DESIGN AND IMPLEMENTATION OF GNSS NETWORK SIMULATION SYSTEM BASED ON HLA

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ABSTRACT

Aiming at the problems of complex management and control and difficult operation and maintenance in the process of navigation constellation networking, an HLA-based simulation system of GNSS network is designed based on the link planning of Ka inter-satellite link of navigation constellation and the deployment of ground facilities. The system can generate, send and receive data frame flow, complete the simulation of inter-satellite network business behaviour, and improve the ability of navigation constellation network management and resource planning. The multi-constraint over minimum delay routing algorithm is pro-posed, respectively, compared the multi-constraint over minimum delay routing algorithm, contact graph routing algorithm, the simulation shows that the performance of the multi-constraint over minimum delay routing algorithm is better, can effectively schedule the routes for data uploading. It provides the theoretical basis and application basis for the generation of reasonable inter-satellite link routing scheme in GNSS network.

KEYWORDS

HLA. GNSS network simulation system, OPNET, node satellites, the multi-constraint over minimum delay routing algorithm

1. INTRODUCTION

The global navigation satellite system (GNSS) provides multi-functional ser-vices such as navigation, positioning and timing for global users in the information age, which plays an irreplaceable role in national economic development and national defence construction. The GNSS can operate through inter-satellite links between satellites and ground stations around the world, which constructed an integrated space-ground and dynamics wireless network with precision measuring and data transmission. It can achieve autonomous navigation and efficient transmission of instructions, information and data, reduce the load on the main payload processing station and the dependence on the ground station, improve the autonomy and robustness of the whole navigation constellation network and the real time and accuracy of transmission [1]. China's navigation system official-ly opened up the basic navigation service in December 2018, and plans to achieve a complete system networking in April 2020.

The application of inter-satellite link technology in GNSS constellation can effectively solve the problem of measurement, operation and control of overseas satellites. At the same time, it also brings many technical problems. Among them, the problem of routing planning becomes the focus of research. Many scholars also have a lot of research results for China's navigation system routing planning. Reference [2-3] analyzed and studied the link optimization problem from the aspects of taking the cross-linked distance as the constraint, taking the cross-linked communication delay as the optimization object, and improving the length and number of time

DOI : 10.5121/ijit.2020.3101

slices within the polling cycle; reference [4] proposes a more comprehensive communication cost evaluation scheme based on TDMA time division multiple access system, and draws the conclusion that the communication performance of inter-satellite link hybrid topology is better than that of ring topology; reference [5] comprehensively considered the link rate, node load, transmission distance and other factors of the navigation constellation to obtain the optimal route; in reference [6], a route optimization method for fast data re-turn from overseas satellite of navigation system is proposed. However, with the rapid increase of the number of satellites in orbit and the shortage of available ground resources, how to use the limited ground resources for data injection routing planning is a problem worthy of study. As for China's navigation system, uplink and downlink routes are different during a limited time because of the time division multiplexing working mode. At present, there are a lot of research results that can be referred to in the design of simulation system of space information network using HLA technology [7-9], but there is little research on the simulation system of GNSS constellation. In this paper, a navigation constellation network simulation system is established based on HLA, and a multi-constraint over minimum delay routing algorithm is proposed. On the basis of establishing the inter-satellite link timeslot table, considering the factors of link rate and node load, the route for data uploading can be effectively planned. The experimental results show that this method can effectively solve the problem of fast data injection for telecontrol of overseas satellites.

2. Analysis of Research

At present, most of the satellite platforms in our country are based on the management of telemetry and telecontrol to manage the platform and resources scheduling. The satellite is connected to the ground network through the ground gateway station. In addition to the navigation constellation, most satellites do not have inter-satellite links. Restricted by the geographical location and number of ground stations, telemetry and telecontrol resources are very valuable. In addition, with the rapid development of China's aerospace industry, the number of satellites in orbit is also increasing year by year. In this case, the conflict be-tween satellite telemetry and telecontrol management requirements and resource constraints will become increasingly fierce. China's navigation system has many kinds of loads and relatively perfect functions. As a more advanced global navigation system, its network application and demand will continue to expand, and new requirements and functions will continue to emerge. Due to China's special national conditions, it is not possible to build a wide range of stations around the world at present. For example, it is of high practical significance and application value to make efficient use of the ground resources in China, take into account the expansion function requirements of navigation, realize the goal of "one satellite visible, the whole network visible, one satellite controllable, and the whole network controllable" of the system, and solve the problem of rapid annotation of telecontrol data of overseas satellites.

In GNSS system, a time-varying link is established between satellites by time division multiple access with a single frequency point, and two-way measurement and data transmission are realized by time division multiplexing half du-plex on a single link. We set the time slot unit of the time division system as 1.5s, and adopt the half duplex working mode. Then we can complete the link building of two satellites every three seconds. We define the time required for the link building of all satellites in the network as a polling cycle. In order to complete the inter-satellite distribution and return of information such as pay-load-management data uploading, telecontrol and telemetry, the following steps are required.

2.1 Designing satellite-station node table

The satellite-station node table is used to indicate which satellite should be selected by the ground station for data transfer. The satellite can be used as the "link" between the ground station and other temporary unable to directly establish communication links.

Because the ground stations for telemetry, track and command (TT&C) and payload management in China are mostly distributed in China, they cannot be built globally. Therefore, it is necessary to solve the problem of information transmission between the visible satellite on the ground and the invisible satellite abroad. We call the visible satellite of the ground station as the domestic satellite and the invisible satellite of the ground station as the overseas satellite. The tele-control data should be injected into the overseas satellite by the ground station, and a "transit station" is necessary for the overseas satellite to send or reply the data to the ground station This transit station, that is, the satellite visible at the same time between the ground and the target overseas satellite, is defined as a node satellite. The node satellite can establish a continuous link with the ground station in a limited period of time through the S-band / Ka band to complete data transmission and return. The number of node satellites is related to the quality of the expand service of GNSS and the occupancy rate of ground resources [10].

2.2 Creating timeslot table

The timeslot table can be used to plan which satellite should be connected with at what time. In this way, the ground station can upload or receive data purposefully and in a planned way, ensuring reliable and controllable transmission of measurement and control data in the backbone network. After the timeslot table is scheduled, the network topology of the entire satellite is determined.

Due to the high real-time requirement of telecontrol information transmission, one of the main problems to be solved in establishing inter-satellite link is to complete the telecontrol data injection of invisible satellites and the downlink transmission of telemetry data through the transfer of node satellites. Therefore, in the process of designing inter-satellite links, the number of linking hops be-tween visible and invisible satellites should be considered as little as possible.

Since the Walker Delta configuration is used for MEO satellites in the GNSS constellation, link planning can be simplified. Since every satellite must have a permanent intersatellite link, the permanent intersatellite link can be used as the basis of link planning when establishing the link time slot table, on which non-continuous visible link can be used to improve the performance of optimized link planning [11].

2.3 Scheduling routing table

The routing table specifies the data transfer path from the source node to the destination node. After the topology of the whole network is determined, the routing table can be planned by referring to the routing design method based on topology snapshot, so that the inter-satellite distribution and return transmission of information such as telecontrol and telemetry, and the uploading of payload data can be completed. When the ground station uploads remote control information to a satellite through the node satellite, the data transmission path is up-link. When a satellite sends telemetry information to the ground, the data trans-mission path is downlink.

Both uplink and downlink data transmission require node satellites forwarding. Therefore, inter-satellite routing table is actually used to specify the data transmission path between node satellite and overseas satellite. Through the routing table, the ground station can send the remote data to the overseas satellites, and the overseas satellites can send the remote data back to the ground station.

3. DESIGN OF GNSS CONSTELLATION NETWORK SIMULATION SYSTEM

3.1 General Research Ideas

GNSS constellation network adopts time division multiplexing (TDM) half-duplex system, and the operation of the whole network has its own characteristics. Taking all elements of the GNSS system into comprehensive consideration, we will coordinate the ground resources, GNSS constellation and various extended users, and analyse the visibility relations among them. Satellite toolkit (STK) can be used to establish the prototype network of GNSS constellation, analyse the inter-satellite/satellite-station visibility, and generate the inter-satellite/satellite-station visibility matrix. A timeslot table can be established according to the requirements of GNSS autonomous navigation PDOP value less than 1.5 and the minimum number of inter-satellite links for single-satellite not less than 9. The creation of timeslot table determines the topology of the whole network in each time slot. As the kernel of network simulation, OPNET can build network simulation scenes by reading the information of STK scenes. Through the timeslot table, OPNET can determine the network topology of the whole network, and can achieve network performance simulation by different route planning.

3.2 Simulation and Interaction Based on HLA

High Level Architecture (HLA) is a general technical framework developed by the U.S. department of national defence for modelling and simulation in the defence field. HLA is an advanced technology that supports distributed simulation. HLA system includes run-time Infrastructure (RTI) and simulation applications on RTI [12]. The HLA-based network simulation system designed in this paper mainly includes parameter configuration members, network simulation members and display members. The parameter configuration member is mainly responsible for the establishment of the scene and the input of various parameters. Network simulation member is the core of the whole system, which simulates the operation of GNSS network and completes the simulation function of the network. At the same time, network simulation members need to complete data interaction with other members. Network simulation members using OPNET network simulation software. Display members display network simulation results in near real-time, including the whole network topology, performance parameters of each node, end-to-end delay of different services, packet loss rate, etc.

Each federated member can interact with external programs through the advanced architecture HLA/RTI bus[13].Through the bridge function of STK/Connect, the RTI-STK middleware realizes the seamless connection between RTI and STK.OPNET has HLA interface, can be used as a federated member of network simulation, and has good compatibility with HLA/RTI. This interface is responsible for managing federated member transactions, time advance management, and data mapping capabilities. The map file of HLA performs the mapping function of data, and the fed file defines the information of interaction class and object class, including node parameters and network simulation index parameters. The running process of the whole simulation control framework is shown in fig.1.

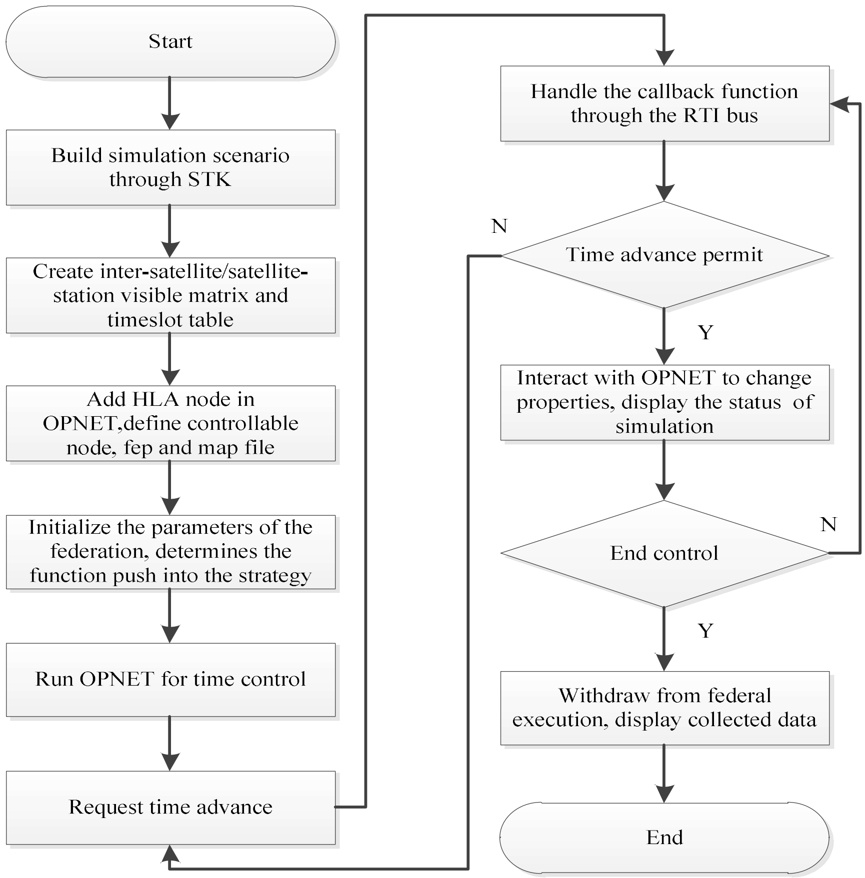

Figure 1. Simulation system running process

4 Routing Scheme Design

4.1 Routing Problem Description

Because the inter-satellite link of the navigation constellation adopts the time division multiplexing (TDM) half-duplex system, its data transmission path is in the general direction. As the direction table of the data transmission path, the route table must be determined [14]. The routing table specifies the data transfer path from the source node to the destination node. In order to simplify the research problem, this paper only considers the uplink data transmission and the downlink data transmission is equivalent. The routing flow for uplink data injection is shown in fig 2.

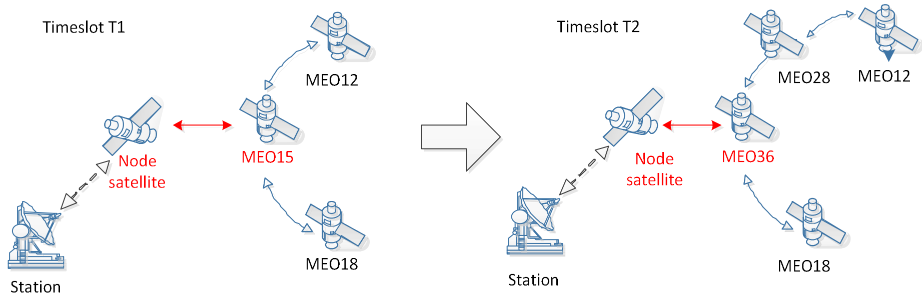

Figure 2. The routing flow for uplink data injection

If the data transmission between the ground station and the node satellite is denoted as zero hop, it can be seen from figure 1 that in T1 slot, node satellite in red build links with MEO15, when the ground station sends data frames to MEO15, it can realize one-hop transmission through the node satellite, while when sending data frames to meo-12 or meo-18, it needs to be forwarded twice through the non-node satellite meo-15.In T2 time slot, node satellite switch link to MEO36, when the data frame reaches meo-12, it needs three-hop transmission, and the data frame cannot reach meo-15.Obviously, the smaller the hops, the smaller the data delay. In addition, the purpose of this paper is to find the optimized routing table. At any time, according to the optimized routing table, the delay used by the ground station to transmit data to the alien is minimized. In the practical engineering application, in addition to the transmission delay, the selection of routing should also consider satellite load, link rate, whether the satellite has other tasks and other factors.

4.2 CGR Routing Algorithm

The Contact Graph Routing (CGR) relies on the connected plan to generate the connected graph of the network, and sends the connected plan information to all satellites before the network starts forwarding data [15][16].Over time, CGR updates the connectivity graph with connectivity plan information, such as adding future connectivity plans or removing expired connectivity plans. In each satellite, CGR uses an algorithm to check the available connectivity, calculates the current forwarding neighbor satellite based on the connectivity graph, and selects the next-hop satellite of the data according to the optimization requirements of the system. In the next hop, CGR performs the same process to calculate the forwarding neighbor satellite. In the simulation process, valid fields can be added to the satellite to judge the satellite state of the satellite. The valid field will be changed after the satellite receives the failure information or full information, indicating that the corresponding satellite is not available, which can be used as a judgment condition in the routing calculation to reduce the complexity of the algorithm. Full fields change when the rest of the local satellite's storage queue changes and can be used to determine whether or not a full message is sent.

4.3 The Multi-constraint over minimum delay routing algorithm

In the execution of satellite measurement, operation and control tasks, the selection of routing should take into account link rate, satellite load, whether the satellite has other tasks, priority of data transmission and other factors [17][18].The problem of route planning based on the above factors can be described by the following mathematical model.

$$\text{Model} = \{S, G, R, L, P\} \quad (1)$$

$$S = \{S_{node}, S_{n\_node}, S_n, G\} \quad (2)$$

Where, S is the satellite set, and there are N satellites in total, among which S_{node} is the node satellite subset, S_{n_node} is the non-node satellite subset, and Sn is the subset of unavailable satellites. G is the collection of ground stations; R is the link capacity; L is the satellite load, that is, the amount of data currently stored at the node; P is the transmission priority, and different task types have different priorities.

According to the above mathematical model, the route planning has the following constraints.

1. Minimum delay condition: select the fastest path from the boundary to the node satellite to ensure the minimum delay from the boundary to the boundary.

2.High rate priority: choose the path with high link rate first.

3.Low load priority: choose the path with low load on the node first.

Important task priority: when a node in a path takes on an important task, change paths. The node load is proportional to the cost of data transmission, while the higher the link rate, the shorter the time consumed by data transmission, so the link capacity is inversely proportional to the cost of data transmission. For the business with different task priorities, when the same transmission path cost is adopted, the higher the priority, the higher the current path, the lower the transmission cost. Based on the above factors, the definition of routing cost Q is given as follows.

$$Q = \frac{L}{L_{\max}} \cdot \frac{R}{R_{\max}} \cdot \frac{\alpha}{P} \quad (3)$$

Where, L is the load of the node, and L_{max} is the maximum load of all nodes; R is the transmission rate, and R_{max} is the maximum information transmission rate between all satellites currently communicating. P is the priority, the higher the priority, the greater the value of P; α is a constant.

The mathematical model for routing optimization is as follows.

$$D_0 = \max\left(T_{end} - T_{start}\right) \quad (4)$$

$$D_1 = average\left(\frac{\sum_{n=1}^{N} D_n}{N}\right) \quad (5)$$

Where, D_0 is the maximum transmission delay of routing table; T is the time slot; T end and T start are the end and start slots of data transfer, and D_1 is the average transfer delay of the overall routing table. Under normal circumstances, the satellite-station node table and timeslot table are annotated once every 7 days, and these tables switch constantly within the set time period (dozens of minutes to an hour), and their data volume is considerable. In order to reduce the storage burden of the satellite, avoid the data packet in the satellite long time storage. In order to simplify the technical state of the satellite, if the satellite does not build a link within a certain time slot, the telecontrol data will be temporarily stored. Otherwise, the satellite will not store the telemetry remote control data, that is, the forward satellite will receive the telemetry remote control data sent by other satellites and immediately send it to the next satellite within the next time slot. In this case, the shortest path is the shortest time delay.

The classical shortest path routing algorithm is distance vector algorithm. The main information generated by this algorithm is the shortest distance to a network and the next hop address. The principle of path updating is to find the shortest distance of the destination network. Based on this idea, a minimum delay over multi-constrained routing algorithm is proposed. The algorithm is based on timeslot table to generate inter-satellite routing table. As input, timeslot table and node satellite table, each time slot corresponds to a routing table. The setting of the maximum forwarding hops determines the maximum hops of the satellite reaching the node, and data packets exceeding the maximum hops will be discarded. Since the number of satellites in the GNSS network is relatively small, the shortest route can be found by the traversal method. The idea of the algorithm is to divide all satellites into node and non-node satellite sets. The route cost is weighted with link rate, satellite load and task priority as constraint conditions. When calculating the route of the target satellite, the route should be calculated according to the time slot in the node-satellite timetable first. If the route can be found, the route information of multiple paths satisfying the requirements shall be recorded in turn. If the route is not calculated in the node satellite timetable, then the route is calculated from the non-node satellite set with the node satellite as the destination address, and the shortest path of the node satellite to all satellites and all satellites to node satellites in the time slice is calculated by traversing the time slot table, and the path information is recorded. When the number of hops for route addressing exceeds the set maximum, the satellite is marked unreachable. Given the complexity and suddenness of space missions, multiple paths with the same cost are recorded simultaneously. The path information format is shown in Table 1.

Table 1 Path information format

Destination	Node satellite path	Next hop path	Next hop path...
	(M1,T1)	(N1,T2)	……
Target satellite	……	……	……
	(M_i,T_i)	(N_j,T_j)	……

It can be seen from Table 1 that the path information of each address aiming at the target satellite is a two-dimensional data, and the length of the path information is variable. Where, Mi represents any node satellite, N_i represents any non-node satellite, and T_i or T_j represents any time slot (i <j). In each time slice, the specific algorithm flow is shown in Figure 3.

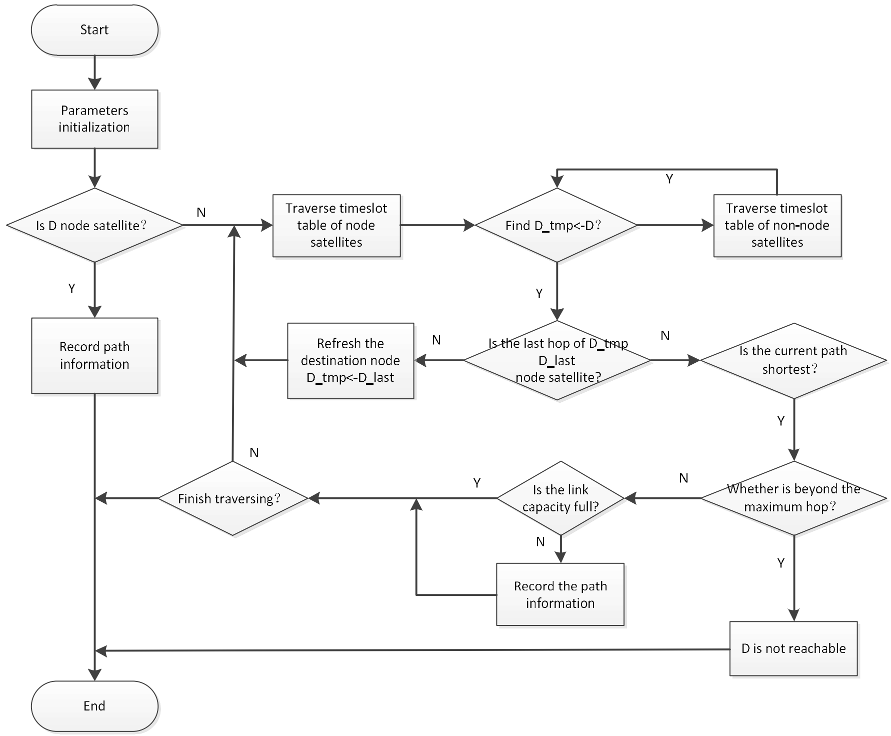

Figure 3. Flowchart of multi-constraint over minimum delay routing algorithm

5 Simulation Analysis

5.1 Establishment of Simulation Scenarios

Combined with the characteristics of GNSS constellation, this paper establishes the network scene of "3GEO+3IGSO+24MEO". In addition, 6 LEO satellites are added to the scenario, and it is assumed that all LEO satellites can establish inter-satellite links with GNSS constellation. The performance of contact graph routing algorithm and multi-constraint over minimum delay routing algorithm are analyzed by upload data into LEO and other satellites. In the simulation experiment, the MEO satellite was numbered and named according to the different orbital planes. The satellite Numbers from 1 to 24 correspond to MEO11 to MEO24 respectively. Four domestic stations and one overseas station were set up, located in Fuyuan, Beijing, Lintong, Hetian and Chile, respectively. The minimum time span was set as 60s, and every 3600s was a polling cycle, that is, another timeslot table was replaced. In the simulation experiment, two kinds of inter-satellite link transmission rates were set, respectively 20.48 kbps and 40.96 kbps. The single-frame size of satellite and ground data frames was 2048bit. The inter-satellite data frame size was 2048bit. Due to the adoption of time division multiple access system, it takes 1.5s for sending and receiving. In order to prevent the occurrence of sending and receiving conflicts and other emergencies, a link protection band of 250ms is set, that is, when the sending slot to the satellite is coming, it will wait for 250ms before sending. The simulation time is set to 8 hours. Specific simulation parameter settings are shown in Table 2.

Table 2 Simulation parameter setting table

Parameter type	Parameter value	Parameter type	Parameter value
Constellation	GNSS+LEO satellite	Length of time slice	60s
Simulation time	8h	Length of timeslot	3s
Step size	60s	timeslot cycle	3600s

5.2 Simulation Results and Analysis

For a routing algorithm, it is important that the scheduled path has a small delay. In the performance comparison experiment of this paper, a poisson data stream containing 5000 packets with an expected time interval of 3 is generated, and the parameters of each node in each simulation are the same. After the simulation began, five ground stations sent data to five different target satellites. Ten non-node satellites were randomly selected every 30 minutes to set high load and different task priorities, and then the average delay statistics for the uplinked data transmission of the whole network were conducted to obtain the comparison graph of figure 4, where red represents the contact graph routing algorithm and blue represents the multi-constraint over minimum delay routing algorithm. The x-coordinate represents the simulation time and the y-coordinate represents the end-to-end transmission delay.

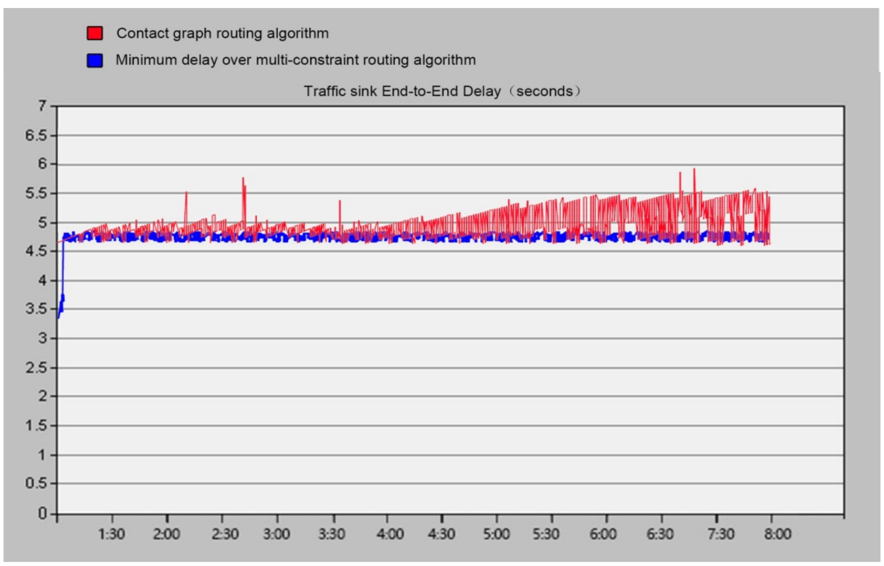

Figure 4. Statistical graph of the average delay of data upload over the whole network

As can be seen from the figure, the minimum average delay of the two routing algorithms is 4.8s, indicating that the minimum average delay of the two algorithms converges to two hops. Among them, the time delay of the multi-constraint routing algorithm based on time slot is relatively stable, while the average time delay of the contact-graph routing algorithm has a small jitter with the switching of satellite state every 30 minutes. With the passage of time, the average delay of the contact-graph routing algorithm increases gradually, but the maximum transmission delay still converges to two hops. It can be seen that the multi-constraint routing algorithm based on minimum time slot has a good adaptability to the change of network topology in resource-limited spatial network.

To compare the packet rate of the two algorithms, the packet rate statistics are conducted every 30 minutes, as shown in figure 5(MDMR is short for multi-constraint over minimum delay routing algorithm).As can be seen from the figure, in the network of 36 satellites, the packet acquisition rate of the two routing algorithms is above 85%.Among them, the multi-constraint over minimum delay routing algorithm has a packet collection rate of 100% at most time points, lowest at 8:00, and a packet collection rate of 95%. However, the graph of packet rate broken line of contact graph routing algorithm fluctuates greatly, and there are a few packets lost in most cases. It can be seen that the multi-constraint over minimum delay routing algorithm has obvious advantages over the contact-graph routing algorithm.

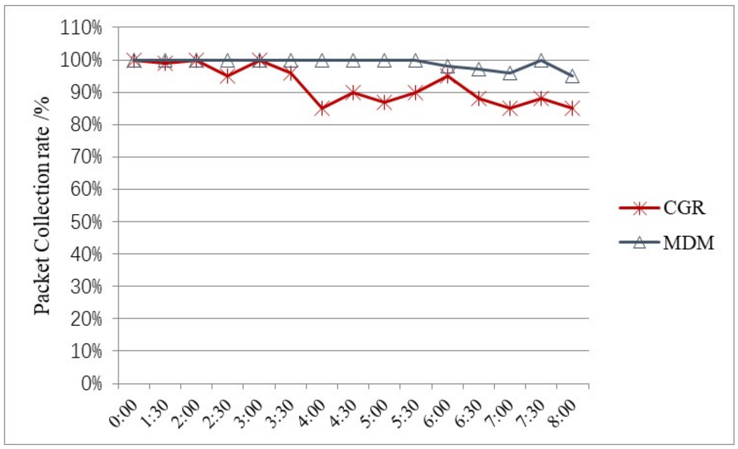

Figure 5. Packet collection rate of uplink data upload over the whole network

1.6 CONCLUSION

Based on the current status and development trend of GNSS system, this paper puts forward the method to be followed in the routing planning that how to upload data of overseas satellite effectively. A navigation constellation network simulation system based on HLA is established, and a multi-constraint over minimum delay routing algorithm is proposed. The simulation results show that the designed navigation constellation network simulation system has better comprehensive performance and efficiency. On the basis of establishing the link-slot table, the multi-constraint over minimum delay routing algorithm can be used to plan the transmission route of uplink data injection. How to improve the existing algorithm for downlink routing planning is the next step to be studied.

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