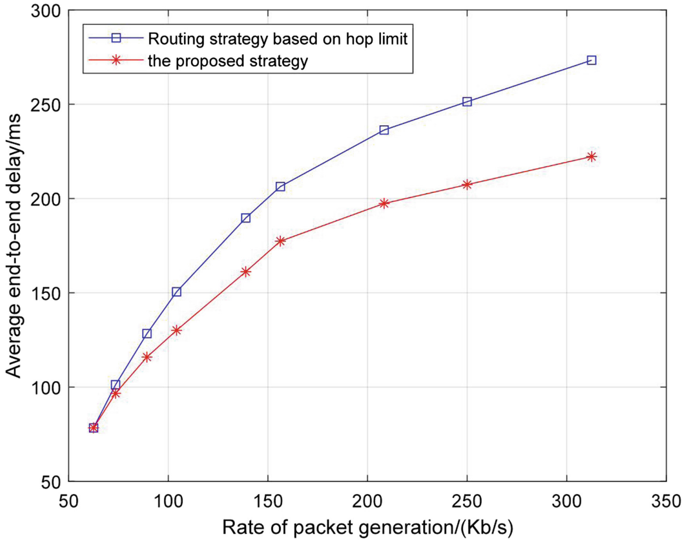

Fig. 9. The average end-to-end latency varies with different traffic

4.3 Throughput

Figure 10 shows the throughput comparison of the two routing strategies with different traffic. When the rate of packet generation is less than 600 Kb/s, the two strategies have close performance in throughput. This is because both strategies take into account the shunting of data packets of the double-layer satellite network. When the rate of packet generation is more than 600 Kb/s, the advantages of the proposed routing strategy are more obvious. At this time, the LEO satellites have achieve their maximal capacities to deal with packet routing and a large number of packets need to be transmitted via GEO satellites. Therefore, the different criteria of the strategies on whether to transmit packets via GEO satellites bring different results. The traditional method uses the number of hops to determine data shunting. However, when the traffic is heavy and unevenly distributed, the number of hops cannot reveal the delay accurately since the queuing delays of different nodes are various but is not taken into consideration. This limits the throughput of the traditional method when the rate of packet generation is relatively high.

However, instead of quantifying the delay by hop number, the routing strategy proposed in this paper uses the historical LEO transmission delay to dynamically estimate the current transmission delay. Moreover, the link load limit is added into the routing strategy. When the link load exceeds the set threshold, the packets are sent directly through GEO satellites, which further reduces the loss of packets and improves the throughput. When the rate of packet generation is about 1100Kb/s, the proposed strategy can improve the throughput of the system by about 16.18% compared with the traditional method.

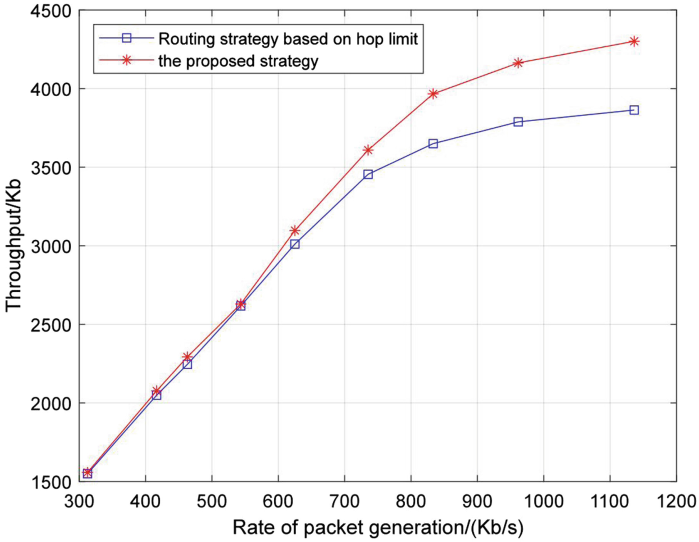

Fig. 10. Throughput varies with with different traffic

4.4 Packet Loss Rate

Figure 11 shows the packet loss rate comparison of the two routing strategies with different traffic. Apparently, the proposed routing strategy can effectively reduce the packet loss rate in the case of congestion. When the rate of packet generation is about 800 Kb/s, it is about 7.5% lower than the traditional routing strategy based on hop limit. There are two reasons for this. First, the routing strategy based on hop limit does not set the threshold of link load. When the link load of LEO satellites exceeds the queue length and does not meet the conditions of GEO transmission, this strategy will cause the loss of data packets to some extent. Secondly, the link cost function of routing strategy based on hop limit only considers the hop number. The hop number can not fully indicate the load of the link, so the response to local network congestion is relatively slow, resulting in a poor ability to balance traffic. However, the link cost function proposed in this paper takes the link load into account. When calculating the routing table, it can avoid the path with higher link load, so it can balance the traffic of LEO layer better and reduce packet loss.

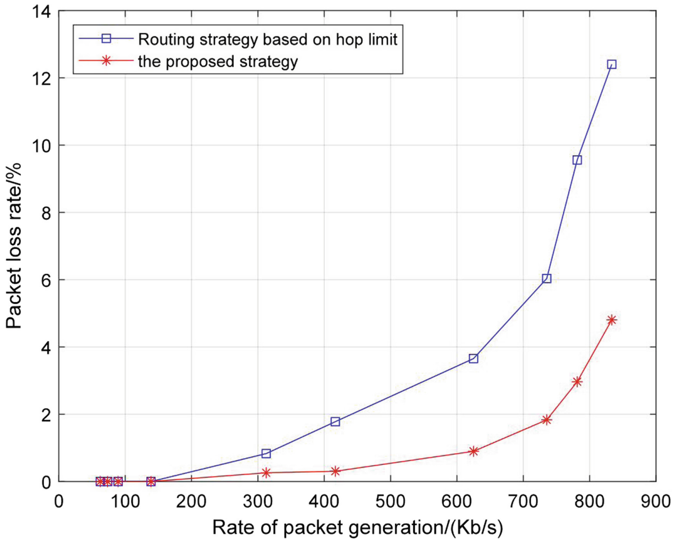

Fig. 11. The packet loss rate varies with different traffic

5 Conclusion

Considering the problems of the current multi-layer satellite routing algorithms, such as high end-to-end delay, high packet loss rate, poor adaptive capability of network congestion and high system overhead, this paper proposes a double-layer satellite routing strategy based on dynamic delay prediction and link control, which can more effectively distribute data packets in the case of local satellite network congestion and reduce the flow pressure in the LEO satellite layer. In addition, in order to improve the self-adaptability of the double-layer satellite routing strategy to network congestion, a new link cost function is proposed, which comprehensively considers the link load and delay in different aspects. Compared with the traditional routing strategy based on hop limit, the proposed approach can reduce the end-to-end delay by 10–50 ms with different volume of traffic, efficiently reduce the packet loss rate by around 7.5% and increase the system throughput by about 16.18% when the traffic is relatively heavy.

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